Profile of Claude Shannon*

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Much to his discomfort, Claude Elwood Shannon, at seventy, is a living legend. What Louis Armstrong was to jazz, Shannon is to the electronic, digital information age, a founding father who laid down its most important principles. His contribution is saluted by the world. Diplomas and prizes stretch along a wall and up a spiral staircase in his home. There would surely be a Nobel too, if one existed in mathematics or information science.

But Shannon doesn't seek prominence. He is as content as an English country gentleman in his privacy. His face is so unfamiliar that when he arrived at a conference last year in Brighton, England, devoted to the field he founded, he was hardly recognized. In the dining hall, a man cried excitedly "Do you know who's coming? Claude Shannon!", when Shannon was sitting at the next table.

Not that he is unsociable. Out of the line of fire of the media, he laughs often, and is variously playful as a gadgeteer and a prankster. He is vividly remembered at Bell Labs for riding a unicycle down its long corridor and back again, juggling all the while. One of the plaques on his wall is from the Wham-O Company for his rocket powered Frisbee. At the end of the Brighton conference, he gave an amusing after dinner speech and pulling three tennis balls from his pockets, demonstrated a juggling "cascade."

Shannon's mathematical genius, on the other hand, is well recognized. He won fame first at 22 as a student at M.I.T., when he wrote an M.Sc. thesis which Howard Gardner, the Harvard mind theorist, in *The Mind's New Science*, judges "possibly the most important, and also the most famous, master's thesis of the century."

This prize winning paper, *A Symbolic Analysis of Relay and Switching Circuits*, put forward a very bright idea. Shannon saw that the branching network of strict logic, Boolean algebra, could be expressed by the relay switching circuits used in telephone exchanges. Essentially, "If the alarm clock rings and it is Monday, then you have to go to work" was equivalent to "If Switch A is closed, and Switch B is closed, then current flows through to the motor."

The insight was "monumental," says Marvin Minsky, M.I.T.'s Artificial Intelligence guru, because it helped to lay the groundwork for constructing computers. "You could use mathematics to calculate if a design was correct instead of using trial and error."

Ten years later, working at Bell Labs, Shannon came out with his masterwork, *The Mathematical Theory of Communication* (University of Illinois Press). At a stroke he transformed the understanding of the process of electronic communication, by providing it with a mathematics, a general set of theorems called 'information theory'. With lucid brilliance, Shannon wrote out the basic principles of the signaling of information. It was like Newton writing out the laws of motion for mechanics.

The slim paper exploded on the scene 'like a bomb', wrote John Pierce, a prominent colleague, and author of *Symbols, Signals and Noise* (Dover). Suddenly, engineers had a language to deal with the major puzzles of telephone and radio communications: how to

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measure information, and how to exploit fully the capacity of a telephone wire, microwaves, a fiber optic cable or any other channel of communication. So wide were the repercussions that Fortune magazine was soon calling the theory one of man's ''proudest and rarest creations, a great scientific theory which could profoundly and rapidly alter man's view of his world.''

What astonished engineers was Shannon's proof that however "noisy" a communications channel, it was always possible to send a signal without distortion. To do so, you have to encode the message in such a way that it is self checking. With the right code, signals could be received with as high accuracy as if there were no interference on the line.

A simple code might involve adding a symbol, a binary digit or ''bit,'' every few bits of message to describe whether a previous group of bits add up to an odd or even number. English is another error correcting code. Noisy party conversation is intelligible partly because half the language is redundant. The extra symbols allow you to fill in what you miss.

Shannon had lit a beacon, showing such codes were possible. Over the next twenty-five years engineers steered into the dark by his light. Powerful codes were worked out, yielding super accurate communications hardware, from space probes and computers to disk drives and compact disc players. Drag a knife point across the surface of a compact disc, and error correcting codes will mask the flaw, thanks to Shannon.

Voyager II sending detailed pictures of Uranus and its ten newly discovered moons to Earth 1.8 million miles away is a tribute to Shannon's inspiration. So are the picture perfect digital TV's and VCR's now joining CD's on the home market. Information theory spurred the digital revolution, where information is sent in discrete bits rather than in the wave form of 'analog' signals, because Shannon's error correcting codes work naturally in digital.

A problem is that the name ''information theory'' is misleading. As opposed to everyday use, in Shannon's theory ''information,'' like ''force'' or ''energy'' in mechanics, is defined very precisely as a commodity, measured in bits per second, unrelated to the meaning of the message. Like the driver of a truckload of sealed packing cases, a communications engineer is concerned only how to deliver the bits most efficiently.

