The History of Converter Products

An interview with Ray Stata by David Mindell for the Computer Museum

Cambridge, MA, March 20th, 2012

DM: OK, this is an oral history interview with Ray Stata on March 20, 2012, in Cambridge, Mass, at MIT. The topic is "interest in the history of analog-to-digital, digital-to-analog converters." The interviewer is David Mindell, professor at MIT in the history of technology.

I'll just start by asking you-- when we look at data converters, or depending on how we want to frame it-- what's the big story? What's the 50-year-story of how we got here? And what's interesting about the analog part of the computing world?

RS: Well first of all, I've come at it from the point of view of instrumentation and industrial controls as opposed to communications and other entry points. But certainly, until the advent of the minicomputer-- the PDP-8, and the PDP-11, and so forth-- there was limited resources in universities and in many companies to use computers to process analog signals. With the availability of low cost computers, engineers got very interested in transitioning back and forth between analog world and the digital world.

We got our start in modular operational amplifiers, and then having achieved leadership in that market we began to ask, where do we go from here? We essentially answered that question by a survey with our customers-- which, by that time, three years into the company, had already amounted to 50,000 to 60,000 engineers.

We got a very strong response from our questionnaire. The basic question was-- if you had an opportunity to buy rather than make other functional circuits what would you select? And we offered a number of possible choices. But converters come out very clearly as top the choice. So that is when we decided our next product line would be converter products.

DM: So that would be about '68?

RS: That's right.

DM: You think, by the way, that the data on that survey response is still around somewhere?

RS: I don't think so. I wish it were because it was very interesting. But as a side note, the insight we got in starting Analog Devices was, in fact, the recognition that there was going to be a transformation from make to buy in the commercial world, and in university laboratories. Until the time of Philbrick and some of the early pioneers of modular op amps, if you wanted to build an instrument, you had to design your own op amps, and manufacture them as an integral part of the instrument. We did that in my first company Solid State Instruments.

When Philbrick, Nexus, and some of the early pioneers began to make modular op-amps available at Solid State Instruments, we looked at the economics of whether we should buy these components or continue to design and make our own. We decided to buy and concluded others would also come to this conclusion. Even though the market was initially very small, that was our motivation for starting Analog Devices, since we assumed the market would grow rapidly and it did. With that insight we looked for other similar opportunities to switch from make to buy beyond op amps.

DM: So Analog Devices was founded in 1965 or that was Solid State Instruments?

RS: Analog Devices was founded in 1965. Solid State Instruments was founded in 1962.

DM: So it's '68, the whole op amp story is really interesting, too, and I think we'll come around to that because the more you look at this the more it's clear-- those two histories are very entangled. And who were these 55,000 engineers, by and large? Can you generalize?

RS: It was, first of all, all the universities building instruments for research where op amps were needed. And beyond that, it was mostly smaller-to-medium size companies and military contractors. Large instrumentation companies like Hewlett-Packard, made their own op amps, and converters and, in many ways, they were the best in the world at doing that-- Why would they buy from a start-up company?

It literally took us 15 years to convince Hewlett-Packard that they should buy rather than make because the economics of scale and the benefits of specialization allowed us to get ahead of them on the technology curve. In many ways, the development of the semiconductor industry, or this part of it, was just a wave of converting functional circuits from make to buy. In the early days of op amps and the converters, the market was for companies and institutions that were not motivated to roll their own. They just wanted the function.

DM: Did you imagine Analog Devices as a semiconductor company at this point?

RS: No, No.

DM: It was more of a module, circuit design, kind of thing?

RS: When we started Analog Devices there weren't any integrated circuit op-amps. It wasn't until, really, 1967 in that time frame, as I remember, that the first really useable IC op amps came on the market. Our market focus was on instruments where the performance of op amps often determined the performance of the instrument. The performance of IC op amps, what we call jelly-beans, was nowhere close to having adequate performance.

