CHAPTER 15 SCIENCE, ART AND EMOTION

Should one emphasize the *science* of design over the *art* of design, or vice versa? What is the role of *emotion* in our work? That word gets scarcely even a mention in modern technocultures; on the rare occasions when it does, it brings into the conversation an embarrassing spiritual dimension that many would say is quite inappropriate to the field of engineering. This peculiar reluctance on the part of some scientists and technologists to recognize the importance of human emotion in their work borders is regrettable.

The distinction between science and art is simple. Science is concerned with observing *'somebody else's black box'* and about drawing conclusions as to how this black box (the atom, the genetic code, the cosmos) works, in all of its various ways. Scientific progress is based on the design of experiments, observation and analysis; from these researchers suggest hypotheses about the underlying laws which might plausibly lead to the observed behavior. These hunches can then be tested, perhaps by dropping sacks of stones and feathers off the Tower of Pisa, or by hurling unsuspecting particles around fiercely potent electromagnetic race tracks.

Over a period of time, often decades, the gathering of experimental evidence, its subsequent refinement, filtering and analysis, and the deductive/inductive process of hypothesis-generation, gradually lead to an *increased confidence*, and *a sense of 'understanding'*. If all goes well, the humble hypothesis gets promoted to the status of Theory, or even Truth. While the creation of Grand Theories can be said to be a constructive, even an artful, endeavor, it often amounts to little more than trying to find ways to figure out how *'somebody else's pieces'* fit together. Science is generally required to be a *rational analytic* activity. Being analytic, these theories are always approximations. In a very important respect, science is about knowing what may be safely overlooked or left out.

'Reverse engineering' is the process of discovering how a competitor was able to achieve performance that was thought impossible, then replicating that very solution. But however classified, the pernicious practice of copying – whether verbatim or more liberally – represents the very *antithesis of innovention*. It's not even a good way to learn.

'Art', on the other hand, has a seemingly quite different character. What we call 'fine art' is predominantly about the elusive human condition, about the things that touch on and mirror human life in so many non-technical ways. *Art is about seeing the world in an ever-fresh way*. The artist may scorn previous conventions as all-but worthless anachronisms. The challenge to the artistic temperament is to *create a new reality*, eschewing old foundations. Thus, the painter sees the blank canvas as an opportunity to portray a personal interpretation of our world (or some other non-world); the keyboard beckons the composer to create a musical statement never before uttered; the blank stage calls out for the illumination of clever words.

Certainly, there is practical skill needed in handling art media (a knowledge of how to mix paints, for example, or of the principles of harmony and counterpoint), but the artist's primary locus is a *creative, striving, synthetic* activity. In the artist's heart pulses the ever-present belief that the prevailing conventions can – and will yet – be pushed far beyond their known limits, or even be overthrown completely. Analysis and post-mortems are foreign to the artistic temperament. Leave that to the critics.

I'm convinced that the painstaking process of innovating sophisticated, competitive IC products embraces a considerable amount of 'art'. This is not a popular idea, and for all I know, it may evoke images of emaciated, goatee-bearded and beret-touting Bohemians, considerably removed from the refined world of 'rational science' or 'precision engineering'. This is a pity, because designing a small-scale linear integrated circuit is *very much like painting a miniature portrait*, or writing a piano sonata. This is particularly true of small-scale standard linear products.

SLIC design is the creation of a novel entity, the ultimate and inevitable distillation of our most strongly-held beliefs, our accumulated experience and our fully-focused powers of concentration, into something small in scale but nevertheless big in importance; it is craftsmanship at the limits of perfection, and, at its best, transcends these very limits into new realms of expression and potency.

When this artistic impulse is faithfully acted upon, *quality* of design will be axiomatic. The science has been sublimated; it's still there, like the innate knowledge of paints or harmony, but it permeates the entire creative process without ever needing to be raised to the top levels of consciousness[113]. True, engineers are not explicitly paid to be artists, and admittedly we'd be in deep trouble if we designed our ICs just so that the layout looked pretty*!*

But that is *not at all* what I have in mind. A better word might be 'artfulness': an approach to design which cannot readily be captured in a formal set of procedures, as perhaps 'mere' craftsmanship could. An artful design is one that draws on a wide range of deeply-felt emotions about the *intrinsic correctness* of certain techniques, which deviate from the commonplace just far enough to crack open new doors, to push the envelope gently but firmly toward ever more refined solutions, in high-spirited anticipation of tomorrow's demands.

[113] We can be thankful that da Vinci, Rembrandt or Beethoven did not have to sign off quality check lists before their works could be released to the world.

Having long held these views about the relevance of art and anticipation in design, I was pleased to discover that they are shared by Joel Arthur Barker, who writes[114]

> Some anticipation can be scientific, but the most important aspect of anticipation is *artistic*. And, just like the artist, *practice and persistence* will dramatically improve your abilities. Your improved ability will, in turn, increase your ability in dealing with the new worlds coming. [My emphases]

Perhaps one can criticize this 'artistic' view of the design challenge as having an appeal only to a certain kind of mind, although it does seem to be generally true that *a love of engineering and a love of the visual and musical arts often walk hand in hand*. I happen to believe an appeal to the artistic temperament, and a willingness to understand the importance of the emotional element in the innovative process, are *central* to the 'quality' theme. I suspect that it is largely overlooked because we work in a business – indeed, live in an age – where it is presumed that everything can be *measured, codified and reduced to a simple emotion-purged algorithm*, and that difficult multidimensional and often disparate problems can be mapped on to three-inch-square yellow or pink labels and within an hour or so; thereby reduced to a set of fundamental insights from which a crisp *list of action items* flows. This is a deeply-flawed philosophy; it seems to be part of the 'instant' culture to which the westernized world (and this includes modern Japan) has succumbed.

Certainly, there are times when we need to get together and attempt to find a consensus as to what are the 'most important problems' standing in the way of progress toward some agreed objective. Sometimes these sessions work, but my experience with them is dismal. All too often *we allow the formal process to take over*, and forget what we're trying to achieve. The strict observance of 'methods', under the guidance of a 'facilitator', who alone knows the right color of marker pen to use, or where to place the Post-Its on the whiteboard, gets slightly ludicrous.

With all these Holy Grail practices that corporations are pursuing today, there's little likelihood that the science will be overlooked; it seems far more likely that we will dangerously underestimate the value of *the art of design*, and the *emotive impulses* that do not lend themselves to clear articulation. Algorithms for enhancing product quality invariably omit some very subtle, and equally crucial, artistic/emotive issues, which are often specific to a particular program or objective or design activity, for the very reason that these are *extremely difficult* to capture and then incorporate into an algorithmic form. It is unwise to have elevated expectations of such rituals, though I recognize they may work well for some people.

114 Ibid.

The innovation of competitive high-quality products is *both a science and an art*. Neither is more important than the other; unfortunately, the art is usually regarded as of secondary importance in engineering design. To be candid, this general deprecation of the arts is a wide-spread malaise of the American culture, which takes pride in being 'practical', which adulates the impossible notion of equality, and which is all-too-ready to label as *elitism* (nowadays invariably used in a pejorative sense) anything that recognizes the special talents and efforts of a small fraction of the population. I see no threat from elitism[115]; I fear much more the mindless uniformity of thought and action of a vast 'common denominator' and its willful, grinning acceptance of mediocrity as the norm.

Americans are apt to compare their prowess in design with that of the Japanese. The following quote[116] is of interest:

> In the West, there is a sharp distinction between design - meaning applied arts such as graphics, utilitarian objects, and architecture - and the fine arts of painting and sculpture. In Japan, such a distinction was unknown before the introduction of Western art and ideas. "The Japanese have struggled to keep alive the traditional unity of all the arts," says Fischer, "and they have succeeded very well." According to that philosophy, a department store's shopping bag design should be as beautiful as a scroll painting. A lacquered bowl should evoke the same feelings of harmony and transcendence as a Zen temple....

I believe that much of the worldwide success of Japanese cars can be attributed not simply to their very high quality of execution, but also to this *Zen-like concern for the integration of form and function* and meticulous attention to the tiniest detail. The West cannot benefit from the Japanese example by simply attempting to capture its component pieces and then seeking to re-engineer them in a sort of algorithmic fashion. The Japanese success is as much as anything due to an innate sensitivity to *the importance of the whole*, and is a reflection of an ancient culture deeply sounded down. It also has much to do with the concern for the *community at large*, which stands in stark contrast to the Western emphasis on the potentiality of the individual. If we wish to draw any benefit from examples in other cultures, we will need to change more than numerous individual practices, each emotionally neutral.

And what of emotion? Are we engineers supposed to be at all times cool and calculating – like our silicon companions, perhaps, who never sleep and never tire? Or is there room in our corporate philosophy for recognizing that, as men and women we are prone to exhibit daily, weekly and monthly *emotional fluctuations*, that we are not always logical, and need to approach our work in an *emotional context?* Such allowances are essential in a comprehensive and realistic view of the innovative environment.

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115 See *In Defense of Elitism*, by William A. Henry III, for a thoughtful discussion (Doubleday, 1994).

116 Delta Airlines *"Sky"* magazine, September 1994, p95

In a fascinating book by David Gelernter[117], the author makes this observation:

.... modern minds ask constantly "given these circumstances, what follows logically?" - but never "given these circumstances, what follows emotionally?"

Gelernter's thesis is that imaginative thought and the creative process do not occur when our minds are in a highly-focused state, but, on the contrary, during times of *'low focus'*. He contrasts the modern emphasis on logical, structured approaches to problem solving with the way ancient minds worked. The central importance of emotion in governing the rational mind is also the subject of a recent essay[118] and book by Antonio R. Damasio. He notes that

The idea that the bastion of logic should not be invaded by emotion and feeling is well established. You will find it in Plato as much as in Kant, but perhaps the idea would never have survived had it not been expressed as powerfully as it was by Descartes, who celebrated the separation of reason from emotion and severed reason from its biological foundation. .... It is not likely that reason begins with thought and language, in a rarefied cognitive domain, but rather that it originates from the biological regulation of a living organism bent on surviving. The brain core of complex organisms such as ours contains, in effect, a sophisticated apparatus for decisions that concern the maintenance of life processes. ... I suspect that rationality depends on the spirited passion for reason that animates such an apparatus.

Citing numerous case histories of people whose frontal lobe had suffered damage (beginning with the famous case of Phineas Gage), Damasio shows that reason alone is an inadequate motivator. Thus, of two patients, he writes[119]:

Rigid and perseverant in their approach to life, they both were unable to organize future activity and hold gainful employment; they lacked originality and creativity .... One way of describing their predicament is by saying that they never constructed an appropriate theory about their persons, or about their person's social role in the perspective of past and future. And what they cannot construct for themselves, they cannot construct for others. They are bereft of a theory of their own mind and the mind of those with whom they interact.

Such people demonstrate "an overall intelligence within expectations", but lack any emotion, and it seems that the latter is deeply connected with "originality and creativity". Damasio defends my position that what we engineers do each day as we pursue our various roles in the corporation – and that includes the technical decisions we make – is *governed as much by emotional forces* as by detached rationalism[120].

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117 David Gelernter, *The Muse in The Machine: Computerizing the Poetry of Human Thought*, The Free Press, New York, 1994, p. 176. Highly recommended reading, though a little eccentric in parts.

118 Antonio R. Damasio, *Descartes' Error and the Future of Human Life*, Scientific American, October 1994, p144. The essay was extracted from his recently-published book, *Descartes' Error*, Grosset/Putnam, 1994. The author is head of the neurology department at the University of Iowa College of Medicine.

119 *Descartes' Error*, p. 58

120 In searching through the index of Damasio's book, I found the fascinating entry: "Decision making. See *Emotion*"

Indeed, I agree with Edward de Bono who says that *all decisions are at root emotional*, and would go so far as to say that allowance has to be made for a considerable amount of *irrationality* in the way we approach our work, without which we are, paradoxically, less likely to find innovative solutions. In my experience, the most literal and logical people I have met have invariably been the least interesting.

There is also an important place for *humor and wit* in the workplace. I'm not talking about Far-Side calendars and the like, but rather the *cerebral tintinnabulation and inner delight* that come from seeing something in a completely new and amusing way. In fact, much verbal and visual humor is based on the principle of setting up a situation, getting it fixed in the mind of the listener (or reader) and then dashing that image with some absurd denouement. In this respect, *finding a new approach to circuit topology is exactly like a joke: it can be intoxicatingly funny*. Both a whimsical sense of humor and high intelligence have to do with this idea of *seeing things in an unexpected new light.* In the studies of creativity conducted by Csikszentmihalyi, he noted that *a sense of fun was pervasive in all of his interviewees*. Of course, our general 'good-humor' will also allow us to better tolerate the numerous little differences that arise between us as team members, particularly when things go wrong. And in a good team, even the occasional light-hearted ribbing ought to be understood as just an attempt to relieve pressure; but choose your jokee carefully*!*

CHAPTER 16 INFORMATION-DRIVEN INNOVATION

It is axiomatic that knowledge is central to life. It is the principal survival tool; it is the source of the human's spectacular capacity to interpret, adapt to, shape and radically alter our environment; it is the playground of every kind of intellectual pleasure. In a 1992 book[121], the Toflers remind us of the centrality of knowledge in economic affairs:

All economic systems sit upon a 'knowledge base'. All business enterprises depend on the preexistence of this socially constructed resource. Unlike capital, labor and land, it is usually neglected by economists and business executives when calculating the inputs needed for production. Yet this resource is now the most important of all.

The *management of innovention* is largely about the *management of knowledge*, more strictly speaking, the management of information. While our business – microelectronics – has become an indispensable servant of knowledge, it has at the same time itself become critically dependent on it. Colin Cherry writes[122]

Man's development and the growth of civilizations have depended, in the main, on progress in a few activities - the discovery of fire, domestication of animals, the division of labor; but above all, in the evolution of means to communicate, and to record, his knowledge, and especially in the development of phonetic writing.

