My Story at Hewlett-Packard and Before Hewlett-Packard Laboratories

by Christopher R. Clare

Foreword

Mr. HP Inventor--Chris Clare

Once John Young was promoted to Microwave Division Manager in 1962, he adjusted his management team to his liking, Paul Ely, Engineering, John Doyle, Manufacturing, and myself as Marketing Manager. Young turned out to become a brilliant industry manager, and of course, was promoted to HP's CEO in 1978. I imagine part of the reason for that came from his Stanford MBA.

Soon after his team was working together, he pronounced that we were going to do a "division audit." While that term meant something to an MBA, we soon found out he meant to take a deep analytical look at our division operations. That turned out to mean ALL our division operations; product strategy, installing triad management, recruiting, technologies, customer measurement trends, and many more. The Hewlett-Packard experience had already shown, in the 25 years since its birth, that hiring brand new engineers directly from college, was a winning idea for HP's growth.

It was not so obvious at the time, because many industrial operations, like Aerospace, needed personnel with deep technical experience and mature judgment to mesh those HUGE teams of equipment and sub-systems suppliers for a moon rocket for example. The NASA global management structure was an exceptionally complex organizing and scheduling and technical venture, requiring immediate contributions, no time for training new people. But at HP, Dave and Bill had found out that with our rapid revenue growth at 15% per year, our technical ranks needed a concerted effort to build our lab and production engineering ranks, and often to spin out brand new divisions.

College recruiting became a year-round process. In early years there were dozens of travelling teams who visited the colleges for interviews with graduating engineers. And some MBAs. The teams did more than just recruit graduates, they worked year-round with key professors and deans to improve the school's curricula. In the Spring, at the campus interviews, they selected those who were offered trips to the HP factories. As the century progressed, HP probably visited over a hundred campuses, offering thousands of plant interviews. And out of that came our expansion brainpower.

I still remember it distinctly, in one of Young's audit meetings, we were looking to provide guidance for our travelling recruiters. What was the typical personal profile we should define, given that there were many attributes that were valuable to our company. Did we expect that engineers with a 4.0 average were preferred over an engineer with a 3.5, but who was president of his student IEEE group? Did we want highly theoretical capabilities, compared to a young person who fixed their own car, or built their own ham radio or high fi amplifier, or had experience making things, and knew which end of a soldering iron to pick up?

Well, of course, we ended up needing them all, brilliant engineers for tough technology projects. But we also were on the lookout for the person who was editor of the student newsletter, who might make a great marketing engineer. Then it was Paul Ely who defined the archetype of the team member we needed in greatest proportion. He called that profile an "Inventor." Understand that in HP engineering teams, there are virtually no technicians, the engineer builds their own hands-on circuits, assembles their own mechanical prototypes. Of course, there was a large tooling and model shop to support the research lab. Over the years, Bill and Dave were "tinkerers" and I don't mean that in a negative sense. Bill especially felt that the thought process that went along with building and assembling circuits worked well together, and reinforced creativity.

So, it took me about one page to figure out that Chris is the Inventor personality. There on the first page of his memoir you see the picture of the Norden bombsight of WWII, disassembled down to the nuts and bolts, all laid out in an "obsessive" and organized array. You know immediately that Chris built things—and sometimes takes apart things, to figure how they work. He showed this in his youth, and in great success in his HP career.

But the next pages that recount his youthful zest for science, with a father who obviously indulged his curiosity and creativity, you will just smile as you read through all his "experiments," from a Jacobs ladder of arcing and sparking noise that interfered with neighbors to a motorized cart, built with a Ford Model A transmission. It was also telling that after a first year at the University of California at Santa Barbara, which was one of our HP prized theoretical engineering campuses, that he found his real calling at Cal Poly in San Luis Obispo. While visiting a friend, he discovered that campus which was REALLY "hands-on" engineering. We factory types who were out doing the interviews knew that Cal Poly engineers knew how to build actual things.

It was probably random chance that his first work project at HP was the scientific desktop 9100, a blockbuster product which was one of the first personal computers. It's transcendental and logarithmic computational power was profound. And he stayed in the HP Labs product team which fairly quickly was able to exploit integrated circuits to build the 9100 functions into a shirt pocket size wizard HP 35. Looking back from today, I would suggest that Chris won the project assignment lottery, with those two jobs right out of college.

But then semiconductor technology was in ferment. The industry was booming with visionary companies—Fairchild and Motorola and Intel and a hundred others— creating not just integrated circuits, but all the merchant suppliers to silicon processing; wafer growers, slicers and dicers, diffusion furnaces, and surface chemical processing and wire bonding apparatus and testers. In that chaos, Dave and Bill and probably Barney made the decision that HP must build our own semiconductor processing labs, to provide unique functionality to HP products. With his HP background already strong, Chris was a natural for appointment to the automatic control and test strategies. And his description of the computer based lab functionality, collection of measurement data for process control, and those successes gave me a truly enjoyable and incisive picture of the HP contributions to the science and applications of crystal technology.

I had forgotten about subjects like algorithmic state machines which revolutionized some digital design, and which Chris documented. His writings and some predictive statements which he dredged up were remarkably prophetic. I love stories like Chris's, it was a time of 20th Century "high tech" that I often describe by noting that "We thought we were pretty hot stuff." And I can say that now, in spite of watching what the 2017 "high tech is doing for us now. Enjoy this story.

--John Minck

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My Early Years

I grew up in Santa Barbara, California in the years following WWII. I was always curious about how things worked and often took things apart to see what made them tick. This earned me the early nickname of Tinker. My dad and I began taking day trips to the surplus stores in San Fernando Valley where I found an endless supply of leftover military stuff, some mechanical and some electronic. I would take apart electronic stuff and carefully sort and store the components for later use. On one trip, I purchased a Norden M9 Bombsight, the same kind that was used to drop Little Boy on Hiroshima in 1945. I was fascinated by how this mechanical device could compute the exact drop point. Of course, I had to take it apart to see how it worked. Many hours later had over 1000 parts spread out on the floor. More amazing to me now is that I put it all back together again.

Norden M9 Bombsight that I took apart when I was about 12 years old.

Soon I found that I could make things as well. My father designed and built custom homes so he had all the tools of that trade and took the time to show be how to use them. He always had a shop at home. I became used to walking around houses under construction and learned about all the trades. My dad also had an early interest in motorcycles and sports cars in England where he grew up. He purchased an MGB in 1950 and soon I was joining him on rallies helping to navigate and keep track of time. This sparked my interest in cars.

Soon, I was attempting to build my own vehicles around any lawnmower engine I could get my hands on. My dad helped in the beginning, then I was on my own. By the time I was a teenager, I had built a variety of scooters with welded tubing frames. My first car project finally ended into a contraption that had Ackermann steering geometry with front suspension (old valve springs), rear tires from my dad’s cement mixer, steering wheel (surplus aircraft), 3-speed transmission (Ford Model A), rear disc brake (handmade), and a steel frame (old garage door hardware).

The entire project evolved over several years with countless trial and error experiments leading to something that worked. I have to admit that I spent more time thinking up new ideas during high school classes than listening to the instructor. I also had an early Go-kart racer built by a local welder that I raced with a group at Santa Barbara airport. You could do that kind of thing in those days. It had a 2-cycle engine from a military drone aircraft that I tuned and ported myself for more power. That is another story.

My home built Go-kart with Ford Model A transmission.

I did OK in High School but my favorite class was drafting that I took every semester and summer until the instructor was making up a class just for me. I learned how to precisely draw and document mechanical things both using pencils and ink.

Hallicrafters 505 TV, 1949

My second interest was electronics. It was the big thing after WWII. My dad was an early adopter of television. We had one of the first consumer TV's in 1949. It must have been a Hallicrafters model 505. When the milkman first noticed the tall antenna on our roof that was required to pick up the signals from Hollywood, he asked to come to see the new marvel. I remember it had a 7-inch round screen in black and white of course. Not long after that, he purchased a large console radio that recorded on metal wire (magnetic tape was not affordable yet). It is another story how I managed to recover one of those recordings made when I was only six years old of my two sisters and I talking to my dad.