But over time the performance of IC op amps improved considerably so I became convinced that we had to get into the semiconductor businesses or our success would be short lived. In shifting from modules to IC's Analog Devices went through a very substantial metamorphosis that took the better part of 10 years. And in the early days, the focus was on op amps. We didn't even dream that monolithic, 12-bit, A-to-D converter would ever be possible. We continued to make converters as modules.

So it was a continuous evolution in our ability to make better op amps and then, step by step, our ability to make monolithic, well, initially hybrid multi-chip devices, and then ultimately monolithic converters.

DM: I mean, that's one of the things that interests me about trying to tell this history is, for one thing, you're always used to reading the history of semiconductors in the digital world as Moore's law and all about density, density, density. But as I read through some of the history coming out of Analog [Devices] on A-to-Ds, and op amps too, it's not always about more and more transistors necessarily but accuracy, precision, stability, other kinds of parameters.

RS: Right.

DM: Can you say a little bit about that?

RS: With analog and mixed signal products it is more about accuracy, dynamic range, frequency response, temperature drift, and cost, as well. A big difference between Moore's law and digital circuits and analog circuits is the tremendous proliferation of application requirements. Unlike digital circuits there was not one process technology that will solve all problems. Optimization depends very much on the application requirements. The early pioneers in converters were Bell Labs, AT&T-- the communication industry. The communications industry pushed the envelope of innovation for converters both for performance and cost. Like Hewlett Packard, those large companies weren't motivated to buy components that were critical to system performance from start-up companies.

DM: AT&T was one of the biggest semiconductor manufacturers.

RS: Yes and like HP who manufactured their own IC's, they were very late in the transition from make to buy. A lot of the early converter business was captive to the large instrument companies and communications companies.

DM: And when you said that you were focusing, sort of, on the instrumentation side-- higher performance, higher precision-- other market segments would have been communication or-- who's buying the jelly-bean op amps?

RS: There were many uses of jelly-beans in all of the markets, consumer, communications, military, including instrumentation, where cost was more important than performance. The volume of jelly-beans op amps was significantly larger than for high performance op-amps where we focused.

DM: And there was also a high-end of the military and communications flash converters that Analog [Devices]was not in, is that correct?

RS: You mean in the early days?

DM: Yeah.

RS: Yes, in the early days we focused on instrumentation where low frequency performance was adequate. But then later, in the late 70's high speed converters that were developed in communications companies like Bell Labs began to spill out into the merchant market. For example, Computer Labs founded by engineers from Bell Labs introduced high sample rate converters in the merchant market. Analog Devices acquired Computer Labs to get access to this technology and to exploit new applications that were emerging for digitally processing analog signals.

DM: Were there particular large volume customers who were pushing the envelope that we're talking to you saying, we need this, to do that, and helping--

RS: No, that evolved over time. In the early days, it was small companies and, strangely enough, military systems companies that were willing to buy from start-up companies. Since they didn't have capability to manufacture IC's and the large semiconductor companies didn't offer these products.

DM: You read about Nike missile tracking systems that needed high speed data acquisition. Were there other projects that have needed high speed data acquisition??

RS: There were but we designed standard off-the-shelf IC's without knowing what customers did with them. If customers needed more performance beyond what we were providing they asked us to push the envelope of standard products and we did. But even without specific requests we believed that if we build higher performance products, customers would find uses for them as they created new applications.

DM: Because the flip side is-- I've seen you say elsewhere and, if you look at Analog Dialogue, a real sense of having to communicate with the customers and making sure they know what the things are for, and how to use them, and sort of a constant educational conversation about as these things change.

RS: Yeah, as a matter of fact, a large part of our mission, in the early days, was educational, tutorial. So we wrote a series of application notes that went back to really basic stuff because there were a lot of engineers who were now using operational-amplifiers for the first time. They had to learn the basics and to learn what products worked best in what applications.

DM: One thing, I think this in the list that I sent you, was about the relationship between design history, innovations in circuit design, circuit architectures, and its relationship to process innovation with more and better processes. And it seems to me like they're very entangled in this story and I'm trying to understand how to think about them.