Just as the invention of writing – on stone, clay, skin, parchment and paper – radically altered all facets of human endeavor, today's computers are again changing the way we interact with knowledge, helping us in numerous knowledge-related contexts to achieve things which only a few years ago were quite impossible. The combined forces of human intellect and the modern computer's Jovian memory, Martian rigor, and Mercurial speed have brought us to a massive change of key and tempo in the Cosmic Symphony.

How can we engineers make more effective use of computers to put knowledge at the disposal of everybody, and in particular, better serve the needs of the innovator?

Like many other high-tech companies, we at Analog Devices have only recently begun to comprehend the *vital necessity* of instant access to critical knowledge. In part, this is a reaction to the increasing complexity of technical project management, and the large amount of raw 'data' on which we nowadays depend to do our job. It is also, of course, a reflection of the fact that computers have only recently become sufficiently cheap and potent to allow their widespread use, and *we had to await the feasibility of networking*. Now, every company, from the individual entrepreneur working out of the spare bedroom, to multi-national megaliths, has a stake in 'Information'. It is likely that by the end of this decade[123], the Internet will become as important to commerce as it is today to the scientific and technological community.

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[121] Alvin and Heidi Toffler, *Creating a New Civilization*, Turner Publishing, Atlanta, 1994, p. 35

[122] Colin Cherry, *On Human Communication*, Wiley, New York, 1957, p. 31.

[123] That was the text of the original 1994 revision called *It Starts With Tomorrow*.

Knowledge and Information

We stand at the portals of a massive thrust forward into the age of what might be called *'Epitronics'*, by which I mean *Electronics in the service of Information*. Epitronic systems are only incidentally electronic: computers came into being, and thereafter evolved because mathematical theories were emerging out of the work of visionaries like Gödel, Turing and Von Neumann, pointing to the possibility of machines that would be capable of representing *any piece of information in a uniform fashion*. The means to test out these possibilities can be traced to the development, even before the beginning of the century, of electromechanical relays; then came vacuum tubes, the transistor and magnetic cores, and finally, integrated microelectronic components which uniquely today provide the needed cheap and fast substrata for the realization of powerful information systems.

But it is important to understand that the development of electronic computers was only *fortuitously due to electronics*. The term *epitronic* points to the high-level aspects of complex data-handling systems: their behavior, their "nature", *transcends* what they are built from (just like us). The internal representation of ideas in general-purpose computers, today's pre-eminent "knowledge engines", is entirely in the form of dimensionless logical symbols. The fact that their processing elements *happen to be electrically-responding gates* is quite incidental. That is, *computers are in no* ***essential*** *way electronic*. Of course, to the extent that no alternatives to electronics are in sight, we will continue – for a log tome yet – to see them that way.

It is tempting to think that information channels from one machine to another handle *knowledge in transit*. Thus, we might formulate the maxim

Knowledge Accumulates when Information Flows

That's true, but it's *not the whole story*. As engineers, we can readily see that in some way knowledge and information make an integral-derivative pair, like voltage and charge. But there is more important distinction to be made between knowledge and information: *the former resides exclusively inside one's head*. It is more closely related to the idea of *experience* than it is to raw information.

Knowledge is Information Activated by Intelligence

There is a huge amount of information in today's world; some is *flowing*, most is *static*, stored in huge data bases. It would be useful to have different words for these concepts. *Intelligence-on-the-go* is analogous to *charge*, while *Intelligence-in-a-place* is analogous to *voltage,* and a *database* is analogous to a *capacitor.*

But that won't happen. The main thing to remember is that *only you, as a thinking being, have knowledge*.

All the data systems in the world combined have but a huge mountain of information, which you can draw off, like water, when you need a little bucket of it, for the price of a few billion electrons.

Unlike their epitronic relatives, while built from essentially the same raw materials, electronic *communication systems* remain physical - they are 'Newtonian' in the sense that *they are necessarily electrical,* and involve *signal representations* that have profoundly significant *dimensionality*, such as voltage, current, power, energy, charge all of which vary over a time-base. In turn these signals exist in components also having *dimensional* attributes, such as resistance, capacitance and inductance. Further, they have *fundamental temperature-dependent* behavior, particularly thermal noise[124].

To the extent that epitronic systems *incidentally* involve any of these peculiarities, they too are physical; but one's approach to the design of a logical processor is entirely different to the way one designs a radio receiver. The different ways in which we utilize electronics may someday lead to two separate fields of endeavor. Even now, few computer architects know how circuits work, nor do they need to. The situation is very different for the communications system designer, who invariably *needs to be well-acquainted with both digital and analog signal-processing techniques*[125], and must be fluent in at least one.

It seems to me that modern buzzwords like 'Information Systems' (IS) or 'Information Technology' (IT) slightly miss the point. In being more effective innovators, we do not need simply more *information*, in small, isolated fragments: rather, we need to be able to expand our *entire, internal knowledge field,* with all of its numerous and *essential connections* fully in place, and activated by intelligence.

The term 'Knowledge Systems' is avoided, not simply because we feel it's too pompous and excessive in describing what *really are* 'merely' Information Systems – just tools, providing little more than snippets and packets, offering scarce help in finding the all-important *connections and relationships* between elements that remain isolated – but also because we implicitly recognize that *knowledge is uniquely human possession*[126], and a very potent one, that is nourished by information, which we turn into actions, out of which emerge Theories and Things, Sculptures and Symphonies.

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124 Electronic noise present in computing systems; however, is not an *intrinsic* aspect of their function, largely because data values are restored to a standard amplitude and- retimed by the system clock after every operation. This the chief reason for their robustness and (dull) dependability.

125 It is interesting to note that the scorn poured on 'old-fashioned' analog approaches is nowadays confined to the pages of the Wall-Street Journal and trade books. The job market has recently woken up to the fact that experienced analog engineers are in very short supply, which ought to have been foreseen.

126 Well, okay, animals have it too, but we can't judge just how much they are motivated by the awareness of their knowledge.

In a recent survey[127] by Erik Brynjolfsson of MIT's Sloan School, the top 500 companies were ranked, and the benefits that they felt accrued from their investment in IS were delineated. GM remains #1, with Ford swapping places with Exxon for second place, while AT&T (who had $3.8 billion budgeted for IS in 1994) dropped from 4th to 5th. Curiously, IBM, generating about the same revenues as AT&T, had a declared IS budget of 'only' $2.8 billion. Both HP, at #26 (up from #39), and DEC, at #54 (slipping from 47) had '94 IS budgets very roughly equal to Analog Devices' entire 1993 sales ($770M and $660M, respectively).

In sifting through this data[128], I was most interested to see how the larger integrated-circuit manufacturers might be positioned with regard to their IS outlay. I found Motorola at #38 (but no IS budget revealed), Intel at #111 (with 2,000 employed in their IS activities on a $435M budget), Texas Instruments at #113 (oddly, with a larger IS staff of 2,100 but only 40% of Intel's IS budget, $173M), Harris at #328, and National Semiconductor at #486 (IS staff of 500, $90M). Another report in the same issue of *Information Week* had this to say:

> In this environment [fierce competition, rising costs, fleeting life-cycles], efficient use of information technology (IT) is more than a strategic goal - it's a corporate imperative. Analysts say that electronics companies are among the leaders in process re-engineering through client-server implementation, software integration, and on-line distribution methods, which keep costs down and production flowing. Besides Intel, Texas Instruments Inc. and Motorola Inc. are often cited as leaders.

At Analog Devices, we have some way to go before we can claim we are doing everything that needs to be done to support engineering with information services. Traditionally, we have relied on our *frequent 'brown bags'* to disseminate and share new ideas. It's hard to know how much time we can afford to spend on these gatherings; most of us feel uncomfortable about having to take time out from our projects to attend them, even though they are often held over the lunch hour. Also, they tend to have a transient quality: we may well find some ideas interesting, even inspiring, yet will leave the meeting without having them sounded down into a deeper place in our minds.

Mentoring will remain an important part of sharing and sounding down critical knowledge throughout a technical community, and much of this can (and should) be carried out through *direct verbal means, in frequent one-on-one sessions*. But while a broad network of informed associates will always be important, it's not enough to cope with these new demands.

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127 *Technology's True Payoff*, by Erik Brynjolfsson, *Information Week*, October 10th, 1994, p34.

128 In another table in the magazine, the top 100 European companies were listed. Siemens (#4) has an IS budget of $1.9 billion; Philips (#13) won't say; Bosch (#28) shows $276M; Telefonica (#86) $495M. It's important to realize, of course, that much of the expenditure on 'IT' is not related to supporting the engineering function.

There is also an obligation on the part of all of us, in my view, to *write* about our various insights at some length, through the semi-formal medium of the technical memorandum. This was a common activity for many of us[129] during the 1970s and '80s, but today it is being replaced by fleeting e-mail messages.

Apart from the obvious value of disseminating potentially useful material to others, and the value of setting down one's ideas in a rather permanent form, for one's own future reference, *the writing of technical memoranda is an excellent way of concentrating and focusing one's own often fragmentary thoughts*. I would go so far as to say that those engineers who keep their best ideas securely between the pages of their lab note books are acting in a very self-serving fashion, and showing little concern for advancing the interests of the technical community at large.

A special responsibility is placed on Analog Devices' Fellows in this crucial regard. They have been nominated to this position largely on the basis of having shown a propensity for generating significant corporate revenues through the application of *novel principles and discoveries*. That being so, they have an obligation to share their ideas, particularly if they were never published in conference proceedings or the professional literature.

Anything less amounts to laziness, a selfish indifference to the critical and widespread need for cerebral nourishment – not only on the part of newcomers to the company, but of all of us who depend on highly-detailed knowledge to be effective in elevating the quantity and quality of our own innoventive output.

Those of us who teach short courses should remember to pass on the useful knowledge contained in our lecture notes for the benefit of people within our own ranks. *We should encourage the development of an extensive library of internal knowledge, arising from such work*. The organizational effort required to effectively pursue this initiative would be considerable, but some kind of interactive library will soon be essential, and we can expect it will be electronic in form. We need ready access to an interconnected fabric of information with numerous dangling valence bonds – *information with hooks* and an appetite for adventure.

Special Agents To The Rescue

It was noted earlier in this essay that our creative triggers may well be random events, little more than *cerebral noise*, and that only when they are coupled into a strong body of experience and encouraged by a lively interest in anticipating – and then actually realizing – the next step, do we have the essence of innovention. Unfortunately, many of us are quite forgetful, and even with the best record-keeping habits cannot quickly recall all that we may have learned during the course of some development. Computers can help us, here. In particular, we are beginning to see the value of *agents*, software "personalities" that look after our personal interests, perhaps

[129] I have almost two thousand that I wrote, up until the early 1990s, stored in a shelf-full of three-inch ring-binders.

like an apprentice might. Indeed, the development of agents may mark a new phase in the stumbling history of artificial intelligence. We should not expect miracles. Today's computers have a long way to go before they can match our abilities to make connections and draw conclusions. We have yet to understand clearly how the brain manages information. There is new evidence that specialized molecular tokens, rather than a uniform style of electrical signals, are involved[130]. *The emulation of humanesque thought in a silicon machine may pose an incomprehensibly more daunting challenge than we ever anticipated.*

One thing is certain: denied *sensory appendages*, it is hardly surprising that present-day computers are not very street-wise. Without immediate access to the rich world of objects and people, *lacking perceptive and cognitive abilities*, we have practically ensured their moronic character. So, what if we equip our machines with *electronic eyes*, to see what we see (perhaps with even higher acuity), and *stereophonic ears*, to hear what we hear (but again, with intensified capabilities)? Alas, these would do little to aid their *intellectual ascent*, if their master architects continue to insist that they must be lamentably literal and devastatingly deterministic[131].

Nonetheless, in spite of the obstacles we have strewn across their path, computers have become better than human minds in certain limited and specialized ways. They are possessed of prodigious, *infinitely accurate memories* (unlike our own, which are invariably fuzzy and which rely heavily on reconstructive fill-in and confabulation). They are also *very quick*, giving back to us what is in their RAM within fractions of a microsecond, information abstracted from many gigabytes of disc within milliseconds, and large information objects from immeasurable terabytes located at thousands of other domains on the network within a few seconds, something quite impossible for us. Is this a kind of emergent pseudo-consciousness? I doubt it, and even if so, it is one which we can never prove. In their accuracy of recall, and perhaps even in actual memory size, computers *really have* become superior, and I don't think there's much point in trying to deny that particular advantage. A computer memory is, in some important sense, 'alive', in a way quite unlike a desk full of lab notebooks, or even all the books in the Library of Congress, because it can fetch specific items on demand.

130 Black, Ibid., particularly Chapter 7 *Molecules and Systems: Trophic Interactions*, pp. 117-131.

131 The issue of *pain sensors* in an interesting one. We have them as part of our survival package. Would we want a damaged machine to complain? Many already do, by automatically signaling that they need repair. Unlike us, these repairs can often be effected over the network, or even in the vast depths of space.

Computers are also very good at relieving us of the burden of computation. There is no virtue in working out tables of logarithms (as Charles Babbage noted, and about which he decided to do something, with the invention of his difference engine[132]). There is no virtue in using those tables, either; *we can, and should, leave such menial tasks to our silicon companions*. Not only are they flawless in calculation – notwithstanding the recent Pentium fiasco – they are also very, very quick. When running a circuit simulator, we are invoking many man-years of experience in the behavior of semiconductor devices. Who can claim to have memorized all of the equations describing current transport in a bipolar or MOS transistor, or would wish to manually construct, and then solve, the circuit matrices invoking these equations?

Computers are far better at this than we are. They're not painting sunflowers like Van Gogh, or writing sonnets like Shakespeare; they don't exhibit the legendary wisdom of Solomon, and never will. But they can run circles around all of us when it comes to *doing sums* and they will faithfully toil night and day on our behalf. While we sleep, the networks chat; updates of the latest software revisions and large databases silently flow over twisted pairs and through optical fibers, and all are put into all the right places, ready for us to do our bidding the next day. We acknowledge that in this way, too, computers have the edge: *people need to black out for a sizable fraction of each day,* to enter into the serious business of dreaming. Do computers dream? The answer must be yes, if dreaming is putting information away in all the right places.