He and I started to read Popular Electronics. It became evident that you needed instruments in order to "see" electronic signals and soon I was building Heath Kit test equipment. I built a Voltmeter first. I could measure voltages and resistors with it. Next, I built a capacitance meter. Now I could discover more about all the surplus parts I had been gathering. I built an audio signal generator and then a simple analog oscilloscope. One of my surplus bargains was a power supply. I built a desk with my dad and pretty soon my bedroom was beginning to look like an electronics lab.

I read an article about tuned port speaker cabinets. I measured some old speakers I had collected and built wooden tuned port enclosures for them checking everything out using my equipment. I learned something new with each one I built. One of our neighbors up the street was an amateur radio operator and hobbyist. He had a real lab with black bench tops and old radio equipment. He was like my local Mr. Wizard. After the launch of the Russian satellite Sputnik I in 1957, he invited my dad and I over to hear a recording he had made of the beeping signal as it passed overhead. Very creepy at the time. He showed me his Foucault pendulum project that he was building for the local science museum. I marveled at how he used magnetic fields to pull on the wire cable to keep the pendulum moving.

A few friends and I were always experimenting and trying out crazy ideas. Once I attached a large spool with half a mile of nylon string wound on it to an old washing machine motor. We launched a large box kit tied to the string and let it out to see how high the kite would fly. The idea was once the kite was flying high, we could use the motor to keep pulling the kite in. We lost the kite and the string. Another time, I took a small wooden boat with a DC electric motor drive for the propeller and tied twenty or thirty batteries together to make it go really fast in the neighbor’s pool. We burned up the motor and batteries caught on fire when the insulation melted.

I built a scooter using an old starter motor and a car battery. I used the starter switch to turn it on with my foot. Everything we tied to the starter to drive the wheel broke. Too much torque. I welded two bicycle frames together to make a tandem, however, I linked the handlebars together so that both steered the bike. That was a scary ride.

I found and a large neon sign transformer at one of the housed my dad was re-building. My dad and I built a Jacobs ladder by attaching aluminum rods the output and enclosed it in a box for safety. Very impressive flame would travel up the rods. I made a Layden Jar capacitor with a glass jar and tin foil and connected it across the ladder. Now it was really noisy with blue glow coming from the glass jar. I later learned I was interfering with every radio and TV for miles.

I had a small Bangsite cannon that would ignite a small amount of acetylene gas produced by dropping some calcium carbide into water making a loud bang. A friend and I figured we would make it better. We put a four-foot long electrical conduit over the barrel and I charged the chamber with acetylene and oxygen from my dad’s acetylene torch. Well, let me tell you that was much more than we expected. Flames shot two feet out of the pipe and we could hear the bang echo off the mountains behind Santa Barbara. We quickly hid the cannon and not long afterward the local sheriff came knocking on the door checking out reports of a large gun being fired. What gun?

There are more stories about re-building a rolled Austin Healy to drive when I reached that age. And teaching myself how paint cars. But eventually I realized I had to decide if I wanted to go to college. After some hasty reorganization of my classes I discovered I could be ready to apply, and chose to try UCSB since it was close and I would live at home. They had a new engineering curriculum. I had not decided if I wanted mechanical or electrical engineering however, there was no choice for freshman year. I took chemistry, statics, dynamics, calculus, English, and history. It did not appear electronics was going to be included anytime soon.

Meanwhile, I visited my cousin who was going to Cal Poly State College in San Luis Obispo and was excited to see real electronic labs and so I decided to transfer the next year with a major in electronics. The first year I had to take all the freshman electronics classes and labs. I really liked the learn-by-doing approach. I stayed on during the summer for an intense catch up of all the sophomore electronics classes and labs so that at the beginning of the next year I was a Junior. Technology was in transition. While many of my classes focused on tube design, transistors were covered as well and by the Senior year I was doing lab experiments with simple integrated logic circuits.

During my first year at Cal Poly, my roommate and I designed a small device that suspended a metal sphere in a magnetic field. He had it published in Popular Electronics. I designed and built several projects on my own while there, including a transistor stereo audio amplifier that compensated for speaker impedance. Surprisingly, my senior project came out of left field. It was a high powered ultrasonic cleaner that was driven a large silicon controlled rectifier in a resonant circuit controlled by a unijunction transistor. I build all the transducer/drivers. I liked to try out new things. Several companies interviewed me on campus including HP. Then HP flew me to Palo Alto for more interviews. I talked to people in several different divisions. I liked HP the best. Their test equipment impressed me when I used it in my lab classes and I was a faithful reader of HP Journal where I was amazed at how HP engineers solved measurement problems. I accepted their offer, found an apartment in Sunnyvale, and reported to work early in the summer of 1966.

HP Labs – HP 9100A

My first day at HP, personnel told me I would be working for HP Labs, Electronic Research Laboratory, ERL, at 1501 Page Mill Road. I never talked to them and had no idea what was to come. It turns out that I would be working on the HP 9100A desktop calculator although no one knew what to call it at that time. They could not tell me about it when I interviewed since it was a confidential project. I started work designing electronics for a keyboard. That may sound mundane in this day and age, but at that time, you could not buy such a thing particularly with the special features HP wanted.

Beside a numeric keypad section, the keys had all sorts of mathematical functions on them. Keep in mind I had never heard of a scientific calculator like this and could not imagine what it would be like. Operations were performed in sequence to complete the desired computation. All my engineering calculations had been done on a slide rule. HP was concerned that while pressing keys you might forget were you were so they wanted each to light up and remain lit until you pressed the next one. Clarence Studley, the ME on the project, had the mechanical switch part built. There wasn’t much else to see since it had not been designed yet.

I met Tom Osborn, who seemed to have most of the design in his head. He had built a full scientific, four-function calculator at home with a rough wooden case that we affectionately called the “green machine” since it was painted green. He showed how numbers could be entered and functions performed using reverse polish notation. That was new to me. His machine had a small CRT display that showed three floating point numbers in a vertical “Stack.” Small green seven segment numbers against black. It was almost comical to seeing him enter numbers by pressing little wooden squares glued to the top of little push buttons, but it worked like magic. I had no idea how he did it.

Eventually I met Dave Cochran who was buried somewhere in the Library at Stanford studying the math behind computing transcendental functions. Other outstanding people joined the team as time went on. I learned about the legend of Barney Oliver and the recent founding of HP Labs to focus on new product categories. I could not imagine a more exciting place to be. Mr. Wizard all over again but this time I was going to find out how everything worked.

Everyone encouraged me to take advantage of the HP Honors Coop program and continue studies at Stanford. I began my Master’s program in September and for the next two years I drove to Stanford for classes, back to HP for work, and studied nights and weekends while helping the HP 9100A become real. I opted out of continuing for a PhD in spite of encouragement from others at HP Labs where more than two thirds of the staff had PhDs. Inventing things was just more fun.

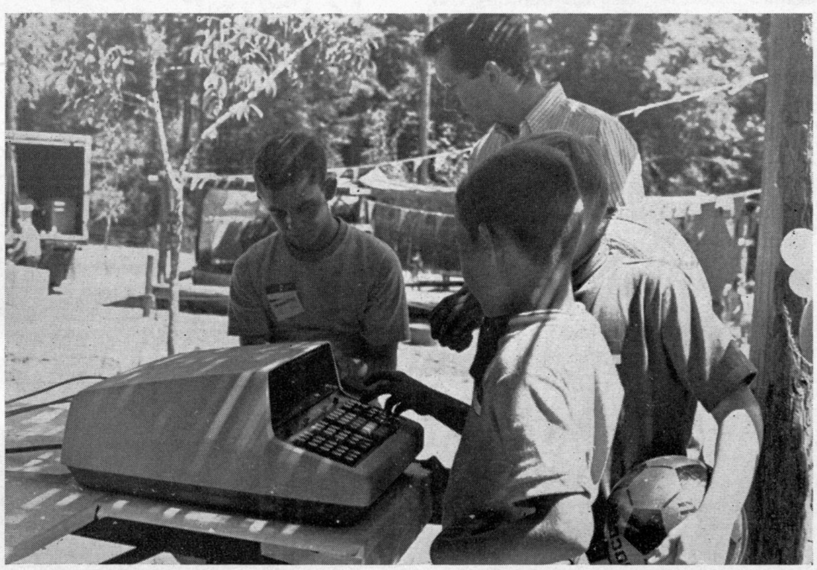
After solving the keyboard design with little neon lights, I moved on to performing worst case design on all the other electronic parts of the machine. I learned the complete architecture. Keep in mind there were no Intel, no microprocessors, no solid-state memories. This entire machine was built using discrete components. All the logic gates were made from discrete diode-resistor logic. There was no software, just data stored in read only memories and some data stored in a tiny 2208-bit magnetic core memory. There were just 40 flip-flops having four transistors each.