Prompted by this misunderstanding, the short treatise, now in its eleventh printing, has inspired great claims that information theory has a significance far beyond communications engineering. Professors of the social sciences and other fields short of mathematical models rushed to adapt the ideas to their own ends. The formulation has been applied to everything from molecular biology and the brain to psychology, art, music, sociology, semantics and linguistics, economics and even landscape gardening.

A wave of enthusiasm for such work came in the fifties, then receded. Now there is renewed interest among some researchers. In one recent book, *Grammatical Man*, science author Jeremy Campbell found enough progress to argue that Shannon's theories are fundamental to understanding the universe, and that ''to the powerful theories of chemistry and physics must be added a later arrival: a theory of information. Nature must be interpreted as matter, energy and information.''

Shannon was in his mid-twenties when he worked out information theory. Born on the prairie in Gaylord, Michigan, he had gone to the University of Michigan, and then M.I.T., where he wrote his Ph.D. thesis on the mathematics of genes and heredity. He joined Bell Laboratories in 1941 and worked on cryptography. A theorem of Shannon's was behind the SIGSALY telephone, the huge speech scrambling apparatus which allowed Churchill to speak to Roosevelt from a special, toilet-sized booth through a coding system that even today is unbreakable.

Shannon left for M.I.T. in 1956, much to the regret of colleagues at Bell. "It was a big loss," says Edgar Gilbert, a colleague. "He was always generating interesting ideas. He would grasp the essence of a problem immediately, and come up with a totally different idea that shed a great deal of light on it."

At M.I.T. Shannon, made Donner Professor in 1958, gave "beautiful" lectures, says a colleague, took a few select graduate students in hand, and refined information theory. By the mid sixties, his preference for working at home became the rule (a friend borrowing his deserted office found a sizable uncashed check more than a year old). He retired in 1978, becoming Professor Emeritus, wealthy from investments in technological companies, some of them founded by his friends. One is Teledyne, where until recently Shannon served on the board of directors.

Not just a theorist, Shannon has always been fond of inventing and building gadgets and machines. A famous one was a mechanical white mouse which could learn its way through a maze, decades before the microchip. Another was Throbac, a calculator which operated in Roman numerals, and a 'mind reading' machine which anticipated whether a challenger would choose heads or tails. (Colleague David Hagelbarger invented this but Shannon's stripped down version outsmarted his "more conservative and pompous design," he says.)

Then there was Hex, a machine which played a board game. Shannon's prankish side came out in the design, which cunningly concealed the fact that the machine had an unfair advantage. A Harvard mathematician got very upset when he lost to Hex, which actually followed a childishly simple strategy, but took an impressively long time to "think." He was all set to try again, when Shannon took pity on him and confessed the truth.

None of these devices made his fortune, though there was one near miss. Shannon and Edward Thorp, author of *Beat The Dealer*, once took a trip to Las Vegas with their wives and a computer, intent on outsmarting the roulette wheels. Unfortunately, the analog computer and the ratio apparatus were primitive by modern standards and so the enterprise failed for technical reasons. This was a pity: a night of testing in Shannon's basement had turned a few hundred imaginary dollars into $24,000.

A visit to his large house, down a shady lane a few miles from M.I.T., suggests that home life for Shannon has not been dull. There is a pile of penciled manuscripts of his mathematical work. Around the house there are five pianos and thirty other musical instruments ranging from piccolos to trumpets. Among a sizeable collection of chess playing machines is one which moves the pieces with a three fingered arm, beeps and makes wry comments. (In 1950 Shannon wrote the pioneering treatise on how a computer could be programmed to play chess.) In the garage, there is a dusty pile of unicycles and penny farthings. The chair lift he built to take his three children 450 feet down to the lakeside has been taken down, however, now that they are grown.

For some time his current interest has been juggling, continuing a life long fascination with balance and controlled instability. His machines include a motorized, gasoline powered pogo stick, a unicycle with an off center wheel (it keeps a rider steady while juggling), and a tandem unicycle that no couple has yet been able to ride. He goes to juggling conventions, and is polishing a paper for *Scientific American*. In the toy room there is a machine with soft bean bags for hands which "juggles" steel balls. His model masterpiece is a tiny stage on which three clowns juggle eleven rings, seven balls and five clubs, all driven by a diabolical mechanism of clockwork and rods, invisible to the viewer in black light illumination.

When I visited him, Shannon was just back from Japan, where he had given a speech and collected a Kyoto award in company with Messaien the composer. He was entertainingly hospitable, ready to show off photos of his family, a computer printout of his stock selections, and all his toys. His gruff laugh made it clear that fun is still his life's motif. Betty Shannon, a math graduate who met Shannon at Bell Labs, was his partner in the constant merriment. Occasionally the overlay of disarming geniality was penetrated, as a question gave him pause. Under the beetle brows his eyes would show the canny depths of genius.