RS: Very much so. In the early days of semiconductors, there weren't any foundries, right? If you were going to manufacture semiconductors you had to builds your own fabrication facilities. Many of the fundamentals for bipolar process technology had already been worked out in universities and large companies so we copied and used these manufacturing processes to the extent to which they achieved our performance requirements.

The approach of the large semiconductors companies like Fairchild, TI, Motorola was to run industry standard processes and to accept whatever product performance they yielded. While they continuously improved their processes there was not a sense of urgency to address the gaps in unfulfilled customer requirements.

But instrumentation customers just wouldn't buy integrated circuits that didn't meet their high performance requirements. The challenge for Analog Devices was to dramatically improve our manufacturing processes first to meet market requirements and second to differentiate us from the larger companies who had a head start in semiconductor manufacturing. You can think of this as market driven innovation.

One of the early process innovations that we brought to the market was the use of thin-film resistors, as opposed to industry standard diffused resistors, to achieve greater stability and then beyond that, we trimmed these resistors as a way to compensate for the manufacturing variances in the semiconductor process. This reduced initial offset voltage and current and reduced offset drift over a wide range of ambient temperature.

DM: So say a little bit about laser trimming and that story. Because it seems pretty fundamental in this whole thing. And how'd it get started, where did come from and all that.

RS: Well the origins came from our experience in manufacturing modular op amps. To reduce voltage offset and drift we manually matched the characteristics of discrete transistors and manually selected resistors in the manufacturing process. It was a labor intensive process to compensate for the variances in characteristics of the transistors we purchased. That was the only way to achieve the performance our customers wanted and needed.

As we got into converter products the need to adjust resistors values in the manufacturing processes was even more important. This lead us to think about using thin film resistors in our manufacturing process which could then be trimmed with lasers.

DM: So the laser trimming actually burns off a piece of the resistor? How does it actually do the trimming of the resistors?

RS: Well imagine having a track of resistance. If you cut a gap laterally across the track you reduce the width and hence increase the resistance. We developed all kind of clever ways of shaping resistors and laser trim them to get greater resolution in the trimming process.

DM: And then the lasers were precise enough in terms of positioning.

RS: Oh yeah. We could physically position lasers to a fraction of a micron and there were commercially available positioning tables on which we mounted the lasers.

DM: And then each unit, as it comes through this process, is trimmed on its own and is actually active for a while to get the sense of what it--

RS: As a first step in developing this process we mounted individual die from the wafer manufacturing process into the final package and then actively laser trimmed each circuit by measuring the output signals from the packaged die as we trimmed it. But this was very labor intensive and expensive. So we learned to actively trim resistors at the wafer level. That is, we actually brought probes in contact the die at the wafer level and then measured the output of the circuit as we trimmed it. To be more precise we first measured and then trimmed iteratively to avoid the noise created in the laser cutting process. When trimming for that die was finished we would step the laser and probes to the next die on the wafer. There were multiple trim sequences on each die to achieve the desired product performance. There are other ways to do resistor trimming today by blowing fuses but still laser trimming is fundamental to our business.

DM: So what were the years in which laser trimming was developed and then introduced?

RS: We began the laser trimming work in the early 70's. But before this in late 60's, for modular converters we had developed manufacturing processes to sand blast thick film resistors to trim their value in the manufacture of converter products. Laser trimming thin films on integrated circuits was just a more refined way to achieve the same results.

DM: Was it a long development process.

RS: As I mentioned we first trimmed die that were mounted in the final package before learning to trim at the wafer level. So there was an extended period of innovation and learning over many years to improve the performance and efficiency of the process.

DM: And does Analog [Devices] hold the patents on these processes, or sub-patents?

RS: It was know-how more than patents that gave us an advantage but also the large companies were not motivated to do it since the market was too small. By the time they figured out it was a good idea we were miles ahead in terms of our understanding of how to do it, economically. So we were able to create and maintain a lead, in terms of know-how and experience. This capability established our technology leadership and differentiated us in the marketplace especially in converter products.

DM: And who were your competitors during this time period?

RS: In terms of the precision market -- Burr-Brown was a very important early competitor, because they also made the transition from modules to ICs.