The work was done by just two state machines that each pointed to a specific wide word of data in a read only memory, ROM. This big one had 32 thousand bits, 512 words of 64 bits each, eventually stored in a novel 16-layer printed circuit board. The smaller logic control state machine used a wire rope ROM where data was stored by the pattern of threading a wire through small magnetic cores consisting of 64 words of 29 bits each.

The smaller state machine generated all the timing and executed sequences based upon data read from the larger ROM. The printed circuit ROM was a risk. I took a long time to develop the new technology to build it. All the development of the algorithms for the machine was performed on a breadboard where the large ROM was “brute force” implemented in hardwired diode-resistor array. Change a step meant adding and/or removing diodes. We had a crazy tech who did this holding the component in one hand, the soldering iron in the other, with solder threaded through a Teflon tube that he held in his mouth.

Dave Cochran did a masterful job tuning all the algorithms. People were amazed at the computational power and the speed as soon as we had the breadboard running, however, it became quite apparent that writing sequences of keystrokes down on paper to remember how to perform a particular or repetitive computation was very tedious and saving these sequences become far more important than lighting up each key as it was pushed. After some investigation, the team discovered a magnetic material made by 3M that we cut into business card sized pieces and designed a reader that would accept the card in a slot, then read it as it spits it back out. This functional storage addition transformed what was conceived as a scientific calculator into a true scientific computer with applications far beyond those originally anticipated.

The HP 9100A, that was transferred to Loveland, Colorado in parallel with the development in HP Labs, exceeded all expectations. Bill Hewlett had one built into his desk. Loveland created a new division to focus on this type of product that became an entirely new business category for HP. Some of the story behind the HP 9100 was revealed to the world in the **September 1968 edition of HP Journal** (click this link to read) that was completely devoted to the product. I had the honor of showing off the product at the next major electronics show and watching the amazement in engineers’ eyes as I would run through a series of floating point calculations



NEW ADDITION to the July 13 picnic this year was HP's 9100A Calculator shown above. It was programmed for multiplication and HP'ites were invited to try their hand at operation with the help of an instructor. It was quite a hit with the younger generation (as one can see). Photo by Bonnie McGhee (5M)

Measurement News story about the HP 9100A at the annual picnic.

using signs and cosines. I even demonstrated one at the 1968 annual company picnic for employees.

Barney Oliver

A few words about working with Barney Oliver, the only true genius I have ever met. He created transcendent moments that are each treasured memories of my time at HP. He was the director of HP Labs until he retired in 1981.

One weekend when I thought I was alone at my desk in the lab on Page Mill Road trying to work out the detailed analysis of a tricky sense amplifier design when Barney suddenly appeared and asked what I was doing. I explained. He looked at the circuit drawn on my engineering pad for about five seconds and asked would you like some help. I said sure. He walked me into an empty conference room, erased all the blackboards on three walls, and for the next half an hour proceeded to derive the closed form solution for the circuit from basic principles. He never looked at my drawing again. He never erased a thing. He showed all his work and explained each step. He filled all three blackboards and when finished he drew two lines under the solution and asked, “Does that help?” What could I say but “Yes sir.” He left the room. I sat there for quite a while absorbing what I had just experienced and then copied it all down.

The HP 9100A project attracted a lot of attention from Bill and Barney who would often stop by to check on progress. Since my desk was across the aisle from the bench top prototype, I kept an eye on activities there. One day Tony Lukes, who was developing the display part of the project, was complaining to a small group that were all staring at the characters displayed on the little CRT. I joined in. He was perplexed that the characters kept jumping around in a seemingly random fashion. He had tried all sorts of circuit modifications and nothing seemed to help. Barney suddenly appear, as he often did, and joined the small band discussing the problem and staring at the display.

After a few seconds observing, Barney proclaimed in his usual deeply resonate voice, “It only moves when you talk.” We were stunned. What did he mean? We didn’t understand. “Let me show you” Barney said. He proceeded to grab both sides of Tony’s head, pressed his own forehead against the back of Tony’s head, and hummed loudly. Tony was stunned when the display jumped all over the place. We saw nothing. Barney patiently explained how our eyes move slightly due the vibration of our voice and normally you compensate for this and never notice it. However, the display is refreshed at a slow rate so that traces from successive sweeps fall on different on different parts of our eyes making us think the display is jumping around. We were skeptical. Barney successively grabbed each of our heads and for our own head-to-head demonstration. Yes, there was nothing wrong with the electronics. Problem solved. Just another example of Barney’s uncanny perception and playful demonstrations. He was grinning from ear to ear.

A couple of years later I had completed an interface between the HP 9100A and an X-Y plotter so that you could draw graphs. Barney stopped by and I showed him how I could use commands to draw a few straight lines on the plotter. Barney grunted in his way that meant he understood and walked away. The next day he returned with a HP 9100A magnetic card. He said try this with a smile on his face. I plugged it in and the plotter started drawing lines and curves all over the paper. After a while it stopped. The plotter had drawn what looked like a Mexican hat. I asked, “What is it?” He says, “That is an isometric project of a first order Bessel Function.” He patiently explained the significance of the function. He said he liked the plotter function, then walked off. You have to understand that Barney did not have a plotter and had written this program without ever seeing it run. And yet, when he walked up to my desk, he knew it would run perfectly as long as my interface worked. Again, I sat there absorbing what I had just experienced. Later I learned a lot more about Bessel functions.

As an engineer, I loved the environment at HP where all stockrooms are fully stocked and open at all times to support the creative experimentation of engineers trying out new ideas on their bench. It was almost unbelievable that such a policy should exist. The story runs that in earlier days, Bill Hewlett was trying out something on a weekend and needed a part, but when he tried to find it, someone had built a metal cage around the stockroom and locked the door. Bill was upset. He found a crowbar. Ripped the door off its hinges, and left a note, something to the effect that all stockrooms shall henceforth remain unlocked signed Bill. The policy was put in place the next day.

Engineers were expected to do their own experimentation. In fact, Barney Oliver had designed the standard engineers' bench that was included in every engineer's office. Small home projects, "G" Jobs as they were called, built with HP parts from the open stockroom just added to an engineer's experience, but none matched Barney Oliver's audio amplifier project. Barney been interested in audio for some time. Dissatisfied with commercial gear, he decided he could design a better one. Even he had his own bench for experimentation.

At the appropriate time, he enlisted the aid of several technicians in the lab to help build his amplifier and soon he had an almost product ready version running on his own bench near his office. Of course, Barney was not shy and began inviting friends and associates over to his home for a demo of how audio should be done and most everyone was blown away. Literally, he played it really loud. They wanted to know how they could get a copy.

Barney Oliver Amplifier Team at HP Labs, 1972

Well, Barney had a lot of influence in the company and years earlier had a number of special TV antennas of his own design built for various employees and friends. So, he set up a plan to make a special manufacturing run of his amplifier in one of the HP plants. He asked for my help in polishing up his design. There wasn't much to do since the design was mostly elegant, but I did make a few small improvements. Eventually, more than 450 were built and sold to employees at cost. One showed up on my desk with an implied thank you for the help. A fantastic experience working with Barney and the ultimate "G" Job. Barney then designed a matching speaker and offered that to employees as a kit. I built two of those. Here is a picture of Barney standing in his office with his HP Labs amplifier team. I am seated to his left, Clarence Studley on his right designed the sheet metal package. The other people were technicians and the layout tech. His amplifier is on the table.

More detail can be found at
http://www.hpmemoryproject.org/news/barney_ampl/barney_page_00.htm .

