

ANALOG DESIGN IN THE INFORMATION AGE

Dr. Barrie Gilbert

Analog Devices Inc. 1100 NW Compton Drive, Suite 301

Beaverton, OR, 97006-1994

barrie.gilbert@analog.com

Abstract

Electronics, broadly defined here as that corpus of knowledge amassed particularly since WW-2 days about signal generation, processing and display using low-inertia electrical elements, is at a critical turning point. We are immersed in two paradigm shifts simultaneously.

First is the transformation of this entire field, but especially the classical analog circuit domain, from a largely technological craft into a commodity business. Design - the choice of form and features, the introduction of key innovative advances, and the optimization of our products through a succession of expert trade-offs while grudgingly recognized as necessary, is increasingly perceived as just a subservient aspect of the struggle to greater competitiveness, profitability and shareholder value. The prevailing view is that time to market and cost are more important than elegance and finesse. This shift in priorities portends the demise of the custom-designed product, to be replaced by Lego-block systems implemented by the re-use of standard analog cells in just the same way as has happened in the digital field.

The second paradigm shift is the ascendancy of the Bit and the common expectation of a digital solution for every problem and an inherently better solution, just by being digital. The stunning successes of the past decade amply prove that. It logically follows that the future world is a place of digital everything. And anyway, putting reason aside, the learned articles in Newsweek and Forbes agree: all that old-fashioned analog stuff is not simply on its way out: its practically stone dead.

Are these assertions about the future shape of our industry really true? This paper will answer that the first is an oversimplification, and that the second is a sheer miscalculation. The analog residue, if it pleases the pundits to think of that way, will continue to be a vital, essential and innovation-rich part of the electronics of the twenty-first century.

I. Analog Design in the Information Age

Just over a hundred years since the discovery of the electron (1897), we can reasonably claim that we have become the masters of this cantankerous quantum object, whose particle nature is still the most useful mental image for electronics engineers. Our special talent is for making these little dots of charge do our every bidding - and much of our thinking, too. We have witnessed continuous, progressive and magnificent progress in our craft; few human lives remain untouched by our products.

But today's electronics is at a critical turning point. We are immersed in two paradigm shifts simultaneously. First is the transformation (metamorphosis is too colorful an allusion to describe what is happening) of what once was a rather refined and essentially scientific/engineering domain of endeavor, into a fiercely competitive commodity business. Advances in technology and design techniques remain essential, in feeding the needs of a marketplace that exhibits a trading-floor mentality, ever clamoring for more value but only at bargain-basement prices. In this climate, the technological and innovative content of our products are increasingly perceived as just a subservient - even incidental - aspect of the overarching struggle to greater competitiveness, profitability and shareholder value.

It is far from coincidence that the label "foundry" is used for a wafer fabrication house. Today's electronics, and the outpouring of intelligent silicon from such foundries, serves the global information society in the same way as pig-iron production fueled the Industrial Revolution. Could this shift in priorities - away from excellence in *cell-level* innovation and refinement through painstaking attention to the physics of devices, multivariate boundary interactions and subtle behavioral details, which is a summary of the analog art, and toward circuit *recycling* and system construction to order using nothing but standardized Lego-blocks - herald the collapse of all that has gone before? This paper will answer. Yes, it certainly does, and must, does, in limited but important ways; but No, it absolutely does not, in any general sense. Analog performance demands a heart-felt pursuit of perfection.

The second paradigm shift is the emergence of the Well Known Fact that to every problem there is a digital solution. What's more, it's inherently a better solution, simply by being digital. It logically follows that the future world is a place of digital everything. And anyway, putting one's own frail reason aside, the learned writers of Newsweek and Forbes have decided: All that old-fashioned analog stuff is not simply on its way out, it's practically stone dead. This sentiment is strongly reflected in our own trade magazines, and by more than a few papers in professional journals. Cheap is in; fancy is out.

It would require a distinctly myopic outlook to deny this shift in the character of electronics, from a once mostly-analog outlook to a mostly-digital one today. Who of us has not been dazzled (if not blinded) by the stunningly successful evolution of the humble, self-replicating NOR-gate? And who has not

come to realize the sheer ubiquity of binary data? The defining quality of the Information Age is surely its super-prolific use of bundles of data of widely varying size using quantized tokens. Truly, the reasons for "going digital" are increasingly compelling.