DM: Where were they located?

RS: In Tucson, Arizona. They were brought, later, by Texas Instruments to facilitate TI's entry into precision converter products. But for modular op amps, early development occurred here in Massachusetts. Philbrick Research was the pioneer in modular op amps followed by Nexus and half dozen companies here and several on the West Coast. But except for Analog Devices and Burr Brown none of these modular companies made to the transition to semiconductors and they were either bought or they didn't survive.

DM: I put on the list the question about Pastoriza and that acquisition. What's the story there, how did that come about?

RS: Well, once we decided strategically to go into converters based upon the survey I mentioned, the question was how to do it. From a technology point of view precision op amps are a key component in converters and resistor trimming was a key technology.

Initially we had our op amp engineers work on developing converter products but they didn't have the knowledge and experience. So I started looking around for engineers with experience in converters and discovered Pastoriza right here in Newton, Massachusetts. Jim Pastoriza was an early pioneer in converter products just as George Philbrick was in op amps. In fact they were friends. Jim had some patents on temperature compensated current switches and a lot of knowhow and experience in converter technology. Again, like op amps, these products were manufactured by hand assembly of discrete components, that is, as modules. Pasteriza was a small company with only about $1 million in sales. But they had the technology and in particular they had Jim Pasteriza, a prolific inventor.

DM: So that acquisition was what year?

RS: That was in 1968. A lot of things happened in '68 and '69. We acquired Pastoriza, we went public, and we launched our entry into semiconductors all within a relatively short period of time.

DM: Now, did you have an eye on the microprocessor revolution during this period, what Intel was doing, and through the '70s.

RS: Back in those days the analog world and the digital world were quite separate except for a few larger companies, like Motorola and T.I. But certainly for the smaller companies, and certainly for Analog Devices as our name implied we had no aspirations for digital technology. We aspired to be the bridge between the analog and digital worlds. Much later in the '80's that changed as we entered the DSP market.

DM: OK, so that's an interesting story. Can you say a little bit about--

RS: Well, here again there were others who pioneered DSP. Companies like AMD made basic logic building blocks that customers could assemble to achieve DSP functionality. But TI was amongst the earliest to introduce a fully integrated DSP product. Interestingly, Intel also introduced a DSP product, but they never followed through on it. TI's products got legs and they established DSP as an important product category.

DM: That would mid '80s, or early '80s?

RS: That was in the early '80s. And so it became clear, from listening to our customers and seeing TI's success, that the ability to efficiently process analog based signals in the digital domain was an important trend. That's when we decided to offer our customers the full signal chain so that they could implement signal processing, either in the analog domain or in the digital domain with converters to transition signals back and forth between the domains. That way Analog Devices could provide more complete solutions.

DM: And that necessitated going much more into the digital world, as it were.

RS: Yeah, so we had to learn how to design digital circuits. That was an extremely painful learning experience that we didn't do well. We tried to turn analog engineers into digital designers, which was not too smart. So it was a slow and painful process.

DM: And were there acquisitions that helped you there?

RS: No, perhaps in retrospect there should have been. It would have accelerated our progress significantly. But we pretty much re-invented it from scratch including, in the early days, actually running digital CMOS process technology in our fabs. By that time we had merged bipolar and CMOS technologies into BiCMOS. So we had rudimentary CMOS technology.

DM: OK, and you don't now.

RS: No. Long ago the foundry model arose.

DM: And the converters were BiCMOS because they had both analog circuits and digital logic.

RS: BiCMOS came later. Our first converters were manufactured with bipolar technology. Converter products require elementary digital circuits to perform logic and switching functions. Pastoriza had invented bipolar current switches that were compensated over a wide temperature range. Their switches were compatible with our analog process. We figured out how to implement logic functions using bipolar I^2L, integrated injection logic. It worked but it was not cost effective. That is when we began to explore CMOS technology for voltage switching and logic. We had a war within the company about what technology would win for converter products, bipolar or CMOS. I listened to arguments on both sides but I couldn't get a very clear answer. So I said, "Let's do both."