HP 35

It wasn't long after the HP 9100A was transferred to Loveland that Bill Hewlett started asking for one that would fit in his pocket. Industrial design made a prototype mockup and pretty soon he started asking if we make it. The feasibility of such a project was discussed for several years. The bulk of the task fell on Dave Cochran. When the pieces fell into place, development was completed in less than a year through the efforts of many people, the HP35 was born in late 1972 at least four years ahead of any competition. This project created yet another new division called Advanced Product Division.

It is hard to describe all the innovations in this product not the least of which was the keyboard. Industrial design had already concluded that you could squeeze the buttons close together if you made them small with space in between. But how should they feel? There was a big push with the HP 9100A to have a keyboard with a "quality feel." No one could agree except that they thought the IBM *Selectric* typewriter felt good.

To better understand, I worked with another HP Labs mechanical engineer to build a device that would plot out force-displacement curves for button pushing. I measures all the keys I could find. This provided quantitative data that I could compare with people's opinions on quality feel. I found correlation with some hysteresis in the force-displacement curve. Although I documented all of these findings in an internal paper, practicality prevailed and the HP 9100A used a simple over-center click switch under each key.

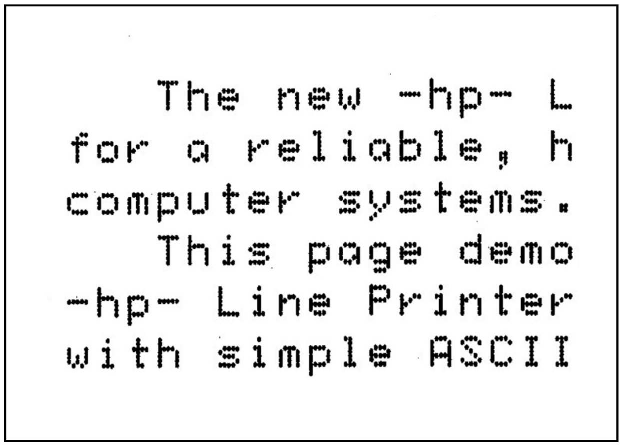
The HP 35 had no room for such things. Clarence Studley again came to the rescue with thin spring design that worked like a frog clicker. Some people called it the oil can click effect. There was debate about whether the key should hinge from the top or the bottom. My earlier study suggested the bottom click would be most natural feeling while the top hinge would cause people to poke at the key rather than depress it. The top hinge won.

Electrosensitive Line Printer

Before the HP 9100A was released, I picked up some early work that had been done on electrosensitive printing to see if I could use it to make a printer for our new HP 2100 minicomputer. The intent was to create a fast and quiet way to print pages of text rather than the large, noisy, and expensive mechanical impact printers showing up in computer centers. There were a number of technical challenges. In electrosensitive printing a mark is made on specially coated paper by burning the silver/white zinc oxide coating with an electric current through a tungsten needle.

The special paper was developed and made by an engineer downstairs who ended up building a large continuous paper coating machine just for this purpose. I worked with a talented mechanical engineer in our lab who figured out how to make an eight-inch wide print head with 480 tungsten fingers. I developed a novel way to produce high voltage pulses that were required to drive the fingers and control electronics using digital design techniques similar to those used on the HP 9100A, except that I used small scale integrated circuits from Fairchild and Texas Instruments for all the logic. Dave Cochran helped with the algorithms.

The characters were formed by burning a 5x9 dot matrix on the paper as it moved by the row of print fingers. I decided to incorporate a complete set of upper and lowercase ASCII characters and symbols. I worked with the Solid-State Lab across the hall to make one of the first examples of a semiconductor Read Only Memory that stored all the 128-character dot matrix patterns. The data was hand encoded on large Mylar sheets with Mylar tape representing each of the semiconductor layers. These were later reduced photographically in another department in HP. When it was completed in late 1968, the printer would silently print 10 lines of 80 characters per second or any desired graphic image which at the time was very impressive. We used fanfold paper held in a drawer in the bottom cabinet. Here is a photograph and close up the printed output.



ES Line Printer Built in HP Labs with printout detail 80 character line, 10 lines/second, and full graphics

I tried to interest a division in picking up the product focusing on San Diego division, which at the time made all the X-Y Plotters and strip chart recorders. However, since the printer required a considerable investment in special paper manufacturing, the division turned it down. I made 10 prototypes that were distributed to a variety of internal user who all loved it. I supported the device for years. Nothing more came of it. There was more interest in the new HP Labs ink jet printer technology and thermal technology was showing promise. One interesting historical note was that there was a faster printer using electro sensitive paper developed by the military supplier Clevite Corporation called the Clevite 4800 that claimed printing up to 80 lines per second on rolled paper. This was an outlier and never appeared on the market. Also, an electrostatic printer called Statos V that was developed by Varian Electrographics division near HP. This technology eventually found its way into laser printers.

Digital Design and Teaching

The HP 9100A broke new ground for HP and created a lot of envy among the divisions who wanted to know how we did it. I made several HP confidential presentations describing the architecture and how the machine functioned, but it did not translate well into how it could help in their projects. After my printer project wound down, the ERL lab director, Paul Stoft, asked me if I could spend some time translating the digital design concepts used into something more useful to HP engineers. I read all the digital design textbooks I could get my hands on and found they all fell short in giving digital designers what they really needed so I decided to write my own.

Paul gave me the time and I spent six months full-time working out all the methodologies required to document detailed control elements as algorithms and then independently build that design using any chosen hardware. No word processors here. It was all written long hand and typed out by a secretary then cut and pasted as required. I worked with HP’s internal publishing department, the same one that produced the HP Journal, and we published an in-house soft-bound book titled, “The Design of Algorithmic State

Machines." In the process, I created a graphical method for documenting a digital design called the "ASM Chart." In early 1970's, I started teaching a compressed one week class on how to do digital design and over the next few years presented it to hundreds of HP division engineers all over the world.

I particularly remember teaching the class to HP's Japanese joint venture, Yokogawa-Hewlett-Packard. It was my first trip to Japan. They flew me there First Class on Japan Airlines. Each morning I traveled by myself from my hotel near Shinjuku Station on a packed commuter train to a little town outside Tokyo where the company was located. The engineers sat quietly through each presentation and when I asked if they understood, they gave a brief, polite nod. I never did figure out how much they understood. Because of the language barrier, I spread out the course over two weeks and learned about their company and way of doing business in between.

On the weekend, one of the engineers and his girlfriend treated took me to Kyoto on the Bullet Train for a tour of ancient temples and to see the cherry blossoms. One evening I had dinner with a young engineer and his wife in his tiny home near the freeway in Tokyo. The single room home was divided into spaces by sliding paper walls. We sat on the floor at a tiny table with our knees under the table cover where a small electric heater kept us warm. There was no heat in the rest of the home. His wife did not eat with us. Instead, she delivered each course on her knees silently entering the space through a sliding wall and re-treating backwards while bowing before closing the wall behind her.

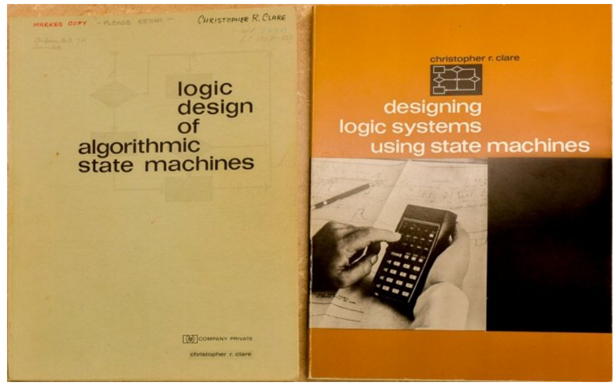
One day, two engineers took me to lunch at a special restaurant on top of a hill more than an hour's drive from the company. The specialty was birds cooked on an open hibachi in the center of the small table. The last evening, the division manager invited me and all the students to share in a lavish spread of Japanese delicacies set up in one of the conference rooms and then proceeded to embarrass me with praise and thanks. In a typical fashion, he gave me gifts, too many in my opinion. The gifts including a hand written, frame scroll commemorating the occasion and a large, highly decorated brass warrior helmet in a black lacquered box all of which they had shipped to my home back in the States.