Providing Access to Information

It is widely stated that knowledge is a modern company's most valuable asset. It often takes the form of 'intellectual property', but, unlike water, oil or land reserves, *it can be shared among many without becoming diluted*. While a great deal has been done to automate manufacturing processes using computers and large databases, progress in making *human design knowledge* widely and rapidly available to engineering groups has been slow. Modern innovators need to be multi-disciplinary, drawing on a deep fund of such knowledge (and raw information) scattered across a broad front. For those of us in the micro-electronics business this includes knowledge of (= information about) one's customers – who they are, where they are, what are their most vexing problems and their present solutions. We also need information about semiconductor device fundamentals and IC process technologies; about circuit techniques and system principles; about of the company's overall manufacturing capabilities and capacity limitations; about of testing methodologies, and much else.

[132] See his memoirs *Passages from the Life of a Philosopher*, published by Rutgers University Press, with an introduction by Martin Campbell-Kelly, 1994, for the background to the invention of the Difference Engine.

Most IC designers will readily be able to recall numerous instances of having to spend hours chasing some trivial piece of information: What is the field-oxide thickness on the process being used for a certain product? Where is there a comprehensive list of all internal memos on band-gap references? Where is there a scale-drawing of a certain IC lead-frame? Many of these quests could be reduced to a few keystrokes, given the right tools. Instead, the search for rudimentary fragments of essential information can (and often does) erode a large fraction of each day, through many phone calls.

In the long run, our effectiveness in reducing development time, in lowering costs, in enhancing quality and much else, is going to increasingly depend on *much more massive* and *interactive* databases – we might call them *'InfoBases'.* Connectivity between objects within these is essential, suggesting that they would be much faster if they were something other than just large serial files. It is widely believed that it is this feature – *near-total interconnectedness* – that makes the brain so powerful.

While primarily having a technology emphasis, such InfoBases and networks would allow querying in a wide variety of ways. They must be *deeply integrated* into our development tools. They must be available throughout the entire development cycle, starting with access to relevant public standards, the market research process, product definition phase and prior art searches, through actual component design and checking, layout and verification, wafer fabrication, early evaluation of first silicon, test development, packaging, data sheet preparation, applications support, and beyond, to customer feedback and the closing of the loop. These electronic repositories would provide information on other vital matters, such as resource scheduling and capacity, *all in one place*, available for searching, browsing, consulting and interacting with, anywhere, anytime, as instantly as keystrokes.

InfoBases will represent the amassed experience of hundreds, maybe thousands, of contributors. The operational shell will need to support more than a search function; it must be *anticipatory, pointing to other sources* of relevant or coupled information, all the while making connections, that is, it will utilize *relational databases*. It should be possible for anybody with the necessary level of authority, but no special skills, to make additions to a InfoBase, and the interaction process should also be amenable to *personalization*. Because of their immense commercial value, protection of access will be needed: some individuals will be permitted to search only certain areas of the InfoBase; as a general rule, the new hire would be given minimum access to critical information, while senior employees would have access to a very wide range of knowledge about the whole business. The whole question of security is fraught with contradictions and dilemmas: knowledge which is so potent that one's very success depends on it would obviously be very dangerous in the wrong hands.

However, that cannot be raised as a fundamental reason for not providing access to essential information. I doubt whether we could remain competitive in the long run without serious attention to such a comprehensive knowledge network.

It will take much imaginative planning and immense effort to turn such a Promethean undertaking into reality. Clearly, this is about the development of a resource that goes far beyond finding valuable tid-bits of isolated information without significant delay. It would become the basis for documenting and propagating virtually all ideas throughout a Corporation, in addition to being used as a mentoring vehicle, in keeping track of one's project schedules (and ensuring that all their interdependencies are properly calculated), in the efficient utilization of resources and manufacturing capacity, back-end and much else. It will have to take advantage of the most recent concepts in the management of large depositories of knowledge, and it would eventually make full use of multimedia facilities.

This is not about 'just another database'; it's a call for a visionary response to what may well emerge as the next frontier in competitiveness. This is something that cannot be achieved by one or two new hires with degrees in Computer Science, or even a few highly-motivated and well-qualified software people. It will require the full-time efforts of a large team, headed up by a respected leader in this field reporting into a high level of the company.

Is it too far-fetched to look forward to the time when companies have not simply a Chief Information Officer, but a **VP of Knowledge**? Many companies already have a post called VP of Information Services[133]. What I have in mind is a sort of fusion of this base function, along with pieces of the VP of Marketing, VP of Technology and VP of Manufacturing. The objectives set before this person would be so broad-ranging – to oversee the acquisition, organization and dissemination of all the vital knowledge on which our business is based – and the fulfillment of them so important, that they could not be left to generalisms and rhetoric; they would need very careful articulation as precise deliverables. This person would be right at the hub of Innovention.

More than any other initiative, I see this as being one that is most likely to bring about real change and be most effective in coping with the vicissitudes of the modern microelectronics world. I would go so far as to assert that is it precisely because the task of information management is *so monumentally difficult* that we are inclined to tinker with the latest management fads, instead, in the hope that there's another one or two percentage points yet to be squeezed out of all the guys and gals through the implementation of some new procedure with another mystical name. Such activities are distractions in which we cannot afford to indulge. There are harder challenges that need our urgent attention.

[133] At the time of writing (1994), it is Albert Brashear at Motorola; at Intel, it is Carlene Ellis; at TI, it is Bob McLendon.

CHAPTER 17 THE ELECTRONIC NOTEBOOK

For ages, going back to Edison – even to the time of Leonardo da Vinci – inventors have kept notebooks. When life was simpler, this was a fairly good way of documenting progress. But the challenge of keeping good development records is getting harder, particularly as we work more in teams. However, with the right approach and proper planning, we could reverse this trend by the year 2000.

Modern engineering documents serve five key purposes:

- They provide a central depository of our essential objectives, and outline the general and specific progress and overall history of each project as it unfolds;
- They are of present and future value to the individual who makes them, as well as to all others who may have access to them, particularly in connection with the discovery and elaboration of new principles;
- Properly kept and attested, they help to legally affirm the invention date of original concepts;
- They can help an organization to ascertain the time and other resources that were consumed in any particular project;
- Working with a lead customer, paying for a development, these records may eventually be needed to support their documentation requirements.

However, to an increasing extent, the capability of the traditional notebook to serve these ends is being strained. While the electronics engineer of twenty years ago might not have found it hard to scribble a schematic or two, jot down an accompanying few words of description or a few pages of mathematical analysis, and paste in some scope photos or graphs, these are nowadays the kinds of 'knowledge objects' that are more likely to be found exclusively in the designer's computer.

Thus, few of us have much use for hand-drawn circuit schematics any more, except for casual doodling on the back of the proverbial envelope. Most of us, I suspect, immediately commit schematics directly to electronic form, as well as all the various support files, which are manually updated and annotated as appropriate. In all likelihood, even the schematic spans many pages in a hierarchical tree. The little notes to ourselves as to why certain experiments were performed are likely to be in the form of addenda to voluminous simulation results (usually, various sorts of plots) which we annotate as we go. Working as part of a team, many of these *fragmentary* knowledge objects are likely to have been generated by, and need to be shared with, other team members in a real-time networked environment.

This is how we do it today. The time has come for a reappraisal of how best to engage computers in helping us to deal with the *formalities of documenting* our work, as it migrates toward being totally supported by our desktop computer, or network of computers, and their hard disks become the primary repository of all our records, project schedules, schematics, simulation results, in the form of numerical and graphical data, notes to ourselves of various kinds, material for patent disclosures, cell layouts, complete layouts, back-annotation of layout parasitics, test procedures and component evaluation results, product characterization, data sheet text and figures and on and on. Without question, the computer's 'where it's at'. By the year 2000, fast approaching, most of these transactions will be carried out over a network such as the World-Wide Web, and engineers will have their own "Web Pages" where their work can be viewed by all that need access.

A Proposal

In this respect, at least, our working habits as engineers are very different from those of Edison's time. The traditional 'lab notebook' is likely to get relegated to a growing pile of unattended paperwork on one's desk: *the TCM imperative is simply not compatible with the recording of elaborate drawings annotated with copperplate handwriting*, a basic modern truth that must be faced.

As IC designers, our work habits have changed very significantly since the 'sixties and 'seventies. In particular, we spend far more of our time in front of a workstation, in a sort of 'virtual reality', rather than at a bench, in front of a real oscilloscope connected to a real circuit. Obviously, this is not to suggest that the 'silicon reality' no longer has any relevance. (Heaven help us if we think *that!*) Even when we have working silicon, though, it is nowadays more than likely that our measurements will be aided by highly-sophisticated systems (using, for example, the HPIB instrument data bus), themselves connected into a network of some sort.

The undeniable fact is that most of what we do as product developers is computer-based. Indeed, when one considers the progress in the use of computers in the world of finance, the expectation that engineers should still keep *hand-written* records is perhaps analogous to the retention of an army of Bob Crackitt's on high-stools, equipped with quills, meticulously entering endless columns of numbers into thick, heavy ledgers. Financial institutions long ago embraced the computer, as did the airlines, the automotive, steel and food industries, and almost everybody else, as their exclusive "knowledge engine".

The phrase "office automation", which sounded so *avant garde* a few short years ago, has become *passé*. Yet ironically, in our electronic engineering context, out of which the modern computer arose, we have quite a way to go before we can feel we've done everything possible to simplify our work through the innovative use of computers doing things other than big calculations. I propose, therefore, that as an ongoing part of 'Creating the New Analog', and in recognition of the increasing importance of innovative IC development to the Corporation, we work toward creating *a new design environment, beginning with the automation, to the fullest extent possible, of all record-keeping obligations associated with the design function*.

I will refer to this as **The Electronic Lab Notebook (ELN)**. It would make the presently-used notebooks obsolete and unnecessary. We will later consider som e other ways in which such design-oriented automation might reduce the delays and overheads associated with product development.

I see the Electronic Lab Notebook as a first step toward eventually developing a fully-integrated and comprehensive **Automated Project Management** program (**APM** – if I may be permitted to add to the long list of TLAs). The availability of such facilities in no way forces anyone to change his or her work habits. For all I know, there may be people who prefer pen and paper (and fat ledgers) for note-keeping, and I suppose there would be no reason why they should stop using them. I know of at least one person – Bob Pease of National – who told me in a lunch line at ISCAS a couple of years ago (as recently as 1992) that he still much prefers to use paper and pencil over a calculator and he is more than a little outspoken about his stubborn preference for breadboards over simulation. He is of course correct to be concerned about the limitations of mathematical modeling; that should be obvious. But Bob takes it to such a passionate extreme that he does a disservice to the younger, more impressionable listener who is looking for "wise guidance from the elders".

The key benefits[134] of the APM concept, of which the ELN is one important component, would be:

- It would provide a central depository of the history, objectives, essential challenges, and the solutions adopted, during each development project, *doing so without any further needed action on the part of the user;*
- Such records would then be *immediately* available for use by all others who may legitimately need access to them, through the computer network;
- If properly designed, the electronic lab notebook would provide *legally-valid affirmation* of the invention date of important concepts;
- It can be used retrospectively to provide an organization with *a complete and accurate summary* of the time and all other resources that were consumed in any particular project.

134 I'm assuming throughout an integrated circuit development project of any complexity or scale.

That is, it could easily do everything that we currently do by hand, and with much greater accuracy. But it could easily go far beyond that, as I hope to demonstrate. By the year 2000, capabilities of this sort will almost certainly become commonplace. We already are seeing the introduction of personal assistants, such as Apple's 'Newton', which presumably represents an anticipatory response to the emergent market need for devices to help us all get organized. Alas, the electronics community often seems to be the last to benefit from its own dazzling advances.

There's a lot more that could be said about the function and structure for an Automated Project Manager and Electronic Lab Notebook. But, since we've already had one little fantasy, looking back to Edison's pursuit of new ideas, perhaps you'll forgive me for resorting at this juncture to another, this one *looking forward* some thirty years – to 2024 – to give some sense of the potential of the APM/ELN concept in a very advanced embodiment.

CHAPTER 18 ANALOG DEVICES 2020

It is 8^{00} am on a future spring morning. We are in the design office of Leslie Bright, fifty-eight years old, and happily unmarried, who has just returned over the past weekend from a trip to a key customer, Toy-Tronics, Inc. in Beijing. The visiting team has managed to convince TTI to engage Analog Devices as the sole developer of a critical new IC component, needed in very large production quantities in time for stocking the shops in USA, Japan and Europe well before Christmas, this same year. It will be challenging project, putting a microwave transceiver, eyes and ears, an olfactory sensor, gyros and a laptop computer into a single chip, making it all operate from a single 1.5V cell and selling it for pennies above cost. It's another robot dog of the sort that Sony first made, decades ago.

Leslie makes herself comfortable and picks up her first cup of coffee, while checking her e-sat-mail for new text messages, sound-bites and video clips. Very little information comes in through any other means, these days. That done, she turns to the main task in hand: getting Project TTI-31416 – as it has already been numbered – started as quickly as possible. Everybody has agreed that it is 'go', and, but for one person, the development team has been fully identified. As Project Leader, it is Leslie's responsibility to organize and manage every step of the program, and also be the key contributor to the analog processing and interface sections of the IC design, which requires solving some tricky architectural issues, and again facing up to the unforgiving Fundaments.

Sipping the coffee, she continues to address her personal workstation, *Sophia*, a General Computers 100Gb, who over the past couple of years has become her close Companion and ally, and whose name she chose. The capabilities of this machine could scarcely have been comprehended back in the 'nineties. No longer just a "tool", Sophia is a critical team member, taking care of numerous chores that formerly had to be done manually; or, more likely, never got done at all. "She" also can converse in several languages and translate between any pair.

