Oral History of Thomas Kailath

Interviewed by:
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Uday Kapoor: Welcome Professor Tom Kailath. It is an honor and a privilege to welcome you to The Computer History Museum for your oral history. My name is Uday Kapoor and I welcome you very much. First I will do a brief introduction. Thomas Kailath, T.K. to many, was born on June 7th 1935 in Pune, India. As the Hitachi America Emeritus Professor of Engineering at Stanford, he has had an exceptionally long and distinguished tenure. Like a colossus he has straddled the worlds of academia and industry, mathematics and engineering for greater than 50 years. He has guided more than 74 doctoral students, mentored more than 40 post-doc fellows and has been conferred at least four honorary doctorates, cofounded at least six companies and has won numerous awards by prestigious institutions and nations. In 2014, Professor Kailath was awarded the National Medal of Science by President Barack Obama for transformative contributions to the fields of information and system science, for distinctive and sustained mentoring of young scholars and for translation of scientific ideas into entrepreneurial ventures that have had a significant impact on industry. So with that we will start with your interview and we want to start from your childhood. You were born in Pune, Maharashtra to a Malayalam speaking Christian, Syrian Christian family named Chittoor. Please tell us more about that.

Thomas Kailath: Well, a Syrian Christian is an interesting designation 'cause Syria's sadly in the news these days very much. Well, actually this is a church that was founded in India more than 2000 years ago by Thomas, the Apostle who came to India. It's a legend but he came to India and founded a church, was martyred in India. The legend is in 52 A. D. So, it's a church that goes back, you know, to the beginnings of Christianity and one of the requirements therefore is when you get baptized you must have a biblical name. Now the Syrian connection came about because the church was languishing and the first historical record is that in around 400 A.D. they wrote to the patriarch of Antioch who was the head of the Eastern Orthodox Church saying, you know, please send us some priests and so on to help us grow and to just help us, okay. And so they came and some of the-- they brought a new liturgy with them which was at that time the Orthodox liturgy and some of the phrases in it, even after it was translated into the local language, Malayalam, are still the Syrian phrases. Stomankarlos [ph?] means stand fast. Kureaylaysan [ph?] and so on. So but for many-- after, you know, a couple of hundred years, I mean much later in this century and I don't know all the details there was a split in the church because between those who still paid allegiance to the Patriarch of Antioch and others who said, look, we, you know, we are now large enough, we are big enough, we should be independent. So they broke off and there's something called the Malankara Orthodox Church. So now we are-- most of us are now known as the Orthodox Church. No longer as Syrian Christians but that's the older tradition.

Kapoor: Right. So, of course that is the history of the Syrian Christian Church in Kerala.

Kailath: Yes.

Kapoor: You were born in Pune. So how did …

Kailath: My parents, I may have mentioned something about that earlier, moved to Pune in the early 30s when my dad-- I'll talk about my parents later.

Kapoor: Yes.

Kailath: But so I was born there and grew up there. It was a nice educational center. My father had a good job as a botanist with one of the leading, the leading seeds, flower and vegetable seeds companies in India and I had a great education in Pune so that's how it got but as you know in India you are always sort of identified with the-- where your parents grew up and where they are from so I'm known as a Malayali.

Kapoor: Right.

Kailath: Though for reasons I won't go into-- it's a long story, basically, I can understand Malayalam but I can speak it in a very broken fashion with a bad accent and so my main language is English, actually.

Kapoor: So did you learn Marathi?

Kailath: No. You know, in that time there was no Maharashtra. I'm from an old generation. Bombay presidency, actually when I was born. And then after independence it was a Bombay province and then it split into two, many years later, Gujrat and Maharashtra. So now it's Maharashtra. So Marathi was a local language. But this goes back to-- so the Pune is divided like many cities in colonial India into a cantonment region and the old city. The cantonment region was where the British troops and the Indian troops who were recruited into the Indian army were lodged and then of course a population grew up around them which was more cosmopolitan than the city which stayed more traditional. And so I went to a school where we had people from all parts of India. It was called Saint Vincent's High School, one of the many Jesuit schools in India which, you know, provided a great education and we had people from Bengal, from Kerala, Maharashtra, from Gujrat, from Rajasthan, from Punjab, Sikhs from Punjab and so on. So the only common language is English. And so I never really learned too much else.

Kapoor: Okay. So what was your childhood like?

Kailath: Well let me continue for a moment with why I don't speak Malayalam. We used to speak Malayalam at home but my mother had put me into the fanciest English school in Pune at St. Mary's and they refused to pass me out of kindergarten. <laughs> So my mother said, well of course that's not my son. The school has something wrong with them but she transferred me out which was very good to St. Vincent's. But they felt that, you know, my feeble brain couldn't handle the fact that the language at home was Malayalam, the language in the street was Marathi and Gujrati and the language in school was English. So though my mother was not very fluent in English they decided to speak to me in English and so that's what happened. But by the time the other kids came around they had wised up and they went back to Malayalam. So I can follow. They can't really hide secrets from me but I still therefore respond in English.

Kapoor: Right. So going back to your family can you say some few words?

Kailath: Yeah, my, you know, as I was saying at lunch you often tend to not appreciate your parents or what they do while they're alive or what they, what their own lives and careers are. At least in those days when, you know, India was a very different country from what it is now and people's careers were mostly partly scientific, partly clerical and so on. So my dad came from a large family with five siblings, all boys which was basically a farming family. The Chittoor Family had estates and so on but he was and, you know, I stand subject to correction, to my knowledge, he was the first one in many generations and among his siblings to get a college degree which he did it with considerable effort because the nearest college was about six miles away and he didn't have enough money for the bus so he would walk there, rent a room for three or four days during the college week and then walk back. yeah and he got a degree in botany and did very well actually and he had an amazing gift for drawing and we still have some-- at least my nephews and others have taken these away, his old notebooks of flowers where the stamens and whatever, all the things I don't know, are shown in great detail so he was very talented in that way. And he started life-- well after he was married and talk about marriage. In those days it was very traditional. My mother was almost finishing high school I think in a different town and one day her father said to her, "Well you are getting married!" And you didn't say anything in those days. "Okay, my own father says getting married. I trust that he has found a good boy for me." And she saw her husband, her future husband in the church at the time of her wedding. <laughs> But though she didn't finish high school and most of her education was in Malayalam, you know, so never the less she was quite an independent and determined and free spirit and she soon began to feel-- and she came from a family where she was well treated though she was a girl, which is not always the case in those days because the expectation is and I'll tell you what my wife said, "You know, you get married. You have children and so on." You don't think of a career and things like that but she had freedom and in her husband's home where she had to live in the beginning she felt too constrained and so on. So, she's persuaded, in fact probably insisted that my father move away and so they first went here the job in the college, in Miraj [ph?] which is a part south but that's a small town. And then he got a nice job as a botanist and in one of the leading, perhaps the leading flower and vegetable seeds companies in India called Pocha [ph?] Seeds, Pestonjee Pocha [ph?], Parsee [ph?] family. So he worked there for many years and in India that and, you know, he-- we were not-- none of the kids except my sister followed in the biology field, but he was a passionate reader and so instilled in us a love of reading. And, you know, my mother was a sort of managed the household with a relatively low salary so she would control the spending and make the small investment she could and so on. But the one thing that she didn't resist my father doing was buying books so he always had books. Sometimes old books with people would come around with collections of old books and that was always a joyful time in the house because he would buy a lot of books.

Kapoor: Right.

Kailath: So I had a, reading has been a big part of my life since then. But my mother was very determined and she taught herself English and taught herself many things and she wanted to make sure that all her children studied hard with discipline, got a good education and so on. So I have two brothers and three sisters. The second-- every two years roughly except of the last one who came after a gap of several years, the second one felt that he wasn't that great in academics and so on so he joined the National Defense Academy which was relatively new at that time for the joint services program in India and he did well there no matter what he had to study and he got the Sword of Honor when he graduated and then he joined the Indian Navy and had a great career there before he retired. The next was my sister who went to medical school and got a medical degree and then got married, moved to Bombay and set up a flourishing practice in gynecology, obstetrics gynecology and it was quite well known. She had a thriving practice. She had a couple of what are called ectopic surgeries where the fetus is outside the womb. So it's very dangerous and so on but she was able to handle that. Okay. Then the next two children were girls. One of them got a college degree and got married and many years later we brought them to this country and she is in the accounting field. And the next sister had some hearing problems, undiagnosed for a long time. So she struggled in school and so on but she got a B.A. and the kids' joke, the family joke is that it's my mother who got the B.A. <laughs>. She did the whole work and so on. Then many years later they, about eight years later, we had my youngest brother who then went into medical school but at that time he couldn't get direct admission to medical schools. He got into dental college but my mother didn't want a dentist. So she maneuvered in various ways after a year to get him into a regular medical college and so he, he's done well and after he graduated we brought him over to this country where he's a very successful oncologist and he lives in Sacramento. And my sister who's an accountant was also brought over to this country and so that's on my family side.

<crew talk>

Kapoor: So let's go to the next phase of your schooling and I read somewhere that you dreaded mathematics in the sixth grade and would duck behind a student in front and you would pass exams …

Kailath: That's an interesting story…

Kapoor: … by memorizing solutions to all the homework problems.

Kailath: Let me elaborate on that. You knowinherited from my father and mother I think I had always a good memory. It's weakening now but I was good in languages, English and so I managed to always top the class in the younger grades except in mathematics when I struggled and would get 35, 40, just barely passing grades, 'till I came to the sixth standard which was an unusual-- by then there were more students in the class. So there were two sections for mathematics and the first section was taught by a very unusual semi-genius type of, frustrated genius type of professor who should have been teaching in a college but, and he came from the city, a famous Brahmin [ph?], so called Chitpavan [ph?] Brahmin [ph] families, you know, who don't really mix with the hoi polloi and so on but he had a job in St. Vincent's so he would himself walk three or four miles not in the western clothing which all the other staff had. We had-- it was a Jesuit school so we had a lot of fathers from Swiss Italian background who wore the cassock [ph?], you know. But he came in a dhoti, you know, which is very untraditional but he didn't bother and he was a very brilliant teacher but very sarcastic and so on. So when I came to that class I was assigned to the section that he would teach and the system was that you were in a classroom. The professors, the teachers came and went. You sat in a fixed position for every class. So Mr. Joshi, Gomati Joshi, said to me, "Oh, welcome to my class. I hear you're the top student. I look forward to having you in my class." That petrified me because he didn't know that what my actual grades were in math. So I was nervous about it, but luck. Luck has played-- luck and people have played a great part in my life. That year there were two extra students in the class so the desks were duplex desks. There were two people at the desk. Two, two, two. That's how the section went. So they put another two, desk of two people right in front of the first row and it so happens, I don't know why, I was in the second row, therefore the second full row, the left most. Now Mr. Joshi's pattern was he would come into class, sit up on the chair, cross his legs and sit in a typical Indian style in his dhoti. Open his snuff [ph?], take a tip of puff of-- what do you call it?

Kapoor: Snuff______

Kailath: Yeah, <laughs> and start questioning the students. Point to the first one and ask him a question. He would stumble. He would humiliate him. Move to the next one and he was too lazy to start again from the left so he would take the natural choice which was the third person whom he saw more easily. So I was never humiliated in class, okay. Secondly, Mr. Joshi, it was beneath him to set the problems for the exam. There would be homework but it was graded by the other teacher who was more of a plodder [ph?] and he would give a lot of homework and then give the solutions at the end and he set the exam but it was well known that he would draw the exams from all the homework. So I used to borrow the notebooks from the other section and memorize with my good memory the problems. But after you do that for a while, especially in geometry you begin to get interested and so Euclid appealed to me because there was logic. You didn't have to rely on memory. So that's how I got into math and we became actually quite good friends, this teacher. I visited him in his home and he had a big influence on me because when I graduated from high school the natural thing to do was to go to the local college in the cantonment which was sort of quote on quote a party school in those days. It was Wadia [ph?] College, a lot of Parsees and so on, more westernized. He said, "You know, you really are an academic. You should go to the city college, Ferguson College, which is much better for you." I said, it's, you know, far away. It's six miles. He says, "No, you should. It's worth it." So I bicycled every day. Pune was relatively friendly except near the college you had to go up. Pune had the largest number of bicycles in the world after Amsterdam. So I went to Ferguson College. I got-- my school education was first class actually. In English-- do I have time to talk about this?

Kapoor: Of course.

Kailath: You know, we had the principal taught us English. He was Swiss Italian but, you know, their English was perfect. Every week or perhaps two weeks, I forget, we had four assignments. One an essay, one paraphrase of some paragraph that you read, a pre-essay of something that you read, and then an appreciation of a poem that you had to memorize. So and then he would redline these essays and paraphrase and so on so you got I thought a very-- and then he would encourage reading and I always was a reader on my own. So I got an excellent education in English which was somewhat augmented at MIT. I'll tell you when I come to it, and to be honest much better than what my kids got in Gunn [ph?] High School which is one of the best high schools in the area but, you know, the discipline of writing is not emphasized that much in the schools here. So and the college was very narrow. You had to choose one of two things, physics, chemistry, biology if you went to medicine; physics, chemistry, mathematics if you went to engineering or Arts if you were in humanities and this was a two year college. And so it happens and so I enjoyed it there and I created a bit of a stir in the old city because the schools there were much more focused on education and ranking in exams and so on, than St. Vincent's which was a more-- I had a lot of sports activities and debating and so on which was not prevalent in the other schools. So there was a flutter in the dovecoats of_________ the old city when a gentile like me stood first in the intermediate exam, right? <laughs> So but that was useful for me because the engineering college admissions in those days were, as in the IITs, there is a rank ordered list from this exam and you get to choose your major depending on your rank.

Kapoor: So I wanted to ask you a question on going back to the teacher that you worked with in geometry because that, for some reason, that made you very interested in mathematics.

