CHAPTER 4 THE WELLSPRINGS OF INVENTION

I have always been curious about mind, insight and the creative processes that fuel an inventor's life, and often wonder about the extent to which creativity can be fostered in the community of one's co-workers. The urge to create something truly novel *ex nihilo* arises from somewhere deep within the human psyche. This intensely personal locus of innovation, powered and guided by broad internal knowledge deeply sounded-down, requires *freedom* and *space* within which to arise and flourish. While technical innovation may be predominantly a *logical* (thus, left-brain) activity, it clearly involves a non-trivial component of *artistic* (right-brain) and *emotional* (frontal lobe) activity[29].

Highly-original invention is rarely – if ever – the outcome of a purely logical process. The creative insight appears as a uninvited, but felicitous, visitor. *Insights* invariably spring from *random and subconscious triggers* in an isolated mind. Under favorable circumstances, of which a keen anticipation of the future is one part, and independent-mindedness and preparedness are others, these Insights can quickly lead to Invention – often in a matter of minutes or hours. Little physical energy is spent in these activities. They are invariably laid-back, casual.

Innovation that *deliberate, step-wise process*, in which the recognized needs of the community ("market" in more abstract terms) – in all of its many facets and dimensions – are matched to the practical ideas, materials, tools and other constructive means at one's disposal. This process requires extensive interaction with one's peers and team members. Long, tiring, frustrating and enervating periods of trouble-shooting are the norm, concentrated on bringing something of enduring utility into existence. Nothing of value comes out of merely "thinking things up" in isolation. It is obvious that a full cast of competent characters is needed to bring modern products to the market. But ideas invariably have a fragile, elusive and highly-localized genesis. While one may sincerely believe in group-consciousness, and the "Wisdom of Teams", this is rarely the domain wherein genuine novelty arises.

Admittedly, this point of view casts doubt on the value of brain-storming and all the other cooperative techniques that promise to generate new insights. Certainly, the sheer scale and complexity of many modern projects demand the use of teams, and team-building skills are a valuable asset of the effective engineering manager. But it is surely rare, if ever, that a team *invents*. The pooling of brainpower can only *transform* singular, unfamiliar, troublesome, non-conforming ideas into tangible realities.

Thus, invention will always remain a highly individual and often lonely quest. It is only innovation, the process through which thinking becomes things, that demands the well-directed effort of a large number of people. Any program aimed at enhancing the quantity and quality

[29] Contemporary brain research suggests that this left-right division is a myth; the brain is more adaptable than that.

of what is loosely called Innovation must fully consider the Janus-like nature of the integrated, cooperative process, which here is called *"Innovention".*

The struggle for individually-distinguished performance on the part of talented technical contributors can be significantly aided by a supportive team, and by a corporation that has *many erstwhile engineers at the top:* people who still have an innate understanding of the often immense technical hurdles; who quickly identify with and recognize talent; who are willing to take a gamble on the promising individual. On the other hand, the environment for innovation can be seriously hampered by a lack-luster infrastructure, run by senior managers who have their minds on generalized corporate goals, or by executives who view their company primarily as a revenue-generating machine, to be optimized through frequent rebuilding and generous oiling with the latest business-school dogmas.

I think that's what may have happened at Tektronix, when the MBA brigade took over. This personal experience left me wary of the results of any diminution in engineering focus at the highest management level. I have worked under a variety of regimes, and can truthfully say that at "my" Tektronix of the 1960's the top executives at that outstanding company succeeded in fostering engineering excellence through the *trust and support* they willingly invested in competent technical contributors, and by extending tolerant and attentive consideration to the idiosyncratic visions and needs of a cadre of exceptional people.

All that disappeared when Tektronix installed a new CEO to replace Howard, in his later years. This individual was not an engineer and appeared to have little understanding of technical matters, or an appreciation of the well-springs of Innovation. His focus on the financial data was made very evident when he mandated that the corporate motto "Committed to Technical Excellence" should be changed to "Committed to Excellence" – which it vaguely was, in every arena except advanced development, prompting many excellent designers to leave what looked like becoming a sinking ship.

Today, Tektronix is striving to compete with the new HP – Agilent. It's showing signs of regaining competitiveness. However, the recent purchase by the huge conglomerate Danaher must leave one wondering about their future as a House of Innovention.

