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Moore's Law: An Intel Perspective

Introduced by Gene Meieran, participants Gordon Moore, Andy Grove, Craig Barrett, Les Vadasz, Ted Hoff, Dov Frohman, and Federico Faggin comment upon how past challenges were overcome and the lessons learned to facilitate innovation and execution in manufacturing. Futurist Ray Kurzweil and silicon device visionary Dr. Carver Mead speak to the paths the lie ahead for the semiconductor industry. Includes comments from (late) Intel Cofounder Robert Noyce on the invention of the integrated circuit.

Gene Meieran: Hi, I'm Gene Meieran. I'm an Intel Fellow and it has been my privilege to have worked with Gordon Moore at Fairchild Semiconductor and Intel for almost 40 years.

Less than 20 years after the invention of the transistor by Shockley and his colleagues at Bell Labs, and less than five years after Bob Noyce and Jack Kilby invented the integrated circuit, Gordon Moore drew a single line on a piece of paper and forever changed our future.

This slide was a prediction of how integrated circuit complexity would evolve over the next decade. But soon this transformed into a challenge sowing the seeds for what was to become Silicon Valley. It was now regarded as a law applied to almost all advances in high technology.

Bob and Gordon founded Intel a few years later. The people they hired and the devices they created followed Moore's Law and altered the way that the world would technologically and economically evolve.

Having been a witness as well as a participant in these remarkable events, I can only view with awe and note with true astonishment that the trend in complexity growth that Gordon observed 35 years ago still remains valid. This simple observation took on a life of its own and became a self-fulfilling prophecy; a law.

And as a result of this law, individuals have at their fingertips exponentially expanding computer power and the ability to wirelessly communicate instantly with almost anyone, anywhere.

It has enabled the launch of humanity's journey to other worlds, and has created a global interconnected electronic economy. Moore's Law and Gordon Moore, a remarkable prediction from a truly remarkable man.

Gordon Moore: Moore's Law is a name that was given to a projection I made actually in 1965. I was given the chore of predicting what would happen in semiconductor components over the next 10 years for the 35th anniversary edition of Electronics Magazine.

That was the early day of integrated circuits. The most complicated ones on the market had something of the order of 30 transistors and resistors. We were working on things of about twice that complexity, about 60 components. And I just plotted these on a piece of semi long paper and noticed that since the first planar transistor was introduced in 1959, with integrated circuits following essentially on the same technology, that the number of components on an integrated circuit was about doubling every year.

Interviewer: Ted Hoff, Intel Fellow. Inventor of the microprocessor.

Ted Hoff: First it was an observation, it was a noticing of what is taking place in the industry. And the next step was to try to understand why that phenomenon is taking place. Why is what we considered the optimum chip or the most reasonable chip to build, getting more complex every year?

Andy Grove: No company in the industry is isolated from the other companies, so if one company does a 1,000 bit memory, everybody else has to bit a 1,000 bit memory. So it was enough for the pace setters to set the pace using Moore's Law, and everybody else then followed the pace setters since they would have had, in effect, followed Moore's Law themselves.

Craig Barrett: I'm not sure Gordon recognized the impact that his little logarithmic plot would have when he did it in the mid 1960s. The impact of Moore's Law in our industry has been phenomenal. It's really been the road map or the sign post that's led us to do everything that we've been doing.

Gordon Moore: Now, I wanted to make the point that integrated circuits were going to be the cheap way to buy electronics sometime down the road. Up until the 1965, integrated circuits were expensive. They were used principally in military systems where the weight and power advantages were most important. But they were not inexpensive compared with what you could build using separate transistors and resistors.

Andy Grove: We followed the curve, the competition followed us, therefore the whole industry followed the curve.

Gordon Moore: I could see at that time that the way the technology was going, that we were going to be able to decrease the cost dramatically. So I did this 10 year extrapolation doubling every year, predicting the complexity of integrated circuits would be 1,000 times as complex in 1975 as it was in 1965. That is, we'd have on the order of 60,000 transistors on an integrated circuit instead of just 60. And that this would be the cheapest way to buy electronics.