OMNI: How many balls can you juggle?

Shannon: I can do four. With five I don't last very long! I can get them up there, but catching them is a different matter!

OMNI: Did your genius come unannounced, or was there science and invention in your background?

Shannon: My grandfather was an inventor who had some patents, a washing machine, stuff like that. He was also very interested in determining the exact turn of the century, how it should be fixed – 1900 or 1901. He owned a farm, and was always inventing farm machinery.

My father Claude was judge of probate in Gaylord, a little town of about 3000 people in Michigan. Small enough that if you walked a couple of blocks, you'd be in the countryside. Here is a picture of me playing the E Flat alto horn in the town band. Here's my mother, who was principal of the high school in Gaylord. Very intelligent person, as was my father. My father was clever mathematically and knew what he was talking about, but he didn't work in mathematics. My mother got glowing recommendations from her University of Michigan professors in languages.

I don't think there was much scientific influence between my father and myself. He was a little distant, and by the time I got to be ten or fifteen he was practically seventy. Although he certainly helped me when he could. I used to work with erector sets, and a friend of mine and I had a telegraph system between our houses, half a mile away, and we built the parts for this line for Morse Code signalling. Later we scrounged telephone equipment from the local exchange and connected up a telephone. I was always interested in building things that had funny motions, but my interest gradually shifted into electronics.

OMNI: Funny motions?

Shannon: Yes, especially like those dancers I used to see as a young man on the stage burlesque theatre! They had an interesting motion. Cheap joke!

OMNI: When was the erector set?

Shannon: In the seventh grade or so. As a matter of fact when Betty and I got married I said I'd always wished I'd got a number ten erector set, as I had only got up to eight and a half, and she gave me one for Christmas!

Betty Shannon: I went out and gave him the biggest erector set you could buy in this country – it was fifty bucks and everyone thought I was insane!

Shannon: Giving it to a grown man! But the fact of the matter is that it was extremely useful and I used it to try out different things. Now I have a number ten Meccano set and two others as well.

OMNI: Ashley Montagu in *Growing Young* says that it's important to remain playful in spirit through life. You seem to agree with that?

Shannon: Yes, I certainly do. I am always building totally useless gadgets, some of which you can see around here, just because I think they're fun to make. They have no commercial value, but I think they may be amusing.

OMNI: Don't you ever worry about the fact that they are not useful?

Shannon: No. That would be the last thing! Here's a picture of me riding a unicycle and juggling at the same time. That was more than thirty years ago. As a matter of fact you wouldn't believe the number of unicycles we have in our garage outside, and similar wheeled vehicles of very odd types. I have a certain fascination for them.

OMNI: You once made an enormous impression riding a unicycle and juggling at the same time in the corridors of Bell Labs!

Shannon: Yes I did! That created quite a stir.

OMNI: Was it such a staid place, Bell Labs, that this could create such a sensation?

Shannon: Oh no. Those people are very far out. But this was something that had never happened in the hall before. Bell Labs was and is the freest research group in the country associated with a commercial firm.

I worked at Bell Labs for fifteen years, and after that I was a consultant there. They gave you great freedom. To begin with you could work on what you wanted, your own ideas; they didn't come and say, "work on this!" At least, not to me. Not only that, but the people in my department in the mathematics research group were all very bright and capable and I had a lot of interaction with them. Yes, it is a great place.

OMNI: Can Bell Labs take credit to some extent for your achievement?

Shannon: I think so. If I had been in another company, more aimed at a particular goal I wouldn't have had the freedom to work that way. I think I could have done it if I had been at a university. Most universities are totally free in which kind of research their professors do, M.I.T. for instance. Bell Labs was very open-minded.

OMNI: Shockley, the inventor of the transistor, was there at Bell Labs when you were there – did you know him well?

Shannon: I remember going into his office, where he had a little object on his desk and I said "What's that?," and he said "It's a solid state amplifier," and explained that it amplified like a vacuum tube. In other words this was the transistor in its first version. Right there I got a little grasp of its importance because of its small size. I consider Shockley and his team there and Bardeen as the inventors of the most important thing discovered this century.

OMNI: Was the university environment less conducive to you?

Shannon: I believe that scientists get their best work done before they are fifty, or even earlier than that. I did most of my best work while I was young.

OMNI: Is there some magical quality which disappears with age?

Shannon: It may be that our brains are not as sharp as when we are young. If you look at the history of great scientists, and read about Newton or Einstein or people in that class, you find that their greatest work was done at a fairly young age, usually between twenty and fifty.