Kailath: Well, you know, I liked the logic of it and I must say and people are sometimes surprised to hear this so we had good friends and we had a team of people who would have a competition with each other, would sit down and pick what they called Riders. These are the problems in Euclid very traditional books, and say who could get the solution first. So after a while, you know, I would say I saw the first step of the proof and so I raised my hand. I have the solution. And while I was talking about that my mind would be working out the next step and so on. So this gives you practice and sort of logical thinking which and so on. So I began to get turned on by the subject actually and geometry I think it is a great subject for that.There's a story of a famous English writer, Thomas Carlyle, who one day was in a friend's house and he happened to see a copy of Euclid open and he started-- he was a lawyer I think or barrister as they called them, and he started reading and said, "Hey, this is very good logic." So he got interested in Euclid. So that happens to many people, you know, that logical thinking. And I have a peculiar theory that people who are good in writing English are often also good in math because to be a good English writer you must organize your thoughts in a logical, sequential manner, not a stream of consciousness essay that you write as things come to you as it's happening to me now, for example. No, you have to be disciplined about it and the logic that you need to do problems in geometry helps you when you organize your writing. So I think both should be taught together.

Kapoor: So we can come back to the topic of mathematics a little later because I was thinking that on one hand the visual, logical aspect of geometry versus the abstract thinking of abstract mathematics, how they are connected, and we can come back to that topic.

Kailath: Well, no I mean though geometry is visual in some ways but, you know, the proofs don't really depend on the diagrams because the diagrams can be misleading. So, you can't guage that so you have to rely on the algebra of it, I mean the logical steps of it to do the reasoning. So actually my spatial memory or visual memory is not as good as my oral memory or the memory that I get from reading so that's peculiar. I have not a good sense of direction because I don't pay attention to that partly because my vision was always quite limited. I had glasses which kept getting higher in power and ended up at minus eight, minus nine. So that's the difference. So it's the logic of the geometry of Euclid that appealed to me.

Kapoor: So, moving on to your career selection. You were contemplating careers in civil service or working for All India Radio, for example. Is that true?

Kailath: Well, there were not many choices of jobs at the time, you know. If you were in engineering the biggest field was civil engineering where there was a lot of construction. That was the main industrial activity. Actually, there was no manufacturing and so on. There was a relatively new field of telecommunications and the College of Engineering in Pune where I-- which is the natural place to go to, had one of the-- it had a relatively new program when I graduated in 1951 that started in 1948 by quite a remarkable-- another person who influenced my life, Professor Chandra Shekhar Aiya [ph?]. So I was told about that program which was quite an elite program. It took only ten students per year and so I would have that opportunity available to me because of my rank and, but what were the jobs there? There were only two kinds of jobs. One was in the radio, All India Radio or in the Post and Telegraphs or in the Railways for the Telecom part of the Railways. But many people would then go into the Indian Administrative Services which was in a way the more prestigious service because it followed, you know, they were-- they became collectors and magistrates and had a lot of influence and, but somehow I felt that I was more inclined to the mathematical field and that so and the Telecom sounded attractive to me and so I decided to do that but this wasn't so much in high school. This decision had to be made in those two years of college.

Kapoor: So you graduated in 1951.

Kailath: From high school, yes.

Kapoor: And I read somewhere that you were exposed to the new field of information theory in an article you read in Popular Science.

Kailath: That's right and I, you know, I think it was probably in '50 or something like that. We couldn't quite find the magazine now again. Ross Bassett, who interviewed me, found it in a Science Digest of around that period, but that intrigued me because this was a subject which had caused a splash when it was new and I remember one of the things that I thought was nice was, you know, television was very new in India at that time and I knew that television, like movies, flashed the same picture with small changes over and over again so that you had a running scheme, but information-- one of the less significant but nevertheless things that appealed to me in that story was, they said people realized in-- after information theory there's so much redundancy there, because each frame is almost the same as the earlier frame, so all you need to keep track of is the differences, which takes much less data and so on, so that is the data compression part of information. So I thought, "Hey, this is"-- and it's mathematical, so nice application and good mathematics, so that's what intrigued me.

Kapoor: So I also read-- you mentioned Prof. Aiya and there was another gentleman by the name of Dr. Jaswant Krishnayya, so apparently they also influenced your...

Kailath: Yeah, there's-- actually, there's a different name. Jaswant is the son who studied with me...

Kapoor: I see.

Kailath: ...but the father was Dr. Steven Krishnayya, G. Steven Krishnayya. Let me come to that story a little later, because you see, so the pattern was that after high school, you went to this two year college, which then led you to medicine, engineering, or a BA. Now, it's in that college that I heard about this program that Prof Aiyaph?] had started.

Kapoor: So this is in Ferguson College?

Kailath: Ferguson College, yeah, where I started basically chemistry, physics, mathematics, and so on, and had some good teachers there, one or two of whom I kept in touch with later, but one was a very unusual young woman, a Tamil Brahmin who married against the opposition of her family a Maharashtrian Brahmin against the opposition of his family <chuckles>. She was a wonderful person and very brilliant woman, came later to this country after having her kids and so on and got a PhD and has been teaching here and she's now in her mid 80s, but still awake and alert and we're in touch with each other, but anyway, so when I got into engineering college, telecom was the field, though it was a three year program and the first year was common to all branches of engineering, so we had things like surveying, engineering drawing workshop, things that are no longer in the curriculum here, metallurgy and so on. The second year was a little more focused for people who are taking electrical engineering and telecom rather than power and metallurgy and so on, so we had courses in electric machines, which again we don't have anymore and so on, and the third year was the focus on telecom. So that was when I began to know more about Norbert Weiner and cybernetics from the library and the mathematics of electrical engineering because the education there was nonmathematical. We had one textbook, a famous textbook around the world of that time, Fred Terman's Radio Engineering. It was the Bible.

Kapoor: I still have it.

Kailath: You still have it, yeah, so that was our only textbook, but it was a good textbook, but no mathematics, very little in mathematics and you had to memorize that, but I discovered Boolean algebra then and we had courses in telephony and telegraphy, so we had to design relay circuits and those textbooks didn't know about Boolean algebra, and so I gave-- read about it and I told Professor Aiya. He said, "Oh, give a lecture to the class about it," so I told them how they could design the circuits more quickly using Boolean algebra, so that was interesting. And then we had differential equations and I discovered Laplace transformers and Heaviside was one of my heroes and so he encouraged me to give evening lectures, of course, on that. And this helped me in my application to MIT, so now comes Dr. Krishnayya. Hardly anyone thought of going overseas for studies in those days. You got a job. In my case, I was interviewed actually after graduation by All Indiaph?] Radio and-- but Dr. Krishnayya, his family used to go to the same church that our family go to, so we knew them as a family and their son was a year senior to me in engineering college, in the telecom program. Dr. Krishnayya was a remarkable person who had got a PhD from Columbia Teacher's College in 1929, went back to India, had a successful career, was inspector of schools. After independence, he was sent by the government as educational attaché in Washington for two years, where his son studied and he would-- as educational attaché, he would visit numerous universities and so on, so he knew America well. So as inspector of schools, he would come to the schools to see how they were doing and of course, St. Vincent's was one of them and in each class or a few classes, they would trot out the good students, so apart from the church he saw me here, so he said to me, "What are you going to do after this?" I said, "Well, you know, All India Radio or Post and Telegraphs, maybe IAS." He said, "Well, you should go overseas, you know. You should go and study abroad." I said, "That's not possible." We have some professors in our school who got Master's degrees from America and I talked to them. They said, "It was a dream for me, but I thought impossible dream." And they discouraged me and said, "It's very hard to get into American colleges and so on, plus very expensive." He said to me, "I'm going"-- he had started the first children's magazine in India called Sunshine, at the time, following the magazines that you could get in America, Scholastic and so on, which the kids get. So he would every couple of years go on a lecture tour of American places, universities, churches, Rotary Clubs, raising funds for this educational purpose, so he said to me, "I'm going to America. Have your-- give me your transcripts and have your professor write me a letter." Now, here is Prof. Aiya. Most people write very bad letters. Often in fact, his colleagues, if you ask them for a letter, they say, “You write it and we’ll sign it.” No, Aiya was trained at Cambridge and very independent soul, very self-confident, streetwise academic, all unusual characteristics in India. He persuaded the government to start this telecom program.Though that was not his field, but he saw it as a coming field, so he decided to do that. He wrote a beautiful letter for me, mentioning my extra classes and my high grades and so on. So he took it with him. That inspired me to at least write a letter of application to Harvard, because he said, “MIT, I’m going to take it.” Lo and behold, after a few months, I got an offer from Harvard as a teaching assistant, but by then I’d discovered information theory, again in a more technical way, and that's an interesting story again. We had external examiners in the courses for an oral. Quite a brilliant Post and Telegraphs man called C.P. Vasudevan[ph?], whose son is a well-known engineer in the Valley now, was the external examiner, and he asked me-- after I answered some of his questions, general questions (I told him about Norbert Weiner and so on) said, “Do you know about self-correcting codes?” I said, “No, what are they?” Says, “In information theory, there is this topic of error correcting codes, so you should learn about that.” Now, that book was not in our library, but fortunately an older student, who was doing his PhD with Aiya-- Aiya started the first PhD program in engineering, at least in electrical engineering and telecom in India. He had that book, so I heard about it and I read the name Shannon, so I’ll tell you about Shannon later. So I waited-- I was tempted by the Harvard letter, but I wanted really researcher-ship at MIT and that offer came through, so that's how I ended up at MIT.

Kapoor: Right. That’s a very, very nice story.

Kailath: And one more thing. So you got admission to MIT. There’s a scholarship and all that. You need money to travel and airplanes were very-- I mean, took a long time to fly here. To go by ship was cheaper, but still more than my family could afford, so my father worked for this I said seeds company, which was run by a Parsee, who, you know, he would meet the kids and so on, and I would be first in class, so he would give me a check for a hundred and one rupees when I graduated. Said, “One rupee is for chocolates.” <laughs>

Kapoor: <laughs>

Kailath: Hundred rupees, give it to your dad. <laughs> So my father told him, you know, “We have this problem because my son has admission to MIT.” He said, “You know, the Tata family, whom I know well, has the Dorabji Tata Trust loan scholarships for travel abroad. Let me write to them.” So he wrote to them and they said, “Yes, you can come and we’ll give you a scholarship,” and there was a formidable Parsee lady called Mrs. Vaysagar[ph?], who after they give you the scholarship, you had to go and spend three or four days in Bombay and she would first of all buy a-- have a suit made for you, then insist that you sit with her, learn how to wear a tie, learn how to use a knife and fork <chuckles>, because in those days we did not. We sat, you know _Kerala_______ style, but we had plates and all that, but _in Kerala you eat on________ banana leaves and so on. So that's how I got money to come to England by ship, first by P&O, terrible British ship with horrible food, and through the Suez Canal, which is interesting, and landed in Southampton, went to London, where a senior student from our college was at Imperial College, so there was 10 days between that and the next flight, so I met some of the professors. They were very available at that time. One was Dennis Gabor, later invented holography and got the Nobel Prize. I visited him. He was very open and he told me, “Oh, you are going to MIT. Yes, Norbert Weiner is there and he's building an adaptive filter with racks and racks of equipment. You know, we are British. We don't have the money. We are doing it with strings and ceiling wax and I'm sure my system will work better than his," and he gave me his notes on quantum, so it was great. So then it was a French ship coming to America with a lot of young American men and women who had spent the summer in Europe going back, and unlike the British ship, where lunches were half an hour and you were pushed out, the lunches were French style, couple of hours, relaxed and so on, so it was a nice experience and then seeing the Statue of Liberty and landing in New York.

Kapoor: So how long did you stay in England?

Kailath: Ten days.

Kapoor: Ten days.

Kailath: In London mostly, and then you had to catch this boat from Southampton.

Kapoor: So you mentioned Prof. Shannon. I understand that you communicated with him.

Kailath: Yeah, you see, so when I learned that I was going to MIT and now that I had this book-- his work was first published in two long papers in the Bell System Technical Journal in 1948 and then reissued as a book a year-- a few months later from University of Illinois with an appendix by Warren Viva, which gave an overview of information theory, but the Bell Labs reports were all-- I couldn't afford to buy the book. I'd only borrowed it. And I mean, my friend-- anyway, so I knew the Bell Labs reports because some of them were in our library, so I wrote to Shannon asking if he would send me his reprints of this and I got a reply from him, a nice letter saying-- and I told him I was going to MIT. Said, "Yes, I'm sending you by separate post my papers, some of my reprints." This came on an aerogram. No, no, maybe an envelope and he says, "I'm happy to hear I'm going to MIT. I must tell you that I'm leaving Bell Labs and I'm moving to MIT myself because apart from Bell Labs, that's where most of the action is information theory," so that was encouraging and I wrote back and said, "I'll see you at MIT" and so on, and so he-- okay, so I went to MIT. Shannon was not there. He had come the year before, but he was invited to the Center for Behavioral Sciences at Stanford, so he spent a year here and when he came, he said after he wrote back, "How can people do any work in this area, because the weather is so beautiful most of the year, so you know this is a gods' country." <chuckles> But he came back to MIT and the system there was in the famous research lab of electronics, where a lot of developments were made, including information theory. It's a long corridor. MIT's full of long corridors, one called the Infinite Corridor when you enter. There's a book by that title, so the students were on one side, professors on the other, so all these famous professors, students three or four in a room, professors in their own room, Farno, Elias, Hoffman, Wiesner, Shannon, so I bump into Shannon in the hall. He didn't teach particularly. He would taught-- teach one seminar course a year, which I took, on his unpublished work. And so I said to him, "You may not remember that I wrote to you and replied." He said, "Well, I don't really remember, but there must have been something unusual because I hardly ever reply to letters. I get too much mail," so that's nice.

Kapoor: Yeah, that speaks well to him, yes.

Kailath: Right.

Kapoor: So talking about MIT, maybe you can describe your experience there, the system of education, which is very different from India.

