Oral History of Peter Hart, part 1

Interviewed by:
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Brock: Well, this is an oral history with Peter Hart for the Computer History Museum and I am David Brock interviewing. So Peter, as I said, to begin at the beginning, could you tell us a bit about when and where you were born?

Hart: I was born in 1941 in Brooklyn, New York.

Brock: And could you tell us a little bit about your family of origin?

Hart: Yeah. My father was a lawyer. My mother was a housewife or home keeper until my sister and I were teenagers and-- at which time she became the administrative head of a university department.

Brock: Which university was that?

Hart: Brooklyn College, and she was the administrative head of the chemistry department for quite a few years.

Brock: And I think that I know who was in the chemistry department then. And your father was part of a firm in Brooklyn or worked on his own?

Hart: No. He eventually worked in the New York state court system and he was a legal researcher for the presiding justice of the appellate division.

Brock: Okay, so was supporting sort of a judicial clerk, that sort of a role or--

Hart: No, I wouldn't say "clerk." He actually wrote the opinions that were then signed off on by the judge he worked for.

Brock: Right, so sort of like people who clerk for a supreme court justice, that sort of a role, very actively involved in--

Hart: Except he was a mature professional. Clerking is usually an academic follow-on whereas he was a mature professional.

Brock: And then it sounds like your family lived in Brooklyn for your entire youth.

Hart: Yes.

Brock: Which sections of Brooklyn did you grow up in?

Hart: Until I was about 13, I grew up in Crown Heights, a few blocks from Ebbets Field, so close in the summertime if the windows were open and Duke Snider hit a home run you could hear the crowd and if you turned on the radio and waited the 30 seconds or so for the tubes to warm up you would hear they hit it over the right-field wall or something like that. When I was about 13 we moved to Flatbush, not that far away but a different neighborhood, and we were just a couple of blocks from Brooklyn College, which made it easy for my mother, and Brooklyn College is adjacent to Midwood High School, which is a good neighborhood high school in Brooklyn, and that's where I went to high school.

Brock: And how would you characterize the neighborhoods in which you grew up?

Hart: So Crown Heights at the time was a very heavily Jewish neighborhood. I'll guess that my elementary school was 75 percent Jewish or more and Flatbush that we moved to was also a very Jewish neighborhood at least at that time and so it was kind of a homogeneous, comfortable place to live. Crown Heights was apartment houses-- we lived in an apartment house-- and Flatbush was beautiful, leafy, green, single-family or two-family homes and so it was really a very lovely residential neighborhood in the center of Brooklyn.

Brock: You talked a little bit about your high school. Did you attend the public schools before that?

Hart: Yes, but with an asterisk. When I was around the fifth grade or so my parents were very concerned that I was totally losing interest in school because it was so boring and they put me through some special-testing- well, I was flunking reading and the reason I was flunking reading is because I never had the place; I was always 200 pages ahead in the reader because it was so boring and the only thing the teacher ever cared about is "Did you have the place when you were called upon? We were reading this page, this sentence." And so they had me tested and they discovered in the fifth grade or so I was reading at a twelfth-year, ninth-month level but maybe higher because that's as high as it went and so they said, "We have to do something." And so they found a public school, PS 208; my wife from California thinks it's hilarious that New York public schools have numbers and not names. So I went from PS 161, which was a half a block away, to PS 208, which was two bus rides away or a bus ride and a train ride away, but this public school had a very special track that was-- today you would consider it a gifted and talented track or by some name, and at that point life got much better. There was science; there was a foreign language. There were all sorts of things in the fifth or sixth grade-- I can't remember-- that really reengaged me with a primary school education.

Brock: Were you traveling there with other students from your--

Hart: Nope.

Brock: -or you were just on your own?

Hart: Nope. These kids came from all over the borough and you got a monthly pass for the transportation needs and you made your way there however you could so as I said I had a choice of two buses or a bus and a train each way.

Brock: Which did you prefer?

Hart: It depended on the weather.

Brock: With that capacity and appetite for reading, was the library a big part of your life?

Hart: Yeah, particularly in the summer. We had a small summer place in northern New Jersey in what's now a metropolitan area but then in those days was-- I guess the word was "bucolic," and I would take out as many books as the local library would allow and I'd finish them in a heartbeat and the next Monday night when the little library was open again I'd swap it out and do it over again.

Brock: What sorts of things were you reading?

Hart: It was pretty omnivorous. I read the earlier fiction about science kids and mystery kids; I read nonfiction. I read just everything in the library.

Brock: And has that appetite for reading continued--

Hart: Oh, of course.

Brock: --throughout your life?

Hart: Sure.

Brock: Was science fiction at all? Did that become a feature--

Hart: Sure.

Brock: --of your reading? Could you talk a little bit about that? Do you think that was significant--

Hart: No.

Brock: --for developing your interests?

Hart: No, I don't. It was just one of many, many things that I was in-- that I read.

Brock: Okay. For many people, their household will have a pronounced theme or themes. For some households, it's education, art, politics, religion, business, reading, technical pursuits. If you had to name some of those themes for your household, which would you choose?

Hart: Family orientation. I was really fortunate. My sister and I grew up in a very close and very loving family. We had a wonderful relationship with our parents until they passed away in late old age. My sister and I still have a very close relationship. She just turned 80. We were just so fortunate compared to so many other families that I've later seen; we just thought it was normal. My father was quite a private person; he wasn't a glad-hand or a get-out-and-about sort of thing. He preferred small-group gatherings, family gatherings to big parties. He was I have to say a brilliant individual who wanted to be an engineer but when he was growing up there was a very strong anti-Semitic streak in the engineering profession. I don’t know if you’ve run across this before in your interviews --you’re the historian so you’d have to verify this --but at least the story that I grew up with was that places like Bell Labs were famously anti-Semitic. I don’t know if that’s true but that was the perception—

Brock: It depends on the time period--

Hart: Well, this would have been 1930 or something like that, very early, so again I am not vouching for the accuracy and I don’t want to cast aspersions. I’ll just say that from the point of view of my father in his formative periods he loved engineering but it was considered to be a non option for that reason again whether it was well-founded or not but that was—

Brock: That was his experience.

Hart: And so he became a lawyer which I don’t think he ever really liked. My mother was a terrific read of people. She had tremendous street smarts and a very good read of people and just very charming and very engaging and I have to say in her younger years quite strikingly good looking and her son did not inherit that, but the one other thing I want to mention about my upbringing because I think it really affected my life and is something I basically had to overcome was that, like many people of their generation, they came of age during the Great Depression, looking for their first jobs in the very depths of the early 1930s and, like so many of that generation, it really marked them for life. They were very conservative in terms of risk taking, very risk averse, very protective of my sister and me because who knows what might happen to you out in the world, and that’s really what I grew up with. And so when I started my professional career I didn’t have a specific personal objective to overcome that, I’m not sure I even recognized that, but with the benefit of 50 years or more of hindsight I can see that the whole arc of my adult life has been sort of overcoming that ,and overcoming shyness. And people who meet me now really find it hard to believe because I meet people very easily. I’ll give you one nontechnical sideline on that: I bike a lot; I bike thousands of miles a year and have done that for 30 years. I bike with a bunch of buddies who have an informal biking group and I’m the administrator of the Google group, the mail group. Almost everybody in that group is there because I met them on the road and started chatting. So I just mentioned that to say well, I’m not shy anymore but it really has been a kind of an odyssey from this early beginning.

Brock: Was that something that you think that in your youth let’s say through high school other people would have described you as shy?

Hart: Not painfully shy but they would not have described me I think of being particularly outgoing and someone who meets people easily and starts conversations easily with almost anybody at any level and any walk of life, which honestly is just second nature to me now and I do it because I like to.

Brock: Just continuing on that line, was there some sort of moment or period in your life where you really made a decision to--

Hart: No.

Brock: --kind of--

Hart: Well, not at all— there was nothing transformative; it was gradual.

Brock: Yeah, interesting.

Hart: --and I think probably was partly due to my wife, who I can talk at length about because she's the love of my life.

Brock: Well, when we get to the point in the chronology when you meet her let's please do that.

Hart: Okay.

Brock: Was religion part of your household?

Hart: Not much, and I thought it was bizarre until I was in my mid twenties and learned more about that. Our family was very strongly Jewish in a cultural sense and not the least bit Jewish in a religious sense and I thought that was, when I was a teenager for example, we are really strange until I learned a little more and I learned that there was an Eastern European tradition of what's called Yiddishkeit, which means the state of being Jewish, which is a cultural and not a religious commitment and it turns out there were quite a few people <laughs> like our family and not that strange at all but we did have a strong Jewish identity and I still do.

Brock: With your father's kind of frustrated interest in a technical career, was he a part of your developing interest in technical things as a youth?

Hart: It's a good question and I think in hindsight probably yes. What I'll say is that in high school-- I don't know how to say this super politely and without coming across as being a little self-important but I was basically good in every subject. In New York City high schools, you got number grades and not letter grades, which again my wife found hilarious because she got A's and A minuses and B pluses and we got 75 percents and 82 percents and I basically got 98 or 99 percent plus in every single subject and won the prize in Spanish or won the prize in whatever. So it wasn't obvious that I had a singular capability and so it's like "Well, what do you want to do?" and probably it was my father's encouragement that I went towards a technical side. I knew I didn't want to be a lawyer and I'm very glad to this day that I never was but I think I could have pursued any sort of career and this is what I chose.

Brock: Was there a time during high school when your movement in that direction toward science, technology and mathematics became more--

Hart: Well, it was quite a bit earlier. When I was in the seventh or eighth grade I won the Westinghouse Science Prize and with the money I bought the largest chemistry set that was made and we built a kind of work lab bench sort of thing in our basement and other than nearly setting the house on fire twice because my favorite section of the gigantic, many-hundred-page manual of chemistry experiments that this came with was a special section called “pyrotechnics.” And it turns out that pyrotechnics was not a good thing to do in a basement with a six-foot ceiling and so <laughs> other than a few horrifying experiments it was great. I did glass blowing and gas bending-- glass bending with Bunsen burners and blow tubes. I could keep a steady stream of air because you learn to inflate your cheeks and keep it going and inhale and so on and so forth so yeah, I became quite adept.

Brock: Well, with the bangs, flashes and stinks you were well on your way to becoming a chemist.

Hart: And here’s a cautionary tale: This is now leaping ahead. My undergraduate school was Renesselaer Polytechnic Institute and at RPI there was a mandatory first-year chemistry class, and it was such a horrible experience taught by such a horrible professor that in one semester it took this young guy’s burning interest in chemistry and decided I am never going to touch that for the rest of my life. So fortunately I’ve had some wonderful academic mentoring but that was an extreme example of a negative one but, yeah, even in the seventh or eighth grade I was very interested in that stuff. And of course it really came to the fore when you had to pick a school or a college when you were in your say junior or senior year and that’s when the die was cast and the direction was set.