Curiously, the Bit, the fundamental token of information, also has an approximately one-hundred year history; it just lacked a name for the first half of the past century. Inspired by the crude, thick Jacquard cards of the weaving industry, which used punched holes as binary marks, Herman Hollerith successfully applied his adaptation to the 12th US Census (1890). During WW-2, a five-hole (32-symbol Baudot) paper tape, encoded using primitive Modulo-2 arithmetic, was used in the German Lorentz machine for ciphered messages. The radical improvement in speed made possible by electronic binary-algorithm processing was realized in the first electronic programmable¹ computer (Colussus) designed in great secrecy by Tommy Flowers at Dollis Hill (the Research Labs of the British Post Office) in 1943, and transferred to Bletchley Park in 1944, for code-breaking. (I had the distinct pleasure of meeting Flowers during a visit to these labs the 1970's). These very same bits are used in today's cell-phones, PCs, DVDs, PDAs, the Internet, and well everything it seems. They have just become smaller.

Many "logic circuits" (some still using mechanical switches², the more advanced using tubes, and sometimes diode arrays) appeared during that period, and throughout the 1950's. But their profoundly revolutionary potential was scarcely recognized by the electronics world of my youth. The primary locus of development remained that of *analog* techniques, serving the burgeoning fields of radio, radar and sonar amplifiers, oscillators, modulators, demodulators, time-bases, waveform generators and much else. The equipment of this era was awesome, inspirational: congregations of glowing tubes teamed up to implement enigmatic signal-generating, processing and sometimes nonlinear computational functions, all showing evidence of great ingenuity. This kaleidoscopic outpouring of analog innovation and engineering stemmed largely, of course, from the primal urge to survive, a pretty good motivator. Much of this marvelous stuff appeared on the surplus market after the war ended, an incredible wind-fall for the teenage inventor.

While the engineers whittled away, the research focus was on advances in new types of electron-tube devices, including most importantly the magnetron, klystron and traveling wave tubes, and many variations on these themes. Further vigorous development of more conventional vacuum tubes brought a gradual progression to higher power-handling, improved

transconductance, shorter transit times, smaller envelopes, greater robustness, and other performance advances. Longer lifetimes were also needed; but an amplifying device that would last forever was too much to hope for. This period also saw the refinement of graphical displays (based mainly on advances in CRTs). These, and new types of numerical displays (for example, Decatrons and Nixie Tubes) were slowly paving the way for the modern, commonplace presentation of electronic data.

II. Binary Bypass

The golden thread woven through these disparate developments was the fundamentally *physical* nature of their component parts. All were essentially analog in their structure, principles and operation. Even when some of the elements could be applied to logical operations, the *circuit* was still the thing. The benefits that might have resulted from the use of binary accessories to analog circuits were hardly realized (however, the opposite flow was common). The work of Claude Shannon (b. 1916), who coined the word Bit (from Binary Information uniT) in a new theoretical field obscurely called Information Theory attracted little general attention. Recently, he has been hailed as "the founding father of the electronic communications age". Rather similar distinctions, but substituting "computer" for the word "communications" (a forgivable confusion today) have also been conferred on Alan Turing (b. 1912) and John von Neumann (b. 1903), both of whom in this same gravid period were thinking about the remote possibility of machine intelligence.

Even as late as the mid-60's the significance of the insights of these three pioneers and the world-shaping potency of the bit were scarcely noticed by the electronics industry of the time. The engineers, with slide-rule in hand, were absorbed in the manipulation of continuous-time signals and the physics of devices, while the theory was focused on utilitarian analytic methods for pen-and-paper design, particularly the optimization of such things as amplifiers, filters and oscillators. A university-trained engineer could be expected to have mastered the equations of Maxwell, the transformation techniques of Laplace and Fourier, and the stability criteria of Bode and Routh-Hurwitz, and to routinely apply them in their everyday work. Dexterity in handling the complexities of advanced mathematics at *both* the device and circuit level was regarded as normal and essential. Even technicians were familiar with the physics of devices, in the sense of how things work at the cell level, and knew many of the relevant equations.