Kailath: Oh, yeah. The system was very different. India, even in telecom, apart from the math course and so on, relied on memory. Terman's book was not an analytical book. He described amplifiers, propagation, and so on. MIT, the courses were-- the problems were what we call thought problems. You didn't have to remember a formula and plug in. You had to reason it out for yourself, and I had the good fortune, first of all, to go as a graduate student and also with a research assistantship, so instead of four courses, which is the normal load, you took two. And secondly, the first three or four months, though you are nominally a research assistant, you weren't bothered by doing research and so on. I mean, this is a theoretical group, so there was no lab work to be done, no experiments. If you're on the physics side, you had to actually work in the lab, so Jack Wozencraft[ph?] was assigned as my advisor, but one of the most famous professors there and late-- even now was Robert Farno. And after meeting the first individual who ran the lab, a salty character called Henry Zimmerman, who used to use American slang quite freely-- I remember with some trepidation, I asked him-- I said, "There are so many courses at MIT. I'm only allowed to take two. Can I audit?" because I'm a researcher-- said, "Young man, there are a hundred and sixty-eight hours in the week. You can do what you want for the six hours"-- <chuckles> so then he said me, "Go and see Farno, who will be your academic advisor," so Farno-- I knock on the door. He says, "Come in." He says <inaudible>. "Hello, what's your name?" I said, "Thomas Kailath." He said, "Oh, we'll call you Tom. Call me Bob." Oh, for many years, I would only call him Prof. Farno. In India, call them sir. You don't-- <chuckles>. So he said, "So what courses are you taking?" "Well," I said, "I've heard about Norbert Weiner and his student Y.W. Lee, who teaches a course on Weiner's book, so I want to take that and the most famous person in circuit theory is Gilliman, Ernest Gilliman, and he's teaching a graduate course. I want to take that course," so excuse my spending time on this, because it shows you-- here's one of the most distinguished professors at MIT who had independently discovered some of Shannon's results and is quoted in Shannon's famous paper. He says to me, "You know there is another course taught by a very brilliant young man called Bill Siebert on stochastic processes and he does in two weeks what Prof. Lee does in one semester, so you should take Siebert's course." I hadn't known of that <inaudible>. Then he says, "Gilliman, you know, Gilliman is my-- was my advisor and he's a great man, but his course is sort of boring. <chuckles> There's a young man who teaches a second level course called Tom Stockham," who later-- "He's an excellent instructor and you should take his class." Okay, so I said, "Fine." Little disappointed because the 300 level classes have more prestige than the 200 level classes, so that's fine. So I went back to my desk in the room. Half an hour later comes Tom Stockham to talk to me, to tell me about-- Farno had told him, "Go and talk to him. Tell him about your course," so he told me. He says, "Yes, sounds very interesting. I'll take your course." So then he said, "What other course are you taking?" I said, "Siebert's course." Then he went back and he came back later. He says, "There's a clash between Siebert's class and yours. Now, Farno wants you to take Siebert's class, so you can't take my course." I said, "There's another section of your course." He said, "No, in that case, take Gilliman's course," <laughs> because he was the better teacher and he didn't-- <laughs> and actually, another stroke of luck: Gilliman was away the first month and one of his brilliant post-docs, Lee, Phillip Lee, taught the first month of it. It was very ____?____ taught. Gilliman sort of followed his book, so you didn't really need to go to his lectures, though he was a pioneer in these thought problems and he used to set unusual problems and the joke was, it was known as Gillimania, his problems and so on. But MIT was a remarkable place and I can talk for a long time about it it was my good fortune. It was the golden age of information theory and I was part of a cohort of brilliant people who've gone on to their own reputations.

Kapoor: So let's go back to some of the comments that I heard from you about your teachers. Can you spend a little more time on Prof. Aiya and also teacher Joshi[ph?] that you mentioned?

Kailath: Yeah, as I said, as everyone knows, teachers really have a great deal of influence on you, together with your parents, but in a way, they spend more active hours with you than your parents, who see you in the mornings and evenings...

Kapoor: Of course.

Kailath: ...generally, so we were fortunate that St. Vincent's was an excellent school which is now celebrating its hundred and fiftieth anniversary ____?_____ and we had this dedicated-- the main teachers were a dedicated group of Swiss Italian fathers who had made India their home. And I'm amazed at how good they were in English and in sports and so on, so the missionary schools have been great for India. These are the so-called missionary schools. Now they're all entirely Indian, but the Jesuit schools still have a number of Jesuit priests, local Jesuit priests, teaching, so that is one thing. Of course, it's a little sad in one way that inevitable class sizes have grown because the Indian population has grown, so the sort of one-on-one nature of the education has suffered there. Now, the other remarkable-- so there was a French teacher, Mr. Coylo[ph?] who was also from Goa, but taught us French and taught us general knowledge in many ways also. So the school was a great experience for me and much of the reading that I remember and so on is what I learned in high school, because in college, till later, one didn't get much time to read. Always managed to, but nevertheless the foundation was laid in India, including memorizing poems, which again somehow I find that they're not so emphasized in the schools here, so my children, for example, are still fascinated by listening to me about them and I say, "Why don't you study it yourselves?" So teachers have a great, as everyone knows, determining role, and certainly made me a mathematician. Prof. Aiya was a remarkable person. He had studied in India with Homi Bhabha, who was another remarkable person, who was at Cambridge a physicist, came back to India, persuaded Nehru to start atomic energy, and sadly passed and founded the Tata Institute for Fundamental Research and was on the board of the Indian Institute of Science, which was also started by the Tatas, a great family, and so he worked as a research assistant with Bhabha at the Indian Institute of Science. Bhabha encouraged him to go to Cambridge, so he went to Cambridge for a couple of years and then came back, studied-- now I forget where he studied, but he says one of his classmates was later a Nobel Laureate, Neville Mott, if I remember correctly, or maybe one of his teachers, sorry. But when he came back, he joined the Bombay Educational Service. You know, the jobs really are with the government in India. There's security and-- like the civil service jobs here. But he was streetwise, so he got to know administrators, got to know people in the community, and so on, so he persuaded the government of Bombay, which sort of funded all the colleges and so on, their education department, to start this new program in telecom in 1948. You know, the transistor had just been invented and electronics was there, but, you know, the tubes era and so on, and broadcasting was-- there was no television, really, in India. I forget; may have started in the US, but he wanted to be ahead of the game, so he started this program and he insisted that it be an elite program. Then he started a PhD program there, so the first few students who graduated, the top students stayed on for three or four years to do a PhD and he was very streetwise in that-- there are some professors I know in India, their PhD students take forever. He said, "No, you must get out of here in three or four years, so let's push you along," and he told us, "It's not what you learn so much that's important. What I want you to get is the ability and the confidence to enter new fields so that you can"-- you know, and whatever, and his was the own example. He would always give lectures on new topics that he read about. He published papers on his research and proceedings of IEEE, unique in India. He started the telecom-- Indian Institute of Telecom Engineers. He was the president and so on, so his students adored him and when he passed on, we have started a trust in his name which supports lectures and scholarships and so on, and we remember him not so much for what he taught (most of us have forgotten because mostly he taught from term and memory and so on) but his influence on our life and attitudes to life and so on, and that is, I think, another important aspect of being a professor, not just the subject, but to infuse in your students certain ambitions and goals and standards. Yeah, so Aiya was a big help in that and as I said, it was his encouragement to give extra lectures rather than pushing them down, and the letter he wrote to MIT-- and I kept in touch with him for many years and when I came back to India. I'll talk about my connections with India later, which have been quite extensive after MIT.

Kapoor: So going back to MIT, you mentioned Jack Wozencraft...

Kailath: Right.

Kapoor: ...was your advisor for your Master's thesis and he suggested a topic: coming up with mathematical model for constantly changing channels in a system for communication.

Kailath: Right.

Kapoor: So maybe you can say a few words about that.

Kailath: Yes, that's interesting, but let me go back to MIT a little bit as the golden age of information theory. Jack Wozencraft had an interesting background. He had gone to West Point and in fact graduated top of his class at West Point, so he was in the Signal Corps, which was the most technologically advanced branch of the Army, and he was-- he spent a lot of his time after boot camp and all that and rising through the ranks in the lab. Fort Monmouth had a research lab for the Army and they recognized his talent and sent him to MIT for his Master's, where he invented a new circuit called an integrated dump circuit, so he'd integrate and then empty it so you could-- and then he went back to the Army and he served in Japan. For example, he told me about his history and so on, but then he got tired. He said, "I really want to do more work, research," so he came back to MIT in 1955. And he did a groundbreaking PhD thesis in 1957 and they-- he was appointed to the faculty and I was assigned as his first student. What was groundbreaking about his thesis? See, Shannon's theory of information, its main contribution is that it sets the limits on what can be possible. How much can you compress a string of digits? It depends on probability and there's something called entropy, which is a measure of this, and I'll come back to that later also. Then sending information through a noisy channel. You know, when-- if you're sending, say, ones and zeroes by converting a one into a waveform called a mark waveform and the zero into another waveform called space, so this is sent out by the antennas as an electromagnetic wave. Noise gets added to it, and it's at the receiver additional-- I mean, it gets distorted in the channel sometimes because channels are varying in time. Ionosphere is shifting in height and so on, and there is something called troposcatter, which allows you to go beyond the horizon by scattering off objects that are moving in the troposphere. So people always believed that you could always get more reliability by repeating the signal. If you sent it three times the person could average what they heard for the one or the detection scheme and decide on it, but if you wanted arbitrarily small error you'd have to repeat it so often that you were not sending the next signal, so they thought that to get perfect reliability you had to have zero transmission rate in the limit. Shannon's revolution was that he said "No, that's not true." For any channel there is a certain non-zero rate, maximum non-zero rate at which you can send with an arbitrarily low probability of error, which you specify. Above that rate nothing you do will help. You'll have very bad probability of error. So this is the fundamental theoretical limit. He also had what is called an existence proof that-- it was an argument called random coding. If you pick a large number of codes at random among them there will always be at least one good code, but how do you find that good code? He had no clue. It's just an existence proof. So between 1948 and 1955 and later people tried various schemes for inventing good codes. They could find codes which were easy to build but very hard to decode, exponential complexity in decoding, so there's one good [ph?], and so the common wisdom was that it's sad, because Shannon said that almost any random code could be good. All the codes we can think of are bad, so it must be that the good codes are those that you can't think of. Wozencraft produced a decoding algorithm called sequential decoding, which for the first time allowed you to send at a non-zero rate, not capacity, it could not reach capacity, but one-third of capacity with a low probability of error. So that was a startling thing, so no wonder he was immediately appointed as a professor, and he was assigned to me. I was assigned to him as his first student, because we had a program called Joint Services Electronics Program, which gave a block grant to several universities, including Stanford, which the university could assign, so Wozencraft had a grant which would allow one or two students, and so I was assigned to him. MIT salaries were low, and they relied on the professors to do one day of consulting, and MIT Lincoln Lab was set-up by the Air Force to do advanced work on radar defense and so on in case the Russian missiles came over the horizon. You have to have a radar fence, yeah. So he was consulting for Lincoln Labs, and the group that he was consulting for, there were two people there, Robert Price and Paul Green, who invented a communication system for randomly varying channels with multipath called Rake. It was called Rake because it was a tapped delay line with a number of taps, and it isolated the multipath channels so that instead of interfering with them you could pick them up individually and recombine them in phase so you got a strong signal. So Rake was a sensation at that time. It hadn't been published in '57. The first paper came out in '58. But Wozencraft said to me "You know, though they've invented it and it sort of works for the purpose which it was invented for," which at that time was not multipath communications, because it used very large band for anti-jamming and was used in the Berlin Airlift to jam the Soviet jammers and so on, "but," he said, "they're running into trouble in certain environments, and it's because though it was based on Price's PhD thesis and so on they don't have a good understanding of the communication channel, so it's a linear channel, but instead of being time invariant [ph?], which is what we mostly study, it's varying with time, so why don't you make a study of that?" I said "Professor Zadeh"-- Lotfi Zadeh, another famous figure-- "his PhD thesis in 1950 was on that, and he's done a lot of work, so what am I to do?" He says "No. You see, Zadeh just studied general linear time variant systems. We're interested in communications where there's a bandwidth limitation, okay, and there is a time spreading also, which is a characteristic of these channels, so why don't you put the bandwidth limitation in and see what impact that has on the linear-- how you can specialize the general theory to this." So that turned out to be a very good topic for me, and I made good progress using what's called Shannon's sampling theorem in making models for it, so-called tap delay line models. With a delay line the signals came in. The first tap had a varying gain. The signal went through that, then the next signal came in, next tap and so on, and so even though you sent a narrow pulse it got stretched out by the time you emerged from the channel, and that was the channel time duration. And because of the time variation even if you put in a sine wave it would get spread in bandwidth so you had a bandwidth. Okay, so I made a communications model for it, which got attention. In fact, I was asked to give this in a famous summer course at MIT in 1959 give lectures on it where every other lecturer was a professor or someone from industry. I was the only graduate student, so got me a lot of visibility at a young age. And so then Wozencraft said "Now the next problem for you is how do you measure the channel. You put an input signal in, you get the output signal. Figure out what the channel is." So I said "We don't know what the channel is, but I have a model for it, so I can try to figure out the model." So he said "Yes, that's good." Now, MIT, you didn't have much interaction with the professors generally. They did their own work. Every now and then he'd bump into you and say "How is it going?" So after a couple of months or some time there I said "You'll have to give me another problem, because I am stuck. No matter what I do, I'm not"-- he said "Okay, that happens, but why don't you before we go on write up what you have done, what you have tried, why it didn't work and so on." That was good advice, because in writing up I got a nice idea, which solved the problem and gave a condition which was that if the product of the bandwidth of the channel and of the time duration was less than unity in particular units then you can measure the channel. If it is above that you could not measure the channel. Now, the proof was very simple in a way. It used some concept which Shannon had proposed called degrees of freedom. If a signal has a long duration T and a bandwidth W it had at most two TW degrees of freedom, and I had used this by the following argument. The input signal has a duration and bandwidth, so it has some degrees of freedom. The output signal has its own duration and bandwidth. Each tap in the channel has its own degrees of freedom. If the sum of the degrees of freedom in the channel plus the degrees of freedom in the input are less than the degrees of freedom in the output then you should be able to figure out the thing, because it turns out there's some matrix algebra involved, and this gives you enough equations to solve. Matrix theory at that time was very rarely used by engineers. MIT avoided it actually and so on. So that result got a lot of attention. First of all, Price and Green at Rake were very interested, because they said "This is exactly the condition under which our system fails," so now we had an explanation for that and the channels-- they didn't have the terminology [ph?]-- an overspread channel where the product is greater than one, an underspread channel where it is less than one. And Lotfi Zadeh was at Columbia, and by then he was a major figure in the field, so it was before fuzzy logic. He was the leader in system theory. He heard about it, and he saw the proof, and he was very taken with it, and he invited me to give a talk, my first international conference. IRE used to have an annual convention in New York every August, so I went there, gave the talk. Zadeh introduced me, praised it, and so I got a lot of visibility. Two years later or so the IRE was formed. Before that it was a group of radio engineers and AIWE, which was electrical party [ph?]. They merged and called it IRE, so to celebrate that they had a collection of review papers in the field, so Zadeh had to write about time varying systems, and he quoted my result very favorably, so that also got attention. Okay, and then in that summer course I was invited to give the lectures on my master's thesis, and they got published in a book two years later, which was-- every other instructor was well-known, including Jerome Wiesner, who later became president of MIT. He was director of RLE, of the research lab then. It was promptly translated to Russian, so my name was well-known in Russia. When I went in '68 they knew all about it. So that was good fortune thanks to Wozencraft, Price and Green and Zadeh.