Key Characteristics of the Creative Persona

Before plunging deeper into further ideas about the *source* of creative thought, it will be useful to catalog the chief characteristics of creative people. Here I draw on the work of Mihaly Csikszentmihalyi, of the University of Chicago, who has made a lifelong study of this subject. His recent book[30] is based on video-taped interviews with ninety-one exceptional individuals, many of them Nobel laureates, which he conducted between 1990 and 1995. He identifies at least three different usages of the term *creative individual*. Here, with respect, I have reworded and augmented his text to complement the objectives of this essay.

A. The first usage refers to those people who express *unusual thoughts*, who are "interesting" or "stimulating", people who appear in conversation or writing to be "unusually bright". But unless such people contribute something of permanent significance to society at large they may – at best – be called simply *"brilliant"*.

B. The second use of the term is in describing people who *see the world in novel and original ways*, whose perceptions are fresh, whose judgments are insightful, and who may even make important discoveries, but ones that *only they know about*. They may have inventive notions, but they don't innovate. Csikszentmihalyi refers to such people as *"personally creative"*. They can't be easily named, because they don't use their ideas; they never turn them into tangible works that the public learns about.

C. The third use of the term applies to individuals like Bach, da Vinci, Newton, Edison, Picasso, Mahler, Einstein who *changed the culture* in important and permanent respects. Such people are "creative" without qualification, since their originality is publicly appreciated and applauded for its *unsurpassed and enduring quality.* They left behind a legacy of *actual works* of benefit to all.

This third sort of creativity was of special interest to Csikszentmihalyi in his study, as it is to us, in better understanding the circumstances that lead to exceptional results in an engineering context. The idea of *bringing about a change in the culture* is of central importance to engineers. Creative ideas, no matter how insightful or iconoclastic, are of little value unless they actually do bring about such change.

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[30] *"Creativity: Flow and the Psychology of Discovery and Invention"*, by Mihaly Csikszentmihalyi, Harper Collins, 1996. This book should be required reading for anyone interested in the topic. My extracts are from Chapter Three, *The Creative Personality*, pp 51-76. In some lively correspondence, Mihaly does not agree with my views about a stochastic, neural component of creativity. His basic position seems to be: "So what, if there is a random element? Does it matter?". I suppose if you are a behavioral psychologist, it doesn't matter one way or the other; but if you are interested in the mechanisms of mind, it clearly is of interest to know whether this hypothesis holds water, and where these sparks come from.

This is the essential difference between Invention (the spark, the Insight, the domain of Thinking) and Innovation (doing, the domain of Things).

Csikszentmihalyi then distilled ten personality traits he found to be shared by creative people. In the following, I have amalgamated some of his professional alembication with amateur observations of my own:

1. Creative individuals have a great deal of *physical energy*, but are often *quiet and at rest*. This energy is under their own control – it is not controlled by the clock or the calendar. They consider the rhythm of activity followed by *idleness or reflection* very important for the success of their work. They work long hours, often throughout the night.

2. Creative individuals tend to be *smart, yet also naive* at the same time. (Goethe wrote that "Naiveté is the most important attribute of genius"). An IQ above about 120 doesn't appear to offer any advantage; indeed, unusually high IQs may merely lead to complacency. Howard Gardner has noted that a certain *immaturity*, both emotional and mental, will often go hand in hand with the deepest insights. The contrasting poles of *wisdom and childishness* are often apparent (*cf.* Mozart).

3. Further contradictions are evident in the contrasts between *playfulness and discipline*, or *responsibility and latitude*. While able to have great fun in joyously exploring a domain, the creative individual is invariably possessed of an unusual *doggedness, seriousness, endurance, and perseverance* – even faced with the certain knowledge that there will be many dead-ends ahead.

4. Creative individuals alternate between *imagination and fantasy* at one moment, and *a deeply-rooted sense of reality* at another. Both attributes are needed to break away from the present, without losing touch with the past. Society often regards new ideas as mere fantasies, without relevance to current realities. However, great art and science alike have always entailed huge leaps of the imagination (e.g., Lloyd-Wright's architecture, the Wright brother's flying machine, the impressionism of Monet and Debussy, Einstein's relativity theory, Hawking's black holes, etc.).

5. Creative individuals express both *extroversion and introversion* within a single personality. The stereotype of the "solitary genius" was given ample support from Csikszentmihalyi's interviews ("Isolation is essential to creative work") yet the importance of meeting people and exchanging ideas is also emphasized. Periods of firmly closed doors must alternate with times when they are wide open. (This idea was mentioned in a conversation I had with Freeman Dyson).