Ted Hoff: There were tremendous advantages economically if you could make a bigger chip and make it smaller. Because it gave you more computing power. And what you're usually buying is bang for the buck. In other words, you're trying to get as much computing power for a given expenditure as you can.

There's a motivation if you can do it, do it, to make the chip faster, higher performance, lower power. In other words, all the things that look good in the chip. And one of the ways you do that is you make things smaller.

Interviewer: Les Vadasz, Executive Vice President. President of Intel Capital.

Les Vadasz: Rather than working on generally on silicon processors, you work on specifically how are you going to be on that line, which is in a way, becomes a directed research which has been very successful in our industry. Research to our then end goal.

Interviewer: Moore's Law states that transistor density will double every two years on integrated circuits, as represented here on a linear scale.

Carried out over a 10-year path, that growth can be charted in this manner. On a logarithmic scale, as done by Moore in 1965, the rate of growth is represented as a straight line. This is an exponential growth, and when viewed over a 40-year period what has occurred is a million fold increase in density, with the bulk of that growth occurring in the past decade alone.

Gordon Moore: Now I was sure of the trend. I had no idea at all that the prediction would be in any respect accurate. But amazingly, we stayed on that curve for the first decade. And one of my friends, I believe it was Dr. Carver Mead, a professor at Cal Tech, dubbed it Moore's Law someplace along that time scale. I don't remember exactly when. But that's how Moore's Law came about.

Dr. Carver Mead: The whole nature of that curve as being some sort of law is a very interesting phenomenon because it's not a phenomenon like a law of physics. It's really a phenomenon about what people are willing to let themselves believe.

And what it did is it gave people a confidence to go take the next step. And after awhile, those things become self fulfilling, because people can believe that they can do it. So they go off and do what's necessary to make it come true. And that's really what happened with Moore's Law. It's really that Gordon gave people permission to believe in the future and they went off and made it happen.

Andy Grove: Those of us in the industry who were in the working trenches then were pretty young and there's this great guy who's been around all through the history of integrated circuit industry, drawing a line and he says, "This is where the appropriate transistor density is going to be."

So, our people were designing integrated circuits with that line in mind, that was the target. Then, the technologies and the fabrication people were designing processes to build the circuits that embodied the transistor count in Moore's Law. So maybe it became a self-fulfilling prophecy. And I don't think we can ever tell the difference.

Ted Hoff: My impression of the industry in the early days was always walking on the edge of disaster. In other words, if you made a chip that was too small, it wasn't economically attractive and you'd end up failing in business.

On the other hand, if you tried to make a chip that was too big, you wouldn't be able to make it, and you'd fail because you couldn't deliver a product. And so it was knowing exactly what size to make, was important. And that's where I think the experience that Bob and Gordon and Andy and all the people that they brought in who really knew processing brought to the company. They know exactly how close to the edge to walk.

Andy Grove: Whether it was a very astute observation of the way the dynamics of the industry worked or whether it was a prescription for how it should work, it ended up working for a long time.

Interviewer: Dov Frohman, inventor of the EPROM. Former general manager, Intel Israel Operations.

Dov Frohman: It was a projection. Then as the projections continued, it became a law. But once it became a law, then I think yes, customers look at it. I mean, everybody basically looks at it as a paradigm that needs to be watched and most important thing is to try to project where it's going to flatten out.

Les Vadasz: It's not really a law of physics. I mean, it's not like Einstein's law of relativity or Newton's law of gravity. It's more of a law of the technical marketplace.

Gordon Moore: I used to be kind of embarrassed. I'd cringe when I heard people call it Moore's Law. But I've heard it enough over the last 20 years or so that I've gotten used to it, so now I can say it with a completely straight face.

Of course there's nothing associated with it that's really a physical law. It's just the rate at which the technology was evolving.

Interviewer: And that rate carried Moore's Law into many other areas of the industry.

Gordon Moore: I guess I was the first one to plot some of these exponential changes in the industry. And now almost anything related to the industry that changes exponentially is called Moore's Law, and I'm happy to take credit for all of it.