Brock: Could you talk about your experience with that Westinghouse prize and what your project was and if that was a big deal for you, which I imagine--

Hart: It was a very big deal.

Brock: --it should have been.

Hart: It was a very big deal probably because there was a certain recognition and partly because we had I would say fairly modest economic means. I mentioned my father was a civil servant and we always had enough to eat; we were never poor but there wasn’t a ton of money and this prize was what allowed me to buy this giant chemistry set. I still remember vividly what our exhibit was and what I did was an exhibit on underground structures-- geological structures that harbored hydrocarbons and so it was all about petroleum, crude oil, and in particular anticlines and synclines and where these deposits or oil fields were and what kind of geology they were based on and how the oil moved through the permeable or impermeable strata and that sort of thing. It was pretty cool and the funny thing is fast forward many decades and I wound up starting the world’s first artificial intelligence center in a commercial corporation – I say that as far as I know it was but we’ll leave it to the historians to confirm that – and I did it for a company called Schlumberger, which is the world’s largest oil field services company. So <laughs> I apparently got an early start in the seventh or eighth grade on that.

Brock: And not an unrelated topic from your expert system Prospector.

Hart: Very related and that. In fact I think Prospector is what caught the eye of Jean Riboud, who was the chairman and CEO of Schlumberger at the time and to call him Louis the Fourteenth would not be to say enough; you would not be giving him enough credit. I mean he dominated one of the world's most profitable companies, Schlumberger, and in '79 or '80 or '81 he said, "Artificial intelligence is the new oil" and through his executive vice president, Tom Roberts, recruited me to start this lab.

Brock: I hope to dig into that in detail.

Hart: Later.

Brock: Was it a Gilbert chemistry set that you bought?

Hart: No. It was Chemcraft.

Brock: Chemcraft.

Hart: You have a tremendous memory. They were two more or less side-by-side competitors. Chemcraft came from I think someplace in Maryland and they had a bunch of sets and this was the giant one and it happened to be almost exactly the price-- well, the price was almost exactly what my prize was so—

Brock: That's fantastic. I mean you were kind of zipping through all your classes in high school but could you describe what your high school was like with their--

Hart: It was a very good neighborhood high school. Before I went there, my parents took me around and we looked into places like Brooklyn Tech and Stuyvesant, which are the obvious ones although quite a long way from where we lived, particularly Stuyvesant in downtown Manhattan, and we talked to college admissions officers and they said, "If it's a good neighborhood high school, that's fine." It was an enormous high school. There were about four thousand kids in it, about a thousand per year. It was probably 75 percent Jewish or more and I think at least 90 percent of us went on to college; it was a college prep high school. I was a handball player. Most people listening or watching or reading about this interview will not know there is something called handball, which is a big East Coast sport, and I was on the handball team in-- for two years. And I also was in the bio lab and the physics lab and the chem lab as a-- and the science honor society and such as a volunteer, but there was one big downside and the big downside of that high school was that it was so overcrowded that we were in multiple sessions starting-- the earliest one started about seven or seven thirty in the morning; the latest one went in-- something to like 6 p.m. And as you progressed through you were supposed to go through different sessions but because they made some changes while I was going through for two years I was in the afternoon session, which would mean that I went to school about noon so what do you do in the morning; you don't play with other-- meet other people; you just hang around doing homework in the morning so you really had no life in the high school. And then in the last two years I had this seven or seven thirty in the morning thing and finished at twelve or one so it really wasn't conducive to a social life because of that so that was the only unfortunate thing, and they did the best they could with the enrollment they had so I'm still a supporter. <laughs>

Brock: Well, as your time in high school was coming to a close and all of your peers are thinking about college, chemistry is on the map for you, what was your university selection process like?

Hart: It was pretty straightforward; it was MIT or RPI and I got into both of them but I had a New York State scholarship to RPI because it's in Troy, New York, and my family financially was in what nowadays would be called a donut hole, namely too much income to qualify for a scholarship at MIT and too little income to have enough to pay and so I said, "Well, that's easy. I'm going to RPI" because there was a New York State scholarship that was not enormous but it was not need based at least at some minimal level and so I went to RPI.

Brock: And was it organic chemistry that was their thing at RPI or--

Hart: Oh, sure.

Brock: --particular draw--

Hart: No.

Brock: --to the chemistry there--

Hart: No.

Brock: --just a good reputation.

Hart: No. It was just a good school and probably wasn't quite at the same level as MIT but it was considered to be a fine technical university or polytechnic or whatever they call it now, but as I said my interest in chemistry was turned off in the first three months and I never looked at it again.

Brock: Well, then how did being kind of repelled from chemistry--

Hart: How did I pick electrical engineering?

Brock: Yeah.

Hart: Well, that was-- so it is a really good question. So I mentioned that I really had pretty broad interests and I still do and what I liked about electrical engineering was that it was so broad that A) it covered lots of things and B) I could foresee that I could specialize out of practically all of it if I got interested in one particular little subspecialty of electrical engineering and in fact that's what eventually happened.

Brock: What was electrical engineering like at RPI in those years? You started there in '50--

Hart: Eight.

Brock: Eight.

Hart: Yeah. So I have to say in all honesty it was a little bit behind the times. They hadn't quite gotten their-- the teaching faculty and RPI at least then was primarily an undergraduate teaching school with a fairly small graduate school. It was a graduate Ph.D.-granting institution but it wasn't very big; it's since gotten I think very different but at that time was primarily undergraduate and they hadn't really quite kept the curriculum refreshed. For example, in a year and a half of electronics there was only a very small amount of time devoted to transistors and that would have been in '61 or '62 and transistors were invented in '48 and that should have been enough time to get a little more solid-state stuff in there so they were a little behind. They were a little behind in offering things like-- or even mandating things like linear algebra and probability theory in the undergraduate curriculum and that was something I paid for dearly at Stanford when I found I was far behind my peers. My first year at Stanford I was struggling because I didn't have these prereqs that were assumed so RPI was good in many ways but it fell a little bit short I'd have to say in those respects. Again because of money I-- for two years-- the last two years there I worked part time in the electronics shop, which was fun because it was in the attic of the double E building that nobody else could go to and you got there by an Otis elevator that was so old, from the 1880s or '90s, that Otis denied ever having built it even though it said in a big brass plate "Otis" on it. <laughs> And I used to do there-- some things were hilarious though. For example, one semester of working there in the afternoons I was building lab setups, six or eight or ten lab setups, for the electronics lab three, which was part of electronics, was mandatory, and the next semester I was in electronics three using those setups and I actually did rather well.

Brock: And was someone in charge of that? What kind of work was it up in that electronics shop? It was--

Hart: Well, it was very varied. So for example we had a lot of scrounged secondhand military equipment that we would scavenge for parts, for components-- electrical components. RPI didn't have a big endowment and still doesn't-- and the-- so we had all sorts of hand-me-downs and castoffs that companies or the military would donate, and I could take apart a typical commercial item and get the tubes out or components or whatever but the mil spec stuff-- the military stuff you practically needed a blowtorch to get those things apart; I mean they were so ruggedized. You just spent all your time on the mechanical aspects like "How do I get inside this thing?" But eventually I'd take it apart and then you grab stuff. So there was everything from that to as I mentioned building electronics labs, student setups, to troubleshooting oscillators that professors were using for demos. It was pretty much everything.

Brock: Did computers then turn into the picture in these years?

Hart: Barely.

Brock: Can you talk about that?

Hart: Barely. It was again I think maybe-- I think maybe at that time RPI was just a little bit slow in coming up to speed so I only had one real computer exposure and that was programming my first machine, which was an IBM 650, would have been around maybe '61 or '2 I did that, which was not a brand-new machine by any means but if I would describe the specs even now it'd be astonishing. Main memory, so-called random access memory, was a magnetic drum with 2000 storage locations. The programming language was pure machine language, pure octal, no symbolic assembler so you didn't say "A-D-D" for "add"; you said "24" or something like that and that was an add instruction. I remember it was a double-address machine and the principal optimization method-- oh, yeah-- you stored variables using absolute memory locations and the principal optimization method was to sprinkle the arguments around the periphery of the drum to minimize drum latency so you didn't have to wait a whole revolution of this drum, "I hope it comes up next!" And of course it was a nightmare to debug even a simple program but every instruction was a two-digit opcode, a four-digit location and a four-digit location and ten octal digits and that was now-- go read that code.

Brock: Yeah. Well, what was your reaction to that?

Hart: It was hard and it made me much more appreciative of high and higher and higher-level languages as the years rolled by because the old joke-- this may sound sexist nowadays-- is real men use assembly language. Well, real men don't actually accomplish that much. <laughs> Yeah, so it was extremely painstaking programming.

Brock: And I'm not getting the sense that it was kind of an aha moment--

Hart: I didn't love it.

Brock: --for you. You didn't love it.

Hart: I didn't love it. I mean I certainly saw the power. I certainly recognized that you stored program. I certainly recognized what it meant to be able to treat programs code like data interchangeably. I certainly got the Von Neumann machine concept but as an intellectual activity it was so painful that it didn't really draw me into it and say, "Boy, I just love doing this." Almost nobody did at that level. It's really hard, painstaking stuff to do even very simple things.

Brock: How did your interest develop during those undergraduate years? Certainly into electronics and electrical engineering. Was there something that you found yourself drawn to?

Hart: Nope. I graduated high in the class and I looked on to the next <laughs> stage in my education.

Brock: In making that bridge to Stanford, was that related to any mentors that you had at RPI?

Hart: I had one mentor at RPI who said, "Get a Ph.D. no matter what you do." I guess he thought maybe I was-- I had maybe a little more than a pulse going for me and he said, "Whatever you do, get a Ph.D. Don't stop" and when I looked at the-- around at various schools Stanford attracted me for two very powerful reasons. The first was I was able to get a full fellowship from Hughes for at least the first year of graduate school and as I mentioned money was always an issue-- money at that scale, at the tuition scale was always a consideration and it was clear that I would get a fellowship only if I went to a

California school; it wasn't an official requirement but it was very clear. The second thing I really liked about Stanford is that when I compared it to Caltech-- I have no idea if this is still true-- Caltech had a very rigid course and curriculum requirement for a degree, almost everything was mandatory and almost no electives, and Stanford at the graduate level was just the opposite; you could do almost anything through electives as long as you put together sequences. They didn't want you to take the first course in every single subject so you did have to put together sequences that made sense but it could be anything; there was I think maybe literally no required classes. So between that freedom, what I can pick and choose, and saying, "At least my first year is paid for" it was a no-brainer—

Brock: How did that Hughes funding come about? How did that--

Hart: It was pretty rigorous. They—

Brock: --materialize?