With her *total immersion and integration* into the ADI community of several thousand similar computers, Sophia was rarely at a loss for needed information to deliver back to the human part of the team. After exchanging a few moments of polite small-talk, Leslie turns to the keyboard and reaches for the mouse. It's an old habit that she finds hard to abandon; the younger engineers routinely use the SpeakEasy interfaces exclusively.

Leslie begins by entering the APM environment, opening a new folder and naming it **TTI:31416**. This step automatically starts the APM program from a zero-initial state. Various menus appear – a short list, at this time, since no project-specific information has yet been accumulated – and Leslie, who has done this many times before, clicks on one labeled **TTI:31416:CUSTOMER**, which opens an editing window.

"Do you wish me to listen to Simon?", asks Sophia. "No thanks, Soph," says Leslie, frowning slightly as she types some things learned about the customer while still fresh in her mind, finding that mode easier and more likely to reinforce her ownership of the ideas than doing a direct data transfer, as Sophia had suggested, from her Personal Pocket Assistant, this one called Simon. PPAs had already become popular at the turn of the century, though less useful in engineering roles than some had predicted they would be.

Finding some pieces of the profile are missing, she next clicks on **ALL CUSTOMERS**. This invokes a very large marketing data-base, since what's needed right now is a little further background on Toy-Tronics Inc. Quickly finding the needed information, Leslie instructs her Companion to append this information to the **TTI:31416:CUSTOMER** file. Closing this window, Sophia, now running APM and diligently watching over the whole process, silently time-stamps the entry. *The project's T-zero has been established*.

Leslie next opens **TTI:31416:OBJECTIVES**, another edit window in the **TTI:31416** folder, into which the general nature of the project is set forth: its origins, the technical aims, it's closest precedents, a few other short paragraphs in free form. Leaving this window open for now, a new window, **TTI:31416:TEAM**, is opened. Like many of the windows in APM, this one is pro-active. It automatically lists the default members of an available team including Marketing Support, Circuit Artists, Layout Artists, Software Artists, Production Developers, Test Developers, CAD Liaison, Foundry Liaison, MCM Assembly, and so on.

Opening a menu item **LAST TEAM**, Leslie uses their previous project to insert some people she trusts and hopes will be available. One layout artist is identified at this point, but a note is made that two will be needed during the peak layout period for this project, assuming the use of the auto-router Gandalf, which was temporarily off-line for design uses, though still very much connected elsewhere, having its InfoBases expanded. At the instant that Leslie closes the **TTI:31416:TEAM** window, Sophia notes that this additional data will eventually be needed, and asks "When would you like me to check back with you on this?". "I dunno, Soph' - try me in a couple of weeks' time. No, wait - why don't you go through the rest of the ADI project manifold and make some suggestions?"

It is 9^{00}am. The team members, a veritable diaspora in design studios scattered across the world, have just received e-sat-mail notification that, as already largely agreed, they would be involved in the next TTI project. Their involvement has also been noted by the master scheduler, Eol'doog, *a fully-analog neural network* of some nine billion synaptic modules with numerous digital I/O ports and sensors, who it was believed resided in the penthouse. (The apocryphal story was that the planners had decided from the outset that this highly resourceful and analytic brain-head ought to have the best view in the house).

Leslie's concentration was momentarily diverted to admire the Boston skyline and the serene view of rowers practicing on the Charles River, from ADI's sparkling new Design Center, not too far from MIKT (the Massachusetts Institute of Knowledge Technologies, formerly called MIT). They built this place just after passing the $10B/yr mark.

She ruefully recalled the primitive surroundings that everyone had to endure when she joined Analog in the 1990's. In retrospect, it was a miracle anything creative ever got done in such an environment. Manufacturing, at the old Woburn Street plant – on 4" wafers*!* – and resource planning was in very primitive state back then. Still, she mused, it was from these early beginnings that ADI had seen the future of "real word signal processing" and communications systems, and the company had not only resolved to become the leader in supplying the needs of these markets, but had also had the good sense to perceive the crucial importance of applying "knowledge-oriented" tools, and hiring some good people to staff that effort.

"Excuse me, Leslie". Her momentary nostalgia shattered, Leslie was forced to refocus her concentration to the job at hand. "What is it, Soph'?". "Eol'doog informs us that Nicole Sanchez cannot be assigned the layout work on **TTI:31416**, as she will be having her first baby just about that time." *Darn it*, thought Leslie; *how could I forget a thing like that!? But that leaves me with only one assigned layout artist.*

Reverting back to her preferred I/O mode, she opened the **TTI:31416:TEAM** window again. The original team had been defined and date-stamped, so she couldn't go back and edit that part of the record. *Casual alterations were, by policy, only additive, never subtractive*. Clicking on the menu **TEAM CHANGES**, she noted Sanchez' absence, closed the editing window and hoped that Sophia would not notice.

Silly thought. "I'm sorry, Leslie", said the too-natural, and therefore somewhat spooky, voice, "but I can't allow that. Without two layout artists identified in the team, we would be ill-advised to proceed with **31416**. Shall I refer this matter back to Eol'doog?". The early morning clouds that were now coming in from the Atlantic seemed a portent that this project wasn't getting off to a most excellent start. "Oh.. okay, Sophie. Do the best you can. I'm going to start this project anyway, though I appreciate your advice."

Leslie turned down the volume of her silicon companion. She had a pretty good idea about the high-level architecture of **TTI:31416**, but she also wanted to quietly and quickly try out some ideas for a new analog cell that she'd thought up during the five hours on the return trip from Beijing to Boston. So she opened the window **TTI:31416:SCHEMATICS** and sketched a simple circuit on the large screen, using a brand-new derivative of an old piece of in-house code called **Tze-Sze**, which had been resurrected and improved, *to the jubilation of many*, as disenchantment with third-party software had grown, and finally led to a full return to the use of in-house software, which actually needed less support than that provided externally. Leslie had a choice of using TC (as she was used to calling it) or other schematic capture programs; but her test circuit was a small one, just a few dozen transistors, and the other programs presented needless complexity for such a simple job.

She reflected on the wisdom of the APM programmers, who had not allowed parts of the work environment to be barred from use just because certain formalities were not yet complete. Happily, the *"Tools Not Rules"* philosophy that had been born in the 1990s had taken root and was now in full blossom. Clicking on **SAVE**, the schematic was time-stamped and put away in her Electronic Lab Notebook. Well, they still called it that. She hadn't the faintest notion where or what that might be, *physically*. Maybe it shared some cyberspace with old Eol'doog. It was enough to know that the records would always be there, whenever she or anybody else wanted them.

After creating a few more short files, she touched **PREPARE**, **OPTIMIZE** and finally **INFORM**. The virtual-reality view-port showed a series of animations of the circuit, from many different perspectives. Components on the schematic scintillated with brilliant life. At one point, Leslie touched a node to listen in to a waveform.

In the old days, at the Ray Stata Technology Center, ADICE would have done the analysis and then allowed the user to poke around in the results space. But that left the door open too far, allowing users to spend endless hours in often fruitless, undocumented effort. Now, each time a new WorkWindow is opened, old entries are presented read-only but the contents can be expanded; *each time the window is closed, the user's results and notes again get date-stamped*.

Since the determination of the time and day is critical to the legality of these records, APM uses clocks whose "honesty" is irreproachable; in the USA, a signal from the standard-time transmitter WWV, was certified, during the last round of Patent Office Reforms, around 2013, as a *legal clock*. Of course, however the APM architects had chosen to incorporate this feature, it would be prone to tampering by the software geeks that hang out in any modern corporation; but in many respects, the problem of certification was no different to informal witnessing and hand-dating of the old Lab Notebooks. The legality of an invention auto-time-stamp had never been challenged in litigation, so far, anyway.

Leslie next pulled down a menu **TECHNOLOGIES**, which informed her of all the available IC processes, with sub-menus to explain these in detail, noting their geographic location, whether captive or foundry, cost guidelines, loading and turn-times, and so on. As always, the choice of process was critical to balancing the performance and cost objectives, though less critical in matters of schedule and quality, since all IC processes were totally controlled by a sub-network of ultra-reliable Silicon Companions operating in concert, worldwide, under the ever-watchful eyes of Eol'doog. Eyes? Well….

In this case, she had no hesitation in selecting **ADI:QMOS:0.1**, a mature 0.1µm QMOS-1 process. (Was the 'Q' for quantum-well? She recollected so, but decided not to bother waking up **ADLIB-2020**, the on-line library, to inquire about that). This was the process that designers had so often yearned for in the past: pure three-terminal transistors fabricated on super-lattices over a deposited diamond epi-substrate of high thermal conductivity, having essentially zero output conductance, no gate current (due to the novel means used to suppress hot carriers), intrinsically high linearity, almost perfect matching, even between opposite-polarity types, picosecond time-constants, and near-zero 1/f noise. Other P- and N-type devices could, if needed, optionally emulate the *wonderful exponential behavior of the old bipolar junction transistor*, which ADI had finally phased out in 2018.

The ever-vigilant Sophia purred to herself "QMOS-1 chosen, and noted". (She liked projects that used this process, since things always went so well when designing on it). While there was little activity that Leslie was aware of that moment, as she oscillated her chair rhythmically to the left and right, in fact a great many things were going on behind the scenes. The loading on manufacturing could not be fully assessed, because Leslie had not yet invoked the product volume and schedule routines, but already tentative connections were being made, and certain frameworks were generated into which the full data would eventually and inexorably be deposited. Computers on the manufacturing floors at three locations had already been advised that another QMOS-1 product (the forty-third that year, and it was still only mid-April) would be out of layout by the end of May. Assembly and test sites were notified that the first **TTI:31416** wafers would be ready (no "probable" about it) for testing on May 20th, and Leslie had noted that evaluation samples would be needed by the Toy-Tronics product artists by the first week in June.

Within minutes, all the local Companions on the various production floors, after having had a brief sat-com auto-conference, had reacted somewhat unfavorably to this schedule. That news had got back to Sophia, but, good Companion that she was, she decided not to bring it to Leslie's attention just then, since she was deep into further exploration of her new cell, now using a three-dimensional animation to visualize its spread-spectrum output. Actually, Sophia had earlier found a very similar cell in the archives, and was able to suggest a couple of improvements, which Leslie had accepted, with a little hesitation and disappointment. The time when one balked at the precocious antics of Companions was long forgotten. For one thing, it was pointless – they were *very* good at what they did, and it was only sensible to heed their placid wisdom. A sort of new-age Jeeves.

Leslie continued to explore the properties of her cell design, about which she was becoming increasingly excited, until about 10^{30}am, by which time she had performed over 3,000 simulation runs. More correctly stated, Sophia had implemented them – with scarcely any prompting – including full optimization for maximum performance, using multi-dimensional sensitivity minimization, as well as the complete cell layout with all parasitics extracted. Sophia had put all the pieces where they belonged in readiness for the next step, which included up-dating the AutoLibrary **ADLIB-2020**, now grown to some 7,300 terabytes.

While Sophia was taking care of these chores, Leslie slipped out through the lobby facing the river, and took a brief walk along the waterfront, enjoying glimpses of the swift, silent rowers on the Charles. The skyline had changed surprisingly little since she'd arrived here. But the Tobin was no longer jammed every morning, because so many people worked at home, and the Tunnel Project was long since completed. Upon returning to her office, she found that Sophia had organized an e-sat-vid with the other team members, as Leslie had requested. Apart from a slight schedule slip in some on-going projects at the Sydney location (too much sunbathing, thought Leslie), the pieces were coming together.

By the end of this spring day in Boston, project **TTI:31416** had moved from concept to a fairly well-honed architecture. "Sophie, I'm going home, now", said Leslie. "Take care of the wrap-up". The request was, of course, entirely superfluous. Several other minor problems that arose earlier in the day had already been resolved by the Companions, and had never even come to Leslie's attention, though Sophia had herself put a brief notification into the ELN, which Leslie could review any time she wished. Instead, knowing that humans are much better equipped to be creative than the Companions, she had left Leslie to do what she did best – *innovent!*

The "Wrap-up" involved a lot of little routine things, including recording all the day's events on an OPTOROM, mostly to keep the attorneys happy. These magneto-optic write-once read-many discs were derivatives of the old CD-ROMs that blossomed in the '90's, and were excellent for simple serial archiving purposes, since they provided up to five recording surfaces on a single 5-cm platter hardly any thicker than the old, first-generation printed CDs. Each layer could store some 50 Gb, so one of these discs could easily take care of all of a day's design transactions. Eol'doog, the wise old neuroputer, worked full-time in the cellar, or wherever it was he *really* lived. (Some still thought it was on the top floor, since things were always very quiet up there, but no-one was certain). It was "he" who supervised the storage of these important records, using some sort of automatic disc handling system that again no-one seemed to know (or care) about, and faithfully performed his daily analysis of the company's progress. No-one had the slightest doubt that he and the Companions had matters fully under control, although some were inclined to wonder about the wisdom of that recent upgrade to the Free-Will module……

CHAPTER 19 HOW MUCH OF THAT IS PURE FANTASY?

Ever since I can remember, I have had a fascination with making computers act like humans. Perhaps this stems from the observation that, in constructing thinking machines, *one discovers more about oneself*; just as in teaching, the teacher becomes the student. While at Mullard in the early sixties, I wrote a program, all in machine code, of which I have to say I'm very proud. *It designed circuits*. Really. One simply entered a list of desiderata, such as the required gain of an amplifier, the load impedance, the available supply voltage, the desired bandwidth, and so on; then it autonomously figured out the optimal transistors to use in each location of the circuit, (taking the price of the discrete transistors of the day into account), and found the optimal value of all the resistor and capacitor values (using the appropriate tolerance series), and finally proceeded with a Monte Carlo analysis of 1,000 instances and reported on yield to the stated objectives[135].

Today's computers have opened our eyes to unimagined possibilities. They help us cope with the increasingly competitive element of the overall innovative challenge. Corporations lacking advanced design tools, and without people having the skills to use them thoughtfully and imaginatively, will be at a severe disadvantage in the chip-biz of the late-nineties and beyond. Concerning the tools we need to aid innovation, it is appropriate to ask whether the design process itself can be significantly aided by expert systems.