Kapoor: So I believe that the understanding in modeling this was a step along the way in the development of the cellphone system. This was mentioned...

Kailath: Sorry. Say this again.

Kapoor: The way that the solution that you came up with was an understanding and modeling this was a step along the way in the development of the cellphone system.

Kailath: Right, yes. Well, because Rake is now used-- every handphone has a version of Rake in it, so I was known-- because my thesis gave the first-- my PhD thesis then-- I'll tell you the story actually, because it's related to my career, but my PhD thesis sort of laid the foundation, gave a theoretical foundation for the Rake system, and now many years later-- wireless was not popular till a dozen years or so ago, so now of course it's universal, and Rake is used in every system.

Kapoor: So communication via randomly varying channels.

Kailath: Right. That's what the wireless is.

Kapoor: Yes.

Kailath: Yes. So let me tell you what the consequence of this was. Bell Labs used to send a recruiter every year, the same person, to keep track of the graduate students in areas of interest to Bell Labs so that when they graduated they had an in and could persuade them to join the Labs. Those days the Labs was the best place to be. It was the premier research institution in the world actually, full of Nobel laureates, all information theorists and so on. So Seth Washburn in switching theory, a well-known name, used to be the recruiter, so he would track me, so when I graduated with my master's he said "You know, Tom, we can offer you a position at Bell Labs which has a much higher salary than a research assistant, plus there are people like Shannon and Slepian [ph?] and Bodi [ph?] and Shelkunoff [ph?]. They give lectures to the technical staff. You can attend them. They're graded, and you can get a PhD at Columbia with this record, so why don't you consider that?" So they flew me out to Bell Labs, wined and dined me and so on. I didn't drink and all that, but nevertheless wined and dined me and made me an offer. In fact, I met some people recently who said "Yeah, we met you there. We knew that Bell Labs was very interested in hiring you." So Wozencraft told Price and Green that Tom is leaving because he has this offer, but anyway my parents-- I mean, I had a scholarship at that time, and tuition was paid, so I had some extra money. I would send it home, which was useful, so a high salary means, first of all, I could buy books more readily than I could as a graduate student, and I could support my parents better and so on. So one day I get a call from Paul Green, who was sort of the older person in the group, and Bob was the technical person. He was more the over-- also very technical himself, but he was the outgoing person.

"Bob Price and I want to have lunch with you, so we'll invite you." So they came from Lincoln Lab, which is about a dozen miles away. I can't go there. It's a classified facility. Anyway, so in the lunch they said "You know, Tom, the hardest thing about getting a PhD is finding a good topic. Once you have a topic if you work hard you can-- you have a topic, you have an area, so why don't you consider finishing your PhD before going to Bell Labs, okay?" Now, they said "We know Wozencraft told us that you're attracted by the fact that you'd get a good salary, and you would be with very good people at Bell Labs, but what we can do is we'll offer you a summer job at Lincoln Lab, and you can work with us, particularly with Bob Price, whose thesis laid the conceptual foundation for Rake but not the complete mathematical, but a conceptual foundation. It was important, his thesis. The only thing is you cannot come to the Labs, because it's classified, so you work at MIT, that's fine, and we'll visit you now and then and so on." So I thought about it and asked Wozencraft. He said "I agree with them. You should stay." So I stayed. That was such a nice decision, because that summer-- so Price will come work with me. I did enough that I basically had the foundation of my PhD thesis, which was not in this area of measuring channels, but signal detection it was called, and so that was good. And in fact it went so well, '59, that there was a famous special issue of IEEE Transactions on information theory in June of 1960 called "Unmatched Filters." It was edited by Paul Green, who was a big figure in the field. First article was by another person who had followed Bob Price three years later in the same field, George Turin, who well-known later was professor at Berkeley, dean at UCLA and so on. And Price worked with me on a paper for that. He was very disciplined in writing, loved putting references together. I had to prepare a memoir. He passed away. I had to prepare a memoir on him for the National Academy of Engineering, so I reviewed a lot of his things. So he would telephone me after I sent him a draft of my thesis typed by someone else, because no one could type in those days, and go line by line, word by word with me over the phone and so on. So that paper got accepted, and that issue was very famous, and I was the only student in it, yeah, so that was another big push for me in my career thanks to Bob Price, and we came lifelong friends and worked together in many ways after that and so on, so that's why I was asked to write the memoir on him later. But there was a handicap, because once you enroll for the PhD you have to take the qualifying examination almost immediately after the first semester. Now that is largely based on undergraduate work, not on your graduate work, okay? The undergraduate work at MIT at that time was quite-- still is, but there was someone called Gordon Brown, who was making a new curriculum for EE, science-based [ph?], and there were eight core courses that you had to take, power systems, electronics, electromagnetics <inaudible> systems, and all professors were supposed to have some time to teach one of these courses. So the qualifying exam was based on that. There were no textbooks yet. There were just bound notes, and I had to take the exam, so three-hour exam-- I may be wrong-- either one-hour exam I think or-- yeah, one-hour exam-- eight one-hour exams on each of those areas, okay? After that if you did reasonably well you had a three to four-hour oral in the presence of three or four faculty, which would-- okay. Now, I managed somehow to do reasonably well in the written so that I was allowed to move to the next step, but I ran into a roadblock in the orals, because one of the professors was a physics professor in electromagnetics, and it turns out that I could not answer his questions, and they said it's fundamental. It's Maxwell's equations. Well, Maxwell's equations never appeared in Terman's [ph?] book. <laughs> So I was a graduate student at MIT. I had my master's, but I didn't know Maxwell's equations because all I knew were information theory. <laughs> So what do they do? They had a dilemma, and they also had a dilemma because a good friend of mine was a very brilliant person called Shmuel Winograd. He may be in the Hall of Fame here actually. He's an IBM Fellow. He had come from

Israel, the Technion. In three years he had finished a bachelor's in math and in EE, and he was taking the quals also with me. He had one of the early material scientists in his committee, so they asked him "How do you harden steel?" <laughs> Poor fellow. He said "You hammer it." <laughs> So what was the solution? They said "Well, Winograd and Tom are friends. They will be the teaching assistants for the core course in electromagnetic theory <laughs> and take the exam next year." So I must tell you that Sam and I worked very hard. We were big experts in electromagnetic things, because the TAs there were serious job. You had to make the problems, you had to give tutorial sections and so on, but I've forgotten most of electromagnetic theory and so has Sam. He went to IBM and was a great success there and so on. So that is the story of my quals. So I failed my quals, and the next year I barely made it because there was an antennas question, but I managed it here. So in 1960 there was a famous conference in London, the fourth London Symposium on Information Theory, so Price encouraged me to send a paper. It got accepted. My friend Bob Gallager told me many years later he had done a very good thesis, but his paper wasn't accepted, and so I was the only student in that conference, where I met many famous people, and I'll tell you about that later, because it had a big role in my career.

Kapoor: There's Norman Abramson.

Kailath: Yeah, I met Norman Abramson. You saw that.

Kapoor: Yeah.

Kailath: But let me just conclude this. A few months later-- so Peter Elias was at that conference. He introduced me, and he said "This is Tom Kailath. He hasn't passed his qualifying exams yet, but here he is," and my talk was well-received. There were all kinds of people there. Marvin Minsky was there. He was on the faculty. John Pierce from Bell Labs, who put up the first satellite and Echo and Telstar and so on. Colin Cherry, Philip Woodward, many famous people, and I was a student there and my first trip to London, but it was interesting, that trip. So let me digress non-technical for a while. How do you travel to these conferences? So I was supported by the Navy Joint Services. You had to fly on military transport. It's called MATS, Military Air Transport System. The seats faced backwards because that's safer. The stewards are Army people and so on, and you couldn't fly from any regular airport. You had to go to a military airport in New Jersey. Millford I think it's called. So I went there, and some sergeant checks me in, and he says "You have your papers?" I said "Yes, here's the travel orders." "Now, you are supposed to fly to Scotland, Mildenhall, but there is some crisis here, and there are no planes for that, but we are to go to Frankfurt, and then you can make your way to London, and we'll pay the expenses and so on." So I said "Well, that's disappointing," but secretly I was not, because my plan was to leave early for this trip and travel through Europe on my own, so this was now at their cost, so I went, and we got down at the Air Force base in Frankfurt. Rhein-Main Base it's called. All the people got into a bus. I got in also. Military people. I was the only civilian. And they went to the base. They all checked in, and I went in and said "Who are you?" "I'm so-and-so." "Are you in the military?" "No, I'm a student at MIT." He says "Sorry. You have to go into town, because you can't"-- I said "I mean, that's not easy" and so on. Then I remembered I had travel orders, so I fished that out. This is a pre-printed form where there's a line for your name and the signature of the-- and it says so-and-so printed, "traveling at the direct orders of the chief of naval staff." <laughs> It's a standard form. So I gave it to him. He said "Oh, why don't you show it to that-- you're on TDY. You're an officer on temporary duty." <laughs> So I could stay. "How much do I have to pay?" "Two dollars a night." Okay. So the next morning I found that I had forgotten my toothpaste, so I asked him "Where can I"-- "Oh, there's something called a PX." I didn't know what that is. "What is that?" He said "It's post exchange." This is a Macy's kind of store, everything tax-free for the military. I don't know if you have experience of these things. So not only did I buy toothpaste, I bought a few other things as well. So I came back. I had to spend a couple of days, then I said "I have to go to Paris," so I forget. I think I flew to Paris. Then I was wise, so I said "What is the military base in Paris?" He said "It's the King George V Hotel off the Champs-Elysees <laughs> for $2 a night." <laughs> So then I went from Paris to Amsterdam. They didn't have a base there. Then I took a train down the Rhine, and I would travel at night, sleep in the train, and I got into Bonn at night, evening, and I got off, and no one spoke English, and I needed a place to stay, so I was stumbling around, and someone overheard me and came to me in English. He says "I can help you," so he found a place for me. I said "How did you learn English?" "I was a prisoner of war in India." <laughs> So all kinds of interesting experiences, yeah. Amsterdam was nice. I was at the train station. There was this weather-beaten person with a typical hat with a parrot on his shoulder like Long John Silver, and London was also fascinating, full of plays and so on, so that was interesting. But then on the flight back there was an interesting story, so all kinds of experiences. The flight was supposed to go to New Jersey, but we were offloaded in Greenland because there had been an accident in Germany where by mistake some shells had landed in the base, so a lot of people were hurt, and so the transport had to be taken for them, so we had to get down and the plane had to go take this crew, because everyone had to stop in Greenland to refuel. You couldn't fly across the Atlantic then. So I got down. As I went down the steps there was someone waiting for me at the stairs, saluted, took me in a Jeep to the mess, offered me a drink. I didn't drink, so I said not. So I asked what's happening. He says "Sir, you are a major. You have rank of major," because they have to give you a GS rating on all these military-- the president is GS20 or something. So this guy, a sergeant in New Jersey, asked me "What's your GS rating?" I don't know what it is. He put down something, GS14 I think. That's major. So for a week or so, two or three weeks, I was a major in the US Air Force <laughs> or Army, so those are the stories. But in London I met Norman Abramson, who was a young professor...

[recording ends abruptly]

Kapoor: You became the first India-born student to earn a PhD at MIT in...

Kailath: No, in electrical engineering. There had been people in physics and so on and Ram Vepa was one[?] No, that was told to me by the foreign student advisor, who was Karl[?] had been verified. There were hardly any Indians in America. There were half a dozen at MIT. One was Kirit [ph?] Parekh [ph?] who was a civil engineer got interest in computers. Went back to India and started research in economics and so on. He is known-- worked on the planning commission and such like, so. So it was a small group but they only took two students from India with fellowships at that time. And there was someone there Gope [ph?] Hingoranii [ph?] who left after his masters. Went to Purdue for his masters and so on. So I was the first graduate, yeah. And the third graduate was someone whom you've interviewed, Suhas Patil [ph?]. He told me he was the third. The second went to Bell Labs Vasant Prabhu probably we don't know what happened to him. So that was a nice feature and so-- what was I saying? Sorry.

Kapoor: You were talking about meeting Abrahamson.

Kailath: Yeah, so in London, I meant to mention one of them was this young professor from Stanford called Norman Abrahamson who worked in information theory. And he liked my talk as well so he kept me in mind. And he was teaching at-- he had graduated from Stanford and was on the faculty teaching information theory, which is a popular subject. So from MIT I had to decide what to do. Well, at that time, MIT, if you wanted an appointment there on the faculty, you could get one. So I was appointed as a lecturer but I said, “Fine, thank you. But I want to take leave for a year to see Caltech because in India, MIT and Caltech are the two famous institutions and I want to see.” And I had been to California the previous-- in October of 1960 and I was blown away by Santa Monica where the conference was, Ocean Avenue. One of the things, there’s a wide street. If you stepped off the street every car came to a stop, which is the opposite of Boston. And the sky was blue. The weather was beautiful and I said, “This is”-- like Earl Shannon said, “This is God’s country.” So how do you get to Caltech? The research lab of electronics> used to have short-term visitorsBenoit Mandelbrot [ph?] used to come for example, and I used to chat with him.

Kapoor: I met him by, the way.

Kailath: You met him, yeah.

Kapoor: <inaudible>

Kailath: He’s passed away now.