Hart: I saw that you could apply so I applied. They actually had me interview physically. I went from Troy, New York, down to a hotel room in Manhattan and met some young but adult <laughs> professional that they sent there and we had a very nice conversation, and a little while later I got a phone call in my apartment I shared with my-- some fraternity brothers in Troy saying, "We're very happy to say that we've offered-- we can offer you a work study or co-op fellowship." And I was aware that Hughes offered two flavors. One was a co-op where you basically worked and-- virtually full time and took a couple of courses and the other was a full fellowship where you were on campus full time. I guess this may have foreshadowed a latent talent but I said-- to the gentleman on the phone I said, "Well, I really don't want to be appear to be negotiating with you," I said as I began to negotiate, "but I've already received exactly the same offer from Bell Labs, which has a work co-op program"-- and I had indeed received it; it was not a bluff and you went to Princeton or wherever the school was-- and I said, "Honestly, I really cannot say if I would accept the Hughes fellowship since Bell Labs is also a pretty attractive place." And immediately-- it's amazing how I remember this so many years later, never forgotten-- he immediately said, "Well, in that case I'm authorized to offer you a full fellowship." I said, "In that case I am delighted to accept" and so it was done deal and the next thing I knew I was driving across country to California.

Brock: Did you visit Stanford before you made the decision--

Hart: Yes. My sister and brother-in-law had moved out to southern California two or three years earlier and we drove up and I saw Stanford and I-- well, what could you say? <laughs>

Brock: Did you meet with any of the faculty?

Hart: No, just drove around and said, "Boy, this is nice."

Brock: Well, so when you arrived you entered into the electrical engineering department?

Hart: Yeah. As a little bit of a precursor, Hughes was really good. They gave me a summer job and even a Christmas job but they gave me a summer job, and I worked in the operations research activity there and I learned a lot about search procedures and a little bit about linear programming. Before I had gotten into it with linear algebra, but I learned some stuff in the summer.

Brock: Was that their operation in Malibu or--

Hart: No. It was in Culver City right alongside a big airstrip which is no long-- no longer there, just below the bluff that Loyola sits on top of, yeah. So it was a great experience, spent the summer, trucked up to Stanford and launched into this master's program and it was the shock of my life; it was the hardest year of my life in a professional or intellectual or academic sense by far.

Brock: For what reason?

Hart: Well, several. So in the first place at RPI, as I mentioned I, was pretty much at the top of every class and president of Eta Kappu Nu and stuff like that and there were lots of people you could count on to fill out the bottom half of the class. At Stanford everybody was smarter than me; there was nobody to fill out the bottom of the distribution. The second thing as I mentioned was that I really was lacking some prerequisites, primarily most especially linear algebra and probability theory, and so I was taking those classes, basically upper-division classes or first-year graduate classes in math, in the math department and in the stat department at the same time that I was taking the electrical engineering graduate classes that depended on that so, "I don't think I've gotten to this yet." And everybody else around me already knew that stuff; it wasn't a problem. So it-- I mean, I never worked harder than I did that year; even starting companies, I never worked harder than that year.

Brock: And the hard work paid off?

Hart: Well, I got A's.

Brock: You were successful?

Hart: Yeah. I got A's, and the other thing that happened, bringing the previous story up to date on the timeline, is that I met my wife two or three months after I arrived at Stanford at a party; I was giving her platonic date a ride and I met her and we sat in the corner of this apartment where the party was in Palo Alto and we must have talked for two or three hours. Then I went home and said, "I'm going to marry her" and about a month or so later, maybe it was two months we decided yeah, we would—

Brock: Wow. That quick.

Hart: --and it took a while longer to actually get married but before she graduated-- she was an undergraduate-- while she was still an undergraduate we were married.

Brock: She was an undergraduate at Stanford.

Hart: In the history department, yeah.

Brock: Is she a native Californian or--

Hart: She is a native Californian and her mother was a native Californian and her father was almost a native Californian; he moved to the state when he was an infant I think, yeah.

Brock: And--

Hart: It seems to have worked out so far. <laughs>

Brock: So as that brutal year comes to a close ,I mean had you joined for specifically a master's program--

Hart: Yeah.

Brock: --or were you--

Hart: --a master's program.

Brock: --and deciding to stay on and continue at Stanford. Could you talk about that?

Hart: Well, when I-- when-- after I met Diane and I knew that this was my fate and my destiny I wasn't going to move anyplace in the country without her and so what happened was that the fellowship was only for one year full time and nine months later I had a master's degree. Three different professors offered me research assistantships to continue on to a Ph.D. in the EE department and one by one all three of them called me over the summer to say their funding had fallen through and they couldn't offer me the assistantship so that was my introduction to contract research funding and so what to do. So I got a job at Philco-Ford, which was on Fabian Way where the Jewish community center is now-- the Oshman Center is now on the-- on-- sort of where Charleston and San Antonio cross-- and they had the great advantage of offering an honors co-op program, which was the only way you could take Stanford classes, so I would take a class or two a quarter and I started studying for the Ph.D. qualifying exams, which is-- you probably know was the hurdle in the double E department. If you pass the quals, you'll probably-- nine times out of ten you will eventually finish a dissertation and get a Ph.D. but the Stanford double E department, then and maybe now, had an actual policy of flunking half of the students who took it and, once again, this is Stanford. There's nobody to fill out the bottom half; <laughs> everybody is brilliant, motivated, prepared, tough competition. So I studied and I took the quals-- and I'll tell you a story about that-- and the quals at least then were orals-- I think they still might be-- and it was a half an hour with each of four professors in four different double E disciplines and the typical deal was they'd ask you a question and if they saw you knew the answer they'd ask you a harder one. So there were people all over the map in electromagnetic field theory and semiconductors and systems and so forth. So one of my professors who was examining me was someone I had for a class. Shall I name the name?

Brock: Please do.

Hart: Tom Kailath who's had a brilliant career. I guess he may be emeritus now but a brilliant, brilliant career; at that time he was an assistant professor. And so he asked me a couple of questions and okay, fine; then he started asking me questions about estimating power spectral densities and there are well-known theoretical issues-- at least 50 years ago there were; <laughs> maybe they're solved now-- but I had to do that and I struggled and struggled and struggled and I just could not get what's the right way to do this. I knew what you're taught and I knew the theoretical inconsistencies of what you were taught because it's explained, but what's the fix? I couldn't get there so I was devastated; I flunked. That was in the morning and thenI'm having lunch with another fellow graduate student who happened to be a Tom Kailath student-- graduate student and he says, "So hey, Peter. How did the quals go?" and I was depressed; I was ready to slit my wrists. And I said, "Well, I think I did pretty well with three of them but I had-- Tom was one of my-- "Oh, was Tom one of your examiners?" And there must be 50 faculty or something. "Yeah, Tom was one of my examiners." He said, "What did he ask?" "Well, I-- he asked me some simple stuff and then he asked me this question about power spectral density and"-- I said "Chuck, I absolutely couldn't get any traction on that." So this good graduate student friend of mine tips back and laughs his head off and I was going to shoot him, like "What's so funny?" And so he said to me-- my friend said to me-- he says-- can I use strong language here?

Brock: Please do.

Hart: He says to me, "That son of a bitch." He said, "That's his current research topic. He has no idea what the answer is either" so I thought-- <laughs>

Brock: Yeah.

Hart: --maybe a reprieve. So that night we were sitting around waiting for phone calls. One of my housemates also took the exams and his call comes in first and he's glum and he sits down and he shakes his head; he flunked; he did not pass; he was in the bottom half. Half an hour later I get-- my advisor calls and he tells me some news and I just nod and I hang up and they said, "Did you pass?" and I-- because my friend—

Brock: --is right there.

Hart: So I just said, "Yes," but my advisor said, "In the forced ranking you came out three out of a hundred and fifty."

Brock: Wow.

Hart: That I didn't want to say out of seemliness. And within a week three different professors called me and said, "We have a research assistantship."

Brock: Who was your advisor at that time?

Hart: Well, my advisor was just what they call a program advisor--

Brock: Okay.

Hart: --so was-- he was an assistant professor who I think never got tenure and I never saw again so he was there for helping with the program because you don't have a thesis topic yet. And so I had wonderful choices with wonderful but very different specialists. Joe Goodman who was a world-class laser person or-- I forget-- anyway, but I opted to go with a systems lab that was doing things in pattern recognition and learning machines and things like that and I thought this was really cool.

Brock: And whose lab was that?

Hart: It was in something called the Applied Electronics Lab, which was a little building next to the Skilling building I think it was-- these are all long since scraped-- and it was really not as academic as a pure tenured faculty lab would be. It was more like a-- of course everything was contract research and grants but there wasn't any actual tenured professor responsible for that but that's where the money was; that's where the assistantship was. I mean I had a boss, Don Grace his name was, great guy, but he wasn't faculty and so there was tremendous freedom to poke around and I can tell you maybe the next story-- stories about my advisor and my thesis maybe.

Brock: I would love to hear that. Before we move into that, could I ask you a quick question about Philco-Ford?

Hart: Yeah.

Brock: Was that the former General Microelectronics operation? I think GME had been bought by Philco and then--

Hart: I don't know. It doesn't ring a bell.

Brock: Was it an integrated circuit operation?

Hart: No, it was not. It was more systems-level stuff and I think Ford bought it about-- I was there for only months but I think Ford bought it about the time-- it might have been just Philco at the time that I was there.

Brock: That would be the right timing.

Hart: Yeah. So—

Brock: What kind of activity was going on there?

Hart: Well, they gave me a job as a trainee where I spent a month or two in each of several different departments so one of the first departments I spent time was with Jim Spilker's department. Jim Spilker went on to be quite famous and a company founder in basically signal processing and pseudorandom sequences for obscuring telecommunication and things of that nature. And then I had some others and spent not much time in each, learned a little bit from each and then was back at Stanford when this-- things opened up.

Brock: Well--

Hart: Thank you, Philco.

Brock: Well, please let's move on to that laboratory that you joined.

Hart: So that was a really nice group of people outside of the double E department building in this small adjunct that had a relative handful of people and I needed a topic and I needed an advisor so somebody said, "There is this guy named Tom Cover who was a recent Stanford Ph.D." Stanford as you know doesn't eat their own young, so he had gone to MIT for a year or two to get I guess sanitized or detoxed or something after which Stanford brought him back and the name "Tom Cover" became a legend. He sadly passed away not too many years ago but Tom was maybe one of the two or three most brilliant people I've ever had a conversation with and just a fabulous individual in every respect, almost otherworldly intellectual powers in certain respects, and so I went over to see him. He had just come back on campus, he didn't have a single student as far as I know, and that first conversation, and I still remember, was a two-hour conversation. At the end of the two hours, I knew two things. First, this was maybe the smartest person I've ever had a two-hour conversation with and second, I really, really, really want him to be my advisor, and that's the way it turned out. And so just to give you a little bit about Tom I mean books should be written about him and Marty Hellman who-- example-- for example was one of his early students. I was Tom's student number one, Marty, who's still a good friend, was maybe three or something like that, and he's had-- Tom had many very distinguished students but I was the first one. And Tom had the ability to for example visualize things in high-dimensional vector spaces and the geometry of high-dimensional vector spaces is so unintuitive that most mortals can't do that. He would see it or he would see the combinatorics of things. I mean he was just-- his mathematical insights were like preternatural; even today it's just-- I'm in awe. So we started working on this and that kind of thing, sequential decision theory, nonparametric decision theory although the double E department-- Tom was a fabulous mathematician and statistician and I think he probably had a dual appointment at some point in statistics but at that point-- By the way, he was an acting assistant professor and as such could not legally sign off on a dissertation but I guess I was a pretty good judge of character even at that tender age and I thought by the time I need a signature I bet he'll be a full assistant professor <laughs> and he was, but at that time I was taking a chance. So we started on this world's simplest pattern classification method called the nearest neighbor rule. Have you heard of that?