What is Design Expertise, anyway? What does it mean to "Capture" it? Is it enough to just capture the expert's knowledge? Don't we really want to *capture the expert* and all of his or her functional skills to solve problems? What is the connection between *expertise and creativity?* If cognition and – more elusively – the *creative spirit and will* is absent in the machine, can we expect expert systems to find interesting *new* ways of doing things? And, without *that*, are they still useful?

Can captured expertise improve time-to-market and product quality? Or, on the other side of the coin, might the use of such systems lead to delayed product introductions, because of the greatly augmented knowledge base and richer opportunities for wide-ranging exploration and endless refinement? Is it possible that, in spite of all the computing power now at the fingertips of the graduate designer, product quality might actually decline because of only superficial understanding and at times a critical ignorance of practical details not captured within the expert system? The questions are endless: *Is it ever cost-effective to develop expert systems?* Are conventional (that is, von Neumann) machines adequate platforms for expert systems? Can solutions forged from analog-cell libraries compete effectively with full-custom analog cells?

[135] For an example of the output of this program, see the paper *Feedback Sampling Channel for Sampling Oscilloscopes* (full reference in footnote 17). The routine use of Monte Carlo analyses for production circuits is common today.

Presuming the answer to that question to be 'No', what can be done using expert systems to put better design capabilities, combining the refinement of custom design with the rapidity of library based design, under the fingers of everyone? Just how much should we expect from this Aladdin's Lamp, anyway? Do we imagine that our future design tools will blend the youthful vigor of an eager apprentice with all the wisdom of a lifetime, or will we settle for fast calculators with very large data-bases? We won't be able to answer all these questions, but it's interesting to think about them for a few minutes.

Learning with The Companions

There is a lot to remember in an engineering job. This demand begins at an early age with the accumulation of basic and essential technical information, often not much more than individual facts, snippets of physical data, a familiarization with prior discoveries, principles, inventions and techniques (both classical and contemporary), an emergent awareness of good design practices, and of the fundamental limitations to realizability, and so on.

These facts are largely a smorgasbord of *other peoples' ideas*, a chance sampling of the whole field. Out of them, the maturing engineer acquires a portfolio of workable solutions, an understanding of modeling, algorithms and procedures, and the like. Later, purely *technical knowledge* is augmented by *market knowledge*. This requires a strong grasp of the potential utility of one's work in a broad field of applications, as well as knowing who the customers are, where they are, what their volumes are likely to be, who they're buying their components from right now, and so on.

As time goes by, all of this grows into *a complex state of mind in which the acquired skills blend*. The ability to cope with numerous interdisciplinary issues assumes an increasingly important role. From using well-established approaches to circuit design, the engineer now adds the ability to create *novel device or circuit topologies*, not to be found in any book or journal, and to instinctively seek to optimize these structures, a process which is most effectively achieved by invoking simplified models and abstractions which stress *fundamental* aspects of behavior, rather than by all-too-quickly appealing to simulation for 'answers' hiding in a morass of details.

Gradually, the individual and innovative content of the designer's work becomes more apparent. Out of all this, a highly-personal corpus of experience is acquired, in which *original achievements* play an increasingly important role, and in which idiosyncratic attitudes, viewpoints and preferences become more strongly manifested. It might be said that this process embodies a gradual shift from a *knowledge-based* world to one in which the elusive human quality of *wisdom* and more dependable insights are manifested. And we think *all this* can be captured in turn-of-the-century machines?

Absolutely not. But it *is likely* that friendly, intelligent machine-companions, *having afferent qualities*, activated by voice and touch, will indeed become increasingly commonplace, a totally-integrated part of our lives, and citizens of the 21st century will not be the least bit disturbed when these exhibit some capabilities that outstrip their own. Indeed, that much is true already. What can reasonable be expected from the knowledge-based systems in the workplace of the future?

I believe there are six Criteria for Companions:

1) They must provide very significant leverage for the human mind.
2) They must do this in some rather specialized and directed manner.
3) They must do so with impeccable accuracy and reliability, to a far greater degree than the innovator would ever expect to be capable.
4) They must be able to modify their behavior with time, that is, they must benefit from past experience and learn new capabilities.
5) They must be allowed to resort to deep heuristics when rationalistic behavior fails to find a solution, that is, they must be allowed a measure of free will.
6) They must sense the human emotional climate and transcend mechanics.

Most IC designers want their silicon Companions to be good at *multiplying their own human abilities* to achieve some particular task. Few are ready for a machine that comes up with brand-new circuit or product ideas, even less, to have to deal with a machine that becomes so good at doing *that* kind of thing that it eventually threatens the human. We need not worry about that for a while. Years from now, we may think differently about this, but for the present, at least, *we want machines to know their position in society*. We want *smart but submissive* Silicon Companions. We don't want machines to become *too* enterprising, because engineering is so much fun. The rush of endorphins at that Aha*!* moment is just too good to share with, and be appreciated by, anyone but another fellow human. The sense of achievement and pleasure in finding clever and novel ways to use all the technology at our disposal is, I believe, *the chief payment* for the long hours spent in the lab and the many other times when we find we've hit yet another dead end.

In other words, we humans want to remain the architects of our grand edifices, but will gladly accept help with the tedium of looking up numerous detailed facts and making countless calculations. *We want mind-muscles*. Just as the invention of the mechanical lever didn't alter the nature of the tasks that men undertook (at least, not for the first few centuries), but just allowed bigger jobs to be undertaken, so today we look for machines which can help us with large computational burdens. In today's highly commercial world, products must be brought to market quickly, and their performance, quality and reliability must be uncompromising.

Future work in the area of capturing design expertise must, at least in part, be focused on aiding us to further hasten the introduction of new products. Consequently, we have an insatiable appetite for machines that not only provide this essential cerebral leverage, but which also that carry out their microminded tasks at speeds that make each last year's model appear glacial.

Our second provisional criterion was that, in our design work we need help in very specific, particular, narrow ways. We want our expert system to be really good in dealing with *minutia and record-keeping* which might tax the resources of the average designer. That's actually what we mean by the term 'expert', in human terms. We don't immediately think of an expert as one who has a wide general knowledge of a field, but rather as one who has devoted his or her life to some rather special topic that only a few people, perhaps in the whole world, know much about. The term 'expert' also implies, not just the ownership of specialized knowledge and experience, but also the idea of accuracy in applying these, *perhaps even a hint of infallibility.* This touches on our third criterion, which calls for our Silicon Companions to be accurate and reliable in all their affairs.

Fourth, we want our expert system to profit from having gone down the same path many times. We may not choose to dignify this by the term 'learning', but the more prosaic aspects of learning and experience can very easily be achieved by machines. It is not *necessary* for an expert system to exhibit creativity to be useful. Indeed, experts in many fields (for example, clinical diagnosis or archeology) can be very effective without being creative in the sense used in this essay. Resourceful, imaginative, wise, learned, careful in the interpretation of the facts: certainly. But we would not want a medical technician to "invent" a diagnosis, or an archeologist to "create" a new species from fossil remains.

Success in the engineering professions is much more critically dependent on an independence of mind and the *creative impulse*. As already noted, the emotional climate is crucial to creative work. Contemporary computers have no idea about the mental state of the user. Yet, it is not beyond the capabilities of even contemporary technologies to provide a significant number of these afferent qualities, such as the recognition of the human's facial expressions, gestures and even moods[136]. Further human attributes will, be harder to capture in a machine, but it is reasonable to assert that it will be useful to do so, and that it will happen in our lifetime. Even *anticipation*, which we have identified as is the major precursor of invention, is emergent in computers at a trivial level.

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[136] Research at MIT's Media Lab is aimed in this direction, and appears to be making good progress. See for example, *Affective Computing* by Roz Picard, MIT Press, 1997, and *Embodied Conversational Agents*, Ed. Justine Castell et al, MIT Press, 2000. This work focuses on the hitherto neglected fact that facial expressions and gestures are an important of human communication, and that we can expect there to be a reciprocal benefit when machines respond in like manner.

CHAPTER 20 REASONABLE EXPECTATIONS

Generally, when we speak of *'Capturing Design Expertise'* we are probably thinking something like this: Specialized knowledge, a distillation of the best of many experts, can be represented by symbols, and then organized in such a way as to allow the original human's facility and proficiency for the subject to be readily acquired and practiced by others much less familiar with the field. Nowadays, the complete contents of several of the well-known works on circuit design, written, one certainly hopes, by experts, could easily be transferred to a single CD-ROM, which could then be readily accessed by key-word searches and the like. Is that capturing expertise?

To some extent, yes. Simply putting all the important facts in one place is indeed very useful. Books and libraries have been doing that for centuries. Engineering Handbooks often contain many tables of 'Useful Data', such as the resistance of common metals, wire gauges, international frequency allocations, and much else. Put into a database - like *adlib* - these facts and figures are even more useful because they can be located by various kinds of key-based searches, and accessed infinitely more quickly than in printed form. And, as a practical matter, a rather large database can readily be stored on common physical media, such as the incredible optical hard disk and CD-ROMs which we already take for granted, and that consume far less space than scores of printed books.

Before the days of the pocket calculator, engineering texts contained endless pages of mathematical tables. Like many others, I learned how to use *log tables* as a kid, and later, routinely used *a slide rule* to design circuits. Several of Analog Devices' most successful products were designed using my beautiful 15" Aristo; they are still in the catalog, still earning their keep, more than thirty years later; and the slide-rule (and, in fact, numerous others*!*) is still on the bench at my home lab. To most new graduates, log tables and slip-sticks are already history. Nowadays, a handful of compact algorithms, embedded in a small ROM in a hand-held calculator[137], can generate all the numbers one will ever need in a lifetime, and to much greater accuracy. This has little to do with capturing expertise, but it an aspect of the picture, nevertheless. The management of numbers and their defining functions is basic to design. Small and large computers alike certainly do some of the things that our interim definition says is characteristic of human expertise, and which are needed in a 'captive expert': the aggregation of raw knowledge objects; a facility for recall of essential data (in more advanced epitronic systems, this might be achieved using associative or content-addressable memories, or even the World-Wide Web); the capability to make decisions (microjudgments) based on this data and rapidly process information through the use of algorithms (fixed procedures); and so on.

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[137] Many years ago I gave Jody Lapham, our leading process developer, an HP41C calculator equipped with the program SUPREM in ROM, which he used to calculate doping profiles before acquiring a computer. Recently, he returned that HP41C to me.

The mere exercise of capturing *one's own expertise* in algorithmic form - as in the case of that 'circuit-designing' program I wrote at Mullard - is a particularly effective way to learn about design methodology. At the start, we envisage our miniature expert system as able to do just the basic calculations, so we try to determine what algorithms might be used, and then support them with a database. But we quickly learn that there are many different ways to achieve some simple objective, many different conditions to be faced, and countless user preferences. So, we add many IF ... THEN statements, or their equivalent branching heuristics. As we do all this, we become painfully aware that we are *not really capturing the essence* of design expertise, but merely codifying as many circumstances as we can foresee. When running a program of this type, some unexpected block to progress frequently arises, and it loops or drops into an error trap and dies. At such times, computers might, if they could, hide behind an idiotic grin and hope to be forgiven.

ADICE is a fine example of a small expert system. It contains algorithms that adequately model the behavior of most of the components we need to use in a modern circuit. That is where the expertise resides in ADICE. The best modeling work of many people has gone into these algorithms. Because of the extraordinary subtlety of analog design, when we run an ADICE session we often are confronted with results which are *at first puzzling and apparently anomalous*. We may even suspect that we have found a fundamental flaw in the program.

As we probe deeper, however, we find that ADICE was in fact correctly pointing us to something we'd overlooked. These are *the rudiments* of the situation I raised earlier - *Can expect machines to offer counsel?* The fact is clearly, yes, they can; but we have to be smart enough to recognize it. Through the very act of invoking the algorithms, encapsulating the best of the minds of numerous experts, we can be *taught by them*. I happen to believe that large expert-system programs like ADICE are already much more than 'mere tools'. They can be consulted about the way things work, and, with a bit of help from we mortals, open up new insights. Of course, we can't leave it at that. After we've been helped to unlock the door, be sure to enter the room, explore it, and test its foundations. In less cryptic terms, use ADICE *as a point of departure*, but be sure to examine all the *fundamental underpinnings* of the circuit yourself.

Can machines help us in the search for *design simplicity?* Here, silicon companions are not of much intrinsic use. Lacking a complete definition of the assignment, the real-world experience, *and our permission*, they cannot resort to *judgment* of this sort. They are not allowed to approximate. Yet this is one of the human's best modes of thinking. We are ever reducing the world around us to analogies, and that always means leaving out huge chunks of reality which are inconvenient to include, or about which we might even be ignorant.

The history of science is, as much as anything else, the history of approximating. But approximations involve risk. We are reluctant to let machines do this for us, because generally speaking our view of machines is that they should always produce results which are as exact as possible. By adopting this view, however, are we unnecessarily burdening machines with a work-load that *we ourselves* couldn't handle? Maybe we should begin to allow machines to *omit* certain aspects of circuit behavior that are unlikely to be crucial. With experience, we know how and when to do this But, how can the machine *know?*

Well, it doesn't have to. A machine is not inconvenienced by having to perform millions of useless calculations. But then, the human is greatly inconvenienced by having to search through a huge results space. In this case, all that is necessary is a simple sort program: we've implemented such in ADICE, and similar simple scripts to make insights more accessible. We must permit our silicon companions to appeal to heuristics as the need arises. Whether this amounts to giving them *free will* is almost a philosophical matter, today. I suspect that in the future, it will be a different issue.