OMNI: Some recent research suggests that the brain physically responds to stimulating interests even in old age, and with growth in dendrites, and so there doesn't seem to be an obvious physical reason why the brain should not operate as well later. The experiments have been on rats, rather than people, of course!

Shannon: What did they do, ask them a hard mathematical question?

OMNI: Did your ambition wane at all?

Shannon: I don't think I was ever motivated by the notion of winning prizes, although I have a couple of dozen of them in the other room. I was more motivated by curiosity. Never by the desire for financial gain. I just wondered how things were put together. Or what laws or rules govern a situation, or if there are theorems about what one can't or can do. Mainly because I wanted to know myself. After I had found the answers it was always painful to write them up or to publish them (which is how you get the acclaim). There are many things I have done and never written up at all. Too lazy, I guess. I have a file upstairs of unfinished papers.

OMNI: You weren't affected by your success in the stock market, were you? Did it take away the necessity to work so hard?

Shannon: Certainly not. It's true we have been very successful in stocks, not just Teledyne, but Hewlett Packard, Motorola and many other companies. Indeed I even did some work on the theory of stocks and the stock market, which is among other papers that I have not published. Everybody wants to know what's in them! (Laughs.) It's funny. I gave a talk at M.I.T. on this subject some twenty years ago and outlined the mathematics, but never published it, and to this day people ask about it. Just last year when we were over in Brighton more than one person came up to me and said "I heard you talked at M.I.T. about the stock market!" I was amazed that anybody would even have remembered it!

OMNI: So your stock market success was based on mathematics?

Shannon: Oh yes. Mathematics and some good friends! More important, that! One of my good friends since college days was Henry Singleton, who is head of Teledyne. He started his company and asked me if I would like to invest in him. I had a good opinion of him and we put as much as we could into Teledyne, and that's gone off like crazy. That was in 1961.

Betty Shannon: We had already had one good experience with Bill Harrison, that taught us what can happen if you're lucky in the market.

Shannon: He started Harrison Laboratories, which merged with Hewlett Packard. That was in 1953. We've had quite a few things like that. But in addition, we do study the graphs and charts. The bottom line is that the mathematics is not as important in my opinion as the people and the product.

OMNI: What was the lecture at M.I.T. about?

Shannon: The best way to balance a portfolio – the optimal amount you should have in different stocks, to maximize the logarithm of the current value of the portfolio, if that is the thing you are trying to maximize. But let me say that a lot of this is negated by the tax laws. If you make money it becomes very painful to sell that stock, because you have to pay a capital gains tax. This tends to negate all the theoretical thinking.

OMNI: It is not about when to buy or sell an individual stock?

Shannon: A lot of people look at the stock price, when they should be looking at the basic company and its earnings. There are many problems concerned with the prediction of stochastic processes, for example the earnings of companies. When we consider a new investment, we look carefully at the earnings of the company, and think a lot about the future prospects of the product. We're fundamentalists, not technicians.

OMNI: Are you lucky too?

Shannon: Far beyond any reasonable expectations.

You know economists talk about the efficient market, and say everything is equalized out and nobody can really make any money, it's all luck and so on. I don't believe that's true at all. These are our current stocks, some of which we have only held a short time. The annual growth rates are punched out by our machine there every night, a prehistoric Apple II which Steve Jobs wired together himself.

The annual compounded growth rates of these stocks since we bought them, most of them quite a few years ago, are 31% a year, 11%, 185% (that one we haven't had too long), 30%, 31%, 181%, 10%, 18%, 114%, 21%, 2% and 27%. (Laughs.) That's the full list of our holdings.

OMNI: Which companies are the big gainers?

Shannon: Teledyne for example, we have held for 25 years, and it's compounded 27 per cent a year. The difference between going up 27 per cent and 10 per cent, such as you might get in a bank, is incredible, especially when that happens for 25 years.

OMNI: Is there a future to using mathematics to predict fluctuations in stock prices?

Shannon: My general feeling is that it is easier to choose companies which are going to succeed, than to predict short term variations, things which last only weeks or months, which they worry about on Wall Street Week. There is a lot more randomness there and things happen which you cannot predict, which cause people to sell or buy a lot of stock. I think it is very hard to predict short term stock fluctuations. Furthermore when you get into short term fluctuations you are always paying short term capital gains. With a long term stock you may never pay taxes because you keep it forever.

OMNI: How did you get to M.I.T.?

Shannon: When I got my bachelor's from Michigan I wasn't sure what I was going to do. There was this little postcard on the wall saying that M.I.T. was looking for somebody to run the differential analyser, a machine which Vannevar Bush had invented to solve differential equations. They wanted a research assistant to run it, and I applied for the job. I spent the next four years at M.I.T. getting first a Master's degree in electrical engineering, and then a doctorate in mathematics. So throughout my life I have been straddling those two fields.