In fact, I say if Gore invented the Internet, I invented the exponential.

Interviewer: Federico Faggin, Chairman of the Board, Synoptics Corporation.

Federico Faggin: The key ingredient that has been able to fuel Moore's Law is what is called scaling. In other words, reducing the size of the devices and reducing in a certain proportion so that as you do that, you decrease dimensions, you increase the speed, lower the power and so on. And that in the days, certainly up until '74 which was the time when I left Intel, there was not talk very much.

It was something that really sprung out later. More like in the mid-70s and later '70s it became a very understood way to continue to push performance and increase the density and so on.

Ted Hoff: Around the 1975 time frame, it seemed that the knowledge of making things smaller became very, very common in the industry. So now it becomes a race how do you make things smaller? And that's been going on ever since.

Gordon Moore: And of course we didn't stay on that doubling every year. In fact in 1975, updating the progress we'd made, I gave a paper in one of the IEEE conferences where I predicted that the slope was going to change to doubling every two years, since we had lost one of the big factors. We had lost it, we had taken full advantage of it. There wasn't any more room to pack things more densely on the chip unless we made them smaller.

So I said we were going to lose that factor and subsequently it would about double every two years.

Interviewer: But somehow along the line, that two year projection got reduced to 18 months.

Gordon Moore: I never understood until recently where the 18 months came from, since it was nothing I had ever said. I figure somebody else re-plotted the data and figured that was better.

But in talking to a former Intel employee, Dave House, he described the origin as plotting the increase in computer performance. And his view was the computer performance was increasing by the increase in complexity, so it was doubling every two years from that. And in addition, the clock frequencies were going up, so the combination gave you an increase in computer performance, doubling about every 18 months.

Ray Kurzweil: I used to ask audiences when I spoke how many people have heard of Moore's Law. I started that maybe five or six years ago and at that time even technical audiences, very few hands would go up. Now in an audience of the general public, almost everybody has heard of it. So it's become emblematic of exponential growth of computation.

Gordon Moore: One thing that has happened here is these exponentials that are lumped together as Moore's Law have become in a real respect, a self-fulfilling prophecy. The participants in the industry all know these trends. In fact, the technology road map that the semiconductor industry association turns out has these exponentials plotted in it.

And all the companies realize that unless they move at that rate, they fall behind the rest of the industry. So there's a tremendous amount of pressure to stay on the curve or to get ahead of it.

Craig Barrett: If you weren't following Moore's Law, you were following behind other people in the industry. And that competitive issue I think has made the entire industry work harder, plan farther ahead, invest more money. And the end result of all that was just to bring a tremendous amount of technology to the end user. And it's been the rule. Microelectronics revolution and the computer revolution.

Gordon Moore: And now that it's accelerating a little bit, Intel has cut the time between process generations from three years to two over the last few generations. And our competitors are trying to keep up with that. So there's a race to stay ahead and it's because we're all looking at these same curves of how fast things evolve.

A peculiar thing about this technology is that the new technology, the one with the smaller structures, not only makes higher performance devices and one thing or another, it also makes them cheaper, because they occupy less area.

Les Vadasz: The unit cost per function dramatically goes down even if manufacturing rises.

Gordon Moore: So anybody that has the new technology is a generation ahead of its competitors, has a tremendous cost advantage over the competitors. So no one wants to be put in the position of being a generation behind.

Ray Kurzweil: It is remarkable that given that computers and computer speed is a result of a very chaotic, competitive process with different companies competing. And you would think if you'd plotted out the power of computers over time per unit cost, you'd get a very jagged line. In fact, it's a very smooth, predictable line on an exponential graph.

So it's remarkable that such a complex, chaotic process produces such a predictable result. But we see the same thing in many other industries.

Gordon Moore: Today you can buy a 64 megabit DRAM for less than we used to sell an individual transistor. A 64 megabit DRAM has something like 66 or 67 million transistors on it. So here you get a 60+ million fold decrease in the cost of a transistor.

And I was trying to look for other products that had undergone that dramatic a change in cost. And I started looking at printed characters, over the long period of time starting with stone tablets. And estimated that maybe they had made a comparable decrease in the cost.