III. The Transistor Age

Meanwhile, semiconductor devices were quietly brewing in back rooms. At first, all the emphasis was placed on applying semiconducting materials to the realization of more robust microwave detector diodes for radar, but the dream of finding a new sort of "solid-state" amplifying device was on the minds of many people, especially at Bell Telephone Labs in Murray Hill, NJ. The fortuitous discovery of bipolar transistor action by Becker and Shrive in a small, instrument-cluttered room in 1947, was a breakthrough of revolutionary

1. More exactly, this was the pre-programmed single-algorithm computer, not a stored-program machine.

2. I recall using a digital voltmeter (from Nonlinear Systems Inc.) that used a relay-based successive approximation ADC (hopefully just to provide the needed MSB accuracy!) and a vacuum tube computer (Elliot 803) programmed by a paper-tape reader, which also boasted a relay-based ADC in its graphical output device, to drive X-Y plotting table. The clatter made by these devices was memorable.

proportions, as today's aspiring high-school engineer is aware, albeit somewhat vaguely. Less well-informed students probably believe that "the invention of the transistor" refers to the arrival of sub-micron CMOS, or perhaps even the microprocessor.

The BJT, the device that is still (one trusts) at the heart of this conference, had arrived. Initially, it was its value in speech-band amplifiers (notably underwater repeaters) that elevated this fragile curiosity to a respected place in electronics. And it was its later application to analog circuit design that received most attention in the following two decades. In 1954, I was exposed to precious first-generation production transistors, and struggled to replace the tubes (12AX7 and 12AU7, mostly) in digital shift-registers and other logic functions in speech-encoding equipment. But they were too slow, too costly and too temperamental to be used in the needed large quantities. Even at the close of that decade, when companies like EMI and Ferranti in Britain were launching "transistorized computers", the pervasive assumption was that electronics remained first and foremost the art of circuit design using a wide variety of function-specific components to manage signals in some way or another. No-one had to ask "What kind of signals?". By 1958, I had comfortably returned to an analog life, after discovering that digital design is remarkably dull.

However, by the end of the 60's improvements in manufacturing had led to more robust, faster and cheaper transistors, which began to be used in generous quantities in many kinds of logic functions, apart from those at the heart of a digital computers "central processing unit" and "memory banks". A key development of the time was that of fast, inexpensive analog-to-digital and digital-to-analog converters. Now, with this crucial bridging function to and from the binary world, the floodgates were opened, and first-generation digital-signal-processing was an inevitable outcome. This began the attack on the analog domain as the primary province of "signals".¹

Operations previously thought to be only possible (by the majority of engineers) using analog cells such as filtering, modulation and demodulation were being devised. Eventually, it looked suspiciously as if a *significant proportion* of these signals were becoming binary in form, and their management appeared to be in grave danger of being stolen from us, the analog community. We finally took notice, and waxed defensive. We wondered - Is this the beginning of the end of a golden age of circuits? (It was, although not the end of analog design). Many of us fought back in this life-and-death struggle. Thus, we have this contemporary assertion from George Philbrick: "It was stylish, even recently, to say that the only good electronics is that which says Yes and No. There is

nothing to be gained in disputing these allegations, least of all by excited rejoinder. [However], the continuous active analog is in its infancy, and time is (literally) running in its favor". Roughly translated: when it comes to analog circuits, you ain't seen nothing yet. George was right. The invention of the planar process by Jean Hoerni of Fairchild would dramatically advance the capabilities of semiconductor circuits in the high-performance analog arena.

But the thin edge of the ax had been driven into the debate, and it has continued to cleave the "electronics" community at large into the Haves and the Have-nots: The Haves are those masters of device physics, circuit analysis and topological innovation, who interpret the modern world as a very exciting place, where more and more opportunities for their skills are popping up every day, fueled by the expansion of electronics to global proportions. The Have-nots are the regiments of graduates who may never experience the joy of making a circle of transistors dance to some new tune, or the pleasure of crafting exquisite gems of invention, small in scale but magnificent in importance; the Have-nots are the Lego-architects of VLSI, who manage to get by with a paucity of knowledge about semiconductor physics, devices or circuits and often without much idea of the realities of hardware or the rigors of manufacturing.