6. Creative individuals are remarkably *humble yet proud* at one and the same time. They are often so focused on present challenges and future projects that their past accomplishments, no matter how outstanding, are of little interest to them. This duality can also be seen as a contrast between *ambition and selflessness*, or between *competition and cooperation*.

7. Creative individuals seem able to escape the rigid gender role stereotyping found in most layers of society. This tendency toward *psychological androgyny* leads to creative people being both *aggressive and nurturing, rigid and sensitive, dominant and submissive*, regardless of gender.

8. Creative people are often *markedly independent* in their thoughts and beliefs, even *rebellious or iconoclastic*. Yet it is quite impossible to be creative without having first internalized and mastered a domain of endeavor. One must learn, and respect, the rules of that domain, hence must to a certain extent be a traditionalist. Once again, we see a *dialectic*: we must accept that many such *tensions and contradictions* are pervasive amongst highly-original thinkers.

9. Creative people are very *passionate* about their work, yet they can at one and the same time be *extremely objective* about it. The energy generated by this conflict between *attachment and detachment* was mentioned by many of his subjects as an important aspect of their work. The passion is essential in following a difficult and untrodden path; but without objectivity, the results will not be viable or robust, nor will they stand up to subsequent testing in the cold light of the real world.

10. Finally, the *openness and sensitivity* of creative individuals often exposes them to *suffering and pain*, yet also to *intense enjoyment* in the fruits of their labors. "Inventors have a low threshold of pain", said Jacob Rabinow; "Things bother them". We can say that they are continually dissatisfied with the status quo. I call this *yearning*. By pushing the limits of expression in their domain, creative people invariably set up *impossible expectations* for themselves, as well as for their co-workers. Even small failures can bring on an exaggerated sense of pain and loss.

Csikszentmihalyi touches on the matter of one's surroundings. He notes that some of the greatest achievements of mankind occurred in humble, even drab, surroundings. Einstein (it is often reported) set down the theory of relativity at a kitchen table in Berne, and James Watt watched a homely tea-kettle. Clearly, one can influence creative flow by altering the environment (such as moving the work to a lakeside hut, as Gustav Mahler often did). Interestingly, it appears from Mihayli's studies that an important aspect of these surroundings is simply *having a few familiar things at hand.*

The Creative Trigger

Existing, as we all must, at that ever-moving, zero-thickness membrane in time that separates all past from all future, the technological innovator is constantly peeping through the few cracks and holes in the construction fence around tomorrow's world, in a restless search for signs of new opportunities. In response to this persistent, vigilant *boundary watch* the innovator needs to be ready with creative, *anticipatory* solutions. It requires a zest for transforming the *world that is* into *worlds that might be*. We might say that Innovation is the "Start of the Art" – a *new* art that will quickly become the *State* of the art; then, very soon, to be ignobly distinguished by becoming the Commonplace.

The essential precursors to innovation are a prolonged and extensive study of one's domain, familiarity with the prevalent, standard solutions, a lively appreciation for their context and modes of use, and total immersion in the *personal challenge* of generating a steady stream of new contributions. Only this fingertip familiarity with the domain can endow its owner with a felicitous aptitude for grasping the value of novel possibilities long before an actual market is identified. Often, *the market has to be created*.

Product concepts having this sort of *independent, non-market-reliant* genesis, and the mavericks who propose them *in anticipation of yet-unarticulated needs,* will still be deserving of the strongest corporate support, in my view, well into the 21st century. But this paradigm is contrary to current trends in engineering.

Whether products are the outcome of market pull or entrepreneurial push, there is an essential need for a *creative trigger* in invention. So how does this crucial component arise? History provides some of the answers. To begin with, we must acknowledge the frequency of the "lucky" observation or the accident: Röntgen with his x-rays, Fleming with his mold; Goodyear with his sulphur spill; Plunkett with Teflon[31]. You inventors reading this will readily recall ideas that came from some entirely accidental discovery.

This raises the question: Might creative *thought* begin with a "cerebral accident"? Some sort of *neural mishap?* Numerous authors have grappled with the enigma of creativity, but few seem willing to allow much room for the role of *accidents of thinking* (in contrast to *observing* accidental serendipity). Some believe that creativity results when normally disparate frames of reference suddenly merge in a moment of insight, as in this quote from Koestler:

[31] *Inventing: How the Masters Did It*, by Byron. M. Vanderbilt, Moore Publishing, 1974.