Kapoor: No, we did not interview him but I met him but I met him at a different function where he had just been honored by Japan, Emperor of Japan. And so then there was a function that I attended.

Kailath: Right, so I knew him. He had given me one of his papers at that time, which I still remember: “How Long Is the Coast of Britain?” Now, that’s the beginning of Fractals [ph?], because what is it? At every scale there is more wiggles. So he was quite a character. And there was a Frenchman called Marco Polo Schutzenberger [ph?], M.P., Marcel Paul. But he was a world traveler for WHO so Marco Polo. And so Solomon Golomb had come for a month. Now Solomon Golomb was leading the communications group at Jet Propulsion Lab, which is a part of Caltech. It was run by Caltech. So he was talking to me. He said, “Oh, come to JPL. I have a group in communications and you could work with us.” So I said, “Okay, I’ll do that but first I’m going to India.” And I had gone in ‘61, by charter by the way. There were no flights to India so the group of Indians would get together and charter a plane which would take us to India and so on. So then, marriages were arranged at-- for me and at that time in India. So my parents had lined up a group of young women to meet and so on and it’s-- but I met Sarah there in a village. She was in a village where she was enterprising. She was-- you’ve met her, I think. She was quite beautiful and a good personality. So she had been sent to study in Madras far away from the village. But, after a year, the teacher, the warden of the hostel who happened to be related to the family, wrote to her father saying, “Take her back. She’s too much of a distraction for the boys.” So-- because the boys would hang around the girls hostel waiting to go by train with her to the college,because the college was away from the hostel, suburban train. So he told her, said, “Someone is coming from MIT to meet you.” He says, <inaudible> “First of all, I am told he only speaks English. And I speak mostly Malyalam_____.” So she was relaxed about it. Anyway, I was struck, of course, and so we got engaged at that time and soon but she was studying. She was twenty and then a B.A. in English. And she was okay as a student but her siblings said to her-- she was much older than her older brothers, one of whom is Raj Mathai's [ph?] father, "You better get a first class, otherwise he won't marry you." So she did. She was okay. So I went back in 1960-- no. So in '61, I went back. I met her and so on. Came back and worked for a month with a company with a setup by an_ MIT professor, one of the early companies. He really wanted me to stay but I said, "No. I'm going to Caltech and to JPL." So I went there. It was a wonderful group that Sol Golomb had assembled. He was a boss of the section of communications research and there were groups under him and my group was led by Andrew Viterbi. So he was my immediate first boss. He didn't have his PhD at that time. He got his masters from MIT and he was studying at USC part-time and finally got his PhD from USC. So he was my boss. There were very distinguished people around me. Irving Reid of Reid Solomon Codes,_____. Gus Solomon. We all reported to Sol who was a mathematician by the way, so. It's interesting, as a sideline, there are three people in information theory besides Shannon who got the national Medal of Science. One was Sol Golomb. The first was Andy Viterbi, 'cause he was famous, as you know...

Kapoor: Viterbi.

Kailath: ...for Viterbi Decoding and Qualcomm. The other was Sol Golomb and next was me. All three from JPL at one time. Sol, unfortunately, was quite active, passed away very suddenly in May.

Kapoor: Ah, I see.

Kailath: Yeah, so that was sad because that was-- my career was built at JPL also because those were the early pioneers in digital communications. And, in fact-- but JPL had plenty of money and relaxed-- in those days, Sputnik--I was also lucky. There wasn't much money for research in America till 1957 when the soviets put up Sputnik. And, all of a sudden, America discovered that though science had been useful in the war, there was-- so the money was poured into universities. Mathematicians who were living on starvation wages suddenly became well-fed and so on. I met several of them at Caltech and so we're good friends. Oh, that was a lifesaver for us. So money was plentiful for research at JPL so travel funds were not a problem. So I still kept close connections at MIT and I would go there every two months.

Kapoor: So, by now, you had your PhD in 1961.

Kailath: Yeah, so this was my post-PhD job. I said I went back to India. I think I met Satish Dhawan [ph?] there. When I talk about India we'll come back to that later and-- either then or the next visit. And, no, so I'd just come back, as I said, looking for a job. Professor Baghdadi [ph?] who had entered that book on the summer school had started one of the first academic companies called Ad Com, Advanced Communications. Adcomm became common from that, Qualcomm and so on. Maycom.

Kapoor: Right. So but you were also given an option or you were a lecturer at MIT?

Kailath: Yes, but that will only start in September because I graduated in June. So I took the time off. And there's another story related to that I'll tell you, but in a moment. But so I was free that summer but I decided to go to India. Now, that was interesting because the following had happened. You may know the name Rudy Kalman.

Kapoor: Mm-hm...

Kailath: Kalman Filtering.

Kapoor: ...Kalman Filtering, of course.

Kailath: Yeah, of course, everyone knows him and Theo.

Kapoor: Yes.

Kailath: So when I went to this conference in Santa Monica, Kalman was one of the speakers Zadeh> was and Danzig, George Danzig, Richard Bellman [ph?] was <inaudible>. So Kalman met me and enjoyed my talk and so on. He gave me a copy of his paper on Kalman Filtering. I couldn't understand it at the time 'cause it used something called state space, which-was- not familiar to people at MIT and so on. And he said, "You know, I am at this institute called Research Institute for Advanced Study in Baltimore called RIAS. Come and spend the summer with me before you go to Caltech." So he sent me an offer but I wanted to go to India to get married and so on. So I-- and to see my parents. I hadn't seen them for four years so I begged off. He didn't quite like that but later I came to Stanford. We are good friends now. I've written many-- I've nominate-- anyway, I have written many letters on his behalf so he likes me in that sense. So I'm a good resource for him. Anyway, and he's offered to write for me but don't quote...

Kapoor: Sure.

Kailath: <Inaudible> okay. But I haven't taken the offer. So anyway, I went to Caltech and so I would go back to MIT because I was still working with Bob Price and I would give seminars there. And there was a remarkable group of students, as I said, and let me go back to that. So Rosencraft [ph?] was '55. Irwin Jacobs was-- I went in '57. Irwin Jacobs graduated in '57, the cofounder of Qualcomm and stayed on the faculty. Bob Gallagher graduated in 1960, stayed on. I graduated in '61. Jacob Zimp [ph?], who is well known for many things including Lemper [ph?] Zimp compression, was '62. Jim Massey, also was '62. Ivan Sutherland was my office mate for a while. And he was one of the only two students that Shannon supervised. Shannon would not take any theoretical students but computer graphics was Ivan's idea and Shannon liked it so he said, "I'll agree to be your supervisor." And the other was a Swiss guy called Hans Ernst. He went to IBM. I don't know what happened, building an artificial hand. Another topic that Shannon loved because Shannon was a juggler, unicycle rider, did mechanical projects and so on. So he didn't take any PhD students. So he was on committees but not advisor. So anyway, that was a digression about Kalman and that summer. So then I went to Caltech. In one month I'd go to MIT-- oh, no, sorry. I want to finish. Then, after that, was David Forney and Elwyn Berlekamp [ph?] who was at Berkeley, well-known also now. And David Forney, who just got the IEEE Medal of Honor this year in May. He is the founder of the modem business. So it was quite <inaudible> Gallagher gave a lecture at Stanford. For my seventieth birthday, my students had organized another conference and endowed an annual lecture. And Gallagher gave the first and his topic was the golden age of information theory. So that was quite a cohort. It was a remarkable time to be there. So, again, my luck, and these all been my good friends since then. So every alternate month, I would come to Stanford and visit Abrahamson and Lotfi A. Zadeh, because Zadeh had moved. He was a big figure in the field. He had moved to Berkeley, which had there many strong people, Charlie [ph?] in system theory. And he was writing his book, famous book on state space and so on. So Zadeh knew me, of course, because of my work. He was such a gracious gentleman. I didn't drive. I would take taxis. But he would drive from Berkeley, pick me up, take me to Berkeley, give the seminar and drop me back and so on, along with other famous visitors, Sidney Darlington and things like that. So we just watched a play, a musical actually, "A Streetcar Named Desire," the musical version of it. The last sentence is always haunting. Have you watched "Streetcar?"

Kapoor: I have but as a play.

Kailath: As a play, yeah. She says at the end when <inaudible> sent off, "All my life, I've depended on the kindness of strangers." And I can say that but, I mean, I've also-- I've benefited for the kindness of strangers <inaudible> all these people. So Zadeh was, in a way, a stranger but this is it. So Abrahamson was so successful at Stanford that they had agreed to add a faculty position in that field. So Abrahamson told me, "We'd like you to join." I said, "I'm not interested." Said, "Meet the chairman." I said, "I'm not interested." But, anyway, the chairman sat in on one of my seminars and liked it. So Abrahamson was persistent and he said, "The dean wants to meet you and you're going to a conference in New York. The dean will be in New York so why don't you meet him." So they sent me an offer but I had not accepted. So the dean met me and then they said, "We should meet Terman," 'cause Terman was-- he was the vice provost but he built Stanford. And he recruited many people directly, so I went to visit him. He didn't know this field. He didn't really know information theory but he had the characteristic that he would read all the documents and he would call people around the country so he knew many people. He was an MIT PhD with Gilliman [ph?] , I think.

Kapoor: I see.

Kailath: Yeah, so he had wrote me and got a good background so he said, "Yes, okay. He's a top candidate." So I had a one hour interview with him where he tried to persuade. He said, "Stanford is now going to be-- there're only two schools west of the Mississippi, engineering schools which are well-known private schools. One is Caltech. Well, Caltech is too small. Stanford is going to be the major university and I'm recruiting people and we think if-- I understand you're also interested in statistics. So I've asked the dean of statistics to come and meet you so that we can give you a joint appointment in statistics," and so on. So I was, of course, flattered by-- and he showed me-- he was-- he loved data. He had a huge collection of facts and statistics. There's a nice story about-- he was really organized. One day, he told his secretary, "I'm going. I have an interview, audit with the IRS." So the secretary said, "Why are you looking so happy?" Says, "I want to show 'em all my data." Every request that they had he had it at his fingertips there. So anyway, so I was at Caltech then. I lived opposite Caltech so I had a visiting assistant professorship at Caltech at the time. I taught a course there and had some interesting-- so Feynman was there. Gell-Mann was there. I just met them in classes. I never met them but more to say about those things. But so, one day, Wilson called me. I think I remember I was sitting on the lawn in our home office at Stanford. It was suggested to me by Ivan Sutherland, who had come to MIT from Caltech and he had lived there. So there were four graduate students, four post docs, renting the place. One of them is a famous-- two of them were famous physicists later and so on. So they toured me with Feynman and Gell-Mann and Abrahamson calls me and says, “Tom, you have to decide. ‘Cause if you are not deciding then we have to.” I said, “You know, MIT is the place where all the action is in information theory so”-- but anyway, to make a-- I don’t want to into the details but they-- he said, “Okay, let me see what I can do.” He called me back in an hour later and says, “Remind me not to play poker with you because they’ve agreed to make you an associate professor.” Okay, who is they? The dean, Petit, who was Terman’s student. He called the dean and the dean called Terman and Terman said, “Okay.” So I said, “Okay, I’ll accept but I cannot come till September.” Oh, this was-- the offer came in December of ‘62.

Kapoor: I see.

Kailath: So I told Caltech and JPL, “I’ll be leaving but I’m going to Berkeley for six months and will JPL support me? Because Bob Price is going from Lincoln lab, who was my mentor-- is going to Berkeley for sabbatical and we want to continue to work together.” JPL said, “Okay, that’s fine.” So I told Stanford, “I will join you in September, after I go to Berkeley.” So it was agreed. A month later, I get a call from the dean, “We have some extra money from Ford Foundation and we would rather you join us first. And we don’t mind but you can go to Berkeley but on our payroll.” So I thought-- I was puzzled, “Why are they being so generous?” And-- but that’s good I said, because JPL-- I’m not returning to JPL. Why should I use their money, though they didn’t mind? So I said, “Okay.” So we went to Berkeley basically on sabbatical, the first six months of my appointment at Stanford.

Kapoor: Stanford.

Kailath: And I got my PhD in June of ‘61 and my Stanford appointment as associate professor started in January of ‘63, 18 months later. So when the department, by the way, heard about this, they said, “He has never taught. So let’s make it acting for a year so that we see whether he’s okay or not.” And I said, “Okay, that’s fine.” I was confident that I could teach. So I was acting associate professor till the next fall when-- I’ll tell you about that later too. But this is too much about myself so let me just stop. So, later, I discovered-- Abrahamson told me they were afraid that Berkeley would make me an offer ‘cause they knew that Zadeh was close to me and we were recently married because-- and Stanford at that time was a village. It was very dull. Berkeley, it was the beginning of the flower children and the Summer of Love was 63, Telegraph Avenue, peaceful. There was not-- there was maybe one analyst that was in the air but, for us, it was a much more attractive place. If Berkeley made me an offered and I hadn’t still confirmed-- I mean, I’d confirmed. I mean, I may have been tempted to stay. So they forestalled that.

Kapoor: I see.

Kailath: Which is good leadership and this is what I think about. Unfortunately, now the system-- there are committees and letters of recommendation. Nobody can act in this quick way. Yeah. But that’s how Terman built Stanford. He recruited all these key faculty and-- did you ever interview Terman?

Kapoor: No.

Kailath: No, but there must be interviews 'cause he's the father of Silicon Valley actually, yeah.

Kapoor: <inaudible>

Kailath: And there's so many things he did at Stanford which put Stanford on the map and helped Silicon Valley.

Kapoor: Of course.

Kailath: He was a remarkable person. Yeah, I would meet him now and then and he would remember my name. He was in a wheelchair by then. But, yeah, so that's how I ended up at Stanford and, yeah, in September of '63 I started teaching. In September of '64, they made me associate professor. In 1968, full professor.

Kapoor: So one comment, I remember reading about is that you preferred the intellectual academic culture with new mathematics and simply stated new problems over starting companies. Because you had an option to look at...