Brock: Well, I just--

Hart: Shall I explain it a little bit?

Brock: --became acquainted with it in-- yes, please.

Hart: So you convert any pattern, visual or any kind of pattern, into a sequence of numbers that forms a vector. So for example if you're classifying humans into male or female based on height and weight, you would have height and weight for each individual and of course there would be a two-dimensional space and of course there'd be a big overlap of distribution because that's a very unreliable way to tell males from females but there is some separation. So pattern classification is about-- mathematical pattern classification is about converting patterns to vectors -- points in vector space -- and then using some method to distinguish a new pattern as being a male or female or one of 97 different patterns or whatever-- different classes, I should say. So that's what pattern classification is about and there are many, many ways of doing it with all sorts of different assumptions and mechanisms; Probably the world's simplest method is called the nearest neighbor method. Here is what you do: Let's say you just have a two-class problem, A and B. You get a bunch of samples of A, you get a bunch of samples of B, and here comes a new sample you're supposed to classify. You look at your new sample and you look around and you say, "What's the nearest neighbor in this vector space?" to your new sample. Whatever the class of that nearest neighbor is that's what I'm going to say the new guy is. Can you think of anything simpler? We used to say it's almost like a caveman thing, that things that look alike probably are alike. That's the most primitive way, <laughs> maybe a caveman would have done it. So it really-- it probably is literally the world's simplest method for classifying patterns and you make no assumptions about anything. I haven't said these are Gaussian distributions or anything of that nature; it's what's called nonparametric, that there's no assumptions about the statistics, just a bunch of samples. If you have five classes, you have five of these bunches of samples. Here comes a new one; what's the closest one; that's it. Here's the surprise: If you had what's called complete statistical information, you knew the statistics of these classes, which is a lot to know, the provably optimal way to classify problems is called the Bayes decision rule, Bayes rule, but it relies on having this complete statistical information about these classes and here is this nearest neighbor thing, no information statistically. Here's the big surprise: One can prove-- and this is what I proved in my dissertation with some of Tom's insights helping-- what I proved was if you have lots and lots of samples this world's simplest pattern classification method comes within less than a factor of two of the Bayes probability of error. So compared to the ideal statistical pattern classification method that relies on perfect statistical information this world's simplest thing is within a factor of two; it's a little more complicated—

Brock: And high numbers of samples.

Hart: Exactly, with high numbers of samples.

Brock: So that is the asymptotic analysis of your dissertation--

Hart: Yep.

Brock: --that with more and more and more samples--

Hart: You get closer and closer.

Brock: --that asymptotically approaches the Bayesian method or something.

Hart: Yeah. For a two-class problem with equal cost, it's actually 2 R times 1 minus R, which is a parabola that looks like this and which is below the two-- twice the risk would be a straight line and this parabola goes like that so it's actually better than twice the Bayes risk asymptotically. I could say—

Brock: It's better than.

Hart: Yeah. So if you want to say—

Brock: --a better classifier?

Hart: No. You cannot be better than the Bayes risk; it's better than twice the Bayes risk.

Brock: Okay.

Hart: So if you say—

Brock: --approach and the path is good.

Hart: Right.

Brock: Yeah.

Hart: Yeah, and actually to say there's a parabolic curve that's less than the two-- so two straight lines but just for conversational purposes we'll say it's no worse than twice the Bayes risk.

Brock: Okay.

Hart: --better than that but no worse.

Brock: And exquisitely simple.

Hart: Yeah.

Brock: What is the surrounding context for a problem like that?

Hart: Where would you use this?

Brock: Yeah. Well, why was this an interesting problem for you and for Tom?

Hart: Well, so pattern classification at least then was a very hot-- I mean ,so many practical problems can be mapped into that whether it's military problems or commercial sampling problems or-- I mean all sorts of problems can be mapped into that.

Brock: Commercial sampling like quality assurance and things like this.

Hart: Yeah, all sorts of things and I'll give you some more recent examples, but-- so it was a very active field and there's lots and lots of places where you use this kind of technology and I say there's a fat textbook that I coauthored full of these sorts of methods.

Brock: This is your 1973 book.

Hart: Yeah. So there's lots of stuff but this is the world's simplest one that you don't have to know anything except you have to have a bunch of samples. So there was lots of motivation to work in this field, it was a very active research area, lots of people publishing and so on, and I got these result-- I'm telling you the main result but there are a bunch of kind of follow-on subsidiary results, generalizations and so on. For example, suppose you have 20 classes to classify; well, there is a generalization that still works. Suppose you want to be computationally efficient and not store every single one of these patterns because it's a lot of computation. Well, I invented an ad hoc or heuristic method that doesn't have any theoretical properties but dramatically collapses the search and for decades nobody could find a better one than that. Well, I got all this-- these results in three months-- in three months I basically had everything, working furiously. I'll tell you a funny story: It was very mathematical stuff, it was very esoteric mathematics, and I was having-- I was struggling with something and I went over to see one of the most brilliant mathematical statisticians at Stanford. I can't quite remember his name. He was a Chinese professor who had translated a fundamental work from Russian to English; that gives you an idea. Somebody listening to this will know who it is. I went over to see him. He asked me about this, I was looking for help, and he says, "Do you know the dominated convergence theorem?", which sounds almost pornographic but it is a mathematical theorem called the dominated convergence theorem, and I said, "Oh, yes." He says, "Do you know Jensen's inequality?" I said, "Oh, yes." He said to me, "Oh, you know enough." He said, "Now you have to be smarter." So in time I was smarter and I used the dominated convergence theorem and Jensen's inequality, which I had already been trying to work with, and I proved everything that needed to be proved. So Tom's going-- getting ready to go away for the summer at MIT I think it was. I had all these results but it's three months. You don't get a Stanford Ph.D. dissertation in three months so he said, "While I'm away why don't you try to generalize the mathematical assumptions" and I said, "It's an extremely mathematical thesis" and he-- I can tell you what it was, to all "measurable functions, as opposed to all functions continuous almost everywhere". Nobody who's not a mathematician will understand what I just said. Let's just say I already had a very general proof and he said, "Could you make it super general?"

Brock: Okay. Thank you. That translation is helpful for me.

Hart: So I almost rolled my eyes; I couldn't do this. So I said, "Okay." He went away for the summer and that summer Diane and I decided to learn how to sail at the Stanford Sailing Club at Lake Vasona off of

Highway 17, and Tom came back and he asked me, “Did you make any progress?” and I honestly said, “No, I didn’t” and he shook his head and he said, “Yeah. I didn’t think you would.” It was one of the times where I followed my lifelong mantra, which is always tell the truth; it always works. But it doesn’t mean you have to say everything that you know. So I didn’t happen to add that I didn’t try very hard. It was totally unsolvable, but anyway-- and so that was that and I got signed off and I was done and I was signed off by the time I was 25.

Brock: Wow. So you went very quickly through that.

Hart: Yeah. I mean I’m not claiming it was a new land speed record but it wasn’t too shabby.

Brock: That’s interesting because I had already seen that there was three years between the master’s and the Ph.D. but if you factor in that time with Philco-Ford slowing down your pace then it’s actually the time you’re actually really at it--

Hart: Pretty snappy.

Brock: --very quick.

Hart: Yeah. So I said I would fast forward—

Brock: Yes.

Hart: --this stuff so-- and you asked me where is the stuff used. Well, I’ll tell you what people have told me and before I do I will tell you I don’t know how anybody can know this, but I’m told that the nearest neighbor rule is the world’s most widely used pattern classification rule and some of this comes from technical friends at Google who say that Google uses it for all sorts of internal purposes that maybe are known to many people but are not known to me. I don’t know whether checking songs or <laughs> copyright infringement, I don’t know where, but technical people-- and in fact a good technical friend of mine once introduced me to some of his colleagues and he said, “Yeah.” He said, “Peter’s the guy that proved the stuff about the nearest neighbor rule and that’s why we use it in all these applications.” So you or the historian or your colleagues will have to figure that out in more detail, I don’t know any more, but it is obviously very widely used and it’s widely used because it’s simple and because it has these theoretical properties that are very desirable and because much smarter people later on found ways to do approximately the same thing with much less computation.

Brock: And the computation is involved in--

Hart: Well, storing zillions of—

Brock: --comparisons.

Hart: Storing zillions of samples and computing the distances and so-- and in these high-dimensional spaces that gets more costly, and so I haven't followed that area for a long time but I do understand that there are methods that have really sped that up while being maybe a little suboptimal but close and much faster so that's a typical tradeoff that people make.

Brock: Is there a distinction that makes a difference between the phrases "pattern classification" and "pattern recognition"?

Hart: Not really.

Brock: Okay. They're nearly synonymous.

Hart: Yeah.

Brock: Thank you.

Hart: Pattern classification maybe sounds a little more mathematical. I mentioned you transform the real-world problem to a vector space and so pattern classification is kind of what do you do in the vector space and maybe pattern recognition is a little more generic but I don't think there's a big difference.

Brock: Okay. And is that problem of pattern classification intrinsically related to what might be called machine vision?

Hart: Not as much as one would hope. So when Dick Duda and I-- and Dick Duda is another legend-- wrote this first edition of "Pattern Classification and Scene Analysis" it was basically two half books, part one and part two. Part one was the mathematical pattern classification part and part two was the scene analysis part and we thought they're sort of be-- related and would go together and we should put them in the same book; that did not happen. And so they are for the most part fairly distinct and in the last five or eight years with deep learning they've become very, very different.

Brock: Well, we'll get to that when we--

Hart: Sure.

Brock: Did you have any connections with the Stanford Research Institute while you were doing this work--

Hart: None.

Brock: --with Tom? None.

Hart: None.

Brock: I mean it seems like you went over there almost immediately after getting your Ph.D. Is that correct?

Hart: Yes.

Brock: How did that come about?