OMNI: What was the differential analyser made of?

Shannon: The main machine was mechanical with spinning discs and integrators, and there was a complicated control circuit with relays. I had to understand both of these. The relay part got me interested. I knew about symbolic logic at the time from a course at Michigan, and I realized that Boolean algebra was just the thing to take care of relay circuits and switching circuits. I went to the library and got all the books I could on symbolic logic and Boolean algebra, started interplaying the two, and wrote my Master's thesis on it. That was the beginning of my great career! (Laughs.)

OMNI: You saw the connection between a relay circuit and Boolean algebra? It was quite an inspiration?

Shannon: Oh yeah. Trivial, actually, once you make it. The connection was not the main thing. The more important, harder part was working out the details, how to interleave the topology of the switching circuits, the way the contacts are connected up and so on, with the

Boolean algebra expressions. Working that out was a lot of fun. I think I had more fun doing that than anything else in my life, creatively speaking. It worked out so well. When I finished, it was shown to several people there, including Vannevar Bush who was then vice-president and dean of engineering at M.I.T.. He was very impressed and wrote a recommendation to get it published, and to get me into the mathematics department there, instead of electrical engineering. So I did my doctorate in mathematics.

OMNI: Was the basic insight that yes/no can be embodied in on/off switches so trivial?

Shannon: It's not so much that a thing is "open" or "closed," the "yes" or "no" that you mentioned. The real point is that two things in series are described by the word "and" in logic, so you would say this "and" this, while two things in parallel are described by the word "or." The word "not" connects with the back contact of a relay rather than the front contact. There are contacts which close when you operate the relay, and there are other contacts which open, so the word "not" is related to that aspect of relays. All of these things together form a more complex connection between Boolean algebra, if you like, or symbolic logic, and relay circuits.

The people who had worked with relay circuits were, of course, aware of how to make these things. But they didn't have the mathematical apparatus or the Boolean algebra to work with them, and to do them efficiently. A lot of my work has to do with minimizing circuits, trying to get the smallest number of contacts, for example. They had done this to a certain extent, but they hadn't gone deeply into the mathematics, so they hadn't done it nearly as well as you could with the Boolean algebra.

OMNI: But they already had some idea, did they, of translating the words "and," "or," and "not" into a physical embodiment?

Shannon: They all knew the simple fact that if you had two contacts in series both had to be closed to make a connection through. Or if they are in parallel, if either one is closed the connection is made. They knew it in that sense, but they didn't write down equations with plus and times, where plus is like a parallel connection and times is like a series connection.

OMNI: Still, making the connection between relay circuits and Boolean algebra was inspired, wasn't it?

Shannon: Well, I don't know what inspiration is. I think you do have flashes of insight. I may have had an insight one day and then I would spend some time in the library, writing equations and so on, and more insights would come.

OMNI: Most people don't know very much about your Ph.D. thesis, which applied mathematics to biology, I understand – it sounds like DNA coding?

Shannon: Yes, it's related to that. Animals have many pairs of chromosomes, long lines of genes, and when two animals mate they get one of a pair from the mother and one from the father, for each of the pairs. More complicated things can happen too. The chromosomes can have a crossover so that you only get a portion of one half and a portion of the other half.

I tried to get a mathematical description of what goes on when you mix these chromosomes in this kind of a process, and more generally when you have whole populations mixing their chromosomes this way – what goes on in the statistics of the different gene frequencies, which determine if your hair is brown, or what color your eyes are, or how tall you are.

So I set up an algebra which described this complicated process. One could calculate, if one wanted to (although not many people have wanted to in spite of my work), the kind of population you would have after a number of generations.

OMNI: So your scheme would tell us, for example, if Americans will eventually turn into a nation of brunettes?

Shannon: I don't know how many genes are related to hair color, I think probably more than one pair, just as IQ is not just one or two genes but probably a great many.

My theory has to do with what happens when you have all the genetic facts. But people don't know all of them, especially for humans. They are pretty well versed on the fruitfly! There they understand that this gene does this, this gene does that. But with regard to humans, it's hard to perform experiments to get the data. I was at a much more theoretical level, assuming that all the genetic facts were available.

OMNI: Before you wrote your classic paper on *The Mathematical Theory of Communication*, Norbert Wiener went round the offices at Bell Labs announcing "information is entropy." Did that remark provoke you in any way to come up with information theory?

Shannon: No. I hadn't even heard of that remark when I started my work. I don't think Wiener had much to do with information theory. He wasn't a big influence on my ideas there, though I once took a course from him. Don't get me wrong, he was a great mathematician. He was an idol of mine when I was a young student at M.I.T.