Kailath: No, in those days, actually, no. No, hardly-- no. There were no startups in those days. I mean, Hewlett Packard was an exception. It was already a big company by the '60s. There were-- what were the companies in the valley? There was Lockheed. There was Litton. There was Varian. No, there were not many and there were no startups really. They was-- ESL was there. I think Bill Perry had started. Sylvania was there. They have since been out. No, and certainly professors didn't have startups. So, no, but my experience was as a consultant to industry, especially-- my field was more related to defense work because, as radar and signal processing and all was sophisticated signal processing was only military needs. So I used to consult and I found that industry, with exceptions, was unusual. They had large groups because they had big contracts but only a few people were the key technical leaders. The others were doing mostly less interesting work. These leaders would have the ideas and lead the thing. And, after they got the project seeded and going, they would write the next proposal. So I didn't think that that was very interesting.

Kapoor: So the subjects of interest to you would be statistics, information theory, applied math. Are these areas that were of the key interest?

Kailath: Right, yeah. They-- because in those days, the field was quite mathematically oriented. People-- you see, Shannon-- there had been complaints that Shannon's work, that was full of ideas-- the mathematicians felt that it was not rigorous. And so there was a great deal of attention to making things rigorous. For example, in control theory, there was something called Pontryagin's maximum principle from Russia. So the Americans-- because the space race was beginning, Sputnik and so on. So one of the PhD theses at Stanford was a rigorous proof of the Pontryagin's maximum principle. So myself and-- and MIT was very non-mathematical at the time. So matrixes and linear algebra now is required. No those were like-- I took only two math courses at MIT. One was linear algebra. One was modern algebra.

Kapoor: I see.

Kailath: And my advisors were not too keen on those, 'cause they said, "We're engineers. We're not mathematicians." But I was more mathematically oriented. So my students and I would take the math courses on real analysis, measure theory, probability theory and so on. And I began to do some work which was more and more mathematical. And Price's work on the estimation in RAKE [ph?], introduced a certain concept based on his mathematical results. But it was physically very interesting. This is not the place to go into it but, mathematically, it had some limitations. And, working with him in my PhD thesis, I simplified some of his work with his encouragement, and he refused to write joint papers with me. So I wrote them and we extended his work. But, as I learned more mathematics, I began to realize that I could extend this. So we put some of Price's work, extended in a quite striking direction, using very advanced probabilistic techniques, some of which had only been published two or three years before my paper and so on, in 1969. And, if you are patient, there are more stories there. So that led me to conferences in mathematics and so on around the world. In France, and I met a lot of people in these fields and this. It was a big experience for me and also other kinds of mathematics and Hilbert spaces and so on. And more about that later. So my work in mathematics has been useful because it brought a new-- it made some breakthroughs on the mathematical side in engineering in these fields, okay. And I might mention one item that has come up recently. I told you that, in my thesis, in this measurement problem of the channel which was-- the result was interesting. I used an assumption saying that a signal of duration t and band width w has 2tw degrees of freedom if 2tw is large. But I also pointed out in my thesis that everyone knows, including the engineers, that mathematically, a signal of finite band width must have infinite duration. The tails may be very, very low but they are there or vice a versa. If it's a finite duration, it must have infinite band width. So I said my argument is heuristic but people at Bell Labs, Paul Ackandau [ph?] and Slepian [ph?] have tried to put a lot more meat into this concept of degrees of freedom. And so that, if you say, "It's not band limited but 95 percent of the energy is within the band and 95 percent of the energy is within the time band, then it was still a good concept. So that was fine. In 2006, there was a paper by two mathematicians in the information theory transactions which gave a rigorous proof...

Kapoor: That's what I was just going to mention, by Gertz [ph?] Frander [ph?]...

Kailath: Frander, yes.

Kapoor: And David Walnut.

Kailath: Right. Right. So I could understand the paper. But the first part of the paper is more intuitive, gives a lot of credit to me for having the ideas, and some people made extensions, then they went off and generalized it. But with the advent of wireless, that topic has become very alive again, and people are writing res-- papers, and rigorous papers, nowadays, extending this result in various ways. So that was a nice bonus of that. But, I got into Hilbert's Space and that lead me to my trips to Russia and interesting discoveries. So, but you may have a question about Stanford some more?

Kapoor: Right, so I was going to-- once you were at Stanford, you worked largely in information and communication theory, and stochastic processes. Initially, you followed the MIT tradition, where professors worked on their own research while guiding doctoral students along different and separate paths. What was the benefit of this approach? An expansion of--

Kailath: I know.

Kapoor: --research, was it changed later?

Kailath: Right, a very good question actually, because it's a significant point. No, that was the MIT pattern at the time that each professor did his own research, because your promotion and reputation depended on the papers that you-- you wrote. And if you had students, generally they said you-- your role was, advisor. You didn't really get too involved in working with them. They did it. So they would write the papers on their own. And each par-- student was roughly assigned a different topic area. So Rosencraft [ph?] had Jacob Ziv [ph?], and me, and I think, Jim Massey, roughly at the same time. Each one year later, but we were his three <inaudible>. Each of us did different things. But we talked to each other, you learn a lot from your students by seeing what-- from your fellow students, always. That's one of the advantages of a resident of a university, as opposed to mooks [ph?]. You can interact, you learn from-- you learn from professors, but you learn more from your fellow students. And it's true for my students too, they learn more from each other than from me. So, that was the pattern which I followed MIT. So my-- with a small exception, my very first student when I came, was two years younger than me. And he had a nice idea because he took-- I would encourage my students to take math course and statistics courses. And I had suggested that he look at a paper of Peter Elias on feedback. And he said, "Oh, I've taken this course in statistics, and there's an algorithm called Stochastic Approximation, I think I have an idea for using that in communications." So he came up with something. But he was a new-- but I thought that was an interesting idea. And he worked out some of the details, but he was new and so and so. He could not quite get it right and get all the-- so I got involved in working with him in doing-- completing the work and doing, and we found a very surprising-- two very surprising results. Channels with feedback are the following, you have a noisy communication link, so that data that you send gets corrupted, but if you can have a feedback noiseless link, then you can modify your transmission and improve the error probability. Okay. So, he-- we found that if we had a noiseless feedback channel, and we said space communications is ideal, because the satellite has low power, and so the link from satellite to ground is noisy, but the ground you can have a lot of power, so the noise-- they upward uplink is noiseless, effectively. So we found that you could achieve channel-- you could signal and race up the channel capacity with a very simple code, and a very simple decoding algorithm. Moreover, with every known scheme at the time, the probability of error, decayed exponentially with the length of the signal. We decayed at double exponential rate which means that almost instantaneous convergence. So this got a lot of attention in the information theory community. We got the outstanding paper prize and so on. But, so-- I joined in the first paper with a student. One of my few joined papers in math, first ten years, but the second paper, I said, "No. You work out this extension and that's yours." And then, my next stud-- I had some other interesting students. One was a Burmese student Mungi [ph?], from AMPEX, Who it turns out was of Indian origin. Because in Burma, there was a big Indian community, but they had to take Burmese names.

Kapoor: I actually knew somebody like that who-- he was a Chinese origin--

Kailath: Right.

Kapoor: --and he, in fact went to IIT, and he spoke English with an Indian accent.

Kailath: Right.

Kapoor: And-- but he was Chinese.

Kailath: Right. Yeah, I know. No, Mungi, no, his parents were Indian, but he had been Burmese. So he didn't have that accent. But I later discovered that he was Indian now, Punjabi actually.

Kapoor: I see.

Kailath: So-- so what was I saying? No, oh yeah, so my Jim Omura was another of my students. And he followed up this first student-- the first student went back to Holland. Peter _______, as I said. So that algorithm, is now-- now it did not get used in space communications because there's a delay and that upset the algorithm. But now, you have networks, and the delays are very short. So this algorithm is now getting used again. So, the 40th anniversary there was a fuss about that and it's quoted in all the books and network coding and so on.

Kapoor: So, going back to Stanford--

Kailath: But Jim Omura, used techniques from control theory, which I didn't know anything about. So I asked him to teach me about control theory, and that lead to my next decade. But Jim Omura had an interesting career. He went to UCLA. And, then he founded one of the first security companies, analog security, called Cylink. It was a pioneer, but financially, he didn't-- didn't do very well. And then he had different projects, but he ended up as CTO of the Gordon Moore Foundation. So we were talking about-- you met Gordon Moore yesterday. So Jim Omura, was Jim Omura here? Did you meet him?

Kapoor: He may have been--

Kailath: May have been you-- yeah, I think he must have been here. Anyway.

Kapoor: So the comment I was going to make is-- what I read was that the first decade of the 60's at Stanford, was-- where you were still an individual contributor. There was a lot of research on your part, with striking new results and approaches in signal detection and estimation theory. Besides, of course, teaching and the students that were-- that you--

Kailath: No, see, my first several students wrote their own papers. So people don't know that they were associated with me. This began to change for certain reasons, which have to do more with Silicon Valley actually. So, but I-- missed, I didn't quite hear your question actually.

Kapoor: So the emphasis in the first decade, was still a lot of your own personal contribution.

Kailath: That's right. That's right.

Kapoor: And the idea of the TK Magic, targeting a challenging set of problems on the new field, inspiring a new set of associate students and all rooted in rigorous mathematics.

Kailath: That yeah-- that began to come a little later. 'Cause I would suggest topics to students that-- they would come up with their own topics and so on. But I began to-- first of all, I found that I began to see that control theory was getting more significant. Because they had launched this moon project, Apollo Moon Project that by '69, you should have a man on the moon. And so there was a lot of effort in the controls and so on. And Kalman Filtering was the topic. And Jim Omura was teaching me control theory. And as I learned from MIT the best way to learn a subject is to start to teach it. So, I started to teach courses in linear systems which is the precursor to the Kalman Filtering kinds of things.

Kapoor: And also your text book.

Kailath: No, that text book came in 1980.

Kapoor: 1980, I see.

Kailath: So I started this move into Kalman Filtering in the late '60's, after I'd already become fellow of the IEEE and full professor, and so on with my work in communications which was largely by myself. When I started work in control, I still did a little bit by myself, but I began to work with students more because I would find-- so we entered this field and I started to teach it. Now the elementary part I could figure out, but we got into the research in linear systems. And then, I started to work with my Ph.D. students, who'd also be teaching assistants, and the text book that I wrote was different from most of the usual textbooks. Because the usual textbooks in the field at that time, the first six chapters were all mathematics, differential equations, linear algorithm, then so on. Then you started some of the applications and the control theory. I said, "No. It's boring to just study math without knowing what you are going to do with it. So we should interleave the math and the application. So if you have a math result, find an application." So my textbook brought applications in. I mean, they are not very significant application, but still they were applications. Some were significant, some were not. But people could see that, "Hey, this piece of mathematics has some value." So, then we began to do research in this field which is not in the textbook usually except in monographs. That's where I use the Ph.D. students. And I took two or three of them, and I said, "Let's all start this together." And so, they worked with me, with each other, I was of course professor, teaching, committees and all that. They were-- so that's how we got into working with groups. And then it really took off with VLSI [ph?] which we'll come to much later.

Kapoor: Yes.

Kailath: Yeah.

Kapoor: So in terms of the '60's, how would you describe the significant achievements in the '60's, of the work and information theory, control theory that--

Kailath: Yeah, well, I mean, I've written a lot of papers. Our very first paper was I moved away from what is called Shannon Information Theory. After the first paper, because I was cleaning up my-- what-- not cleaning up, but extending and generalizing in a much more rigorous and mathematical way the results of my work with Price and my Ph.D. thesis. And that lead me into quite a lot of mathematics. In fact, I became a fellow of the Institute of Mathematical Statistics, okay. And then I also got into Hilbert Space

Theory because I began to see the need for that. And actually that was pushed along by two people. One was a professor of statistics, Emmanuel Parson, who was at Stanford and he was working in a somewhat arcane subject called Reproducing Kernal[?] Hilbert's Spaces and he was at the Santa Monica conference. But he was trying to persuade engineers to use that theory, but all it did was redo results in a somewhat different way, so people were not-- didn't-- but Parson told me about it. And I wasn't too interested. I went to a conference in Russia. They were just opening up interchange between the IEEE and the Popov Society in Russia. So, I think, the second or third exchange group was-- I was on one of them. They would pick ten IEEE people, would go for-- to a conference there and spend a week or two there. There was another person from the valley, a very interesting person called Gerd Wallenstein, who was a vice president at Lenkurt [ph?] Electronics at the time. He had a very checkered history, very briefly, he was a Jewish origin in Germany. So he was forced out-- and he had a radio business. He was forced out of Germany, tried to land in India, they wouldn't allow him. So he ended up in Mongolia. In [?]_______, he started a business there. The Japanese came and chased him out of Mongolia into China, and he went to Shanghai and started a business there. Then the communists took over and he was forced out of Shanghai. He took the boat, and he landed in the Bay Area. And he got a job on the shop floor of Lenkurt. But his abilities were recognized. So when I met him, he was vice president. He said, "Tom,"

we discovered that we are both going together they told us. "Oh, I'm going take-- learn Russian, I'm taking a Berlitz course." I said, "No, I can't do that." He did. So, instead of going to Moscow for the conference first, we said we'll go to Leningrad. So went and we had a very nice experiences. Beautiful city it was. The Hermitage Museum. We were walking by there was a ballet, _Maya Plisetskaya_________. We could just go in. So the next year, we're walking, and he said, "There's a nice book store here." I said, "I want to go in there." I said, "What am I to do in a-- I don't read Russian." So he said, "No, you look at the pictures." Cause they-- Russians have a lot of art books. Wonderful books. And they had cheap books. They were published-- records were cheap, you could buy, -- LP's for fifty cents and so on. So, he said, "Okay, look at the pictures." So after looking at the pictures for a while, I wandered over, I could recognize the words Mathematica, 'cause you know, Greek alphabet is used in math. So, I said, Mathematica, okay, this I know. And I picked up a book it said, "Gilbert's Space." So I know that the Russian's can't say "H," so I picked up the book. It was a used book for sale. I was browsing, I couldn't-- but I could recognize the equations. And in the middle of the book, suddenly I found equations which are very close to the work I was doing. So I said, "Hey, this is relevant." So I said-- I bought the book. It was marked as 1.6 Rubles or something. I said, "It's used shouldn't you give it to me..." He says, "No." Anyway, so I bought the book, and I was flipping through it, but hard to read without the text. But one day, we were living in Sunnyvale at the time, just before moving to Stanford. I was at the Safeway standing in line, behind someone whom I knew, called Amiel Feinstein [ph?], who was a student of _Farno________. Had given the first rigorous proof at MIT of Shannon's Coding Theorem. So he was famous for that. And he wrote a book on it, and he wrote some papers, but then he moved away from research and was teaching at San Jose State. But he was a Russian background, so he knew Russian. And there was a big industry translating Russian books so that we could keep up with the Russians. So I Was asking him what have you translated recently. Turns out it was the book that I had. So I said, "that's very interesting, can I have it?" So he said, "Okay, if you'll pay for the Xeroxing." And he gave me his manuscript so I could read the book. And it gave me lots of ideas for my research. Fact I wrote a very nice paper on it which drew me to the attention of some very famous Russian mathematicians. And in the acknowledgments, I thanked Gerd Wallenstein for his insisting on my browsing. So that's-- a lucky accident, and Gerd Wallenstein, another stranger from whose kindness I benefited.