Hart: It happened two ways. So I mentioned handball playing and at RPI I became a four-wall handball player, which is even more obscure, and there was at the time a small gym in Menlo Park long since gone that had a four-wall handball court. And one of the people I played with was exactly the same age as my father and he was a vice president at SRI and he decided that maybe I could do more than play handball and he was going to introduce me to people at SRI. In parallel but unknown to me, Tom Cover had a relationship with the people who -- first it was called the Learning Machine group and then it became called the Artificial Intelligence group -- Charlie Rosen and Nils Nilsson, and I'll speak more about them later because they deserve some focus. And between these two I had an interview and I can describe a little bit about that and I was quickly hired.

Brock: So you're heading over to the Stanford Research Institute to talk to the Artificial Intelligence group.

Hart: So—

Brock: What did you see there?

Hart: Well, so as a preface for this I'll say I was beyond lucky to hook up at the right time with the most wonderful, remarkable, extraordinary talents that you could imagine and I'll mention three, Charlie Rosen, Nils Nilsson and Dick Duda. So Charlie interviewed me and he asked me a couple of questions and then he drew something on a whiteboard and it was a graph with a curve and he asked me something about it and he asked me what I thought about it. And I look at him and I say, "That doesn't make any sense at all" and he looked at me and says, "Oh!" so I got hired. <laughs> Nils of course is legendary and Dick interviewed me and I thought Dick is the clearest, most brilliant, most gentlemanly person. I mean Dick is just fabulous and so I took the job. I was offered being the head of a group at Lockheed and I was offered other positions around the country and I thought "Who's doing the most interesting stuff?" and "Where will I learn the most?" and it was so obvious so I was there.

Brock: What were the other opportunities? I mean I think that's interesting to compare them to--

Hart: Oh, I don't even remember-- I remember Lockheed wanted me to be the head of a lab and I thought I don't know anything. <laughs> I remember that one specifically; I don't remember all the others but it was just so clear that this was the place to be.

Brock: And could you describe SRI at this moment-- so we're now in 1966-- just the context of the place. What was it like? Was it bustling with activity?

Hart: Absolutely, because of --something else I do: I serve on the board of the Cornell Lab of Ornithology and I'm doing a project there and as part of that I was interviewing Bill Mark, who is the president of the information technology division of SRI. It hasn't changed, the modus operandi, the business model; certain aspects have changed but the basic operation is the same 50 plus years later. So it was terrific, lots going on all over the place. Fast-forwarding just a little bit, I was down the hall from Doug Engelbart when he was doing his stuff. I was in the famous Mother of all Demos; I was in the audience. Doug and his wife and Diane and I used to go backpacking in Yosemite, believe it or not I'm one of the few people who have the honor of having skinny-dipped with Doug, but-- so it was terrific intellectual tone and of course it was the glory days of ARPA, maybe pre DARPA, and we had the smartest people in the world working on-- some of the most interesting people in the world, with not lavish but with adequate funding. And as I later used to tell people, "If you don't like this, I really think you need to find some other chosen profession because it's not going to get any better" so it was fabulous.

Brock: And Charlie Rosen had a big chunk of it.

Hart: Well, Charlie was the head of first the AI Group and then the AI Center; it got renamed. Let me talk a little bit about Charlie because he's an individual who I think has not gotten nearly the recognition that he deserves. Charlie is one of only two or three people I've met in a very long career who truly deserves the overworked labels of "renaissance man," "polymath," "no known bandwidth limitations," "DC to light." Charlie was beyond phenomenal. He knew about communication theory; he knew about industrial automation from his World War II experience in Britain. He did early stuff in learning machines. You know he was a cofounder of Ridge Vineyards, which is a very famous local high-end boutique vineyard-- winery, not just vineyard but winery. He was into hydroponics. He knew a lot about fine art. He was just everywhere and he had such an associative mind. He'd put together ideas from such different fields of endeavor and make the connections and nine times out of ten it was screwy but one time out of ten it was brilliant. He had this enormous knowledge base, an insatiable reader, just soaked up everything, and as one of my best professors at Stanford, Bill Linvill, used to say, "You can't invent with something in a book. You can only invent with what's in your head." You need what he called portable concepts. You can always look up the details later; but to invent you need stuff in your head. Charlie had it. He was also a fabulous mentor, I mean he mentored scores of people, and a terrific humanitarian. I mean you just cannot say enough. He was the principal founder of the Machine Intelligence Corp. as well as Ridge and as well as some other things, but maybe I'll tell one story about Charlie that's also a little bit about my career. This—

Brock: Please do.

Hart: --fast-forward a little bit. Well, but let me give a little bit of background.

Brock: Yeah.

Hart: So I worked very quickly at SRI. I started on the Shakey the robot project on day one and maybe we'll talk more about Shakey later.

Brock: Okay. Interesting. I was wondering--

Hart: --but that-- I worked on Shakey from the day it officially started to the day it ended. Later I was the head of the project and I'll talk to you a little bit about what I did at various stages, but I also worked on the world's first program to recognize human faces, which was done for an unmentionable agency but it was 30 years before anybody <laughs> else did it and of course not publishable so I worked on stuff like that. On Shakey I worked on almost every part of artificial intelligence as then existed other than natural language processing and you could do it then because almost nothing had been done. And I don't know where you'd like the conversation to go at this point. I can—

Brock: Well, I have kind of a detailed roster of some of the things that you were involved in but I would love to hear the story that you wanted to tell about Charlie Rosen and your career.

Hart: So on the Shakey project itself I worked very quickly on something called the A Star [A*] algorithm, which is a shortest-path algorithm which I did with Nils Nilsson and Bert Raphael. I guess I was the lead author maybe just for alphabetic reasons. And that A Star [A*] algorithm is the foundation of all-- everybody's route finding today. When you have your route computed for you A Star [A*] is doing the heavy lifting even though it's got layers of newer stuff on top, and in fact that same algorithm in a slightly different form is what navigates the Mars Rover because there is a forty-minute or an hour signal transmission time. You can't drive a car when it takes an hour between when you do something and you see the effects so A Star [A*]-- it's also by the way what computes the path of characters in video games. So A Star [A*] is everywhere either in its original form or with several layers of elaboration. So I worked on stuff like that and we invented A Star [A*] at that time, but the main thing I worked on initially was the computer vision part, which is not the same as pattern classification, and so Shakey-- absolutely it was mission critical. Shakey needed some way to know what was around it for it to do anything, and to give you an example of what we were working with everything was homemade. You couldn't buy even an A to D converter, we had to make it, and so Shakey's vision system, the robot that's downstairs in this museum, I will tell you delivered digital images at a resolution of a hundred twenty by a hundred twenty pixels, four bits deep, so sixteen levels of gray from black to white on a hundred twenty pixel squared grid. Try to get your head around those numbers the next time you look at your smart phone and you see what your camera does and how many thousands and millions of colors and so forth. So this was early. So here's a story about Charlie and about me; this really was a turning point in my life and it was because of Charlie: Charlie had me in his office and here's the scene: He and I were standing literally toe to toe. His famously bushy black eyebrows were quivering. He jabbed me in the chest with a surprisingly sturdy forefinger and he demanded to know "What are you scared of?" That's an opener. So what's the story? Charlie had just asked me to become head of the computer-- what we called the Vision group-- it was a computer—scene-analysis computer vision group-- and I was being a little hesitant and that's what provoked this sharp poke in the chest and "What are you scared of?" Well, I was the youngest person in the group, the least experienced; the-- we were having trouble making progress. The world's entire literature on computer vision of three-dimensional scenes consisted of exactly one worthwhile paper done by a brilliant guy named Larry Roberts at MIT—

Brock: Oh, yeah, sure.

Hart: --and we were trying to apply some of Larry's stuff to the Shakey situation and hadn't gotten very far and yeah, I was being a little hesitant, "Wouldn't one of the more experienced people be better?", and I was a little hesitant but here's what that poke in the chest provoked: I started asking myself, "Yeah, what are you scared of?" so I started thinking and I started developing a few alternative scenarios as to how the future might unfold if I took this job. I mean the upside was obvious, it'd be great, one of the few groups in the world and I'd be-- the upside was obvious. The downside: So I started thinking about these alternative scenarios and for each I asked myself was it survivable-- was the worst case survivable professionally, maybe even economically in various ways and the answer was "Well, of course it's survivable" so I took the job. And that experience set a lifelong pattern for me because whenever I'm considering alternatives-- they may be opportunities; they may be how to deal with present issues-- current issues-- I habitually try to envision the most likely scenarios and the worst-case outcome. If it's a business deal, where's the exit door on this deal if it doesn't go the way I want, what'll it cost, and I'm always asking, "Is it survivable?" maybe not so much for me but for the organization I'm running let's say or for what-- whatever and most of the time you discover that yeah, the downside is manageable. Of course there are always boundaries but they're usually much further out than you initially imagined. I mean there are limits. I'm not going to play high-stakes poker with Zuckerberg and Bill Gates and I'm not thinking of-- I don't know-- crossing Niagara Falls on a high wire. I mean there are-- obviously there are limits but they're usually further out than you think, and for me that pattern of thought that began with that poke in the chest has been absolutely liberating because it's allowed me to try all sorts of adventurous things, exciting things that I wouldn't otherwise have tried. And it's one of the things that got me away from this very risk-averse, cautious upbringing that I talked about earlier about taking chances and be careful and so on and so forth and the fundamental strategy is will you be able to manage the downside if the downside happens, and maybe it happens in three different ways but if the downside is manageable and the upside is worth it, you can take the chance. So that pattern of thought has been absolutely liberating for me. It's been lifelong and it all started with Charlie asking, "What are you scared of?"

Brock: Good question.

Hart: It turns out not much.

Brock: Well, let's--

Hart: So I went on and became head of the Vision group. Not too much later I became head of the whole project ,so at Shakey's peak I was the project leader. And not too much after that I became head of the Artificial Intelligence Center there, so that poke on the chest really set a path.

Brock: Well, let's begin to dig into the Shakey story. You started on day one of the project. What--

Hart: Well, I started-- yeah, I started on the project-- not my first day at SRI-- it was some little month or two mismatch-- but I started on the first day of the project.

Brock: First day of the effort.

Hart: Yeah.

Brock: What's the lead-up to the effort? Where does it come from? What's the discussion about it?

Hart: That's a good question.

Brock: What did the sponsors think?