OMNI: When *The Mathematical Theory of Communication* was published, there was an indignant review by a certain mathematician, accusing you of mathematical dishonesty because your results weren't proved, he said, with mathematical rigor. Did you think that plain silly, or did you think, Well, maybe I should work hard to meet his criticisms?

Shannon: I didn't like his review. He hadn't read the paper carefully. You can write mathematics line by line with each tiny inference indicated, or you can assume that the reader understands what you are talking about. I was confident I was correct, not only in an intuitive way but in a rigorous way. I knew exactly what I was doing, and it all came out exactly right.

OMNI: How would you explain the impact of your information theory on communications engineering?

Shannon: On the philosophical level, one is able to understand the communication process and measure what is being sent, measure information in so many bits or choices per second. On the actual operational level, it enables you to combat noise and send information efficiently and use the right amount of redundancy to allow you to decode at the receiving end in spite of noisy communication.

OMNI: What about its importance in other fields? In the fifties, you criticized what you called the bandwagon effect, where people in your view over-enthusiastically applied your ideas to fields other than communications. Recently, the book *Grammatical Man* has again suggested that it may be widely applicable. Are you as skeptical as you were in the fifties about there being something more to it?

Shannon: I'd have to say I am interested in information theory and always was in the narrow sense of communication work, on problems of coding and so on. You can broaden the meaning of the term information theory to apply to all kinds of things, like genetics and how the brain works and so on.

Many people now see it in a much broader context than I ever did. They apply it for example to the nervous system of animals or humans, where information is transmitted along nerve networks, and there is redundancy, because the system is not very precise and accurate. This is a noisy system.

A similar thing happens in the social system where we have lots of aids to communication. If you're talking to me I might say "what?" which is a feedback system to overcome some of the noise, and to get correct transmission.

OMNI: Does your theory give a hint of how life might have evolved, seemingly in the face of the second law of thermodynamics, which says that order should slowly disintegrate?

Shannon: The evolution of the universe is certainly a very puzzling thing to me as well as to everybody else. It's fantastic we've ever come to the level of organization we have, starting from a big bang. Nonetheless, I believe in the big bang.

The second law of thermodynamics is not quite so simple as to say that from that big bang you couldn't get anything more than disorganization. There's a lot of energy involved. You could get local organization at the cost of overall increase of entropy. I'm a firm believer in an increase in entropy as time goes on. But you can use some of it to increase order elsewhere. In a steam engine, you can use disorganized heat energy to produce organized mechanical energy but only at a certain cost. So I think it's kind of that way in the universe.

I've puzzled many hours about the gradual organization of life and the structure of knowledge, and all the things we humans have. To me it's the most incredible thing! I don't happen to be a religious man and I don't think it would help if I were!

OMNI: You wouldn't want to say information theory is a substitute for belief in a God?

Shannon: I certainly would not!

OMNI: Marvin Minsky said you stopped working on information theory because you felt all the important theorems were proved. Is that correct?

Shannon: No, I just developed different interests. As life goes on, you change your direction.

OMNI: You have avoided the press over the years, have you?

Betty Shannon: Not deliberately. On the other hand, we haven't sought them either. We live very quietly.

Shannon: I'll tell you this, I'm not too crazy about interviews.

OMNI: Did you feel you were destined for fame?

Shannon: I don't think so. I always thought I was quite sharp scientifically, but scientists by and large don't get the press that politicians or authors or other people do. I thought my paper on switching was quite good, and I got a prize for it, and I thought my information paper was very good, and I got all kinds of acclaim for that – there's a wallful of prizes and stuff in the other room.

OMNI: Do you find fame a burden?

Shannon: Not too much. I have people like you coming and wasting my afternoons, but that isn't too much of a burden!

OMNI: Why is juggling so interesting to you, especially mathematically?

Shannon: I did write a paper for *Scientific American*, as yet unpublished. There is a theorem which relates to how many balls you are juggling, and how long each one is in the air. I talk about a uniform juggle where every time you throw a ball it stays in the air the same amount of time, and when it hits your hand it stays there the same amount of time. We visualize a person not just with two hands but with several hands, or there could be several different people involved. The theorem relates five quantities, the number of hands, the number of balls, the vacant time when your hand has nothing in it, the contact time and the flight time. These five things are all connected by a very simple relationship, which would be exciting to nobody except a few mathematically inclined jugglers!

OMNI: Would it lead to a way of juggling more objects than ever before?

Shannon: You have to throw the balls higher to get more time, and it gives an indication of how much higher you have to throw them, as a function of the number of balls you are juggling.