And interestingly enough when I did that, the cost of a printed character in something like The New York Sunday Times was about equal to the cost of the transistor in a DRAM. Amazing that we can make a high technology part as complex as the processing is, for the same price that they can stamp some ink on a piece of paper. I think it shows the unique characteristic of the semiconductor technology.

Craig Barrett: Naturally our core competency, and that's what Moore's Law is all about. Our job is to be the technology leader in integrated circuits. You achieve that in this day and age by being able to follow Moore's Law. Continue to pump out more transistors in the same silicon area. Continue to double the processor performance, to get twice as many flash memory bits in a chip every 18 months.

So regardless of what we do, if it's processing, if it's memories, if it's networking chips, communication chips, core fundamental is always integrated circuit technology. And the fundamental driving force there is Gordon's Law.

Interviewer: So the question arises. What limits the continuation of Moore's Law?

Gordon Moore: No physical thing can continue to change exponentially forever. The nature of the exponential is that it grows so big or so small so rapidly that you come to some kind of a physical limit.

Federico Faggin: As we begin to approach the limits of the granular structure of matter imposed by the [unintelligible] structural matter. You can no longer keep on going. Certainly, you can no longer keep on going with the old strategy which is to completely reduce dimensions.

Gordon Moore: Even in our present technologies, some of the layers are only a few molecular layers thick. But as we approach the atomic dimensions, the materials don't behave the same way anymore. We get a lot of new leakage currents coming in, standard circuit design doesn't work, and eventually we really come across something fundamental, that there's a size below which the electronic functions don't work.

Ted Hoff: Now the other thing that happens when you make the circuit smaller, the impact of a single electron becomes more important. As the capacitance gets smaller, so the impact of an electron on the capacitor becomes bigger. And that represents a noise voltage.

So what's happening as you make things smaller, the noise is getting bigger and the signal is getting smaller. Now if you want to build a reliable logic circuit, you have to maintain a certain amount of signal to noise ratio. And as we make things smaller, that ratio is degrading.

Gordon Moore: Something below a tenth of a micron, probably 0.05 microns looks like its getting very close to that limit.

Les Vadasz: I think increasingly though that we will start facing some other challenges and number one of those is going to be how do you manage the power dissipated in these products?

Gordon Moore: Now 0.05 microns is about three generations of technology away from the 0.13 that we're currently developing. And given the usual time for generation of a few years, it gives us something of the order of 10 years from where we are before we can't go any further in what we're doing in the technology.

Les Vadasz: But then again, five years ago we were 10 years [unintelligible] from Moore's Law ending and it seems like that we really find the end as we go along because we keep finding new ways to extend the life of the technology.

Gordon Moore: So sometime between 2010 and 2020 I think we're going to be up against this physical limit and making things smaller doesn't help anymore.

But that is not really the end of Moore's Law. Now, it maintains the slope, because a very important part of being able to make more complex and faster devices, has been making things smaller.

But it's not the only thing. Even with the limit we have had, we'll be putting a billion transistors on a logic chip. With a budge of a billion transistors, our engineers will have phenomenal ability to innovate. Almost anything they can think of can be realized in that complexity. So it's not the end of progress in the industry.

Interviewer: Moore's Law and scaling; looking ahead.

Federico Faggin: Moore's Law will continue to devise based on silicon for another 40 to 50 years. That's my thought. Now of course it will slow down a bit, instead of doubling every 18 months, then you double every two years then you double every 2.5 years. But there will be a gradual slow down. But still it will be by and large still a close to an exponential growth.

Les Vadasz: There will be other than silicon for many of the functions of the future. Moore's Law or no Moore's Law. There are certain limitations that silicon has. Moore's Law attends primarily to the density. But for example, when you get to the optical structures, you're talking about speeds that we cannot do with silicon.

So suddenly you're going to see marrying other exotic materials like indium phosphide based integrated circuits with silicon based integrated circuits so that the total function can still be done and partly it will be silicon at the higher speed elements of the function will use some other materials, other than silicon. And that's already happening in a way.