Hart: Perfect question but I-- and I happen to know the history in quite some detail. So it was Charlie Rosen's inspiration and Charlie's inspiration was to build a single experimental testbed for integrating all of the subfields of artificial intelligence as then understood. So that included scene analysis, problem solving, language-- natural language, learning. I mean anything you can think of we wanted to integrate into a single experimental platform. And Charlie-- at some point with help from Nils Nilsson, Charlie started promoting that probably two or three years before. And he promoted it to ARPA, and I think it was Ivan Sutherland who was at ARPA at the time who wrote a memo saying, "Yeah, this is great. We should go do it"; there is some memo. Nils Nilsson has this book, "The Quest for Artificial Intelligence," which is the history of-- very comprehensive history up to a few years ago and he has some of I think the original documents in there perhaps. Well, then Ivan Sutherland left the head of-- the director's position and Charlie had to do a reset but eventually got it might have been a half million dollars, and if you look up the GDP deflator there's about a factor of six from then until now so that would be maybe a three-million-dollar grant today, something in that ballpark, and so that's what got it off the ground. Now interestingly enough, we didn't dare call it a robot because you have to remember that until Shakey robots literally were fictional. You know where the word comes from, the play, and you know the toy robots and the science-fiction robots and so forth. So we called it an automaton and because it was the Department of Defense it had to have a mission so the mission was going to be reconnaissance. And if you look at the initial proposal it was for an automaton for reconnaissance applications but that was basically a cover story and the real motivation was a testbed for integrating all of artificial intelligence technologies that then existed, and so the concept was we weren't necessarily going to advance any of the individual parts of AI; we were going to integrate them. Except as I mentioned in the story about computer vision, that part didn't exist. So we had to do a lot of invention and the same thing was true for route finding and so we had to do some invention but that's what research is about.

Brock: For you in particular, did see your work in pattern classification as being part of artificial intelligence in those first three months where you really got it?

Hart: We didn't think about it much; we didn't care about the classifications. Whatever problem was interesting and whatever technology was applicable that's what we thought about; we didn't really think about the taxonomy of the field so to speak.

Brock: When you were initially doing the pattern--

Hart: I never did it.

Brock: --classification. You didn’t--

Hart: No.

Brock: Did you come to identify as being part of an AI community--

Hart: Instantly.

Brock: --at some point? Instantly.

Hart: Very quickly, yeah. So for example I mentioned the facial recognition stuff, so that had a classification aspect obviously but it quickly became obvious that the statistical methods that are kind of foundational were not going to be very helpful in this world of robots; the scene analysis stuff for example was very obvious. You needed to know some mathematics. For example, I worked out the mathematics of perspective transformations for probably the hundredth time in a hundred years, but I did it for us so we could do the projective geometry. So for example if a camera was here and looking down and you saw a point you knew that’s where it was in the real world if it intersected the floor and you knew where the floor was and the mathematics was useful elsewhere. I worked on something in vision. There’s something called the Hough transform you may have heard of.

Brock: That’s on this list.

Hart: Yeah. So that had nothing to do with classification but it did have to do with some mathematics, not very complicated mathematics. I don’t know if you want to talk about that story.

Brock: I do but I want to--

Hart: You want to follow this—

Brock: --dig into the-- The integrative project is also very expansive so I just wanted to chase down a couple lines and just tack down a couple things. Was your facial recognition effort for the three-letter agency before--

Hart: Before.

Brock: --Shakey.

Hart: Before and separate, yeah.

Brock: Interesting. Okay. So I suppose it’s a pattern classification in part.

Hart: It was really a combination because there is a photograph of a face and then a classification so it was one of the examples where you did need to do both.

Brock: Okay. Your comment about the paper on machine vision by Larry Roberts evoked for me the question about Larry Roberts I think in the same period is doing this work on computer graphics and the block worlds and things like--

Hart: Yeah. That was unrelated.

Brock: You were talking about these transforms and perspectives. Is there a relationship between some of that--

Hart: Yeah, the mathematics are the same but—

Brock: In the vision and the graphics.

Hart: Yeah, the sort of output and input you might say, but the blocks world came at MIT just a bit sooner than Stanford but probably a year or two or three after Shakey started. You can check. I don't know the exact dates but—

Brock: I don't know. Yeah.

Hart: --but I think probably just a little bit later. Yeah. So these perspective transformations is just hundred-year old mathematics. There's nothing that we had to invent; we just to apply it correctly.

Brock: And you mentioned Doug Engelbart and his laboratory. Yeah, it was going by the time you arrived. What was the interaction and circulation of ideas like between--

Hart: Not much. I mean we were friendly. Doug and I would go to principal investigator-- ARPA PI meetings for example together and there was some-- a little bit of movement of personnel, I think Jeff Rulifson for example might have been one person who moved between or something, but for the most part we were sister groups doing different stuff and sort of aware. I saw the demos and the first mouse and so forth but we really didn't work together in any meaningful way.

Brock: And one of the laboratories that Charlie Rosen had--

Hart: It was called the Applied Physics Lab.

Brock: Well, also within that there was Ken Shoulders' microelectronics operation--

Hart: Yeah.

Brock: That wound down at that time?

Hart: Yeah.

Brock: That was kind of at the end of that--

Hart: Ken was there when I joined but that ended at some point. In fact, Ted Brain, another physicist-- English physicist-- there was a shoulder, a brain and a heart so you can imagine lots of jokes about that.

Brock: It was a very interesting project and ambitious project in terms of microelectronics from that era. Did you have any impression or interaction with Shoulders and his group?

Hart: No, just social. No.

Brock: Okay. Well, to get back into Shakey then, did your nearest neighbor rule work come directly into the Shakey--

Hart: Not at all.

Brock: Not at all.

Hart: Not at all.

Brock: Simple. And the A Star [A*] search algorithm was the initial work that you got into on Shakey. Is that correct?

Hart: It was probably in parallel with the vision stuff; I don't remember exactly what it was. I mean the A Star [A*] algorithm was a really nice little story.

Brock: I would love to hear that. It's had--

Hart: So—

Brock: --such a long life.

Hart: Yeah. I'll tell the story briefly. So Nils Nilsson and Bert Raphael had cooked up this algorithm. One of them had some idea and told the other, I can't remember which was first, and then the other one said, "Here's a way to make it better" and then I was just walking down the hall and see them in the office and I drop by to see what they're doing and they showed me what-- they said, "We think this is a way we can navigate Shakey." So I understood it, it was very simple, and I went home and thought about it and I still remember sitting in an armchair and staring at the opposite wall of the living room and thinking "You know, this algorithm is special." I didn't have all the steps of the mathematical proof in my head but I was absolutely certain that we'd be able to mathematically prove two things about this algorithm. First, it always works; it will always find the shortest path or the least-cost path. And the model is you have a network and the network has numbers on the arcs between the intersections like distance or time or something and you want to find a path from A to B that minimizes the sum of those; that's the statement of the problem. "This will always find the shortest path," I said, and then I thought not only that but I'll bet that I can prove that it will do this computation with less effort than any other conceivable algorithm that's also guaranteed to find the shortest path. Now you do something like always turn right, that might be faster but it won't always work-- <laughs>

Brock: I get it, yeah.

Hart: --so you've got to-- so mathematically you can use a term from statistics like admissibility, like we'll only consider admissible algorithms, admissible algorithms are those that are guaranteed to always work under all circumstances, and then if you consider the class of admissible algorithms this will do the least amount of computation. And then there's another refinement because this was a heuristic algorithm, which means that it has a kind of a look-ahead function and look-ahead functions can be anything you want and so if your algorithm uses a far more complicated look-ahead function, for example maybe it secretly goes ahead and solves a whole graph and then comes back and say, "Look what I've got." So you need some notion of when the look-ahead functions are comparable or more or less informed so you need some niceties to kind of make it a well-posed problem, but if you say-- you compare A Star [A*] to any other conceivable algorithm that always works and that doesn't have any more information than you give A Star [A*] that other algorithm cannot do less computation.. That's pretty attractive and that's what-- well, that's what made it so widely used and it also was what created almost a cottage industry of elaborations and refinements. So for example in practice today if you want to go from Mountain View to Times Square and you say to Google Maps or something, "Plot me a route, compute me a route," Google Maps may have an absolute detailed street map of the entire U.S. but A* will not operate or its search algorithm will not operate on that level where it considers every conceivable turn. It'll be hierarchical.

Brock: Interesting.

Hart: It'll say, "Oh, let's get in a couple stages to the freeway system, and now we'll compute at the freeway system and then when we get close to New York, then we'll go back down to--"

Brock: Back to the surface, yeah.

Hart: Yeah. So that's not probably optimal anymore, but it's a lot faster, <laughs> and so there are things like that that are what's used and practiced, and practiced today, but the core, the heavy lifting, is still A*.

Brock: And that was kind of a mathematical intuition that you had?

Hart: Yeah. I can tell you how I thought about it. The way I thought about it was in terms of optimistic and pessimistic algorithms, and so we thought that if this look-ahead function-- here you are, you're a computer program exploring this network, and you're at some intermediate intersection. Which way shall I turn, left, or right, or go straight? And there's the goal. My look-ahead function is going to be very simple. You could have many, but here's a very useful and simple one. I'm going to compute the airline distance from this intersection to the goal, to my destination. It's really easy to compute and it's a lower bound on the actual road cost, right. Whatever the road distance is, it's going to be longer, and so as long as that look-ahead function is a lower bound on the actual true cost, unknown at the moment, but whatever it is, then A* will be optimal and maximally efficient. When I thought about it in terms of optimism and pessimism, I said, “You know, this A* algorithm is optimistic because it thinks, ‘Gosh, maybe I can get there that <laughs> fast.’”

Brock: That quickly, yeah. Yeah, yeah, yeah.

Hart: It’s optimistic. So if A* chooses a right turn at this point or a left turn at this point, and your algorithm, your competing algorithm does not, you might miss it. Because you cannot rule out based on the information you have, that might be the shortest route. So any algorithm that fails to explore the possible paths that my A* algorithm is exploring, cannot be guaranteed to always find the shortest route. It’s got to miss something. As long as it has no additional information.

Brock: Right.

Hart: Anyway, that was the intuition, and it only took us weeks. Bertram, Nils and I were running to each other’s offices nonstop and so on and so forth and we got a mathematical proof.

Brock: And how do you-- and forgive the ignorance of this question, because it is just my ignorance, but you’ve got an algorithm, okay, and that’s, you know, a set of explicit kind of rules in the procedure, and I’m wondering, what is-- so you need a language, a mathematical language that is descriptive of the algorithm so you could come up with a proof like this. What kind of mathematics is that? You know, what is that mathematical language for doing these sorts of proofs about algorithms?

Hart: You know, that’s a really good question. I’m not quite sure how to answer it. It’s not pseudo code. It’s not a programming language that you’re manipulating. You’re describing the algor-- well, the pseudo code is extremely simple. It’s saying, “Here’s the algorithm. You’re going to start at the start and you’re going to expand,” which means where’s all the places you can get to in one jump without going through any more nodes on a graph or intersections on a map?

Brock: Right.

Hart: And now you’re at this set of things and, “Here’s what you’re going to compute at each of these intersections or nodes. I’ll tell you exactly how it’s going to be computed, and based on the results of those computations, here is the node from which you’re going to generate the next set of offspring, the next set of route segments.”

Brock: Right.