Sometimes, even we humans pick the wrong 'trick' out of the bag. As long as we are unprepared to allow computers *to make mistakes*, they are going to continue being as dull as dishwater. An important element of human creativity is the willingness to *guess* at the next step, often in a subconscious and automatic way, then cope with the inevitable errors that arise when the choice is a bad one, and finally recover and try again. But for machines, this will require abandoning, or at least augmenting, strong-physical-symbol representations of 'reality' and perhaps invoking the power of richly-connectionist systems to *approximate* a powerful aspect of human thought, namely, *our propensity for seeing the whole picture from many different angles*.

If they are to emulate this human paradigm, the expert systems of tomorrow will necessarily have to become more fuzzy, more unpredictable, far less slavish than those of today, and will give a new meaning to the expression "man-machine relationship". Looking into the distant future, I believe it is likely that we will grow quite used to cooperating with temperamental, even moody, machines. The thought of "machine emotions" is anathema to many in the field of computers, but in my view they are missing the most exciting opportunity to broaden the appeal and ubiquity of what are still called by this calculation-oriented, but outdated and outmoded, name.

CHAPTER 21 ON BEING A SUCCESSFUL INNOVENTOR

Having spoken of the dangers latent in an excessive dependence on rules and methodologies, it may seem be inconsistent to now delineate some principles for "being a successful innovator"[138]. *Certainly, there are no algorithms for success*, which, rather, is largely a manifestation of endless years of devoted work; either that, or an unfair run of luck. Still, it's probably useful to offer these few guiding principles, particularly when pressed by young graduates seeking one's wise counsel….

First, narrow down your career options as soon as possible. Knowing where you want to go in life is the surest way of getting there. Try to formulate a strategy that identifies your key strengths and knowledge to date, and leverage these to the fullest.

Second, don't expect to find all the expertise you'll ever need within the pages of textbooks, or in those meticulous college notes you took, or residing in your desktop expert system. It usually won't be there. The local 'experts' should be respected; their knowledge was probably hard-won. But they don't have all the answers, either, and they may even be impeded by a myopic or faded view of their field. *You must be your own expert system*. You must develop your own internal databases, invest in your own talent to invent and forge *new solutions and circuit topologies*, trust your own judgment and always have the courage of your convictions.

Third, never neglect the fundamentals. Long before you reach for your shirt-pocket Cray, or wake up your silicon companion for a little chat, think about the things that *really matter* in both enabling and limiting your concepts. Often, a simple thought experiment is all it takes to reveal that a certain proposal or expectation lies outside of the circle of fundamental realizability, or conversely, that certain – perhaps missing – basic conditions are essential precursors to meeting your performance objectives.

Fourth, always be suspicious of overly complicated solutions, and always be on the lookout for things to throw out: beauty, simplicity and elegance are as important in the world of circuit design as in the world of physics and art.

Fifth, in the adventurous pursuit of novelty, don't overlook the fact that eventually your grand scheme must be implemented using real materials, which frequently operate in devious ways, themselves being oblivious of the idealized mathematics which you might have chosen to model their behavior. It is all too easy to be seduced by the realism of a simulation, presented on a high-resolution display in living color.

[138] John Doyle, who sits on Analog's Board of Directors, pointed out to me that this section may seem like 'Gilbert's Rules' for being a good designer. But I'm not making rules (I greatly dislike them), only suggestions. Rules all too often eclipse important *underlying principles* in their rigid and dogmatic formulations. A rule seems like 'something to be enforced' –as mindless as a traffic light – with more than a hint of "obedience" implied; whereas a principle is 'something to be embraced and employed', appealing to both the heart and the intellect.

Sixth, always be anticipating the next step. It's all too easy to think that the job has been done when all the simulations are complete, whereas in fact, the *innovative* challenge (the "making things happen" part of innovention) has barely just begun.

We began this section by posing a long list of questions about artificial expert systems, but we've only just begun to answer them. It is striking, however, that by merely formulating that list of questions, each following inevitably on the heels of the last, we soon realize that *we are also questioning some aspects of our own behavior*, and defining *our own limitations*.

In our quest for answers and our appeal to *expertise-on-demand*, we cannot avoid the inescapable fact that the responsibility for uncovering insights and finding truth – whether about the optimal solution to some design challenge, or about theories of everything – cannot be delegated to any machine, no matter how well-endowed, *nor even to another person*, no matter how experienced and wise. The search for truth will always and unavoidably be *an individual, lonely and never-ending one*.

Action Items for Leaders in Innovation

What can leaders do to encourage, elevate and propagate the innovative spirit? Well, *simply offering encouragement* can often make a big difference. I recall how valuable it was to me to be commended for my minor (and often deviant*!*) accomplishments as a new boy at Tektronix. It immensely strengthened my resolve to do something the next day that was *truly deserving* of praise*!* And the atmosphere at Tektronix was so refreshingly different from the cold, bureaucratic, authoritarian, *rule-bound* strictures under which I had once worked as a junior in England.

Those of us having managerial and mentoring responsibilities need to do all we can to *help new hires to see tangible proof of their value to the company*, as quickly as practicable – and that may be before such praise is justified. From the very start, we need to provide and sustain *an elevated sense of the possible*. The cultivation of a *sense of worth* is very important in raising expectations, and in actually fulfilling them.

Beyond that, *new designers need to get out into the field*, and talk one-on-one with customers, now seen in the context of their own working environment, as three-dimensional people, not just buyers of the product in development. Our customers are not automatically right, but when they are we can't afford to miss their message. But that is too narrow a description of the challenge. In addition to listening to specific customers, we need to pay attention to numerous other voices, including the quiet, internal **Voice of Conviction,** advising us of which projects make sense and worth pursuing which are likely to be dead-ends, and the **Voice of Commitment** to the mission. These Voices can compensate for a certain amount of misjudgment, an idea echoed by these words by Ray Stata:

[During the days] of Nova Devices [now ADI] there couldn't be a better example of the necessity of a lot of will power and commitment because it was a very, very rocky experience. In these companies which are basically high risk in nature, you really have to have somebody who decides on a course of action – I don't know whether fanatical is the word – but with tremendous conviction in terms of what they want to do and why it's necessary to be done. ... All the reasons why it cannot be done are somehow submerged, even those with validity. There has to be a capacity to take great risks and not all that much concern about the fact that you might not make it.

(From an interview conducted by Goodloe Suttler, at the Amos Tuck School of Business, 1980)

If we feel *we are trusted* to make good decisions, *empowered* to achieve great results, and then *provided with powerful tools*, we almost certainly will succeed. A palpable, routine interest *from the top of the corporation* is of inestimable value. While working at Tektronix in the mid-sixties, I was very greatly impressed by the fact that no less a personage than its President, Howard Vollum, and the Vice-President of Engineering, Bill Walker, would frequently tour the engineering areas, usually dressed down in jeans and sneakers, and talk with us designers about our latest ideas, at length, and with a boyish interest. They would push buttons, twiddle knobs, *and administer sincere words of praise, advice and encouragement.* That kind of involvement "in the trenches" is an essential aspect of management, in my view.

We and our team members need to have the very best tools. The IC designer's most important tool is of course the high-speed work-station. Time-to-market considerations, accuracy of simulation, increased circuit complexity and design for manufacturability demand that our machines be state-of-the-art. A study of work habits would almost certainly reveal that a circuit designer[139] is seriously bounded by machine speed, and spends a large part of the day simply waiting for results.

This seems like a confession of poor work habits. It may be asked: so, why don't you do something else during that time? The answer is simple. First, many simulations involve fairly small cells undergoing intensive optimization: there is a lot going on in one's mind as each simulation is launched; small changes are being explored, the consequences are being compared; and while that is happening, the next experiment is already being assembled in the shunting yard of the mind. *The process is a fluttering dynamic,* demanding instant resolution. We want at all times to be limited solely by our wits, not by the limitations of a slow CPU. Typically, when a simulation is launched, the result is expected to be available in perhaps ten seconds, perhaps twenty seconds, perhaps half a minute. None of these intervals are long enough to start another project of any magnitude. So instead of being completely idle, we may on occasions find ourselves pecking away a bit unproductively at some text file in another window on our CRT.

The fact is that the design process requires strong focus and full concentration to achieve our rapidly-developing objectives. It's difficult to deflect one's attention from a flood of conscious thought about these goals toward some secondary cerebral occupation. These machine delays

[139] Other computer users, such as layout designers and test engineers, also need fast machines, but it is particularly the computationally-intensive aspect of circuit simulation that can delay the development of a new circuit.

evoke a frustration not unlike trying to enjoy an exciting adventure movie on a VCR with the pause button depressed for much of the time by a mischievous prankster.

We have a long way to go before we can be completely happy with the performance of work-stations in a circuit development context. We have seen significant improvements in such things as memory space: the most advanced workstations[140] (such as those from Silicon Graphics Inc.) provide up to 512Mbytes of RAM, and most of us nowadays call on several giga-bytes of data on a bank of hard-disks. Raising CPU clock rates to 1GHz, and the use of superscalar instruction cycles and multiple parallel processors, represent the new challenges of this frontier. Perhaps it will not be too long before we will begin to see the first-fruits of multiple CPU developments on our desktop computer. These will doubtless be expensive, but hopefully, we will only be limited by what the computer suppliers can provide, and never by poor judgment on the part of managers as to how much one can afford to spend on these fast machines.

Our competitors are faced with exactly the same limitations as we are (unless their computer budget is significantly larger); thus the challenge facing each of us is to find ways of improving our efficient use of the machines we already have. Part of the solution may be in revising our work habits, although the problems of *machine-gated creativity*, just described, are real. Another piece of the solution, though, is to continue to emphasize the special value of proprietary software. When one considers the critical role played by computers and software in today's competitive arenas, and the importance of operational knowledge, there can be little doubt that the most important way in which management can help to advance one's innovative potency is through the establishment of a much larger CAD activity. I do not think this is the time to be winding down or holding steady, relying exclusively on third-party vendors of so-called 'turn-key' software.

IC companies need to be especially careful about harboring the naive belief that large software houses are exclusively capable of providing the tools needed for making tomorrow's world. One may on occasions choose to buy some stand-alone software, but it is axiomatic that, being forced to use generally the same software as everyone else, and to an increasing extent, obliged to use the same technologies as everyone else (such as foundry-based sub-micron CMOS) one's competitive advantage will be limited to what can be achieved with marketing prowess and design skills alone.

[140] These "computer expectations" are already hilariously out of date, only a few years since originally penned.

Beefing Up CAD

In my view, the future success of any company that aspires to a high rate of innovation will significantly depend on a *very strong in-house CAD activity*. A major and urgent objective of that CAD Group would be the on-going development of proprietary simulation tools. They may also have a new role to play in the support of an interactive knowledge network embodying massive amounts of specialized technical information, organized in such a way as to be not only readily accessible, but also in some way able to offer help proactively.

It will be the incredible potential of networked computers to tirelessly inform and illuminate our lives as engineers, as well as their continued use as calculating tools, that will bring about the largest improvements in innovative productivity. The more effective union of thinking machines and cerebrally-sparkling human minds promises to radically alter everything we do. But we should not imagine that the demands on human energy and the need for creative thrust and sparkle will be lessened. Norbert Wiener has this to say[141]:

> The future offers very little hope for those who expect that our new mechanical slaves will offer us a world in which we may rest from thinking. Help us they may, but at the cost of supreme demand upon our honesty and intelligence. The world of the future will be an ever more demanding struggle against the limitations of our intelligence, not a comfortable hammock in which we can lie down to be waited upon by our robot slaves.

Nevertheless, the computers we will be using, as we pass into the next millennium, some 5,000 years since the invention of writing, will be more like *Silicon Companions* than mere tools; even less, like 'robot slaves'. Before that can happen, we will need to radically revise our ideas about what our machines *ought* to be allowed to do, and ideas about how much *free will* we wish to impart to them. This is destined to be an area of tremendous innovation in its own right, though also an *evolutionary process*.

Many of the computer experts I've talked to about this disagree with me. They seem to wish machines to be *forever deterministic*. They would argue that if, for example, one enters a command with a slightly deviant syntax, or points to a non-existent directory, or allows a spelling error to creep into a file name, it is not up to the machine to look for a plausible meaning and offer it back to the human for further consideration. That might lead to anarchy*!* I disagree. Please*!* - *Let the computer make these suggestions*, and help me, it's fumbling, memory-lapsing human user. Many of these 'little things' are easily performed on present-day machines. Thus, the Unix command *set filec* will usefully expand a truncated file name into its completed form[142].

Offering help to a flailing user is a very easy thing to arrange in a modern computing environment. Sadly, even using the most recent work-stations, we get sometimes get very nearly the

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141 In his book *God and Golem Inc.*

142 If one believes that creativity is merely what happens "when normally disparate frames of reference suddenly merge", as Koestler advocates, then could one would have to say that, in some tiny way, this computer machine is doing a creative act.

same old 'Huh?' reactions to our aberrant requests as we did back in the dark DOS days. A handful of heuristics is invariably helpful. That's often the human's most important way forward. *Why shouldn't machines be given the same advantage?* Of course, there is little point in attempting to make machines "like us". Erich Harth writes[143]

> Still, it is intriguing to ask the question 'What if?' *What if* our engineers succeed in constructing a truly thinking computer? And what if, to complete the illusion, we could clothe it in an audio-animatronic body, making a perfect android, a human recreated in silicon hyper-reality? Would it have been worth the effort? Certainly there is value in the exercise, the challenge to our ingenuity. But the final product would be as useless as Vaucanson's duck. The ultimate kitsch*!* There are easier ways of making people, and anyway, there are too many of us already.

The image of *a perfect android* isn't at all what we should have in mind. Such a diabolical creepy creature would be of as much value as a distinctly dull-minded junior assistant. This description completely fails to take into account what a *"silicon hyper-reality"* could do. Freed of our own frail forgetfulness and our limited fluency with numbers, knowledgeable of all of the best circuit tricks we have accumulated over the decades, our *imperfect*, but *highly-specialized,* android, ***The KnowledgeMaster Mk. I****,* would be a great asset. It need not move, but remote sight would be useful (in scanning those old papers of Widlar that Counts leaves scattered on his desk), and hearing will be essential, not only in freeing up our fingers, but in learning from the engineering community[144].