Kapoor: So the whole field of control theory, from what I remember, of course, there are different areas like optimization--

Kailath: Right.

Kapoor: --stability--

Kailath: Right.

Kapoor: --and I know that the Russians did a lot of work--

Kailath: Right.

Kapoor: --in the stability area, the Lyapunov.

Kailath: Lyapunov, yes.

Kapoor: So, was there any interaction with the--

Kailath: No, you see, Kalman was-- some of his early papers, Kalman knew Russian too. So he-- his early work was Lyapunov stability.

Kapoor: I see.

Kailath: But he was one of the first to bring Lyapunov's work to the attention of American engineers. And Pontryagin's work in optimization, the maximum principle, was translated by different people and so on. But there are many branches of control theory, and I never got into optimization except in one particular kind called Linear Quadratic Optimization. And this is because, my work in detection theory involved some estimation but Weiner type estimation. Kalman had something else which used__________ something called State Space. They're actually closely related but however-- but Kalman's allowed time varying systems to be used, which is what you needed for space. And a group at NASA picked up Kalman's work, and extended it and popularized it. So that got the worldwide attention. So I wanted to study, I was teaching, I was studying Kalman, what else can I do in this field? And here's an interesting cross fertilization, I said, "One of the strengths of Kalman filtering is that whether you-- you have a model of a system, whose behavior you're trying to track. The system can depend on time or not. The algorithm, and the number of computations is indifferent to whether the parameters change with time or not. So, I said, that is interesting, but as a strength, if the system changes with time, you just put a bracket T for the thing. Algorithms basically remain the same, except for bracket T's. But I said, there should be some simplification when the model is time invariant. What can that be? Now, I knew about Wheeler filtering which had sort of Kalman filtering had replaced, but that dealt with time invariant systems. And there were efforts to extend it unsuccessful. That's when Kalman came along and made a new model of the problem, and that broke the Gordian Knot so to speak and that took off. So, my book in linear systems was about state space because I-- that was a preliminary to understanding Kalman filtering. And then we did research on it, and I got the education medal for that book. 'Cause it changed the way systems was taught which is the precursor to foundation for control is the systems. So, one day-- so I knew about the other thing. One day, one of Bellman students came and gave a seminar on a new way of thinking about estimation, using some results from radiative transfer theory, that Bellman had known about and used in some-- which Bellman had extended in some way called Invar-- Bellman invented Dynamic Programming.

Kapoor: Yes.

Kailath: But LC [ph?] was then working on something called Invariant Embedding. It turns out it was an idea from the famous Indian astronomer, Chandra Shekhar [ph?] and a Russian astronomer, Columbart Sumian [ph?] who had studied the propagation of light through the atmosphere and so on. It turns out that they had found an equation called the Riccati equation, a partial differential equation. Kalman and his work had found the Riccati equation also ordinary differential. So that intrigued my connection. I said, "Hey this is something to look into." So I started to look into that field and I found that Chandra Shekhar had an algorithm, which exploited time invariance. And I adapted that to the state space context, system theory context, and got new algorithms, which in the time invariant case were an order of magnitude faster. So there are certain applications in image processing and so on where the time is not a factor. So these algorithms reduce the computation from the first application had 500 variables. Instead of 500 cubed computations verse iteration, you had 500 squared. Well, 500 cubed is trillions of something. 500 squared is millions. It's negligible. Yeah, it's a rounding error for the-- so this att-- we called it Chandra Shekhar type algorithms. And we extended in various ways, and to adaptive filtering which has become quite useful in communications and that work, it's mathematical work, is also used in cell phones.

Kapoor: So, I had a question on-- two questions, one is as the computers and computing became more prevalent and better technology, did that affect-- I think it affected the control theory.

Kailath: That's right. So, the computation as the pro-- people started attacking from larger dimension, and you already ran into cursive dimensionality. So, this was one simplification there. But, no, computers and integrative circuits enabled many of the algorithms that we had mathemat-- to be implemented. So, that was a synergistic connection. But even then, if you can reduce the number of computations, that's still a help because you reduce the power requirements in the computation, so that came up later in our work. But, after control, I got into signal processing.

Kapoor: So I had another question on control which is operations research. Was that related to--

Kailath: Yeah, no. Yeah, there are some-- I mean, people use linear programming and dynamic programming and later, one of my colleagues was a pioneer and picking up some Russian work on what are called, interior pro-- nonlinear programming. Because linear programming by George Dantzig was universal. And these people found that by using what I called, interior methods, they could improve on linear programming and make it faster. And there's an Indian called, Narendra Karmarkar [ph?], who is at Bell Labs. And Bell Labs patented his algorithm and made a big splash. Saying that in all the operations research algorithms, that could speed up things. When there were extensions of it by the Russians called semi definite programming and convex optimization. Instead of least squares criterion, you could have a--

and Steven Boyd at Stanford became a pioneer in picking those ideas and finding numerous applications and teaching very, very popular courses at Stanford in that field. So that is now a big field of research for nonlinear problems using these ideas that grew up in operations research. So the next phase after control, to follow up on your question, began towards the-- towards the end of the 80's. And it came about again through different sets of circumstances and luck. John Linville and Jim Meindl [ph?] at Stanford had the vision that the prevalent integrated circuit technology at the time was LSI. Hundred thousand transistors on a chip. So they introduced via-- very large scale integration which would be a million transistors. And Linville wanted to start a center at Stanford, which later, I think was called the Center for Integrated Systems which is ironic cause the first company that we started was integrated systems, earlier than that, around that time, I think. So, there was a committee formed of Jim Meindl from integrated circuits, lead by John Linville. Jim Gibbons from the solid state side, Mike-- Michael Flynn from the computer systems side, and-- because Forest Basket [ph?] also was there, but Mike Flynn was the leader of the group. And one of the questions that came up is it's all fine to have a million transistors on the chip, but how do you build them? First of all, what architecture and then, what do you do with it? So I was on the executive committee where this new center was being discussed. And I said, "Well, you know, signal processing has huge computational demands, the more transistors you have, the more computation you can do. So I'm sure that signal processing will ha-- that can be the-- an image processing even more demands. So that could be the field of application." So I began to do some thinking about that. And so there was a gang of four, that used to go around making presentations to Bob Noyce, HP, George Highermyer [ph?], DARPA and so on about the need for an integrated approach. Not just VLSI, but applications, computer app-- and Forest Basket started to work on workstations at the time. So, we then made a proposal to DARPA and actually Stanford got the first DARPA proposal in the VLSI field. Partly because, I mean, on its own merit, but of course the person who awarded it was someone we knew from information theory days at MIT, Bob Kahn. Who did later the TC/IP-- IP protocol-- with Vince Serf [ph?]. So, a troika [ph?] of Jim Meindl, Forrest Basket and me got the first VLSI contract in the country. The CS was formed, and then every university had its own version of these things.

Kapoor: I know Berkeley did.

Kailath: Different acronyms, yeah. So, what was I going to do in VLSI? I mean, Basket knew what he wanted to do, which was build a workstation. Okay. So, the first piece of luck was that I had a stu-- there were-- I had a student _called______. Sun Yung Koon [ph?] who's now at Princeton, his job was at USC, and Tom Cover [ph?] had a student who also took my classes about Abbas ElGamal [ph?], who's now the chair of the department at Stanford. And he had gone to USC. So I would visit USC also because I had many friends there. Sol Golomb was there now. After I left JPL, Andy left for UCLA, Golomb left for USC, Irving Reed went to USC and so on. So, <speaking foreign language> but, what was I saying now? Yeah, so they would ask me, what should we work on? I said, "The next area is VLSI." So Abbas [ph?] got interested in that. And Abbas got a visiting appointment at Stanford. He really wanted to come back to Stanford. And there were two young people who your friend Fairbairn knows about, Newkirk and Matthews, who also knew about this field, and-- I don't know what they were-- they were graduate students, but interested in the field. No, I think they had finished their-- I forget. They had finished their graduate work, I think. They wanted to teach the Mead_______ Conway book. So, I made a proposal to John Linville that we give-- he give me three billets by that time, the free-- — flowing appointment system had all been tightened up by Bill Miller, who is one of your people too. And there were billets departments were given billets and usually only when someone retired could that billet be filled or when you knew he was going to retire and so on. So, to get three billets at one lab, was unusual, but I said, well, they may be temporary, but we need to get going in VLSI, _Mead______ Conway is the buzz word. These guys are ready to teach it, no one else is. So, Linville agreed. Also, he had-- he was a little bit autonomous in his thinking. He listened to people's advice, but he made up his own mind which is I think the way a decision maker has to work. Rather than , take a committee vote and go with the consensus. Yeah, if there is a consensus or whatever. So, we got that. -- Newkirk and Matthews taught the course. They were close to Carver Mead> who used to come up too. And, the projects were sent off to Southern California to be manufactured through HP, I think. And Jim Clark was on the faculty, he took the course, and as we heard, he designed his geometry engine in the class and implemented it at-- where was it? Xerox.

Kapoor: Xerox, yeah.

Kailath: Xerox Park on the Alto. Then, Kung [ph?], my student got interested and then said we should use VLSI and signal processing, which is my field. And he started the first IEEE special interest group in VLSI signal processing, and he got a journal started in that field, and we had annual conferences, and Carver Mead-- gave the keynote at the first conference. And, so I in fact, I introduced him, in quite a humorous way, he was quite pleased, shall I dive-- digress to that?

Kapoor: Sure.

Kailath: Yeah. So I said, Carver Mead-- I learned many interesting things about him. First of all, he has a big peanut orchard in Oregon. I said, "Oh, that makes sense, because there is this definition of a farmer, Carver is a farmer, he is a man, outstanding in this field." Out standing in his field. Then I said, Carver is of course at Cal Tech, we all know, which is a very rarified atmosphere, Cal Tech, it's all science and this and that. There was a famous mathematician in relativity theory called Robertson. And the story is, that he used to walk with-- he was walking with his young son one day in the streets of Pasadena, and the boy says to his dad, "Daddy, daddy what is that building with the plus sign on top?" He was an atheist. And I forget-- oh, and the third joke was this is-- because Carver had said something which I don't think we-- everyone agreed with. I said, "In logic there's a theorem, that without-- if you have a false hypothesis, you can prove anything." So Bertrand Russell is a famous logician, and there's a story, probably untrue, but there's a story, that someone said to Bertrand Russell, well, you know, if that is true, how about the following, if two plus two is equal to five, prove that Russell is the Pope. Russell was an atheist.

Kapoor: Right. Right.

Kailath: So, apparently Russell gave the answer, he says, Okay. Two plus two equals five and therefore four is equal to five, then for five is equal to four. All right, okay, take away three from both sides, therefore two is equal to one.

Kapoor: Right.

Kailath: Now the Pope and I are two, therefore the Pope and I are one.

Kapoor: One.

Kailath: So, Carver loved these three jokes. I repeated them at his eightieth birthday when-- which was in Pasadena last year, I think, or the year before. So VLSI, what am I to do in VLSI, well, by then I had learned, I said, we know nothing about this field. I hired three students. Two from India, one from IIT Dehli, and one from IIT Madras. And then a student from Brooklyn Poly who was Spanish, but wrote a very interesting letter to me which intrigued me. Juan Jove [ph?], so I-- and I hired a post doc, one of my students had stayed on Hanok LeVaree [ph?]. I said, let's learn about VLSI. And we had another visitor. So we knew nothing about the field, the jargon and all that. And we slowly learned, and began to find problems and so on. And each of them ended up with a different thesis. And Sailesh Rao [ph?] with a thesis on exploiting the structure of VLSI to adapt it to signal processing algorithms. And the structure of VLSI is that each transistor is only connected to it's four neighbors, okay? And modular. So that was the easiest thing to build. So he found algorithms for exploiting that structure, and define what I call regular Iterative [ph?] Arrays for implementing different kinds of algorithms in signal processing. Matrix multiplication, solving linear equations, Fourier Transform-- and someone called H.D. Kung [ph?] had come up with systolic arrays, which is the same thing, data going in and out and so on. So we ex-- use systolic concept and he did his thesis on that. Jagdeesh_______ did his thesis on scheduling and timing problems because signals have different parts to go in the chip, and you have to arrange the computations so that the right pieces come together at the right time. So, he did some interesting work on that. Saying that, often when you-- when you study circuits and books, they have-- they use what I call Z-transforms, and you have delayed blocks between the adders and multipliers, and each delay block has a delay. But when you actually build a circuit, sometimes there's enough delay in the-- and in the theory of digital DSP, adding and multiplication takes no time. They're instantaneous, and-- because otherwise you can't do the transforms. And all the delays in this delay block, but in the real world, adding and multiplying take time. And so sometimes, there's enough delay there, in these operations that you don't need any more delay. So he worked out that algorithm, by using graph theory. You need precedence and so on. So, he did that. And Juan did some kind of computation honestly, and Juan won't mind my saying it, I wouldn't accept his thesis-- in fact, I had to work on it myself, which I-- by that time I wasn't doing. And there was still more to do, but he wanted to graduate and so on. He said, "There are-- yeah, there are still gaps, but my friends will fill it in." Sailesh was one of his friends and so on. So anyway, I signed his thesis. That year, Bell Labs, hired all three of them. 'Cause like MIT, they had a recruiter at Stanford, Scott Canard [ph?] who has now passed away. And he was tracking these students, and he liked them. And he-- he proposed that they hire these three. So his boss said to him, "How come? One professor, three students? No diversity?" So on and he_______ says, well, they're very good students, and you know Kailath has the reputation that his students do three Ph.D. theses by the time they graduate. So that's the sort of showing off. So, we did theses on VLSI and then two or three students followed them. But Sailesh-- they all went to Bell Labs. And Sailesh was at Holmdel [ph?], working with Victor Lawrence who was under Bob Lucky in the electronics group. And he heard-- he was doing his stuff, I forget what it was. That HDTV was the big challenge in the 80's because the Japanese were eating our lunch and manufacturing. And so it was decided that we could break through in HDTV and catch up with them. But he had heard that the chip designers, no matter how experienced at Bell Labs, were having a lot of trouble meeting the specs, area specs, power specs. So Sailesh said, "My Ph.D. thesis was on how to design architectures for these computations." So he told Mehdi Hatamian [?]_______ and his office mate, let's have a crack at it. And they persuaded their boss Ron Auckland to do. And then a few months, they produced a chip, which more than met the specs. Unfortunately, I can't remember the numbers right now. And, there was an article on it in the Holmdel magazine with Sailesh and the chip, showing it and giving it all the specs. But he left Bell Labs, for a reason I'll tell you later. And he couldn't find it, and I can't find it, and he didn't remember all these numbers, so. I can't-- but they were significantly less. Therefore then other people come to them and say, this is the next most important chip in Bell Labs history, please design it for us. After they did a few of these, they said why are-- and they got promoted at Bell Labs because of all this, made MTS, highest salary and all that. Why are we doing on this Bell Lab salary, we could do it ourselves. They went and told Bob Lucky. He said, "Bob Lucky, we've done the best you can for us, if you want to leave, you can leave. But we'll never give you another job, so you may starve-- you may not be very successful." Well, within a few months, six months or so, they started getting jobs from Bell Labs. And the company-- it was called Silicon Design Experts Incorporated was quite successful. It was acquired by Level One. And Juan, this third student, was a friend-- joined-- he had gone to the venture division of Bell Labs. And then, when Sailesh formed this company, he also quit, was the marketing man for Sailesh. And they sold the company and Juan then promptly re-- retired and lives in Florida with other causes, social causes. And, actually Gay Rights. And he has been a big force in pushing forward Gay Rights, which suddenly, accelerated and now is widely accepted.