Hart: And so that’s the language in which you describe that and then the proof says, “Well, the reason its optimal--” got two things to prove, right. That it always works and that it’s minimum computation. Minimum computation, by the way, is not in terms of computational complexity. It’s in terms of the number of nodes that your algorithm expands, that it visits and sprouts segments from. So we didn’t do it in terms of computational complexity, which was in its infancy at the time, but in terms of how many nodes have to be expanded to generate the successors. You know, "I'm at this intersection. Am I going to go and look at the next set?"

Brock: Right. Which would be, sounds to me, like it is, you know, just intuitively, the more nodes you have to do that expands the work on the--

Hart: The more work.

Brock: --more cost of the machine whirring away. Yeah.

Hart: And that was exact-- and that was exactly our approach. We would use the number of nodes expanded as a proxy for computation.

Brock: Yeah.

Hart: That's pretty reasonable.

Brock: So I'm sorry. You were saying, so the--

Hart: I don't know that I have a better explanation. So you describe the algorithm in that way and then you prove the admissibility. In other words, it always works, by saying that at the time that the algorithm terminates, with a path, every other possible route that's been partially but not fully explored, it guaranteed to be more costly. So it's safe to stop searching, because everything else is going to be longer distance, or longer time, or more costly by whatever the measure is. So that's, that's the way...

Brock: So it's the same sort of proof that you would be doing in propositional logic or in geometry?

Hart: Yeah. Yeah.

Brock: That kind of way of creating the argument.

Hart: Yeah. It's not calculus. It's not statistics. It's not modern algebra with group theory.

Brock: Yeah, I get it. Right.

Hart: It's kind of a strict mathematical, analytical sort of thing. I'm not sure. Yeah.

Brock: I get it. I get it. And what did that, with the articulation of the A* algorithm and this proof in hand, was your thought, "Wow. We really have something great that we're going to use for Shakey," or, you know, "Boy. We've just come across a really general purpose?"

Hart: The latter.

Brock: The latter.

Hart: And I'm not sure how much we actually used it for Shakey, because the search spaces were so small that we might not have needed it all the time. But here's the interesting thing from a historical perspective. The three of us, Bert Raphael, Nils Nilsson and myself, thought, "Man, this is dynamite." You have to remember that in artificial intelligence, and we considered this part of artificial intelligence, there's almost never a mathematical proof of anything, at least at that time.

Brock: <laughs>

Hart: I mean, in formal logic you can say, "Yes, this is a sound proof procedure," and so forth, but most of the stuff in AI, you don't prove things. And this is a heuristic thing, because we have this heuristic look-ahead function like the airline distance, and so to be able to prove something that solid and that practical-- and by the way, I always say the most practical thing in the world is a good theory, because you have a good theory, it lets you know the properties of what it is you're planning to do. You don't need to do a thousand experiments. You know the properties. So here is something, the theory matches the practice, and I can prove the properties. We thought, "This is dynamite." Couldn't get it published anywhere.

Brock: Hm. There was no natural home for it or...

Hart: There was, and they kept rejecting it. So for example--

Brock: Why was that?

Hart: Well, for-- we would put it in-- I think, I don't remember exactly. I think we got rejected at least from the ACM journal and from the CACM, if I recall. I can't remember for sure, but I might've given you previously a box of materials that might've had that. <laughs>

Brock: Okay.

Hart: I'm not sure.

Brock: I'll look for it.

Hart: Anyway--

Brock: I don't remember seeing it.

Hart: I don't know. Anyway, and I think the reason was something like the following. Now, the reviewers are anonymous and they don't tell you every detail of their rationale for rejecting it. So to some extent I'm reading between the lines.

Brock: Yeah.

Hart: Ed McCluskey was the editor, and we teased him much later and he said, “What can I tell you? I got three reviews and they were all negative,” you know.

<laughter>

Hart: But... Do I have the name right? Ed McCluskey? Am I remembering the name? Yeah, anyway...

Brock: I think that’s the right name.

Hart: So here’s what I think happens. The editor gets this-- whichever journal it was. The editor gets this manuscript, flips through the pages and sees that it’s full of theorems. Boy, you don’t get that too often. Theorems? Better give it to a mathematician. So you find some mathematician. The mathematician skims the paper and he sees that, for what I will tell you were very technical reasons, I had to put in a condition in order to make the proofs go through. I had to put in a condition. Remember, I said every arc on the graph has to have a number, which is a cost, like, the time or distance?

Brock: Yeah. This is the weight, so to speak.

Hart: Well, not really the weight.

Brock: Is that what they’re called?

Hart: It’s really the cost.

Brock: Cost.

Hart: It’s really a cost function. It’s a metric.

Brock: Okay. Okay.

Hart: And we’re going to minimize the sum. So think of it as distance in the case of mapping.

Brock: Yeah, great. Yeah.

Hart: Okay. So for very technical reasons, I had to put in,as a condition of proving these theorems, that the cost of every arc was bounded away from zero. In other words, I couldn’t allow a sequence of arcs to have ever-diminishing costs that approach zero but never get to zero, because then the path length can become infinite. So for that very technical mathematical reason, I had to say that the cost of every arc was at least some number bigger than anything you like. It could be 10 to the minus 6 but you got to give me a number and say, “It’s always bigger than that.” Well, what that means is that-- let me think about this a second. That might’ve been one reason. The other reason is that I think I might’ve had to have a finite graph. In other words, you’re not allowed to have an infinite number of nodes because--

Brock: Then nothing will ever finish.

Hart: --the map would never terminate.

Brock: Yeah.

Hart: Yeah. So I think what might've happened, and this is just conjecture, but it's, as Carl Sagan used to say, "This is consistent with the observables. You cannot disprove <laughs> my conjecture." But it--

Brock: Probably true all of history. <laughs>

Hart: But-- yeah. But it may not be right.

Brock: Yeah.

Hart: I think what could've happened is a mathematician looks at it and says, "Hey, this whole thing is just for finite graphs. Who cares about finite graphs? They're trivial." From a mathematical perspective. Because a mathematician might not appreciate that there's a difference between a graph with 10 nodes and a graph with, let's say, 10 to the hundredth nodes.

Brock: Right.

Hart: But for computer scientists, that matters.

Brock: It's everything. Everything. Yeah, yeah, yeah.

Hart: So that's just speculation. It's fun to wonder. We'll never know. But we kept getting rejection after rejection. We finally sent it in to the IEEE Transactions on maybe it was called Systems Science and Cybernetics. Name changed over time.

Brock: Yeah.

Hart: And they published it and, you know, the rest, as you would say, is history. <laughs>

Brock: Well, what was the reaction of the community once you got it out there?

Hart: I don't know. And <laughs> I sort of ignored it. We went on to other stuff and then years later you find out it's one of the most cited papers. <laughs>

Brock: So that really, I mean--

Hart: It's used everywhere.

Brock: --honestly, you didn't know that--

Hart: No.

Brock: --people were using it so much.

Hart: No.

Brock: Really?

Hart: No.

Brock: Huh. That's surprising.

Hart: Went on to other stuff. So some people, you know, mine the same research vein for a very long time.

Brock: No. That does not seem to be your case.

Hart: That was not my path.

Brock: <laughs> Well, I just wanted to-- I thought maybe we could spend, talking about the Shakey project, you know, and talk about just-- so it ran from--

Hart: '66 to '72.

Brock: --'66 to 72, and in those years was it-- did the group rapidly expand?

Hart: No. No. The-- of course, the Shakey hardware was very primitive. Reason we called it Shakey, and the reason it shook, by the way, was I think because of the stepping motors that we used. But the software's what changed the world, and after the hardware was built, there was a separate hardware team and they pretty much dissipated except maybe for very occasional maintenance or something. So it didn't really grow. It probably shrunk--

Brock: I see.

Hart: --a bit. A bit over time, but there were few core people who were there from beginning to end, Nils, me, Dick Duda, I think Bert Raphael probably. Richard Fikes for at least a good part of it, and I'm sure Helen Wolf.

Brock: Yeah.

Hart: And I'm sure I'm leaving out, you know, a number of others...

Brock: Could you talk about Helen's role? She was the-- that was the only--

Hart: Yes.

Brock: --female appearing name that I read.

Hart: I have proposed publicly, including when there was the Shakey event, when it became an IEEE milestone in history.

Brock: Yeah.

Hart: I proposed Helen as being the lady Ada Lovelace of robotics.

Brock: Wow.

Hart: Because my particular opinion, and it's hard to really establish this, Mike Wilber was there very early too, a programmer. I think Helen has a pretty strong claim to being the world's first programmer of robots. That is to say she wasn't a researcher. She wouldn't claim to be. There were othesr, we had a very important systems honcho named Len Chaitin who lives up in Oregon now, who was responsible for first the SDS 940 and then the PDP-10 that replaced it, and the PDP-15 combination. I mean, there were certainly other people writing software, but in terms of people who actually had the job primarily as a programmer, someone who implemented ideas from somewhere, I think Helen has a pretty good claim and I've, you know, <laughs> made that argument quite a few times. <laughs>

Brock: So she was programming in LISP too?

Hart: I think she was mostly not. I was programming some stuff in LISP, but I think she was mostly programming in-- I don't know what it might've been, for the vision, the detailed vision calculation. It might've been FORTRAN. I don't remember what it was.

Brock: Was that what she-- I mean, was she--

Hart: She worked on the vision calculations, like the perspective transformation, for example, and I think she probably implemented the Hough transform for me, if I remember. We used that a lot, the Hough, in quotes "Hough." It's actually, I should've-- I was little too modest to rename it, but yeah.

Brock: <laughs>

Hart: That was, turned out be very, very important and that allowed us to make much less use of the range finder than we ever thought we would need.

Brock: And the range finder was like a laser?

Hart: It was a laser-- it was homemade. If you look at Shakey downstairs, you'll see it's got two lenses. One is for the video-- actually a Vidicon tube camera. The other is the pickup lens for the range finder. If you look in this aluminum angular casing, if you ever peer inside, what you'll see is a three-sided mirror.

Brock: Oh.

Hart: And that three-sided mirror spun.

Brock: Spinning.

Hart: And there was a little laser pointing up, and that mirror would sweep a vertical beam and the lens would pick it up, and when you looked at the angle of the mirror and you knew the separation, you could do a triangulation and you knew how far away. So it was not time of flight, it was a triangulating, homemade triangulating. Ted Brain, the English physicist, developed that. But we made almost no use of it because it turned out that we could-- see those baseboards over here?

Brock: Yes.

Hart: We could make use of things like the baseboards of the room and my version of the Hough transform to figure out fairly accurately where Shakey was, and that was used to update the error that accumulated in the dead reckoning. Because I mentioned the stepping motors, which caused the shaking.

Brock: So it's counting as it moves.