There was fierce competition between the CMOS group in Ireland and the bipolar group in Wilmington, Ma., about who could build the best converters. Since there was little competition in the open market, this rivalry served a useful purpose in spurring competition and innovation. Sometime later, both sides agreed to merge bipolar and CMOS technologies to make life easier for everyone.

DM: You mentioned your old analog engineers, trying to teach them to do digital design. So can you say a little bit about the people who are designing these circuits. Who are these guys, where do you find them, how many of them have skills that they bring into the company with them versus developing them in house.

RS: Well, there weren't many senior analog IC designers around. They were mostly found in instrumentation companies. We hired one of our early gurus [Barrie Gilbert] from Tektronix who used state-of-the-art analog technology to do build oscilloscopes. We hired Paul Brokaw came from, ADL [Arthur D. Little], a research and consulting firm in Boston. We hired design and process engineers from Sprague Electric out in Western Massachusetts who had experienced analog engineers.

The founders of Nova Devices come out of Transitron, an early semiconductor company in Boston. We picked off Hank Krabbe from a West Coast modular competitor. With a hand full of very senior designers we then hired young engineers from universities and taught them how to design precision analog circuits. And we hired some experienced engineers too , mostly from instrumentation companies.

DM: So that's interesting. Even when I was in school in the '80s people say well young engineers don't know how to design analog design anymore because they just had to buy the chips and whatnot. Engineers focused more on digital design and process technology. Did this make it more difficult to hire engineers with analog experience?

RS: Oh, certainly, going back in the mid '60s, there was this widely held belief that everything was going to become digital. So why would you want to work on analog technology. But the facts are that the real world will always be analog and thus analog technology will always be required to interface man and machines to the real world. Universities recognized this as well so they maintained the expertise to teach analog circuit design and process technology.

But it was very hard to develop the organization because there weren't a lot of people that knew how to design analog circuits, particularly if you're going to do it at the extreme end of the performance spectrum where we were focused.

DM: I mean, and did you as a company sort of fight against the-- in the broader world-- a notion that analog was somehow obsolete, and outdated, and-- like with investors, or--

RS: Certainly--

DM: -or other people thinking that.

RS: Absolutely, especially investors. It was difficult to interest investors. And most engineers coming out of school, were more interested in computers and digital technology. Still, there were great analog professors who planted the seed that analog circuit design is challenging and interesting.

DM: And did the perception gradually change over the years?

RS: It took a long time. But now it has become clear that as we got into more sophisticated converters and op amps and into RF there are some really challenging engineering work to be done whereas on the digital side, circuit design became more automated. Also, the depth of the interaction between process technology and circuit design is more intense in analog.

At Analog we could recruit great young analog engineers because we had industry gurus like Gilbert and Brokaw from whom they could learn.

DM: Did anybody tell you should change the name of the company?

RS: Oh yes, that topic came up often since analog was perceived by many as dying technology. Certainly when we entered DSP that question arose again. So yes, there was a lot of discussions but we stuck it out, and now the world has changed and analog is where the action is both technically and business wise.

DM: What was it that made that happen? How did that world get there?

RS: Computers and digital devices drove the early growth of the semiconductor industry. Most of the government funded research in universities focused on driving down Moore's curve, since that was seen as the bottleneck. While there is still work to be done in digital technology, the bottleneck to growth for many applications has now shifted to "More than Moore" technologies, which is really a code word for analog technologies. Wireless communications, automotive electronics, medical systems and industrial controls require a diverse array of analog technologies for, power management , sensors, amplifiers and converters and RF radios for wireless communications. Semiconductor companies and the government for decades focused research on "More Moore" that is digital technologies. Today more university research is being focused on "More than Moore" that is analog.

DM: Power.

RS: Yes, power but also process technologies for RF, MEMS, high speed and high voltage processes. We now have collaboration between industry, government and universities to create roadmaps to guide research in these "More than Moore" technologies.