A brief consideration of some earlier projections of what computers might "one day" do leads us to be struck by how limited these visions invariably are. Isaac Asimov, another noted visionary, imagined a time when robots might *check our texts*. But he evidently didn't anticipate how utterly commonplace and powerful the modern word processor, and in particular, the ubiquitous spelling-checker, would become. In his science-fiction story[145] *Galley Slave* he creates an android named Easy who specialized in the task of checking galley-proofs. The storyteller marvels at how

> With a slow and steady manipulation of metal fingers, Easy turned page after page of the book, glancing at the left page, then the right.. and so on for minute after minute... The robot said, "This is a most accurate book, and there is little to which I can point. On line 22 of page 27, the word 'positive' is spelled p-o-i-s-t-i-v-e. The comma in line 6 of page 32 is superfluous, whereas one should have been used on line 13 of page 54...."

143 Erich Harth, *The Creative Loop; How the Brain Makes a Mind*, Addison-Wesley, 1993, pp. 171-172.

144 As did HAL, in *2001—A Space Odyssey*, another vision from the neurally-noisy mind of Arthur C. Clarke

145 *Galley Slave,* December, 1957 issue of Galaxy magazine.

I wonder how many young users Microsoft *Word* know that, less than forty years ago, its capabilities were solely the province of sci-fi? Probably very few people living back then would have believed that robots who could correct our spelling and even check our grammar would become commonplace so soon. A page or two later in Asimov's story we hear the robot's promoter say, over objections about allowing such powerful machines to enter into our daily affairs:

The uses would be infinite*!*. Robotic labor has so far been used only to relieve physical drudgery. Isn't there such a thing as mental drudgery? When a professor capable of the most creative thought is forced to spend two weeks painfully checking the spelling of lines of print and I offer you a machine that can do it in thirty minutes, is that picayune?

Thirty minutes! We are already irritated if it takes more than *one* minute to perform a spelling check on something of about the length of this essay. Note in passing how much we depend on being able to *personalize* the dictionaries and rules behind these checkers; my little Macintosh ***PowerBook 180***, on "whom" I daily cast various spells, has quickly become a serviceable, though eminently dull, companion. I've taught it words that it never knew about. Similar to spell-checking, schematic verification can be carried out on a design (what is the equivalent of a grammar checker for circuits?)

We should not be shortsighted in estimating the extent to which tomorrow's knowledge engines will serve our needs as innovators. Even without an independent spirit, there is much they can yet help us with. Eventually freed from the frustrations of not being able to find the all information we need to do our job (*Vive* adlib*!*), aided by more liberally minded machines, and permitted to operate in an enlightened, strongly anticipatory, tool-enhanced, rule-diminished environment, human designers in all fields will make great strides toward more rapid (*Vive* TCM*!*), more accurate (*Vive* DFM*!*) development of new products of the highest quality (*Vive* TQM*!*).

Our visionary use of the leverage afforded by *prodigious auxiliary minds* will make an immense difference to our ability to invent. Ultimately, we may even decide that it's not so stupid to build into these machines, very cautiously at first, *some sections of code which are 'afflicted' by noise*. We'll have to get used to the idea that these may not behave in the same way every day. They may even cause our silicon Companion to have moods. *But it is this very propensity for unpredictability and irrationality that make people interesting.*

Like the inventive electro-pioneers of the early 1900s, we are, insofar as machine intelligence is concerned, just on the threshold of a whole new world of opportunity, a future (not *so* far off, either) in which we will, for the first time in human history, need to be sensitive to *the emerging question of machine rights*...... There are no ready-made solutions, ripe for exploitation, in this domain; we will need to decide what kind of assistance we, as innovators, *want* our knowledge-gatherers and collators to do for us, and just how much of the excitement of engineering we want to share with them.

A rational vision of this future is offered by David Gelernter[146], who writes

Why would anyone *want* to build a realistic fake mind? Is this really a good idea? Or is it pointless – or even dangerous? That's an important question, but in one sense also irrelevant. The urge to build fake minds stands at the nexus of two of the most powerful tendencies in the histories of civilization. These two are so powerful that it's pointless even to contemplate *not* pursuing this kind of research. It will be pursued, to the end. *People have always had the urge to build machines.* And *people have always had the urge to create people*, by any means at their disposal - for example, by art. ... The drive to make a machine-person is ... the grand culminating *tour de force* of the history of technology and the history of art, simultaneously. Will we attempt this feat? It is predestined that we will. [Original italics]

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[146] Gelernter, Ibid., p. 48.

CHAPTER 22 THE TURNING POINT

Years ago, Jerry Fishman, Analog Device's present CEO, and I were talking about the domains of microelectronics in which we would *never* strategically engage, and we agreed that we'd never make *digital circuits*: wasn't in our mission statement, wasn't in our name. We agreed that we'd never make *cheap jelly-beans*; we could afford to let others own the consumer market. We were not going to serve the *automotive sector*, either, demanding MIL-specs at minimum margins. And for sure, we don't do *radios*, far less *microwave circuits* operating at many gigahertz*!* Nowadays, we "do" all these things, and quite profitably, too.

There are many reasons for those changes, and the many disparate projects that we nowadays routinely undertake. Most, as one might expect, are due to external factors: *the profound impact of VLSI on system realization*; the diminished emphasis on defense electronics, where the big profits used to lurk; the broadening of international trade and *the increasing penetration of commodity electronics into every corner of modern life*. The concomitant intensification of emphasis in recent times on quality, time-and-cost-to-market, robustness etc. could be viewed as strictly internal and voluntary (though prudent) initiatives. In reality, they are also part of *a necessary alignment* with the norms of our industry and the imperatives of competition.

The most exciting aspect of the turning point at which we now stand, though, is our growing involvement in *the communications thrust.* The burgeoning utilization of communication systems of all types has been behind so much of the historical drama of the past few years, with the demolishing of walls – literally and figuratively – at all four corners of the planet, with stunning implications. Communication – between humans *and* between 'machines' – promises to be the key to breaking down the cultural biases that go back to medieval times; the path to *an intellectually healthier planet*. We can only hope that in the long run, aided by advanced sensors (on earth, as well as in satellites) and the immense future potential of technology, *this fragile spaceship may also be restored to an ecologically healthier home.*

We can feel proud about being associated with an industry that is making our planet a better place. In many ways, we are helping to pull down barriers separating one people from another. With every nation getting ready to embrace the 21st century the possibilities for new ways of connecting one person to another – to talk, to hear, to see, to learn – or between one machine and another, are endless.

However, unlike the heavy, power-hungry and expensive systems that held me transfixed in the Dome of Discovery in 1951, new communication systems will be incredibly tiny, micro-powered and cheap; some so cheap that they will end up in toys and numerous disposable applications, transforming the character of the industry yet again. The recent *marriage of computers and communications* is likewise leading to a whole new world of possibilities. We are witnessing nothing less than the transformation of electronics from an industry based on a purely Newtonian paradigm into something combining these more mature components with advanced VLSI structures of immense potency, whose function transcends the merely-physical.

This is due to the *embedded information* which these incredible 'chips' contain: in short, to **Epitronics**. It is a little-known fact (at least, a lot of people are surprised when I mention it) that Analog's most advanced digital signal processing chip – the Sharc, co-developed with MIT – contains many more transistors than Intel's Pentium (nearly 30 million versus 5.7 million). Admittedly, many of them are consumed in large tracts of memory; but this is what makes this product so powerful and valuable.

Simply being aware of the breadth of such developments should elevate our *'sense of the possible'* and the enormous potential of Epitronics to transform our world. We cannot afford to dwell gloomily on the many ways in which we as a race are beset with problems and crises of our own making. *We need to recognize the innoventor's role as provider of tomorrow's world*, to see the opportunities opening up ahead, and try, to the best of our abilities, to work on those things which we as engineers can do to improve the lot of mankind.

The challenge to every one of us – as participants in a successful and enterprising corporation – is to push the limits of performance, forge new functions, integrate ever larger systems, open up new markets, seek out new talent and new ideas. Whether we face it with the power of individual vision and a flair for anticipating needs before they are articulated, or through an appeal to teams and a more structured approach to servicing an established market, matters little. The objective is the same: to produce *life-transforming* products. We will succeed if we see the value of our work in human terms, recognizing *the interdependence of opportunity and service*.

Much will happen in further applying electronics to the management of information. I've seen a major slice of the history of electronics, and regard it all of as merely a preparatory exercise to the emergence of Epitronics, the spring-board to the advent *truly interesting artificial minds*. Of course, when the day comes that such do exist, and become commonplace, they will be no more synthetic than yours or mine, simply made of different materials and adapted to do certain things better.

What we personally choose to do with our internal storehouses of knowledge – and empower others to use theirs – will shape the affairs of Earthtown for centuries to come. One thing seems certain: our silicon-headed Companions (it's hard from this vantage point to see silicon ever going totally out of fashion) will be powerfully involved in graciously helping we engineers *to cope with our ideas and aspirations at an emotional level far more sophisticated than possible today*. They will be right in the thick of the innoventive process – which may even include having original ideas, for which we will certainly need to risk *the essential appeal to indeterminism*.

Maybe our descendants will still be teaching the value of something called **'VOC'** well into the next century. But to them, this dusty acronym will have long ago become a reference to the wisdom of listening to the **Voice of the Computer** (the old-fashioned name we use today), but which then will be called – reflecting the diminution of its erstwhile merely-calculating function, the advent of large special-purpose neural sub-systems to handle non-algorithmic tasks, and the commonplace acceptance of the seamless symbiosis with human minds – ***The Voice of the Companion.***

CODA

Since first writing this, in the mid-1990's, the microelectronics industry has undergone dramatic upheavals; but one dominant theme remains unchanged. *Invention* – following the *moment* of sudden insight – is not a corporate activity, but *an intensely personal one*; and *innovation* – the *process* of making things happen – still requires the coordinated efforts of skilled *teams*. Nonetheless, a great corporate environment, like Analog Devices can provide the near-ideal nutrients for *a fulfilling and productive career in both invention and innovation*. We are very lucky in this respect.

The most likely next phase in the development of the microelectronics business at large is *the transition to totally "fab-less" design.* Not long ago, small companies that tried to muscle into the IC business had limited access to technologies – mostly vanilla CMOS from a few foundries. That put them at a significant disadvantage over the main-stream IC companies such as ADI, TI, LTC, National, Motorola and Harris in the linear field. Now, the tables are turning. Huge, disciplined, well-funded and well-managed foundries like TSMC not only offer highly reliable wafer fabrication services, with quick turn-times and reasonable prices, but they are *now at the leading edge of their field*. No longer producers only of vanilla CMOS, numerous foundries are developing processes much more like the "boutique" technologies of "full-service" providers of only a few years ago.

TSMC is at the leading edge in specialized sub-micron CMOS tuned to the needs the HF communications sector, and they are vigorously pursuing advanced digital CMOS, as well as the latest front-runner, silicon germanium (SiGe) that is to say, a BIPOLAR process, at a time when less-thoughtful people have been preaching that "everything that matters will soon be made exclusively on cheap CMOS". I have locked horns with a number of authorities on this front – including university professors with whom I've developed a cordial relationship over the years in the lecture circuit – who are quite adamant about this issue, and *refuse to "waste their time" on bipolar design*, or teach it in their courses of study.

As a well-seasoned engineer versed in bipolar circuit theory, processes and techniques, I understandably find that opinion quite irritating. The fact of the matter is that *bipolar transistors will remain at center-stage for mixed-signal applications*, with GaAs and other exotic III-V materials spearheading microwave developments. Now that TSMC and other foundries are providing bipolar technologies featuring advanced SiGe structures, I feel vindicated in my early views.

Consequently, the viability of "full-service" IC producers is threatened. I believe one can safely predict *a new revolution* in the business of microelectronics, which has become such an indispensable commodity in the modern world. The sheer cost of developing and supporting inhouse manufacturing processes will become prohibitive in at some point in the future, and numerous fledgling "fabless design" companies will emerge, and become increasingly commonplace, along with auxiliary enterprises serving the needs for packaging and testing. This will usher in a new and challenging phase in our industry: a time of *new imperatives, new trade-offs and new tensions*.

We already see plenty of evidence of emergence of *specialized support enterprises* – companies that neither design ICs, nor manufacture semiconductor wafers, but rather, provide essential back-end functions (assembly, testing and various customer support services). One can argue that these three domains – marketing/design, wafer processing and back end support – each demand a quite different set of skills and resources. Comparing this with the situation in other *commodity businesses* – which is exactly what the integrated circuit business is gravitating toward – we see similar divisions of specialization. We can expect the IC marketing research and design roles to become part of a new "service sector", using the wafer foundries and the assembly and testing houses, aided by other specialist agencies. Perhaps the most exciting aspect of this prospect is that *highly-motivated individual innoventors* will now be empowered to pursue their visions unencumbered by the *organizational inertia* that inevitably arises in every growing corporation, beset with its own dilemmas and compromises in the matter of allocating resources.

However, while such opportunities may appear to be giddily liberating, there's still much to be said for those whose principle strengths lie in *inspirational invention,* with a reduced propensity for *innovating,* to remain inside the protective shell of a large company, able to provide the teams for the follow-through. The aggregated experience, stability, long-standing connections in the marketplace of a mature company, its hard-earned reputation and brand recognition to defend and extend, all have further value, *when considering an optimal springboard for one's career.*

The key danger here is that the large company will frequently *brush-aside, devalue, or even suppress* (by withholding development resources, reckoned to be more urgently needed elsewhere) **the singular vision**, which, as this essay attempts to prove, is the true life blood of a progressive, independently-minded organization with its corporate eyes always keenly cast toward the far horizon. In the words of the old and dying shipping tycoon, Sir Anthony Gloster:

> *And they asked me how I did it, and I gave 'em the Scripture text,*
> *You just keep your light a-shining, a little in front o' the next!*
> *They copied all they could follow, but they couldn't copy my mind,*
> *And I left 'em sweating and stealing, a year and a half behind.*
>
> Rudyard Kipling, 1894

These are exciting times, but the best is yet to come. Electronics is still a youngster, a recent arrival on the human scene, with scarcely 100 years of history. I hope to be a part of the next thrust, but if that is not possible, I hope at least that my protégés will embrace this field of endeavor with as much zest and passion in the years ahead, and with as much joy and satisfaction from the pursuit of innovention, as I have been so very fortunate to have experienced.