IV. The Role of Analog Cell Re-use

In today's Information Age, the electronics industry is witnessing the disappearance of passionate and resourceful analog cell inventors. We are already at a time when many constructors of mixed-signal ICs draw their basic cells (pre-cut; some assembly required), from a library of circuits, conceived, one must assume, by the gods. Many of these young people seriously expect that they should be able to always find the precise analog solution to some problem they are facing "out there", perhaps at a company's internal website; or from a book, a trade magazine, or a manufacturers application note. Students often ask me: "What is the *best* way to make a [certain analog circuit]?" I am quite baffled by this perspective, and at a loss for the "best" answer.

In the event-driven world of logic design - where most data-processing blocks can be viewed and understood as pure, abstract logical elements that just happen to be built of transistors the extensive re-use of cells and "IP on Tap" are legitimate. Recycling of proven solutions is also appropriate, because there is no virtue in redesigning a family of logic cells for every new application. And it is necessary, in order to formalize the process of system construction, using highly automated placement and routing tools; and in the minimization of risk; and in speeding the development to market. (Better be quick, because today's digital ICs have the half-life of a candle; their shine is short). Unfortunately, in the analog world, this increasing dependence on re-utilization is causing many eminently useful, powerful and robust cell concepts to be forgotten, and valuable new ones to be passed by, in the rush to market. Now, it is less important to know how to implement an analog function from scratch than to know the URL where a ready-made solution is to be found. A

1. In 1972, I was asked by Ray Stata, then president of Analog Devices, for whom I was consulting, about the possibility of a monolithic ADC and whether I would be interested in designing one. I declined, stating that I did not want to have any part in hastening the digital takeover of the analog domain. That challenge was picked up instead by Paul Brokaw, who designed ADI's first monolithic ADC. Its SAR used 1²L logic.

firm grip on device physics is no longer commonplace. Indeed, it is becoming rare. One often hears: "That stuff is for those other guys. Its not my business to deal with the weird peculiarities of devices". This rather dismal characterization of the contemporary scene is enough to lead an old-timer to declare that we must be in the wrong age - surely not the Age of Information, but the Age of the Ignoramus, at least in analog matters.

Is this state of affairs bad? That's a purely philosophical question. It is inevitable? Yes. Precisely *because* electronics is now a service industry, our business is changing radically. The pursuit of perfection is in danger of being replaced by pallid pragmatism; that seems to be the rule, rather than a ghastly aberration. Deprived of the power of the throne, we analog designers cannot presume to have the slightest impact on halting the inexorable descent into the digital underworld. On the other hand, up here, there is no need to run around the analog lab declaring that the sky is falling. On the contrary, if anything the outlook is extremely favorable for analog design, of the genuine sort: at the cell level. Here, opportunities for invention abound and new markets are waiting. And while some of the rules are in flux, we can be sure this doesn't include the rules of device physics.

V. "Your Analog Solution is too Expensive"

It has been said that nowadays there are five factors determining the success of a new IC product: cost, cost, cost, cost and cost. The warm welcome once enjoyed by a creative and potentially valuable new analog IC function is now replaced by the dull-eyed question: How much does it cost? The more sophisticated customer may ask: What is the chip area? then quickly figure out the manufacturing cost, based on a worth of about 1 microcent per square micron (which is about the going rate). Parenthetically, we must note that software vendors can distribute their product on a 20-cent CD-ROM, but charge \$129.95 for a copy, while the IC designer may invest a sizable chunk of a lifetime developing a masterpiece of perfectly-proportioned analog sophistication, and not get much more for it than the cost of a few milligrams of silicon, in his marketplace. This is a surprising disparity, since the success of both depend equally on their intellectual content. How often is ones IC product exciting even joyous - in its conception, stimulating during its simulation, and the best in its league when it hits the market, only to be tagged at 35c? How can it be that these sapphires and emeralds of ingenuity and fine craft are sold at cut-glass prices? Could *this* be why the industry is not generating a new generation of talented analog designers?