Following this gathering, the division manager invited me to his apartment in a high rise near Tokyo. It was small and well appointed. We shared a toast of his favorite whiskey in his private study. I was later told that this is an honor reserved only for his closest friends. This whole experience left a lasting impression far beyond the usual business trip. I still remember sitting in my hotel room with a book of Kanji translations trying to figure out the sign on top of Shinjuku Station. It seemed to say something like "land of plenty delights." I believe it was a department store.

Everywhere I taught the class was a revelation to many analog and digital designers, like the fog of confusion had lifted. The compressed format, my rapid-fire delivery, and the flood of new methods all combined was described by many engineers as standing in the stream of a fire hose. I heard stories of engineers throwing out designs in process and starting all over again. It was the dawn of the digital era at HP. Certainly one of the more satisfying experiences of my career.

After a few years, Paul thought we should share these ideas with the world and had the book published by McGraw-Hill. I taught a lab course at Stanford one quarter and an extension course an UC Berkeley. Although the students loved it, the professors found my work interesting, but too different from the way traditional logic was taught. However, some universities later included the methods, including the University of Glasgow and a university in India. 10,000 copies were sold before I declined the offer to write an update. Teaching was not my future.

Computer Architecture



My internal book and the McGraw-Hill Version

I explored alternate computer architectures and machine design for a while with the brilliant investigator, Steve Walther. We focused on the problems between software and hardware, investigating in particular, a stack-based architecture called the Euler machine as described by Wirth and Weber. This investigation led to some interesting conclusions. In September 1971, I wrote in the summary:

"The computer is a particularly intriguing piece of electronic equipment because it is perhaps more widely known than any other, and yet poorly understood. Television and radio are the only two devices which may exceed a computer in terms of recognition. Even movies are made which center on the computer's mysterious powers. A computer conjures emotions of fear, hate, envy, or awe unlike any other piece of electronic equipment. Yet, for the businessman, the computer offers a new economies and efficiency of operation. And as education improves and applications broaden, the computer industry promises to be one of the most active consumer industries, but not with computers as they stand today. - - - Unfortunately, the design of computers is in its infancy, and as yet the merger of application and design is unrefined. There are no standard solutions or convenient theories to use. Each new design emerges as another step towards the merger of the two areas now called software and hardware and should be leading to a new curriculum called software engineering."

Reading this today after many decades, I have to admit it is some very forward-looking thinking. However, my interest was more toward hardware and integrated circuits seemed to be the future for logic and computers.

Semiconductor Design

Intel and Motorola had come out with the first 8-bit microprocessors. I became involved with the design for a new semiconductor random access memory. I had taken a course in semiconductor physics at Stanford taught by HP Labs' own Zvonko Fazarinc. Following that, I participated in the compilation of HP's first Semiconductor Design Handbook along with some knowledgeable consultants working for HP. I jumped in and designed some memory cells and access circuits, laying them out by hand as was the norm at that time.

Another engineer in the lab, Jim Eaton, and I planned a set of experimental runs that were made in the SSL lab across the hall. SSL was an experimental facility assembled to explore a wide variety of semiconductor devices such as laser diodes, light emitting diodes, and field effect transistors. It was not up to the task of building integrated logic circuits. We were frustrated by the difficulty in testing the devices as well as enduring mistakes made in processing the device that made them non-functional. It took many weeks to make each run, so progress was very slow. While I was waiting, I started designing a better way to probe the wafer what would eventually allow automatic stepping between die to speed up testing and be interfaced to a computer. I could not buy what I wanted so I hired a summer student from MIT to help build an automated probe station. It was a lead-screw design driven by stepper motors with proper digital controls. We began to collect more data, but still very slow.

Integrated Circuits Processing Laboratory

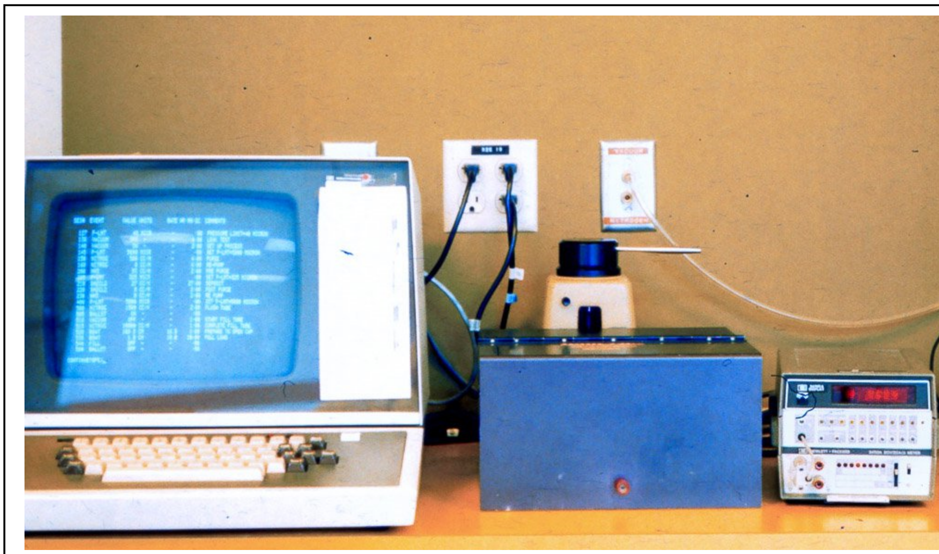
I wrote a memo describing the frustration and challenges of attempting to build IC devices and gave it Paul Stoft. See the full text here: **Memo_from_1974.pdf** (click this link to read). Little did I know that this memo would set in motion my next 5 years at HP Labs. The memo was incorporated into the first part of my automation proposal completed six months later. This proposal outlined how we would model the process flow and link it to the parameters in the processing equipment. It outlines how computers would be linked together and coordinated with each other using communication links and how we would use a CRT based interface available to all the staff to access common in-process information.

In late 1975, I wrote these prophetic notes to myself:

"Major contributions in process control can only go so far without equipment development to provide automatic features and system compatibility. In order for equipment development to be done by equipment manufacturers, we will have to work on some standards among the automation attempt. Otherwise every manufacturer will go his own way being therefore incompatible with each other. - - - in order for vendors to want to produce this type of system there must be a market. In other words, more than HP must want to buy this equipment. The vendors have a lot to learn in this area. - - (It will take years) - - In particular the equipment should use a conventional standard interface with widest acceptance and least compatibility problem." (I go on to outline three possible levels of automation; 1. Lot tracking only. 2. Monitor equipment only, a half way measure. 3. Monitor and control equipment has the most promise.)

It became clear that in order to stay in the forefront of integrated circuit processing something different than SSL was required. Bob Grimm, coming from experience with computerized HP test system, joined to help pull resources together. Pat Castro joined the effort bringing manufacturing expertise from the semiconductor industry. Gerry Alonzo joined to add his instrumentation experience. I continued to flesh out a proposal for how computers could be used to bring the production process under control.

The decision was finally made create a new lab department and to build a new facility. Bob was chosen to head the effort and he asked me to lead a group to make the facility computer controlled. Pat Castro would head up the processing lab. Bob hired researchers to begin developing new processes for divisions. The new facility would use the then state-of-the-art 4-inch wafer production equipment and would be built nearby in a building on Deer Creek Road that was purchased from Fairchild. It was quite exciting to start from the ground up like this, walking around the empty building with Bob and Pat, discussing where things might be located and what might be accomplished. Pat Castro designed the fab as a series of aisles with windows at the end so that visitors could see the entire operation. She also established a specific orange and white color scheme for all the equipment. She even had her car painted in the same colors.



Gerry Alonzo's 4-Point Probe Meter on Right.

Even though I was slated to be the manager of the automation department, I continued to have an engineering bench in my office and contributed design assistance where required.

Automate 4-Point Probe

While the building planning and extensive re-modeling were underway, Gerry Alonzo designed and built a new four-point-probe instrument with a serial interface around an HP clamshell type of voltmeter. The performance of this instrument was far above those commercially available at the time and started the process of automating all the elements of process control. We ended up making many of these instruments and transferring them to HP divisions.