Hart: Yeah, to count the pulses. But of course dead reckoning error accumulates, and so we would periodically update the-- update the-- but, you know, sometimes surprising things happened. So every now and then, we would do experiments that were very lengthy and laborious and you didn't do it every day or every week. But every now and then Shakey would stop in the middle of whatever it was doing and it would do a pirouette. It would, like, do a 360 or something, and then it would continue on its way like nothing ever happened. I'm, "What was that all about?" So Mike Wilber, another programmer, I think it was he who dug into the code, and this what we found. The first couple years or so or more of Shakey's life, it was connected to the computer by a giant cumbersome umbilical cord that went through a pulley arrangement in the ceiling, and the reason was it took us forever to get FCC approval for experimental use of a radio link. And so it turned out that buried somewhere in the code was a little piece of code that counted the revolutions that Shakey had made and would reverse it to unwind the cable so the cable--

Brock: Oh, my gosh.

Hart: --didn't get... <laughs> Well, one thing that Shakey did that totally surprised us and it had this funny, low-level reason. You know, years later we have a radio link and we had all forgotten about that.

Brock: Oh. So that was an artifact leftover from the tether.

Hart: From the cable.

Brock: Oh, my gosh.

Hart: Yeah. From the-- it was a quite-- if you look at the pictures of the day, the photographs, it's quite a heavy bundle, actually, a bundle of cables, and so that was, that was really quite... Let me tell you one other story from a--

Brock: Yes, please. Please do.

Hart: From about that year. It might've been a little bit later. But if-- we're so far into the future that if we have a few years' round-off error we're not going to worry about it. So did I tell you my story about the government auditor?

Brock: No.

Hart: This is one for the annals.

Brock: <laughs>

Hart: So one day, I get a call from our contracts office saying, "The government auditor is coming." Like, they come, I don't know, once a year or whatever. So in other words, I should be on my best behavior. Well, pretty soon an auditor comes around. He might've been an ex-Marine. He was all business. He came into my office with a fat briefcase. He sat at the edge of his chair upright, no pleasantries. Pulls a file out. Looks at it. No preamble, he says, "Dr. Hart?" I'm looking around to see, "Who's he talking to right now?" I guess that's me. "It says here that you've taken delivery of-- 9,473,000,000-something-something packets of bits. Is that true?" I hadn't seen that one coming. But I'm on my best behavior, so I say, "Well, that sounds about right. I can check it if you'd like." "That's all right." Literally checks it off. Next question, he says, "Did you set up any procedures to inspect the condition of the incoming packets?" Now I can start to <laughs> get where that's going. I think to myself, "You know, I'll bet there's an error detecting code somewhere in the communication path." Close enough. So I said, "Yes." Checks. Then he says to me, "Dr. Hart, did those packets arrive in good condition? Was there any tarnish or corrosion on any of the bits?" <laughs> Trying hard to keep a straight face. "No, sir. There was no tarnish or corrosion on any of the bits." Check. Has one last question for me. He says, "And did you have adequate warehousing facilities to store all of these packets?" I'm thinking, "Didn't he see all those disk drives in the machine room across from my office?" <laughs> But I was on my best behavior, so I just said, "Yes." He thanked me, stuffed his file back in the fat briefcase. <claps>

Brock: That was that.

Hart: Apparently we passed.

Brock: Oh, my God. Crazy.

Hart: You can't make this stuff up, right.

Brock: Just crazy. Well, it does--

Hart: That's what the world was like then.

Brock: It does lead to the question though about what kind of computing resources were you-- did you require for doing this, the whole Shakey project?

Hart: Well, the big machine-- we started with an SDS 940 and two or three years later we got a PDP-10, with a PDP-15, which was the communication controller for the robot. So I remember signing off on some stuff. It was, you know, big as a room, many, many racks. My favorite rack was you opened the door, it was completely blank panels. Just front panels, just blank panels, except for one little knob in the middle with like a cheesy 25 cent rheostat, and it said, "Speed control, slow, fast."

<laughter>

Hart: I was like, "Oh, what--"

<laughter>

Brock: All the way up. Yeah.

Hart: I don't know what it did but I'm guessing it was a system clock and if you pushed it too fast you'll probably start getting bits dropping. I'm guessing. But anyway, Len Chaitin the system programmer, told me, he'd, you know, murder me if I touched that knob.

<laughter>

Hart: But here's a statistic that you might like to know.

Brock: Yes.

Hart: A key part of that system was a gigantic magnetic drum made by Bryant, long defunct, that was bigger than refrigerator. It rotated on a vertical axis. It was wider than a standard 19-inch rack, and it was a swapping drum used by the timeshare system to swap jobs in and out.

Brock: Oh, yeah. Sure.

Hart: I remember the specs on that. I signed off on that. It had a 256K word capacity and I don't remember they were eight-bit or nine-bit. Wait a sec. I think it might've been 36-bit words, so that's like a little more than 8, than 8-bit bytes. So it's like a little more than a megabyte. It's a little more than 4 bytes per word, so 256. So it's a little more than a megabyte and I remember that it cost $250,000 in early 1970 dollars, and I've looked it up and it's this factor of six and so that's about a million and a half dollars in today's dollars.

Brock: Oh, my God.

Hart: And so it was a dollar a byte and, you know, try to get your head around that number next time you wander down to Fry's and you buy, you know, terabytes or petabytes of all sorts of memory for almost pocket change. So there was-- people today can't imagine that you could write those kinds of programs with those kinds of resources. I want to go back to this Hough transform thing, because I know there's more.

Brock: Yes, please. I was actually-- you saw me shuffling through my papers. I know I had that written down somewhere in my questions but I couldn't pick it out.

Hart: So that turned out to be also very important because, again, of computation limitations and the need to be able to find lines and images. Remember, the Shakey world--

Brock: This is to find the edges of things?

Hart: Well, once you've found the edges, how do you fit straight lines?

Brock: Okay.

Hart: So finding the edges is kind of an image processing step where you do some sort of spatial differentiation or something of the sort to find the discontinuities and the intensities, the brightness. But now all you have is bunch of points, and you--

Brock: And then how do you draw the line?

Hart: You've got to have lines, because I mentioned, we should ask the cameraman to point the camera at that baseboard because that is exactly what it looked like in the Shakey blocks world environment.

Brock: Okay.

Hart: And so you need to fit lines so you know the room and you know the geometry and you know where you are, and so it's easy to spend a lot of computation trying all sorts of things. Well, somebody had-- I guess I had read Azriel Rosenfeld's book and he had a paragraph on this thing called the Hough transform, which was a patent invented by a guy named Paul Hough when he was at the Atomic Energy Commission and was looking at cloud chamber photographs and you get these little dot--

Brock: Streaks.

Hart: Streaks and you wanted to fit straight lines.

Brock: Oh. Yeah, yeah, yeah.

Hart: And so he had invented a, quite a clever method, for transforming those points, all the points in an image, into a transform plane, and his transform plane, each point in the original image corresponded to a straight line in the transform plane, and you could trivially prove in one or two lines that intersecting straight lines in the transform plane corresponded to collinear points in the original image. Oh. Obviously two points are collinear, so yeah, two lines intersect. You know, pair, and if there're three or four or five, then you have that. So it was very clever but it had one fatal flaw computationally and the fatal flaw was that because they were straight lines, using a y=mx+b parameterization for straight lines, slopes go to infinity, which means that the transform plane was unbounded, which is really inconvenient in computers to have an unbounded array. Around that time, Nils Nilsson, who somehow just knows this stuff, suggested that I look into an obscure branch of 19th century mathematics called integral geometry, which by the way, isn't about either integrals or geometry.

Brock: <laughs>

Hart: So I'm looking through this obscure 19th century stuff, and I see that the geometers of the day had very good reasons for using a parameterization of a straight line which I had never seen before. In high school, I learned y=mx+b, just like you did.

Brock: Yeah.

Hart: And instead, they used something called a rho/theta or normal parameterization, which parameterizes a straight line by drawing another line from the origin of the coordinate system perpendicular to the straight line you have and you look at that angle that that line makes--

Brock: Oh, yeah, yeah, yeah, yeah, yeah, yeah.

Hart: --and that distance to the perpendicular intersect, and so there's a sine, cosine kind of thing that says, "So that's perfectly good." Except here's what's beautiful about it. What's beautiful about it is you can parameterize the lines in your space on a bounded transform space where one dimension is, like, 0 to pi, 0 to 180 degrees or something like that, and the other dimension is the extent of your image. How big is your-- you don't have an infinite plane. You know, you've got a square of an image. So that determines the length of the radius, maximum, and the angle, as I mentioned, goes I think was 0 to 180 degrees, 0 to pi, and so your transform space is now beautifully bounded in this tight square.

Brock: I see. Yeah.

Hart: And doesn't go to infinity in one direction, and moreover, also it has rotation invariance so it doesn't matter how you choose your coordinate access, you'll get the same thing. So I said, "Aha." We wrote a paper. Dick Duda and I wrote a paper. We added some clustering at the end because you don't have exact intersections because points aren't exactly colinear, and we just called-- I forget what we called it. Generalized or modified or something, Hough transform, and if I knew how popular that would've been I wouldn't have just continued to name it after Paul Hough. You know, I would've called it a Hart transform, but, you know, I covered myself with boyish modesty and my wife says, "If you were the sort of person who did that you probably would've been intolerable to live with."

Brock: <laughter>

Hart: So was a great tradeoff.

Brock: Well, so how did that immediately pay off in the Shakey project?

Hart: We used that all the time in the image analysis stuff for for multiple applications. One was to look at these geometric big boxes or blocks that we had. Remember, Shakey was in a kind of a giant block world with big cubes and wedges and stuff.

Brock: Right.

Hart: And so we analyzed the image. I mean, there's--

Brock: Coming out of the camera.

Hart: Yeah, that was the basic tool. You do differentiation and Hough transform and-- or Hart transform-- and yeah.

Brock: Hmm, and then-- well, let's trace that line forward. How does that-- that establishes its utility in Shakey and then how does it--

Hart: Well, that--

Brock: --get out into the wild?

Hart: Well, so there's a whole literature on this now. Some people extended it again, built in on that, but what I've been told, and again, I don't know how people know this stuff. Maybe they look at Google Scholar or something. So I don't vouch for any of this. I'm just repeating rumors. But I'm told that it's the most widely used basic image processing algorithm. Now, by the way, this is before you look at modern deep learning stuff that does no preprocessing, right. Modern deep learning stuff and all the fabulous results people are getting now in terms of image analysis. You just put in whole images into a deep learning network and, you know, a 10 or whatever deep neuron, neural--

Brock: Layers.

Hart: Yeah.

Brock: Yeah.

Hart: Layered kind of thing, but at least until relatively recently when people were doing preprocessing of the image itself to try to extract features and fit lines, that's what I've been told. Again, I don't know if that's true. At the very least it was a very popular <laughs> algorithm.

Brock: And that was-- was that also kind of early in the project?

Hart: Yeah.

Brock: Was another one of these--

Hart: Yeah.

Brock: Yeah. Because it set the kind of course.

Hart: Probably early '70s, I would think, or late '60s. I don't remember the date.

END OF THE INTERVIEW