VI. Information: Analog, Binalog and Binary

The question arises: How much "information" can be represented by a single analog voltage? In a certain sense, it seems infinite: a DC voltage can have any value in a continuous range, putting aside for the moment the important matter of *information rate*. As an extreme example, suppose a voltage can span the range 0 to 1V, and is generated by an accurate 20-bit DAC (~1ppm resolution). After being "sent" to another node, it is applied to a similarly accurate ADC. Thus,

one million states (voltage zones) can be encoded and decoded. Using suitable look-up tables, every entry in the Oxford English Dictionary (OED) could be selected by a unique voltage.

Such a proposal is entirely devoid of practical common sense. Errors of many kinds limit this method of "information transfer" to about 100 states (<7 bits). However, multi-level analog voltages have been used successfully in precisely this way, in the transmission of information. For example, Tektronix 7000-series of laboratory oscilloscopes used a staircase current of 100uA increments, defined by switched resistors in a plug-in unit, to convey the operating status to an on-screen display. Using two wires and ten-level current-mode codes the data matrix was squared. This "knob readout" system also contained much else analog (including the vector character generators) that would today be far more effectively implemented in a host CPU. But this technique (which met with considerable opposition from my more level-headed colleagues) proved the viability, in a mass manufacturing context, where robustness is essential, of transmitting quantized "information" using multi-level analog current-coding on a single pair of wires, although admittedly in a closed environment, where a common voltage reference could be shared.

The basic limitations of such hare-brained methods arise in four ways: *scaling errors*, *offsets*, *nonlinearity* and *noise*. As it happens, these same phenomena are central to the realization of all analog circuits and are responsible for so much of the hand-wringing they engender. The first three are technological in nature, arising from the limitations of physical components; they may be imagined as becoming of vanishing importance, with advances in materials and device structure. In high-performance analog ICs, laser-trimming is very effective in reducing these errors to negligible proportions¹. Noise is less accommodating, but given long enough to convey the signal, it too can be reduced to under 1ppm using averaging.

Real circuits and propagation media have finite *bandwidth*, which is a measure of a channel to convey changes in data representation from one value to another in a given time span. But raw bandwidth is not enough. For our 1-million word OED encoder we also will encounter the issue of settling time; even fully-linear wideband channels can have very long settling times to the 1ppm level. A coaxial cable or twisted-pair of wires exhibits "dribble-up" due to time-dispersion, and many circuits (non-minimal phase networks) have similar time-domain responses due to peculiarities in signal phase versus frequency. A further settling-time limitation occurs in nonlinear analog circuits (that is, all of them) when large

1. The use of wafer-level trimming in the reduction of nonlinearities is unusual, but not unprecedented. The high performance of the AD734, an analog multiplier/divider developed in the 1980's, was achieved mostly by design rigor from the outset, but aided appreciably by special automated trimming techniques that use "distortion sniffers", based on very sensitive synchronous demodulators, to search for discrete harmonic components and eradicate them one by one.

transitions temporarily drive then into overdrive; this is the familiar *slew-rate* phenomenon, the inability of a circuit to remain linear when exposed to high rates of change.

We have come face-to-face with the "seven deadly sins" of pure-analog signals and systems, not only as vehicles for the transportation of data but in all other applications: (1) inaccurate scaling (gain); offsets (in DC-based signals); (3) nonlinearity in the transfer characteristic; (4) noise (about which the less said the better); (5) finite bandwidth; (6) dribble-up in the step-response (poor phase behavior); and (7) slew rate (time-domain nonlinearity). To this list of accusations we can add the impact of process variations and parameter shifts, the effects of temperature and supply voltage, and component aging. In aggregate, these remain the most prevailing problems of analog signals, and the factors most are responsible for the popular outcry against them; no purely digital system need suffer from any of them.