Computer Controlled Diffusion Furnaces

I knew that we could not automate everything at the same time. We did a survey of all processing machines we wanted to include in the new facility, and of those, decided to focus first on the large array of diffusion furnaces. We decided to work with manufacturer Thermco in Orange County since they seemed to make solid hardware, although they just had simple analog controls. They did not know how to use computers to run their machines.

Gerry worked on the power control for the heaters while I focused on the temperature control. I modeled the furnace thermal behavior and using a finite difference method learned from HP's own Zvanko Fazarinc, I wrote a Basic language program to simulate the digital control of temperature in the furnace. Our intent was to control the furnace with a computer and teach Thermco how to build it into their product. It was our first major joint effort with a vendor. The simulations convinced Thermco that it would work better than anything they had. Gerry continued to work closely with their engineering to meet our objectives. Four banks of eight furnaces were delivered and installed. Much of the rest of the facility was equipped with the best system available at the time. A group of semiconductor process researchers were added to ICPL and they soon started to run wafer experiments through the fab.

Computer Controlled Diffusion Furnaces, 4 tubes of 32 in ICPL Fab. Each tube was run by a computer with all process parameters download from PCS according to the lot being processed and all in process monitor data uploaded to PCS for later study.

It took a while to work out the software bugs so that the furnaces ran smoothly, however, the furnaces ran in a standalone mode until we made more progress on our process control system, PCS. When we were ready, we made further upgrades to the furnace software to handle communication with PCS. Then we could finally demonstrate our vision of process equipment fully integrated into factory computer control. The breakthrough featured the equipment to be set up automatically to perform the process step as described in a "recipe" written by the process engineer. It provided for pre-determining the sequence of steps specified ahead of time for the specific lot being tracked by the system.

Gerry continued with a similar treatment for a computer controlled Low Pressure Vapor Deposition system.

Process Control System, PCS

I continued to imagine how computers would be used throughout the facility and how they would talk to each other to accomplish our goals. I also laid out the types of information that would be presented to process engineers and how the processes themselves would be described in such a way to facility automatic programming of the equipment. I hired Gary Modrell from the microwave division to help design software for the HP mini-computer to make this happen. I knew by this time that in order for my vision to be realized that the semiconductor fabrication equipment makers had to embrace the idea of computer control and communications, but we could only work with them one at a time.

Process Control System, Facility Monitoring on Left, Tape Backup, and Computer were located in a room next to the Fab. On Wall Behind Charts of Facility Monitoring, Computer Network, and Floor Plan of Fab

I decided for many reasons to use a simple serial interface based upon the industry standard RS-232. I knew that the equipment in the facility would probably generate a lot of electrical noise so I designed a simple optical isolation scheme. The primary user interface was a CRT, text based computer terminal that could display a page of text and update at 9600 Baud. We planned to use the optical isolation method for the terminals as well so that they could be driven many hundreds of feet from the mini-computer and therefore be located all over the building.

Gary continued to develop software demonstrations of the methods we planned to use. Early experiments exposed limitations imposed by the HP minicomputer and operating system. I hired Shane Dickey fresh from success with HP's first timeshare-like system based on the HP computer. Gary and Shane put together a combination of modifications to the operating system and a special way to write application software so that enough people could simultaneously access data and have the software still fit into the limited memory space available. Even the serial ports were a bottleneck.

I hired an MIT engineer and he designed and built a 32-channel serial port front end computer using newly available Motorola 6800 microprocessors. The serial ports could be used to connect to automated equipment or display terminals. We powered the system from an uninterruptible supply and had a separate master time clock with battery backup. I hired more staff to flesh out the various software components. We finally had a platform able to support our envisioned process control system. I continued to define all the user interactions, screens, and data analysis.

Slowly the system came alive, one function at a time. We trained process engineers and technicians how to use it and benefited from their feedback. Word spread about our computer controlled facility and soon a parade of visitors came including those from HP, from our customer, and even our competitors. I presented a few papers at electronics shows discussing what we had built. After a few years, we concluded that we had invested about 20 man years into the software development of the system. It really was quite impressive to our visitors and even to ourselves. Our process engineers loved it. Eventually, a new HP facility built in Santa Rosa adopted our PCS control system. I described PCS in an article that appeared in the **June 1981 edition of HP Journal** (click this link to read).

Facility Monitoring

An adjunct function of the PCS system was to continuously monitor many physical parameters about the facility itself such as temperature, air pressure, DI water conductivity, and gas supply pressures such as from the liquid nitrogen tanks in the rear of the building. These values were logged and limits set to trip alarms as required. The history of this data could be pulled up on any of the PCS terminals.

This monitoring had a few unexpected outcomes. Pat Castro was troubled with unexplained variations in the particle contamination levels in the fab. Gary Modrell worked with her and found a correlation between these unexplained events and a sudden drop in the air pressure in the facility when no one was supposed to be there. The investigation eventually uncovered that the night time janitors were entering the clean room in their street clothes at night and using fuzzy dust mops to sweep the floors like they did the rest of the building. No one had apparently told them that this was a special area that they should not enter.

In a more serious example, in the latter part of 1970's near the height of the complaints about the military industrial complex, someone planted an explosive device at the bottom of the liquid nitrogen storage tank outside the back of HP's building 25 and set it off. It blew out the bottom of the tank and the back wall of the maintenance storage area. We lost all the nitrogen plus the powdered insulation was everywhere. The FBI investigated. Fortunately, they did not pick as their target the liquid hydrogen tank just 50 feet away behind a fence. That would have been 100 times worse. Gary was able to pinpoint the exact time of the explosion by noting the sudden drop of nitrogen pressure recorded on our facility monitoring equipment. This information was greatly appreciated by the FBI who seemed impressed by our monitoring. From that point on, security was a serious matter at all HP facilities throughout the world. A fence and gates went up around building 25 where there were none before. It previously had been a quiet pastoral setting, set in the Stanford foothills.

Automated Thin Film Measurement

The semiconductor process involves a long sequence of processing steps some of which grow transparent oxide layers on the wafer. Like other parameters, the thickness of this film is critical. Several laboratory-like instruments were used for this measurement. We were looking for a production worthy system not requiring a PhD to operate. We found such a system just being made by a young company in Santa Clara called Nanometrics. They had a small optical system with microprocessor control that looked like a microscope and measured the kind of films we were interested in. We worked with the engineers at Nanometrics to add a serial interface so that measurements could be automatically collected by PCS.

Since we used a standard RS-232 interface, they soon were able to add the functionality we required. This became the second in-process tool after the four-point-probe that Gerry had developed.

Special Serial Interface was added to a Thin Film Measurement Tool by Nanometrics Readings appears on PCS Terminal to right.

Automated CV System

My group focused on process control. However, that required an ability to accurately monitor key factors of the process. One of the emerging problems we tackled was monitoring mobile ion contamination in silicon oxide. This problem seemed to plague all HP IC facilities and significantly degraded the reliability of metal oxide semiconductor, MOS, devices. The tools available to measure this parameter were crude and relied upon the skill of the person making the measurement. This made it really difficult to compare, for example, what Loveland was getting to what HP Labs was getting.

Automated CV Plotter designed and programmed by Chris Clare to automatically measure, plot, and analyze CV curves for characterization of mobile ion drift in oxide layers. Dr. Fred Schwetmann studying his results in ICPL.

I took on the challenge to design a robust, computer controlled measuring system that would make measurements about 10 times as fast and eliminate the human factor and skill required. It evolved over a period of a year. I drew on all the available textbooks such as on one by Intel's Andy Grove, papers on the subject, and internal PhD researchers at HP Labs to put together a comprehensive automated analysis of the measured data resulting in reliable, quantitative results without human interpretation. The first practical system was controlled by a new HP 9830 desktop, an evolution of the original HP 9100A, that operated with a Basic programming language and it used a new precision digital capacitance made by Yokogawa-Hewlett-Packard in Japan. Unlike any previous system, this one measured five spots at the same time. It produced two outputs for each measurement, an annotated plot of the CV curve and a full page report listing all the measured and computed values for each of the five spots. Incidentally, the full-page printer was developed by HP Ft. Collins division. It used thermal rolled paper and was sort of a more compact version of the printer I had developed seven years earlier.