DM: Very interesting. If I look at some of this data converter history, and I look at the footnotes, a lot of it is really industry publications. And you have the sense that a lot of the conversations and the things that were happening were more in the industrial domain than in university research. Can you say a little bit about what kind of converter technology, if anything, was coming out of academia versus industry?

RS: You're probably going to learn more about this from interviews with others who were more directly connected with university research. Government funding drives university research. Digital CMOS was an industry standard process technology so everyone benefited from the research funding. Analog process technology is more fragmented so it was more difficult to reach a consensus on what research the government should fund so industry had to fund a large percent of process research. As I mentioned, now that is changing and universities will play a greater role in the future.

DM: Is A-to-D history and D-to-A history just as interesting? Or is one of them more interesting than the other?

RS: They're integral. You've got to connect in both directions. The development of IC DAC's preceded ADC's since ADC's are more complex and challenging than DAC's. In fact DAC's are building blocks for many ADC's. Thus, the availability of monolithic ADC's lagged significantly behind monolithic DAC's.

DM: Back on the topic of design. You said at one point in the story that there was a proliferation of different architectures to address different applications requirements. And then, way back in the early days there were probably three, four, five architectures that everybody used. Can you say a little bit about what they were and, how the segmentation evolved?

RS: For instrumentation dual slop converters, which we extended to quad slope was focused on accuracy and dynamic range. Conversion speed was not that important. So dual slope and quad slope converters, which essentially digitized the time it took for a linear generated reference voltage to ramp to the input voltage level to be measured, worked well. With the introduction of minicomputers conversation speed became more of an issue and thus SAR or successful approximation converters became prevalent. Later, Sigma delta converters became popular since they could be implemented in CMOS technology without the need to trim resistors to achieve precision.

Today, Sigma delta has become a very pervasive technology, not only in terms of accuracy and dynamic range, but also for of high-speed applications . Moreover, analog CMOS process technology is compatible with digital CMOS circuits for designing complex SOC's or systems on a chip.

DM: And were there particular moments or particular people who were innovative on the design side?

RS: Bernie Gordon at Epsco was the pioneer in SAR converters. But Analog Devices pioneered the development of monolithic IC SAR converters. We did not introduce sigma delta technology but we were quick to catch up and to become a leader in this space once we saw its advantages.

Communications was a very different market where most of the innovations were developed in research labs like Bell Labs to push conversion speed. For example Bell Labs pioneered the development of pipelined converters. A group from Bell Labs spun out to form Computer Labs to commercialize very high speed converters for a broader range of applications than just communications. We acquired Computer Labs when it was still a small company to assimilate this new technology.

DM: What year was that?

RS: 1978. At that point these pipelined converters sold for thousands of dollars each. There was a market in research labs in universities and industry to develop applications for very high speed conversion rates. As a larger company we were able to drive the cost down and to evangelize the adoption of this technology in emerging new applications to digitize video signals and many other high speed communication and instrumentation signals.

DM: One thing you recently mentioned which also happens during these decades is the rise of design automation and simulations as a design tool. Can you say a little bit about what that looked like?

RS: Again the CAD industry focused mostly on design and simulation of digital circuits. There were some analog design tools developed in universities for analog circuits but they were not adequate to achieve the level of performance required by our customers. So Analog invested heavily to extent the capability of industry standard SPICE tools to what we called ADICE. One of the reasons we were able to stay ahead of competition was that we had much more sophisticated analog design tools.

DM: Your own proprietary code, software, basically.

RS: Yes. We still use ADICE today and continue to embellish it capability although the CAD industry has caught up.

DM: Did you have a relationship with CAD suppliers for this sort of work?

RS: Gradually, over time. But in the beginning these tools were our jewels which we wanted to protect. CAD suppliers wanted to learn about our jewels. So we had an adversarial relationship. As they caught up, the relationship with CAD suppliers has become more collaborative.

DM: Let's me see what else I have from the list here. So as I begin to go around and talk to some of these other folks, what do you think are interesting questions to be asking them?