I've measured jugglers with stopwatches and observed how they do it, and if they're juggling seven balls, which is a very hard thing to do, they have to throw them very high. I even had them put metallic strips on jugglers' hands and had them juggling metal covered balls so they would close a contact when they were holding the balls, and ran this data into electronic clocks.

OMNI: Does it show what the limits of juggling are? Can we say that no one will ever juggle more than fifteen balls, for example?

Shannon: No. All you have to do is throw them higher and be quicker. Indeed a friend of ours holds the world record of twelve rings.

OMNI: It's remarkable that you've never commercialized your delightful juggling clowns.

Betty Shannon: Oh fiddle!

Shannon: Well, I don't think there would be too much of a market.

Betty Shannon: We don't really believe in commercializing fun.

OMNI: You have a nice array of computerized chess machines in your toy room. Do you still play chess?

Shannon: I don't play at all.

Betty Shannon: He used to play very well. Good enough to play Botvinnik in Moscow. Claude at one point got the exchange. Botvinnik was worried. He finally won, but it was close.

OMNI: Do you find it depressing that chess computers are getting so strong?

Shannon: I am not depressed by it. I am rooting for machines. I have always been on the machines' side.

Betty Shannon: Some people get very angry when he says that.

Shannon: I am not depressed by machines getting better. Whether people are going to be replaced by machines, I don't know. That's a hard question. It may be possible within a century or so, that machines are going to be doing almost everything better than we do. They already do a lot of things better than we do. An automobile can go down the street a heck of a lot faster than any person can, for example. They can do factory work of all kinds better than we can. The highly intellectual stuff is going to come later.

But I wouldn't be at all surprised, no.

OMNI: Do you agree with Norbert Wiener, who is reported to have denied any basic distinction between life and non-life, man and machine?

Shannon: That's a heavily loaded question! Let me say this. I am an atheist to begin with. I believe in evolutionary theory and that we are basically machines, but a very complex type, far more so than any machine man has made yet. So in a way that's both a Yes and a No. We are kind of an extreme case of mechanical device – by mechanical I don't mean just metals are involved, of course, gears and so on. A natural device. I see no God involved or anything like that.

OMNI: Will robots be complex enough to be friends of people, do you think?

Shannon: I think so. But it's quite a way away.

OMNI: Could you imagine being friends with a robot?

Shannon: Yes I could. I could imagine that happening very easily. I see no limit to the capability of machines. The microchips are getting smaller and smaller and faster and faster and I can see them getting better than we are. I can visualize sometime in the future we will be to robots as dogs are to humans.

OMNI: Can you imagine a robot President of the United States?

Shannon: Could be! I think by then you wouldn't speak of the United States any more. It would be a totally different organization.

OMNI: Is your famous proof that a reliable circuit can be built using unreliable components relevant to the brain's operations? Could the brain be making use of such design?

Shannon: How the brain manages to work so well with the kinds of elements it has is quite a puzzle. It must make some use of redundancy in its connections. We know the brain can suffer all kinds of damage and in particular neurons can go out of operation and it can still handle things pretty well. So it must use some redundancy to take care of faulty operations. But whether it does it the way we discussed in that paper is a much deeper and harder question.

In a modern desk computer there is generally no redundancy. If one part gets into trouble that will show up in later operation. It seems to me that the way the brain works and how we manage to live in spite of all kinds of internal troubles shows that there must be a great deal of redundancy there, and a design which involves some kind of concept of multiple units or parallelism.

OMNI: But your paper involved more than redundancy – you showed that even if you had relays which closed only 60 per cent of the time when triggered, you could still cleverly design a circuit which would work. Could the brain be using such an approach?

Shannon: The brain has ten billion neurons, or some such huge number, so probably it is cheaper for biology to make more components than to work out sophisticated circuits. But I wouldn't put it past evolution to do some very clever things like that! I am totally astounded by how clever and sophisticated some of the things we see in the human or animal bodies are, due to long evolutionary changes, I presume. This could be happening in the brain, but an easier way would be parallelism. The brain is pretty sophisticated in other directions, as we know. When it really gets going we have all these clever people like Einstein.

OMNI: Why aren't you more involved with computers, personally? One would think you would love playing with them. Aren't they the ultimate gadget?

Shannon: I don't mess around with programming at all. I find that kind of dull, feeding stuff into a computer. Designing computers would be more my taste, but I haven't been feeling much like it lately. I guess I've had a bellyful of that game. There was the differential analyser, then relay circuits, and all those things that were leading up to these computers, and I've written papers on all those subjects.

OMNI: Perhaps you like machines that you can build yourself, rather than computers which you can't build from scratch any more?

Shannon: I do like the physical aspects of these things, but you're oversimplifying to say I don't really like the symbolic things too. Mathematics itself involves symbolics.