We duplicated this system many times and transferred copies to other IC facilities within HP. Finally, different facilities could compare their results and share methods for controlling this problematic contamination. It wasn't long before the commercial heated chuck began failing since it had never seen the kind of service we required. The vendor was of no help so we designed our own, heavy duty heated chuck and controller. We made multiple copies of this new design and updated all the exiting CV systems. The new design ran even faster. We had no failures.

I mention this Automated CV system because it was one of the typical project undertaken by my automation group. It resulted in something that was not available on the open market and provided a significant contribution to process control.

Automated Parametric Test System

To evaluate the success of any process under development, the process engineers relied on simple electrical test parts to evaluate their process. Testing these parts was slow and it took a long time to gather enough statistical data to evaluate experiments. A few expensive IC test systems were available on the market primarily aimed at testing digital devices. They did not lend themselves well to measuring analog test parts.

I had seen some interesting small test equipment built by Santa Clara IC facility for evaluating test parts and thought that we could expand that concept into a computer controlled version capable of testing more complex parts. I hired another HP engineer, Ulrich Kaempf, and we designed a four-quadrant digital power supply that could source and sink current as well as measure voltage and current in all four quadrants. We miniaturized this to the point that we could bolt 32 of these supplies to the back of a rack holding an HP minicomputer system.

Gary Modrell helped write software extension to BASIC so that we could write and run test programs BASIC. I added an interface to a new automatic X-Y probe station that had just become available on the market and we had a powerful measurement system to gather parametric data from test wafers in rapid order. The test parts were simultaneously probed in each die location, electrical test performed, data was saved, and then the probe station moved to the next location.

We did build one copy of this system as I remember it for use in another division. No pictures remain.

It was not our intention to create a product with this system, but we did share a lot with a group in Santa Clara that were developing IC test equipment. We were surprised to later see a measurement instrument developed by HP Japan that utilized the concept of a four-quadrant power supply for semiconductor evaluation.

Mass Flow Controller Calibrator

Much of the complex processing equipment found in any IC facility used gases of various types that had to be precisely regulated during a run to achieve the desired result. The special devices that did this were called Mass Flow Controllers. Basically, they contained a variable valve, gas flow measurement device, and control electronics to

Computerized Mass Flow Controller Calibrator built by ICPL Automation Lab.

maintain a requested flow rate. They needed to be calibrated on a regular basis by outside vendors. We found that that service was too slow and unreliable.

Since accurate gas flow was so important for process control, we decided to build our own calibration system. I used one of my best ME’s with an aerospace background, Bill Goodman, to design it. The measurement was based on lab standard for such measurement, a glass cylinder with a precision piston sealed with liquid mercury. As the gas flowed into the cylinder from the bottom, the piston would rise. We measured the piston movement with an HP laser interferometer. We used another HP Ft. Collins instrument controller to run the system. The system proved very effective.

A very little-known fact about our automation group was that while modifying and building process equipment, we became very familiar with gas delivery systems. I even hired a welder who specialized in building stainless steel gas delivery systems and set him up with special welding equipment in his own shop downstairs in building 25. Piping integrity was crucial when delivering gases which were toxic like arsine and others.

Low Pressure Plasma Etching System

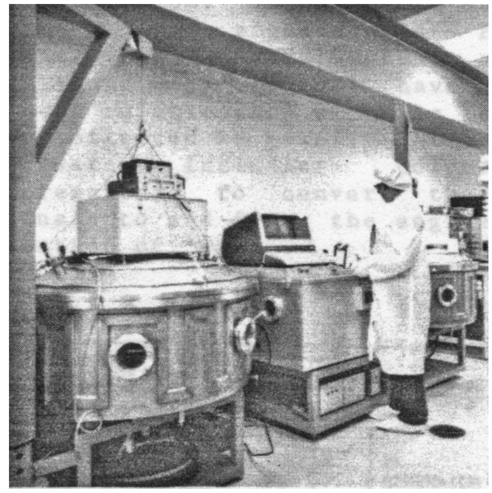
The automation group focused mostly on building our factory wide process control system, PCS, working with vendors to automate their equipment that included a serial interface to our PCS system. Other monitoring and measurement systems improved process control and development until we began discussions with a process engineer, Dr. David Lam, who had been recently hired to research the area of plasma etching. He was very interested in equipment that could solve the particular challenges of utilizing this technology for semiconductor manufacturing. HP agreed. Eventually, we decided we should design our own plasma etching system that would accept wafers from a standard storage cassette, load them into the vacuum chamber without breaking the vacuum in the processing part of machine, process an entire lot of 24 wafers at a time, have a wide variety of process gases available for use, and provide complete computer control connected PCS.

Thus, began our most ambitious equipment design project without ever knowing if plasma etching was really practical. A large part of my automation group worked on this project. In the end, we designed and built a large circular vacuum chamber, more than three feet across with two parallel plates. We designed a robotic loading arm that would move wafers from the cassette and place them around the bottom plate while under vacuum.

Custom Plasma Etching System designed and built by my Automation Department of ICPL shown in the engineering area about 1979.

The loading mechanism was in a separate vacuum chamber separated from the process chamber with a large gate valve. We purchased a 2KW RF generator and matching network to drive the plates. We used two large vacuum pumps one of which had a roots blower front end for high volume pumping of the process chamber. We built a complex gas delivery system with many mass flow controllers. All parts of the system were controlled by an HP minicomputer with a graphics display. Process pressure and flow was controlled by the computer and an electrically driven butterfly valve in the main 4” vacuum line to the process chamber. I helped out the team by designing the stepper motor positioning system for the loading arm.

Two such systems were eventually built. A quarter of a million dollars was invested in the first machine. These machines proved invaluable in developing and proving the value of plasma etching. At the same time, this effort stretched the role of the automation effort at ICPL. Ulrich Kaempf later wrote and presented a paper on PCS and the control of this plasma system at a 1984 conference of American Automatic Control Council.


Two Plasma Systems as Installed in ICPL Facility

The irony here is that Dr. Lam left HP to start his own plasma equipment company in 1980, Lam Research, which introduced its own automated plasma etching system in 1982. Lam Research grew to become very successful, eventually joining the Fortune 500 list in 2016.

SMIF Development

I left the management of the automation group to Mihir Parikh about 1980 to pursue other matters related to process development engineering within HP Labs. Meanwhile, the remaining automation group undertook an interesting project to reduce contaminants when moving wafers from machine to machine by enclosing the cassette in an air tight plastic container with a containment free way of loading the cassette into the equipment. The core development team was led by Ulrich Kaempf as engineering manager, under the direction of Mihir Parikh.

The core team that developed the technology was driven by Barclay Tullis, who held most of the patents, with Dave Thrasher, who later joined the Silicon Valley Group, and Thomas Atchison, a member of the technical staff under direction of Barclay Tullis. Mihir later provided the technology to SEMI, and then licensed a copy for himself. He then left HP and started Asyst Technologies to provide the technology commercially. Asyst has grown and become successful. Virtually every 300mm semiconductor factory in the world now uses Asyst products.

HP Labs Networking

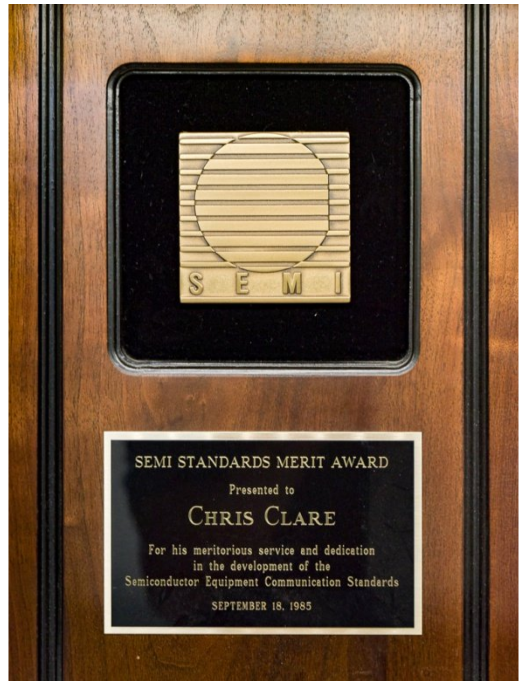
It seems hard to imagine a world without Ethernet and Wi-Fi but, that was the case in 1980 when engineers began wanting access to PCS and to other computers available within HP Labs. The standard Interface in those days was a CRT Terminal connected to the computer using RS-232 serial interface. On top of that, building 25 was located a few miles from the rest of HP-Labs on Page Mill Road where some of the faster computers were located. I worked with the IS guys in the computer research lab to come up with a common solution. We agreed to all use a similar RS-232 switching system that would allow a terminal on an engineer’s desk to be connected to RS-232 ports on many different computers. We jointly wrote a mass wiring standard using telephone-like punch-down panels distributed throughout HP-Labs. I then contracted for the entire building 25 to be re-wired using this new system.