RS: ADI's success was largely built on innovations from our engineering community. What motivated them to innovate in the ways that they did. How were we able to stay ahead of the pack from their perspective? For example, Paul Brokaw was the pioneer in the development of precision monolithic voltage references which are an essential part of precision ADC's. How did he figure this out?

And there was always the push for higher speeds, more accuracy, lower cost. Designers were constantly thinking about how you do this stuff better and better. How do you add bells and whistles? The performance which designers can achieve is ultimately limited by the performance of the manufacturing processes. How did they collaborate with process development engineers to anticipate future requirements? For example, Analog pioneered the development of bonded SOI wafers and trench isolation for high speed analog circuits. How did this come about?

DM: SOI? Silicon-on-insulator?

RS: Right. We did a lot of early work to develop that technology and the trenching techniques to be able to make much higher frequency devices. This gave us a tremendous competitive edge in the market. The symbiotic relationship between process development and circuit design was critical to our success.

DM: And they were on the same site?

RS: Yeah, well they were back in those days. Today it's a whole different story.

DM: So as we think about telling this story to the public what do you think they ought to know?

RS: Well we need to identify the applications for computers and embedded processor which require converters and which are pivotal to addressing important societal problems and opportunities. Clarify the distinction between real world signals and digital representation with specific examples. Demonstrate and explain the function of converters. Show that evolution of converter technology has paralleled the evolution of microprocessor technology and why in many applications breakthroughs in both technologies were necessary to make progress.

Maybe the best way to do this is to focus one or two applications to make these points. Certainly wireless communications would be one example and maybe medical imaging systems like CT scanners would be another.

Some historical perspective about what gave rise to the ability to build ever more complex, high performance converters and the roadmap of performance overtime. It's really remarkable that with 22nm we are able to build amazing digital complexity. But it is equally remarkable that converters can achieve 16 bit resolution at 10MHz. It is amazing that , speed and resolution continue to improve.

So it is important to develop a perspective on just how sophisticated the technology is and what it needs to be in order to address different application domains. So I think it has a lot to do with, focusing on the application domains. And the drivers in terms of performance.

DM: Are there any that are just favorites for you as far as being paradigmatic?

RS: Well, instrumentation and communications, broadly speaking and I mention cell phones and CT scanners specifically. Projection of internet traffic is one way to illustrate the demand for ever increasing performance.

DM: Well, I always find the RF example out of a cell phone is the easiest way to communicate to someone that there are important things in the world that aren't digital.

RS: Right, right. In terms of grabbing attention, I agree that mobility and RF are applications that most people can understand. Likewise in the medical world CT scanners and other diagnosis instruments would not be possible without the continuous improvement in converter technology.

DM: Are those customers who needed to measure pico and femtoamps?

RS: Sure. Technicon was one of our early customers. They built blood analyzers and had to measure femtoamps (10^{-15}amps).

And there is lots going on in the automotive world in terms of safety systems, the airbag crash sensors, anti-skid devices, navigation systems and cruise controls that automatically slow you down when you are closing too fast on the car in front of you. Automobiles are essentially, a platform to deliver electronics to the user world. And incidentally, it's got an engine, four wheels and steering wheel that goes with it..

DM: I mean, if you could imagine yourself walking into the computer museum and seeing either-- this may be two different questions. One is an independent exhibit about the analog part of the computing world. And the other would be an exhibit that's part of their standard computer exhibit but the application includes analog functionality. What do think it would capture?

RS: I think that the computer museum does a great job with tutorials. In explaining here's the technology, how does it work, why it is relevant. They need to explain what's an A-to-D converter anyway? What does it mean to go from the analog domain to the digital domain? Why is this necessary to deploy computer in real world applications. And, perhaps, show an early converter, and its profile of cost, compared to today's converter chips that are so small you can hardly see them, with performance and cost that are 1000 times better. They could show how that has evolved in terms of the technology.

DM: Do you know if they have any of these early converters, like the Bernie Gordon's--

RS: I don't believe they do. I saw one exhibit there, which was op amps, with a few trinkets in a small space. But I didn't see anything about converters. One interesting exhibit would show block diagrams of a cellphone and the actual hardware to illustrate where converters fit in.