Barrie Gilbert, 2009

There is a Part 2 of this essay in preparation, which explores in depth the nature of neuronal behavior and develops the theory of thermal noise as responsible for the "spark of Insight" that seems to "come from nowhere", in a more quantitative way. It is still undergoing refinement, and will only be released when the ideas proposed therein appear to be validated by contemporary research in the field of experimental neurology.

THE MUCH-TOO-LONG BIO

I was born in Bournemouth, England, in 1937, two days after the death of the one who provided my name, Sir James Barrie, the author of *Peter Pan*; and three years before my town was bombed and my father lost his life. We were already poor; now we were wretched. My drift toward manhood, in the lean years after the war, began, of necessity, with rudimentary things. At six or seven, I was making my own 'aeroplanes' from thin planks of wood, salvaged from packing boxes begged from the local grocer's shop. One plank was the 'fuselage', the other, attached at right angles, re-using a couple of rusty nails, was the 'wing'. As far as I could see, there wasn't any need for a tail assembly.

By eight – using jam-jars, tin-lids, bottles and straws in lieu of test-tubes, flasks, retorts and pipettes (which my mother certainly couldn't afford to buy for me) and using the sparsely-equipped kitchen as my lab – I was led by Dr. Curiosity to combine, and sometimes heat, many (mostly benign) chemicals, just to see what would happen. Asking **"What if?"** became a lifelong habit from that time forward. Such basic reagents as salt, rocks of soda, baking-powder and vinegar were "borrowed" from the kitchen shelves. The serious stuff – iron filings, beautiful blue crystals of copper sulphate, the fine powder of yellow sulphur, purple shards of potassium permanganate – came from the "Chemist Shop", in little, slightly damp cardboard boxes. My mother, bless her heart, did see fit to provide these for me, and an occasional bottle of glycerin, dilute HCl, H_2SO_4 or a violet-tinted alcohol called 'methylated sprits', squandering scarce pennies. Later, I describe some of the decidedly reckless experiments carried out in this tiny electricity-deprived kitchen; and others, after that more potent ingredient eventually became available.

Pretty soon, my interest in chemistry morphed into a fascination with mechanics. Using my first small Meccano set (a gift from Uncle Fred) I designed and constructed gadgets of all sorts: cars, bridges, balances, tractors, cranes. I vividly recall the intense disdain I felt for following a design out of the little brochure of models that was supplied with these green and red girders and plates, axles, wheels, and plenty of nuts and bolts. To build something, no matter how neat, to *somebody else's* plan seemed to me to be an utter waste of time. These projects, and many more kitchen experiments – now 'physics' rather than 'chemistry' – supplied a steady stream of insights into the nature of things.

At some point I became old enough to earn pocket-money from an evening paper route; later, from both a morning and an evening route. But before that, I continued to badger my mother to dig into her almost barren purse; and with her help, and the windfall gifts described later, I acquired the basic materials to build a working steam engine, pretty much from scratch. At age nine, I began to make numerous models from balsa wood. Sometimes I'd design them, and draw a plan before starting. But often, the form of the object appeared only after whittling away on the solid chunks of this featherweight wood. In many cases each was "whatever it was" after finishing touches were applied. In retrospect, I think I was pursuing an appreciation of art, as much as engineering.

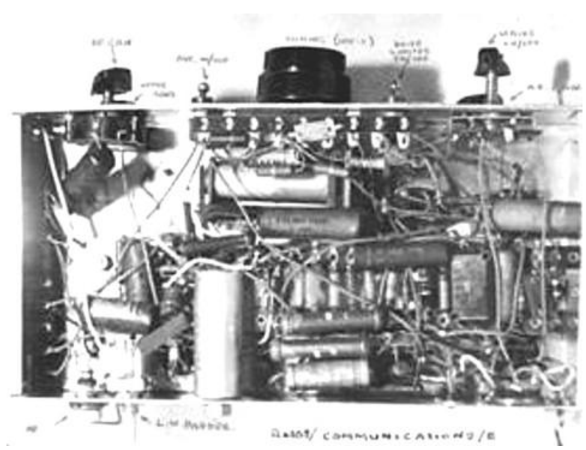
This largely-unconscious yearning for a theme, a focus, was resolved by the time I was ten. My all-consuming passion for anything electrical had to be given voice*!* This latest shift of interest, though, was not merely an Augmentation; it was an Epiphany. Hour after hour, week after week in my "lab", my Far-Seeing-Place – a tiny, upstairs bedroom scarcely bigger than a refrigerator – I experimented all alone (my brother, eleven years my senior, was deep into photography and he only stopped by my lab to take an occasional snapshot). Unwittingly, I began to lay down the foundations of my lifelong career.

It started with modest pursuits: making little DC motors, large hand-wound solenoids, electromechanical oscillators. I devised an "electric game" that baffled my school-pals (page 15) I made high-voltage generators, a la Tesla – my trusty coils spinning four-inch long fizzling filaments of dancing blue plasma. Then on to dull-witted crystal sets, on which I could receive but two stations; but later, more energetic one-valve short-wave receivers. By simply asking "What If?" I discovered selectivity-enhancing 'regeneration', and, in its extreme form, the periodically-oscillating 'super-regenerative' receiver; only later learning that some superstar called Armstrong got there first*!* I even mischievously went on the air, with a pitifully underpowered and unlicensed transmitter, on 40 metres.

But without 'mains electricity' in the house, these gadgets could only occasionally be brought to life by using the 2-V accumulator and 120-V 'HT battery' borrowed ("Please*!* Just for a *minute*, Mum*!*") from the only official wireless set in the house, downstairs – a Murphy superhet, provided by a company called *Radio Rentals* for a small monthly fee.

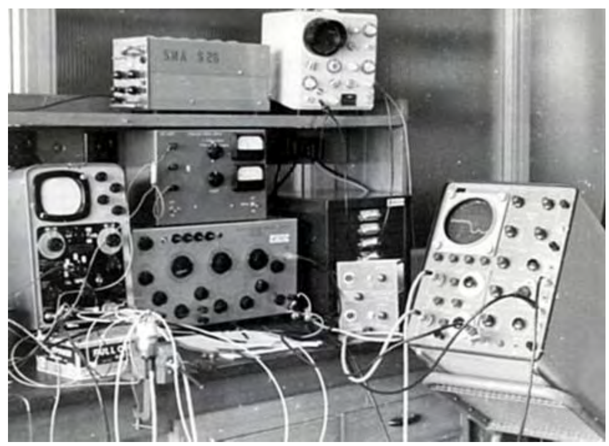
With the arrival of power from the street, I could at last build and operate 'large' motors – ones whose spindles were hard to stop with the grasping hand - and bigger spark machines whose much beefier blue fluid now snarled and hum-growled. My radios soon became full-coverage superhets of my own design: messy rats' nests, underside, like the 100kHz to 30MHz communications receiver shown below, built when I was ten. I'm not proud of the ratty wiring, but nonetheless, each was a work of sheer delight, and personal pride; and more importantly, these were days of *learning by doing*.

Beauty on Top



Ugly Pragmatism Below-decks

But it was in designing my own oscilloscopes and television receivers, starting at eleven, and building them using military surplus equipment, that my deep and abiding passion for electronics took an unshakable hold on my life. Much later, during 1958-59, while working for Mullard Ltd., I designed and built a pace-setting sampling scope, shown on right in each of the pictures below. It was a direct outcome of my many years of prior scope-building experience in my home lab. The an earlier version of the a Tektronix 545 scope shown in the colored photograph (I think it was a 535) was the source of my inspiration. This came largely from three sources: all the front-panel controls did exactly what they were labeled – something no other scope I had used ever did. The planning of this interface – its ergonomics - were also excellent. Secondly, the ultra-linear fully calibrated display was generated by a beautiful, flat-faced CRT, with a very fine spot, in a precise 4-cm by 10-cm field. Thirdly, the view inside spoke of pride of workmanship, exceedingly high quality, in short, it was beautiful. My immediate impulse was to design a scope that looked and felt like the Tektronix, yet provided a leap forward in bandwidth to 700MHz. It took months to build. The 535 was also one of the first scopes to use a variety of plug-ins, and I followed suit*!*



My “for-pay” career began in 1954, straight from high school, as an ‘Assistant, Scientific’ at the Signals Development and Research Establishment (Christchurch, England). The labs, bristling with antennas, were perched atop white cliffs on the English Channel. I built and tested speech scramblers (some using CRT A/D Converters*!*) and much else.

At age 18, I faced a tribunal as a Conscientious Objector. It decided that there was no merit to my reasoned case, so I was ordered to serve a jail sentence. (This was very common in the fiercely patriotic years after the War). On appeal, I was directed to work for two years as an Orderly in a hospital ward for the chronically sick. The conditions were poor, and the things I had to do were base and unpleasant. Most grotesque was holding the hands of young men dying of ugly cancers, talking quietly with them through a dark night, and in the sunny morning single-handedly preparing them for the morgue.

However, I fell considerably in love with hospital service and opted to stay two more years. Incredible as it must surely seem, that second voluntary period was spent side-by-side with surgeons and anesthetists in the two operating rooms, fully scrubbed up, assisting directly in every sort of procedure. I was not qualified, of course, but they were always shorthanded and my record for the prior period seemed to have immediately earned their confidence. I was often left in charge of a fully-anesthetized patient, watching vital signs, the gas flow rates, all the time maintaining breathing, while the anesthetist rushed to a second operating room to work on another patient. Before long, I was even *inducing* anesthesia, using Pentothal, with curare or a synthetic called Flaxedil as a muscle relaxant, although under a watchful eye. Of course, this would be a huge cause célèbre today.

Leaving the hospital with more than a tinge of heartache, I had hoped to find work in a company developing medical electronics, but there was nothing local, and I felt it necessary to stay close to home to care for my widowed mother. So I worked on several projects for the Atomic Energy Research Establishment including the design of triply-redundant PID control systems for ZETA (Zero Energy Thermonuclear Assembly) and proposed and built a sensitive sodium vapor detector, before moving to the Semiconductor Applications Labs of Mullard Ltd. Officially an Applications Engineer at this early transistor company, instead, I smuggled time to pioneer advances in the field of sampling oscilloscopes.

In 1964, I emigrated to the USA to work at Tektronix, initially on this specialization, then as a lead designer for the 7000-series oscilloscopes. To this day I'm amazed that in one year I developed 14 ICs (on Tek's foundry) for the on-screen character generator I proposed and developed, to display the setting of the tiny knobs used in this new generation of scopes. For the first time, a kid in his mid-twenties, I enjoyed the exhilarating experience of *actually being valued* as an **Innoventor**. I laid down the foundations of what I later named Translinear Circuits, and the fabrication and evaluation of numerous general concepts in analog IC design, as well as the development of super-integrated devices of all kinds. All these ideas remain as bright stars in my current constellation of concepts.

Returning in England in 1970, for what was meant to be a short leave of absence, I joined the Plessey Research Labs as a Group Leader, where I supervised the development of an experimental holographic mass-memory, and managed a team developing a high-accuracy optical character recognition (OCR) system for the British Post-Office. (My analog front-end sections, immediately after the imaging array used *adaptive thresholding* principles, which today are identified with *neural networks*, to accurately slice the photo-waveforms). I also designed a variety of data-communications ICs, including modems, mixers, log amps, etc. I recall that in order to give a paper at the ISSCC on a monolithic phase-locked-loop for FSK decoding, Plessey management balked at funding the trip. So I paid my own way, and the paper won that year's Outstanding Paper Award. Later, they coughed up*!*

In 1972, still in England, I was lucky to be contacted by Ray Stata, and for the next five years, as a consultant to Analog Devices, I designed a family of nonlinear IC products, many of which have become classics, and still generate substantial revenues - a testament to the durability of analog functions. Then in 1979, after two years back at Tektronix, doing giga-hertzy things, I was lured back to ADI, as first Fellow. I have been directing operations at the Northwest Labs, ADI's first remote design center, in Beaverton, Oregon, since then.

I've published in the *Journal of Solid State Circuits*, *Analog Integrated Circuits and Signal Processing*, *Transactions on Circuits and Systems*, *Electronics Letters,* and elsewhere; contributed to several text-books and co-edited others; and served on editorial boards and program committees. For work on multipliers and on merged logic (the precursor of I^2L), I received two IEEE Outstanding Achievement Awards; and the IEEE Solid-State Circuits Council Outstanding Development Award for "Contributions to Nonlinear Signal Processing". I was voted "Oregon Researcher of the Year" in 1990, and received the IEEE Solid-State Circuits Award in 1992. The ISSCC Outstanding Paper Award fell to me five years in succession, the ESSCIRC Best Paper Award twice. Many of these analog circuit concepts are described in ~100 patents issued worldwide. In 1997, I received an Honorary Doctorate from Oregon State University, citing a lifetime dedicated to analog circuit design. I am also a Life Fellow of the IEEE, and a Member of the National Academy of Engineering.

For recreation, my wife Alicia and I collect small works of art – including paintings and bronze sculptures – and we enjoy music at home, at symphony concerts and the Opera, and reading just about everything. I occasionally write poetry, and compose and arrange music in a classical vein, which I perform either on a virtual orchestra, in a well-equipped synthesizer studio, or the old-fashioned way – by hand – on the grandest of my three wonderful pianos. I greatly enjoy times spent in communion with our feline companions, one of whom, a gentle Tokinese called Bisquit, is at this very moment stepping over the keys of this laptop – his not-so subtle way of reminding me it's time to quit for the night.