OMNI: Where did you find all your chess machines?

Shannon: There's a store in Los Angeles which has all these different chess machines.

Mrs. Shannon: Claude went hog wild.

Shannon: Yes. Bought one of each.

OMNI: Did you make the motorized pogo stick hanging in your garage?

Shannon: No, I bought it, from a guy in New Jersey who made it. I don't think he had much success with it. I may have been one of the few buyers. It's gasoline driven. There's a piston in it which fires each time it comes down, so you go along at great velocity! But I found it very uncomfortable. It was kind of a shock each time the thing exploded there and so it didn't ever get much use.

OMNI: When you went to Las Vegas equipped with computer and radio to win at roulette, why did you abandon the project?

Shannon: The thing worked very well here in the house. The roulette wheel is up in the attic now. A real professional one you know. The predictor would predict not in which hole the ball was going to fall but which half of the wheel. It was a lot better than a 50-50 prognosis. Two thirds of the time it would pick the right half of the wheel. This improved the odds so that you would win at a very good rate if it kept going.

OMNI: It worked extremely well, then, on that roulette wheel at least. How did it do it?

Shannon: Part of it depended on the fact that wheels in Las Vegas and elsewhere are somewhat tilted, and they don't level them up well. We examined many wheels and we could see some of them were tilted quite strongly. If you pick those out then there is a strong probability that the ball will fall in a certain segment of the outside of the wheel, and you can tell quite well how long it will take for that to happen.

If you time the spinning of the wheel you can see where the wheel is going to be when the ball falls in. The wheel is going around one way and the ball is going around the other, and you find the concurrence of those two things, where the wheel is going to be when the ball falls in. It's a simple dynamical system with very little friction.

OMNI: Why wouldn't you have to take into account the strength of the croupier's throw?

Shannon: The device we used timed both the wheel and the ball. The person standing there would press a button when they gave the wheel a good spin, and the double zero went by a certain point, and also when the ball was thrown and passed a certain point, and came around again to that point. The croupier could throw it at different speeds, true, but this was taken into account in the computation.

OMNI: But you had to see where it started?

Shannon: You had to both time the wheel and get an indication of when the ball left the croupier's hand. Both of those things were involved in this little computer that we made. But we had a lot of practical problems, and we never made any money really.

OMNI: But could you have made money if you had worked hard to solve these purely practical problems?

Shannon: I think so, if we had been willing to spend another month cleaning up details. But we got discouraged after we spent a lot of time and effort.

OMNI: You once wrote that the redundancy of a language determined whether you could have crossword puzzles in that language, and that since English has a redundancy of about half, you couldn't have three dimensional crossword puzzles in English. Is that right?

Shannon: Yes. You can't build big ones in three dimensions. In English there are more constraints among the letters, and it gets harder to find other words which will tie them together in a two dimensional pattern. A fortiori, if I may use another English word, it gets even harder to tie them together in three dimensions.

OMNI: Your interest in balance and controlled instability which shows up in your unicycles and juggling is very relevant to robots and their control systems. Are the robot designers making the pilgrimage to your house to ask about robots?

Shannon: I have built a number of robotic devices and juggling machines. They are more a matter of entertainment for me than practical devices for the rest of the world. I like to show them off to people but I don't expect to sell very many.

OMNI: If you were funded to the full would you build a robot that would ride a bicycle?

Shannon: Oh, I have built little bicycle riders already. I have one four inches high that rides a tiny two wheeled bicycle. That's almost trivial to do, actually. I worked on a little mechanical unicycle rider but I never got that working very well.

OMNI: Is it true you investigated the idea of mirrored rooms?

Shannon: Yes, I tried to work out all the possible mirrored rooms that made sense, in that if you looked everywhere from inside one, space would be divided into a bunch of rooms, and you would be in each room and this would go on to infinity without contradiction. That is, you'd move your head around and everything would look sensible. I think there were seven types of room. I planned to build them all in my extra room here and give people an exciting tour.

The simplest case would be a cube where you would just see an infinite series of yourself receding into the distance. All of space would be divided sensibly into these cubical patterns. But other ones, tetrahedra and so on, yield much more complex and interesting patterns. I will build them if I can finish all my other projects!

At the moment I am working on another juggling machine, which might juggle five balls. I am using an air hockey table, and plan to juggle disks by tilting the table.

OMNI: What's your secret in remaining so carefree?

Shannon: I do what comes naturally, and usefulness is not my main goal. I like to solve new problems all the time. I keep asking myself, *How would you do this? Is it possible to make a machine to do that? Can you prove this theorem?* These are my kind of problems. Not because I am going to do something useful.

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