Not ready to give up, the unrelenting analogger may turn to frequency as a representation modality. Using common synthesizer techniques any one of millions of frequencies can be defined, in principle to atomic clock accuracy, and used to encode information. The reverse process implemented in a receiver then recovers the data to the same exquisite accuracy. Frequency cannot be corrupted (in point-to-point channels) and the frequency domain can in principle be infinitely divided, and readily to the 1Hz-in-1GHz level. This looks more promising, as a way to remote-select any word in the OED with one analog variable. Unfortunately, noise, the plague of analog systems, steps in to limit our enthusiasm. This time it is in the form of a smearing of the power density over a small, but nonetheless damaging, range of frequencies. This is often primarily stochastic in nature, although there may also be some systematic perturbations. Given long enough, this smearing can be averaged out. But the transmission of a 20-bit frequency word that might require a millisecond to classify is of little use¹. At the technological level, component drifts and supply- and temperature sensitivities in the reference-frequency source may set a practical limit to the "information capacity" of a single frequency, and Doppler shifts in mobile systems cause frequency errors at the receiver (and at a fixed-location transmitter, too, from a relativistic viewpoint).

This overview of limitations reminds us yet again of the intensely *physical* nature of analog signals and circuits, which are the result not only of the wide scope of distinguishable "data values" (voltage or currents, frequency or phase, etc.), but which are deeply rooted in the properties of the materials from which the components are made. They are physical in a further crucial way: all analog signals and circuit components

alike are characterized by quantities having *dimensional* units, which connect them with the "real world". For these reasons, I use the term "Newtonian" to describe analog systems. The dimensionless data representations that arise in digital systems are far different. It is principally a matter of *convenience* that electronic techniques are used in them: the devices are very tiny, very fast and very cheap. But any other technology having the same properties and an equivalent level of maturity and manufacturing base would work just as well.

That cannot be said of analog circuits: they are the quintessential locus of electronics, and can be said to define this field in a profound way. There is an interesting middle-road, however, that does not yet seem to enjoy identification in the taxonomy of electronic types. This is the practice of representing signals and thereby conveying information by the use of variable *duty-cycle* of a *two-level* (but not binary *coded*) voltage or current. The duty-cycle span can be divided continuously, as is the case in a classical delta-modulator, or in discrete time steps as in modern sigma-delta ($\Sigma\Delta$) data converters.

There are two key principles at work here. First is the possibility of transforming analog signals to two-level form using extremely simple and robust "front end" circuits; second is the immediate applicability of inexpensive, robust logical gates to perform a variety of powerful signal-processing functions, in both the time and amplitude domain. These are often embedded into the system, as in a sigma-delta ADC. Such signals and devices fall into is a unique class of circuits, for which the term "bialog" is here suggested. A bialog signal has only two amplitude states but a very large number of duty-cycle values (16 million in a 24-bit $\Sigma\Delta$ converters), or essentially an infinite number in an asynchronous delta modulator. Of course, in this domain, too, basic physical analog limitations intrude. One not mentioned so far is *time-jitter*. In a continuously-divided duty-cycle, the "information capacity" (here referring to the capacity of a system to distinguish a unique state out of many possible ones) is seriously reduced by the effects of noise always making an appearance, in both voltage-mode and current-mode forms - which again smear the transitions. Jitter is the close cousin of phase noise in frequency-encoded channels.

It is already clear that bialog systems are able to address a large number of important practical challenges in signal-processing. Very powerful noise reduction (strictly, noise shaping) techniques permit extraordinary high resolution and measurement accuracy in a $\Sigma\Delta$ ADC. One of the more notable developments in this arena has been the application of frequency-response shaping, and the use of sophisticated feedback techniques implemented in the z-domain through the mediation of pure binary circuits, to realize band-pass analog-to-digital conversion. With these techniques, an ADC can be rendered insensitive to a wide range of signal frequencies, while accurately encoding those within its pass-band, thus providing a measure of selectivity, and with it, a reduction of input-referred noise (measured here in terms of LSBs).

1. Spectrally-pure emergency locators used by the military can emit a signature frequency of better than 1Hz in accuracy. This greatly improves security because the rescuers know precisely where to listen, using an ultra-narrow-band receiver. Also, the very low noise power in a 1Hz search bandwidth allows very high signal-to-noise ratios, improving the probability of a successful mission. However, Doppler effects require a spatially-stable platform for both transmitter and receiver.