Now, the interesting question, what are the dynamics associated with that other material? Will its manufacturability advance according to Moore's Law?

Ray Kurzweil: Another approach that's very powerful is to emulate the digital controlled analog computations that take place in the human brain. Most of the computations in the brain are not done digitally, they're done analog with some sort of digital control and people like Dr. Carver Mead at Cal Tech have experimented using silicon, but actually emulating the actual architecture of digital controlled analog computations done massively parallel.

And a number of his chips are actually attempts to recreate what we know about the neural architecture in certain regions of the brain, such as visual processing or auditory processing.

And doing, approaching computation that way we can for those specialized functions actually get a 1,000 to one speed up immediately.

Dr. Carver Mead: Looking at the computation and an architectural level and trying to understand what architectural breakthroughs have happened in the brain to cut down on the wiring congestion for example. And to be able to do these very complex computations that even our most powerful computer can't touch today.

Les Vadasz: The power of incremental is tremendous. To build and accumulate a learning and that's what silicon technology is all about.

Dr. Carver Mead: Well I know only one thing about where things are going, and that is just about the time people think they've figure id it out it takes a right angle turn.

I remember back in the 60s, we were all working on device physics and we were in love with the transistors and trying to make new kinds of transistors and then here comes Bob Noyce and says, "Hey, it isn't the transistors, it's how you hook the transistors up." And that was the integrated circuit.

And all of a sudden, bingo, we had a whole new art form. And as I said, it became essentially 100% how you do the wiring.

Robert Noyce: Its effect has been revolutionary. But in terms of the development, I think most developments are linear extrapolations of things that have happened in the past. And finally you get to the point where the effect has been revolutionary.

But in terms of the integrated circuit, it was a reasonably logical thing to do considering how transistors were being made, all in one chunk of the silicon when you made them. You might as well leave them that way and produce the final product right at that point.

So it was evolutionary, you couldn't have done without the transistor certainly. It wasn't a development that went around the development of the transistor, but it was more of an extrapolation from it.

Certainly if you look at what has happened as a result of the integrated circuit, that has been revolutionary.

Dr. Carver Mead: Once we see it, we'll say, "Of course, that's obvious." Just like when we saw the integrated circuit. It was everybody's idea once they saw it. But it was none of our idea until Bob went off and pointed it out.

Gordon Moore: I have really a different take on all of this. Maybe I've just gotten old and set in my ways, but I don't think the question of what after silicon is the right question. I don't see anything taking the place of what we've done with the integrated circuit technology.

We may change some of the materials. I doubt we do in the mainstream, but we may use a different semiconductor. But I think that the technology we've developed, this building a complex pile of materials with a complex microstructure layer by layer by depositions and etchings, depositions and etchings, is a fundamental technology for making microstructures. And rather than that being replaced by something else, it's more nearly going the other way. That is finding its way into several other fields.

Andy Grove: The laws of physics are not breakable, so evolution of semiconductor technology will continue, but it will have to take steps that make it go on in spite of the limitations that physics imposes on it or skirting them. And I think it will do that. I am confident it will do that. But it is going to require pretty original out of the box thinking on the part of technologists and device designers.

Craig Barrett: We can see how to continue this behavior for at least another 10 or 15 years. And that's just using the standard CMOS transistor.

It's going to be difficult. It's going to just take a fantastic amount of intense engineering effort, hundreds of millions of dollars of research, developing new lithography tools, new etching tools, new circuit designs. But it can be done.

Gordon Moore: There's a long way to go before we've run out the string of what we can do with solid state electronics.

Craig Barrett: Gordon's impact on the industry has been immeasurable. He is the fundamental driving force behind this industry, he's the technologist's technology. So competent in his assessment of what you can do and what you can't do. And always just a gentle prod. You guys can do this.

He and Bob Noyce, really were at Fairchild, and started this whole era of integrated circuits. And they formed Intel and Andy Grove joined them and Les Vadasz joined them and they really made integrated circuits real at Intel.

So, they're at the start, and some 35 or 40 years later, I still go to them for advice. He's the real thing.

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