DM: especially now that the computer is supposedly disappearing.

RS: Right, right. And you could show a micro base station and how the handset is connected.

DM: This is slightly different topic but did you know that this was a momentous year because Bob Pease and Jim Williams both passed away within a couple of weeks of each other. And apparently they have the workbench of Williams, I think, at the museum. Did you know those guys?

RS: I did know them. Bob Pease died in an accident coming from Jim William's wake.--

DM: Yeah, right. I mean, I used to read their columns all the time. That strikes me, and a lot of people said at the time, as a kind of passing of a generation, in a way, or changing of the guard, at the very least.

RS: Yeah, and there was Bob Widlar, Pease, and Williams at Natural Semiconductor, and then Gilbert and Brokaw at ADI. They were the giants in in analog world and there's others we could list in that category. But these guys were transformational in terms of innovation and leadership.

DM: How many other guys like him would be around him? I can't believe that a company that big relies totally on one guy--

RS: Widlar was the transformational leader, first at Fairchild and later at NSC. Pease was important, but he didn't play a leadership role. Bob] Dobkin who was Wilder's protégé at NSC and later founder of Linear Technology. And George Erdi was an important player at Presidion Monolithics, a company that Analog bought, and David Fullagar first at Fairchild and then a found of Maxim

DM: Was there a sense of community? I mean, did you see them at conferences and--

RS: Oh yeah. The Solid State Circuits Conference was the place they came together. They presented papers on product breakthroughs and competed with each other on who came up with the best ideas. They knew each other maybe not as close friends, but as professional colleagues.

DM: Do you feel like Analog [Devices] is successful these days at recruiting young engineers who are analog types?

RS: Yes, yes. We're able to get our share. Fewer and fewer engineering graduates focus on analog technology. That is now changing somewhat as RF and wireless communications has become so important.

DM: So are there enough?

RS: Well there's different levels of enough. There is never enough who can contribute at the pinnacle of innovation. There are many more that do layouts, write test programs and do spins that don't push the state of the art. A lot of these jobs will go to China and places like the Philippines. We started in the Philippines doing assembly, mostly women. But then we started doing testing which required a higher skill level. Now we are doing test development and product engineering. Inevitability we'll do spins which requires design skills. There are good engineering schools in the Philippines and a lot of engineering graduates.

DM: I mean how many would you say are, sort of, the core, innovative core.

RS: Well, we have a level at Analog Devices, about 100 or 1% of the design engineers which we refer to as Fellows. To reach the Fellow level you've had to have created innovative products that have achieved conspicuous commercial success.

DM: And when was that program started?

RS: That was started quite early. Barrie Gilbert and Paul Brokaw were the first Fellows, and they were anointed at the same time in 1978.

DM: And what was the motivation for creating the Fellows program.

RS: A disease in industry is that in the start- up world the technologists are highly respected and appreciated because you depend on them for success. Without them, there's no jobs for anybody else. As an organization grows in size and complexity, you require managers. What happens in many companies is that the power in the organization shifts to the managers. They are the ones who call shots and therefore engineers tend to drift toward second class and unrecognized citizens.

At Analog [Devices], we wanted to head that off. So I created a parallel ladder for engineers who want to continue to do technical work but who want recognition and rewards that are commiserate with managers. And it is not just the money and not just technical decisions. We want the voice of the technical community the carry weight, to be heard on the kind of work place we want to sustain and what kind of business opportunities we should pursue. The Idea is to give a voice to the technical community and to recognize and honor the significant contributions which engineers make to the company's success.

This is now embedded into the culture so at Analog [Devices]. There's a tremendous respect for engineers.

DM: And then they continue to innovate and--

RS: Oh yes.

DM: Was it based on the IBM fellows, or any of these other kind of things we read about?

RS: There wasn't any model that I was trying to replicate. There's lots of fellows programs, but, when you examine them, they really don't work that well because there is not the right balance of power between the technical and management communities. There is not respect for engineers at the top of the company.