To solve the remote access to Page Mill Road, I had a microwave link installed that bounced off a reflector we had to place on Stanford property to get around a hill. The RS-232 switching system took care of time domain multiplexing connections over the microwaves T1 link. Now engineers in building 25 had access to DEC PDP-10s located in other labs as well as to PCS.

The microwave link operated until a complicated and expensive underground conduit was laid between the buildings and a broad band cable system installed. The conduit had to be installed down Page Mill Road, under Central Expressway, and across Stanford property.

SEMI SECS Standard

As publicity of our automated IC facility grew, interest grew in how we managed to get all the equipment to talk to one another. Around 1978, I was asked to participate in a round table discussion by the Semiconductor Equipment and Material Institute, SEMI where the need for communications between equipment and a host computer was discussed. When the question came up "does anyone know how to do this?" I raised my hand saying that I did and in fact had it up and running at HP to prove it. Just like that I became the committee chairman for this new group.



SEMI Merit Award for early leadership in the SECS standards effort.

Over the next months, I refined and documented the basic serial protocol that we had implemented for PCS and presented a draft at the next committee meeting. The immediate reaction was that what I proposed was too complicated. I knew in fact based upon our experience at HP that what this protocol was just the tip-of-iceberg so to say. I persevered explain why each feature was required for a reliable factory interface. Over the period of the next year, I made numerous presentation at these SEMI sponsored standards meetings with participation from most of the major semiconductor and equipment companies in the US. Finally, the protocol was approved as an international standard and called SEMI Equipment Communications Protocol, SECS. I found myself subject to many jokes due to the obvious homophone when I was called the "Father of SECS." (sound it out!)

As companies began to try to use the protocol almost immediately they realized that they did not know what data to send back and forth, the tip-of-iceberg. Thus, began my second effort to define standard data encoding methods and equipment models. I wrote all the original drafts for this new standard that eventually was approved as SECS-II several years later. The original standard was now called SECS-I. I presented numerous workshops on both SECS-I and SECS-II. The SEMI communications standards committee grew in participation. Industry participation became substantial. Companies sprang up selling SECS software modules for users to build into their products. Another company, Promise Systems, building a PCS like lot management system began offering interfaces to equipment.

The interest continued to grow taking on a life of its own. After five years as committee chairman, I turned over the committee to others who now made equipment communications their career. SEMI was appreciative of my efforts and surprised me in 1985 at a SEMI dinner for several hundred industry representatives with the first ever Merit Award given to an industry volunteer. I thank HP for allowing me to participate in this effort. It benefits HP and the industry as a whole. I can't help but think back to my prophetic notes from 1975.

The SECS standard has now been actively supported for more than thirty years. SECS-I now supports serial and Ethernet implementations. Parts of SECS-II have been incorporated into generic equipment models, GEM, that facilitates communications between a host computer and process equipment. The current active standard is now collectively known as SECS/GEM and is used internationally.

Yield Improvement

After leaving the automation group, I spent a couple of years researching and writing many internal technical reports on a variety of subjects supporting semiconductor process development and manufacturing. The process engineers were struggling with the development of a double layer metal process with high enough yield to be used on complex integrated circuits being designed in HP. They were processing parts in the ICPL facility and making little progress. I was asked to help by Fred Schwettman who was leading the effort. I saw this situation. The process engineers were trying to make a target memory device with complexity consistent with the type of products the designers wanted to fabricate with the new process. The problem was that in every experimental run, the yield was zero. Experiments were based on speculation as to what was going on since no guidance was provided by zero yield.

I realized that the process engineers need some quantitative, non-zero yield to determine if an experiment improved anything. I dug deep into statistical methods and designed a strategy for designing test parts that would give the process engineers what they wanted and allow them to make progress. The unique feature of my design was that I could calculate the yield of the target device with a defined confidence limit over four orders of magnitude of defect density of all types and prioritize which type of defect was causing the greatest yield loss just by measuring a set of carefully designed test parts. I wrote a comprehensive technical paper on the subject.

The process engineers were skeptical. I had already dug into other statistical methods for process control, design of experiments, and confidence limits and was sure it would help. I ended up designing the required test pattern which had many test parts. Masks were made and the first parts fabricated. I wrote a complex test program for the parametric test system built by my automation group several years before. The test parts were probed simultaneously with a probe card and the test system collected data across an entire wafer. The test program then used my analysis methods to project the yield of the target device and the contribution of each defect mechanism to the overall yield. The still skeptical process engineers nevertheless focused on improving the highest priority defect and it wasn't long before they had improved the process enough that they could get some actual yield on their target device. Several process engineers read my paper more closely and began applying the ideas to other projects. A satisfying conclusion.


Tina and I married in 1980. My new 12-year old daughter stands in front. Gary Modrell to right.

My Personal Life at HP

HP was my family for 14 years until I married in 1980. I worked hard and played hard. I participated in company ski trips where I learned how to ski and ice skate. I backpacked all over the nearby Sierra Nevada mountains with friends from HP. I learned how to sail in San Francisco Bay and ended up buying a 32-foot sloop that I jointly owned first with Gary Modrell and then with Jim Eaton both from HP Labs. When Gary and I owned the boat, we would take off many evenings after work for a peaceful sail on the bay. Then Jim and I raced the boat in the South Bay Yacht Racing Association winning a number of races. I spent many weekends upgrading equipment and maintaining the boat until I finally sold my share in 1983.

Through initial contacts made while I was at Stanford, I became active with local bicycle riders and ended up leading a local bicycle club for several years. We were active in organizing local rides, rides from Palo Alto over the coastal range to the Pacific, and other bicycle trips outside of the bay area. One such ride was a three-day challenge where ten of us started at the West entrance to Yosemite, rode down Hwy 120 and Hwy 49 to Sonora, then up Hwy 108 over Sonora Pass to Bridgeport, and finally through Lee Vining, up and over Tioga Pass through Yosemite back to the West Entrance. Once in a lifetime for me.

My wife had a 12-year old daughter whom I later adopted. I sold my home in Palo Alto and we moved to Los Altos Hills. I spent more time with my family and my daughter. After graduating from Chico State, my daughter married and now has three sons that bring great joy to my wife and me.

Leaving HP

HP had changed a lot by 1985. Bill, Dave, and Barney were gone. John Young, an MBA from Stanford, now led the company. The once instrument-based company was becoming dominated by commercial business computers like the HP 3000. Development was starting to be business driven rather than engineer driven. Joel Birnbaum had come from IBM to lead the development of a new RISC architecture in the Computer Research Center of HP Labs. He became vice president and Director of HP Labs in 1984.

It just seemed like time to go. I ventured out into the world of small companies and start-ups for rest of my career. Some work was for a Motorola funded startup where I built special factory system tools like a factory wide equipment up-time management with large graphic displays. Then I made an important shift in my career to medical device design. I designed an EEG monitoring system for one startup. I designed a surgical fluid pump and monitoring system for another. Finally, I finished my career designing many different types of surgical lasers for retinal repair. I received 12 medical device patents for things done after leaving HP.

I learned a lot in all these ventures, but nothing matched the experience at HP Labs, the people I met there, the support of the company and the many challenging projects. I had the opportunity to create entirely new product categories, to help bring HP into the digital age, to introduce automation to semiconductor factories, and in turn, influence the entire semiconductor industry. While there, I went from extrapolating what computers might be in 1971 to seeing the introduction of the IBM PC and the Apple Macintosh by 1984. What a ride.

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