Kapoor: So Level One was-- I was at Fujitsu at one time and we were working with Level One.

Kailath: I see.

Kapoor: --in designing an analog circuit with them. And that time, it was being run by Bob Pepper. Dr. Bob Pepper, from--

Kailath: <Inaudible>.

Kapoor: --originally professor at Berkley.

Kailath: I see.

Kapoor: But he was brought in by the venture capital community to run the company. And later on it was sold.

Kailath: Sailesh probably knew him. He must have been involved in the acquisition. So Sailesh worked there for a while til, in Level One was acquired by Intel.

Kapoor: Intel, yes.

Kailath: And then, after a while Sailesh left, he had some issues there with-- Intel was too big a company.

Kapoor: Right.

Kailath: But, so that VLSI <inaudible>, and _Jagdeesh______ went off into another area, databases, and he's a well-known world authority now in databases. So I've been very proud of my students. They've all formed remarkable careers, about 50 of these are-- if you count post-docs, at least 50, more than half, are IEEE fellows. Half a dozen are members of national academies. And so for my sixtieth birthday, they organized a five day international conference. They brought together the-- in five fields that I had worked in, communications, control, signal processing, manufacturing that came later, and mathematics.

Kapoor: So this is the -- publication--

Kailath: That was the book, it was a book and a big conference. For my seventieth birthday, they've organized an annual lecture, which Don Knuth [ph?] is one of those who gave the lectures and so on. So, that's how I got into VLSI with groups.

Kapoor: Right. And Professor Gibbons, of course, wrote a very nice letter on the occasion.

Kailath: Yes, I know that, yes.

Kapoor: And we'll come back to that. Although I can say, just in one-liner, that he wrote about you that, "Professor Kailath your career has been an extraordinary success, many times over. And for a different set of reasons each decade." So-- and then, of course, it went on because there's really nice words.

Kapoor: Right, that was in 1995. Because there was a big banquet where my admin, Chris Linkey [ph?] had done a terrific job organizing this, had collected letters from my friends, and colleagues, and students in a memorial volume. And Gibbons could not attend the banquet, so h sent this letter. And it's-- it's a good-- I was very flattered by the letter, it's a very nice letter, he's-- whatever Jim does, he does very well. Have you interviewed him? He should be a candidate, I think, yeah. As a semiconductor pioneer for ion implantation among other things. I know, a Dean at Stanford.

Kapoor: So this gentleman that I sent you the link of Luc Bauer [ph?], he was a pioneer in ion implantation at Hughes Aircraft and he also was at JetPropulsion at Cal Tech. He did his Ph.D. from Cal Tech.

Kailath: Okay. Really, yeah, I knew that-- one of Norm Abramson's_______ students was at Cal Tech, then moved to Hughes and did good work there. They've all now retired, of course. So the other area was adaptive filtering. And that came about as an accident. I knew that Kalman Filtering should-- when I had worked in-- I started to write a book, the first book on Linear System took eight years and five Ph.D. theses. And this other book took fifteen years, I think, or so. And more Ph.D. theses. But, I knew that there was a field called adaptive filtering in which Bernie Woodrow [ph?] Professor Woodrow, is a pioneer. But, again, the mathematics of that field were-- I thought the field should be closely related to Kalman Filtering. And, so I suggested to some students to work-- they didn't have much success. But then, I had a post doc visitor form India, Professor Reddy, he said, What should I..>. I said, "Look into adaptive filtering as field, because communications now modems are using adaptive filtering. Bob Lucky had built one of the first modems and Bell Labs. And Dave Forney was using it, and so on. So, apart from the communications QAM and so one. So, he started to look into that, and we got into it. And then, an engineer from ESL, called Ralph Schmidt, came to me and said, "I have this interesting work on this direction finding problem. It uses mathematical techniques linear algebra, and I'd like to make a Ph.D.

thesis out of this." Okay. So, by then, I had a group and I had very brilliant student call Martin _Morf______ who was very intuitive person with a-- so we-- and he was a research assistant and then on the faculty for a while. And, we had a got a contract from DARPA through Bob Kahn and others to make studies in adaptive filtering. And we picked up this algorithm of Ralph Schmidt called music. And I-- we didn't have much background. Said, okay, let's form a group and study this field. And in fact we made quite an impact on the field by developing a number of algorithms, but there was seven Ph.D. thesis in this field, and one of them is on top-- in an algorithm called Esprit_______ which is also now used in workplace. And it came about through a visitor I had, and that'll be a story for next time, Paulraj, who has just retired as research professor.

Kapoor: <Inaudible>.

Kailath: And is a pioneer of MIMO. So I said to him, let's look into this area. And he had been sent by the Indian Navy. So he came up with this idea of Esprit and-- but then he had to return to India, he wanted to return to India, and we give it to Dick Roy for his Ph.D. thesis. And that-- so when Paulraj came back for my sixtieth birthday conference, he had a poster, which I'll show you sometime. It says, The Kailath Comet. These seven students and the different areas they worked in. So, but Paulraj went away and then came back. So this has been used quite a bit, all these algorithms, and all of those students are fellows of the IEEE now. And so on. And have formed companies of their own, some of them. Others are professors. And what was I going to say, yes. But, Paulraj came back from India because he was frustrated by the politics-- internal politics there and so on. And I supported him for a couple of years with my grants, until I managed to persuade Stanford to appoint him to a research position, which is not a tenured positioned but you have to raise 90 percent of your salary from outside. And so-- but Paul-- so I said to Paulraj, look into the communications aspects of these-- or he had come up with these ideas. And, that lead-- which you can talk about later, HDTV was part of the inspiration for this. The problem in HDTV is you have to send 18-megahertz signal, where the usual TV channels are 6 megahertz. So there are two routes, one is you can use compression, and MIT worked on that. You can use compression and do it. Paulraj had another interesting idea, he says, "We have all these results in direction finding. So suppose for TV, HDTV, you put three transmitters around a metropolitan area. Each of them sends, they take these 18 megahertz, divide it into three, 6 megahertz packets-- groups, send it from three directions to each receiver. Use our algorithms to recombine them. 'Cause we can identify where the signals are coming from and combine it. So that was an interesting idea, and that in fact, helped him to get the research position at Stanford, which is not so easy these days. But, and took-- in fact, exceptional effort. But, he had also put in the claims for the patent that this can apply in the wireless context, because you have scattering in the wireless context, and that produces independence just as angles prove an independence. That is a potential application, and then after he came back Stanford, he started a company called I-- first called Gigabyte Wireless, but then they called it IO Span, which showed actually that you-- this concept worked. You could combine-- you could use-- the concept was using multiple antennas therefore at the transmitter and in the hand-- handset and in the receiver. But it was too early for its time. And the field wasn't ready for it. Nobody believed in multiple antennas so it was sold to Intel mostly for the IP. But Paulraj persisted, and he had people who banked him, and he came up with WIMAX [ph?], which use multiple antennas and then, LT took off and now multiple antennas are de rigeur. Every phone has at least two or three. So you can send three times what you could do before, because you have three antennas. And the word MIMO, multiple input, multi output-- became a buy word. And Marconi and Paulraj last year got the Marconi award for MIMO. And he's a world authority in that field. And the basic patent to Stanford. But unfortunately it was never licensed in time to get it. So people are using it, but--

Kapoor: So, I want to go back before we end the session, about ISL, and your directorship of ISL.

Kailath: Oh yeah, right.

Kapoor: --at Stanford. Because that was a key launch for a lot of the companies later--

Kailath: Well, yeah.

Kapoor: --technology transfer.

Kailath: So the integrated systems lab, it had started when I came to Stanford there was a group called the System Theory Lab run by two people in the control field, Gene Franklin, very well known in controls, and Robert Cannon, who was in the arrow department. And then-- so I joined-- and Abramson was in that group at the time. And some people in circuit theory, and I was the communica-- Abramson and I were the communication theory people. And then we took on one of Abrahamson's students, Tom Cover [ph?] who is very famous and just passed away. Unfortunately, very sadly a couple of years ago. So then, Ed McCluskey from Princeton, came into our group. 'Cause that was the only natural group. 'Cause Stanford is mostly well known for its semiconductor solid state work. And it's electro magnetics work, radio physics and so on. But McCluskey was a live wire and a dynamo, and he also just passed away. We had a memorial service for him at Stanford, and I don't know if he is also on the list here.

Kapoor: Yeah, I'm not sure.

Kailath: I think he should be. He was the first president of the computer society and so on. So, ISL-- our group was still known as system theory, he said, no, we need a digital systems laboratory. So after a couple of years, he branched off and started that. And, he started the computer forum, and the computer society. He was the first president. And at that time, we changed the name to information systems. And, Franklin was the director for a while, and then I became director in '72. And I moved it to the Duran Building and I built it up. When I-- took over as director, there were three full professors. Professor Woodrow, myself, and Franklin and a couple assistant professors, I think. One associate, Newcomb, who left soon after. No, Newcomb had gone. Anyway, but I built it up to about 13 faculty. It was one of the larger groups in ISL. And, we-- we were well known as the leading group in information theory. One of the people we hired was Tom Cover's student called Marty Hellman, who came up with the idea of public <inaudible> cryptography. And actually this year, on June 11th, he's getting the Turing Award. <Inaudible>, his student Diffy [?]_______ and Marty Hellman are getting the touring award.

Kapoor: I see.

Kailath: And-- so Tom Cover was there. Bob Gray was hired, became a big name in infor-- in signal compression, factor quantization, speech compression and so on. We hired a person in the computer field called John Gill from Berkley, complexity theory of computation. And that lead to a fir-- to my brush with computers, since we're in the Computer History Museum, I should tell you about that. My first brush was in 1957 or '58, when I came to MIT, and MIT had just acquired the big IBM computer called, I think, the 703. I forget what the first name or 701 or something. And, _Farno______ said, "Oh computers are the big thing, we all have to learn how to program." So all the graduate students had to write program in Fortran. Now-- so I wrote a program and I was sure-- it was a little laborious, I don't know if you ever wroteFortran.

Kapoor: I did.

Kailath: You did. I was sure that-- so you had to give this program to the computer center and punch cards.

Kapoor: Yes.

Kailath: Yeah. It came back and there were mistakes, I said, how can that be. Well, it took three or four iterations before I got it running. So after that, I never programmed.

Kapoor: We have one of those computers here.

Kailath: Oh you have?

Kapoor: And the punch cards.

Kailath: Oh yeah, with the Fortran, yeah.

Kapoor: Fourty seven <inaudible>.

Kailath: I'm sure Jim _Bacchus [?]______ may be here too.

Kapoor: Yes.

Kailath: But, yeah, so my next brush with computers many, many years later at Stanford when we had a new dean, called Bill Kays, and something called TRS, the radio shack computer had come about. And he was intrigued in it. And he said, "Oh, the computers-- desktop computers," because microprocessors had come and so on, commodore and also had built a computer. He said, "Anyone who writes a program which it can demonstrate to me, the Dean, works, I'll give him a free TRS80." So I wrote a communications program an autocorrelation in basic, I thi-- basic, is that the language? Yeah, basic, but after that I've never written a program. And my students are all experts, and Matlab, they don't even use. Matlab. But that's my brush with computers. But, I was director of the lab, and every year, the department would give out money for equipment, and it was always go to the radio physics people, or the solid state people, or the _______, I said, you know, we need some money too. For what do you need money? Computers. I want to buy a computer. And John Gill was with me, he was a-- he loved com-- he builds computer on his own. So he said, we'll buy, I forget, PDP 11? That was one-- the first computer. So there was a lot of opposition in the lab, especially by Bob Gray, he says, "What do we do with computers? We are paper and pencil computers." He became one of the biggest users of computers in the group later. So it changed the culture, we could do simulations, and with-- then we upgraded the system. And ISL was the first lab that had its own computer network. And when the department was envious about it. And so they-- we built one for the department and so on. So that's my brush with computers and so on.

END OF INTERVIEW