VII. The Outlook for Analog Innovation

This paper started with a review of some of the key developments in electronics that, in the space of some sixty short years, brought us to where we are today. It was noted that, in a certain sense, we can look back on this period as the "Golden Age" of analog power and supremacy, as we witness with regret the transition of electronics from a strictly technological craft to a commodity business. So, it that it? Curtains? So it may seem, to most outsiders; and it is a matter of certainty a *fait accompli* in the minds of the journalists. Even the well-informed among us may be forgiven for supposing that with so many good circuits behind us, the opportunities for invention are now scarce. That is as reliable an outlook as declaring that all the best ideas for novels, or for symphonies, sculptures, architecture, and numerous other creative endeavors, have already been expressed. It is surely more reasonable to take the view that the very brevity of "electronics" the broader and more pervasive outgrowth of "wireless" is still a young and vigorous enterprise.

We can safely assert, for example, that "radios are forever". These represent a major proportion of today's electronics and the relevant techniques are clearly of a fundamental quality, and in anything of increasing, rather than diminishing importance and impact on society. One can imagine endless new forms of radio communication devices; in the near future, these will be tied to the struggle to introduce new services using the "3G" networks; wireless LANs operating in the 6GHz region will soon become vital to the office and factory, and cheaper short-range data links will become common in the ISM bands at lower carrier frequencies. In this regard, the possibility of tailoring the power and range of the transmitter to only short ranges will address the always-vexing matter of limited spectrum space. We can expect to see autonomous networks using self-organizing linkages between many tiny repeaters, which may enter into service when needed and become quiescent when not; new RF techniques are being developed for many identification purposes (packages, pallets and people).

This growth in the use of radios will be seen in all other fields. In automobiles, we can expect an increasing reliance on radio techniques in all kinds of telemetry, toll gate check points, the exploitation of the many opportunities afford by GPS and satellite, including the autonomous signalling of emergencies and subsequent rapid location, in collision avoidance radar, and much else. Microradios will become "consumables". Thus, in medicine we can expect to see the commonplace use of radio pills and disposable radios for numerous monitoring and diagnostic purposes. The medical, biological and nanotechnology fields also will be the territory for inquiries into the interesting question: How small can a radio be? We know a large number of molecules will be essential, but what is the minimum number (or mass) for a useful range?

Similar demands on analog talents will be felt in the endless variety of products having significant analog content, that is, practically every one. Notably, the modern computer will continue to depend on the services of numerous analog

subsystems and analog sensors for self-monitoring and self-optimization, such as the accurate measurement of CPU temperature and the control of its several supply voltages to maintain maximum speed only when needed and minimum power consumption. And in the context of computers, we might pause and wonder what ever happened to the analog computer so crucial to simulation studies of all kinds during the mid-point of the past century. It did not die and become obsolete (again, the journalists need to dig deeper). Quite the opposite is true. In the 21st century we are, and will increasingly be, surrounded by millions of tiny, inexpensive and highly specialized analog computers that just don't get called that. They are woven so deeply into the tapestry of our world that we don't even notice them. Think about that.

There is so much for a talented analog designer to look forward to with keen anticipation. Nevertheless, the rules have been changed forever. Nowadays, it is more important to embrace a much broader view, based not on the arrogant and opposing positions of "the haves", the analog designers that have the physics in their heads, and the "have-nots", who live only in the black, white and gray world of digital data and algorithms, but on the far greater importance of cooperation between these disciplines, and the realization of an even more powerful union. A few of the new rules are: 1) There is no virtue in analog innovation as an abstract pursuit of something called elegance; 2) If a general function can be implemented fully in the digital domain, it should be; 3) In the mastery of modern electronics, never imagine that you can afford to leave it to someone else to understand the analog world, or, conversely, the digital world; 4) If you need an unfamiliar analog function in your mixed-signal IC, don't expect to be able to order it, like pizza; 5) When you locate that precious cell, never dream of incorporating it into your product without first understanding it; be prepared to modify it, for analog an circuit is not event-driven state machines, but bidirectional at its boundaries; 6) Be prepared for major organizational changes in our industry and understand why they are inevitable. This last topic will be addressed in the presentation.