.. a familiar and unnoticed phenomenon ... is suddenly perceived at an unfamiliar and significant angle. Discovery often means simply the uncovering of something which *has always been there* but was hidden from the eye by the blinkers of habit.[32]

Certainly, many examples of *discovery* as an immediate precursor to invention readily come to mind: Archimedes and his tub, and that story about Watt and the energetically dancing kettle lid (probably apocryphal). But I believe the widely-held notion that radically creative concepts arise out of a *methodical, logical, conscious*, process is quite inadequate. The tub and the kettle were just props. Immunologist and philosopher Peter Medawar (who was awarded the Nobel Prize for Medicine in 1960) has another idea[33]. He says that it's a matter of 'hypothetico-deduction'. He states that hypothesis generation is

... a creative act in the sense that it is the invention of a possible world, or a possible fragment of the world; experiments are then done to find out whether the imagined world is, to a good enough approximation, the real one.

According to Medawar, the creative process begins with an act of imagination, more like an act of faith, bereft of a strong factual basis; the testing of the hypothesis that must follow, on the other hand, requires deduction, a quite different activity[34]. Edward de Bono[35] insistently declares the related notion of 'lateral thinking'. In this scenario, one makes a conscious effort to jump "out of the box" - the familiar boundaries of the known world - into a what-if-world, where the rules are quite different, then establish a workable structure which is self-consistent within this temporary frame of reference, and finally seek to re-establish connections with the real world. You may relate to this. I am certainly aware of a strong dependence on lateral thinking in striving toward novel circuit structures. The questions *"What if .....?," "Why not ....?"* and *"How about .... ?"* will be asked regularly and instinctively. But, while a useful technique, this process is not much more than the *conscious* application of heuristics. I feel this explanation fails to ring true as the dominant mechanism by which creative events occur, those *unexpected* flashes of clarity and insight.

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[32] Arthur Koestler, *The Act of Creation: A Study of the Conscious and Unconscious in Science and Art*, Dell Publishing Co., New York, 1967, p108.

[33] P. B. Medawar, *The Art of the Soluble*, Methuen & Co. Ltd., London, 1967, p. 89.

[34] *The Listener* (BBC Publications), *The Reith Lectures Are Discussed*, Jan. 11, 1968, p. 41.

[35] See, for example, *de Bono's Thinking Course*, Facts on File Publications, 1982.

Joseph Weizenbaum[36] notes the importance of something we call intuition:

... human creativity depends not only on intellect but also crucially on an interplay between intellect and other modalities of thought, such as intuition and wisdom...

Intuition is certainly an important 'sixth sense', though its sources remain mysterious. It is a major field of research in its own right, spawning its own conferences, even. What we call wisdom is less enigmatic, being a direct descendent of all our experience. But these attributes surely don't *equate* to creativity; they are merely resources, like being well-informed, logical and analytical. I suspect that the unusually creative person is not particularly 'smart' in this sense. Research provides plenty of examples of people who would be considered seriously afflicted by any normal measures of intelligence, yet who exhibit astonishing abilities – even genius qualities – in very narrow fields[37].

Necessarily, creativity is an intensely personal experience. Oliver Sacks writes[38]

Creativity, as usually understood, entails not only a "what", a talent, but a "who" - strong personal characteristics, a strong identity, personal sensibility, *a personal style*, which flow into the talent, interfuse it, give it personal body and form. Creativity in this sense involves the power to originate, *to break away from the existing way of looking at things*, to move freely in the realm of the imagination, to create and recreate world's fully in one's mind - while supervising all this with a critical inner eye. Creativity has to do with the *inner-life* - with the flow of new ideas and strong feelings. [My italics]

Tacit in Sacks' comments, although they still make no reference to stochastic mechanisms, is my own idea is that "strong feelings" find expression in works that only later externalize these creative ideas. Their owner may have to be very assertive in order to gain acceptance by the community at large, because of the novelty, unfamiliarity and unacceptability of these iconoclastic visions, which flagrantly defy the prevailing norms.

Artists are trained to be alert to their *internal emotional forces*, while engineers and scientists are advised to *repress them*, as decidedly unhealthy*!* In their place, a quite unrealistic emphasis is placed on *analysis*, on step-wise *logical procedures* (math in particular), on meticulous *verification*, and on the use of *proofs*, all of which are processes whereby opaque premises are made public, and thereby become transparent to a moderately informed observer. Built into this training is an exaggerated expectation that, by pursuing such codified rigors, insights will accrue, and these will surely pave the way to novelty*!* Who has not met the young PhD student who knows that for a fact?

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[36] Joseph Weizenbaum, *Computer Power and Human Reason: From Judgment to Calculation*, W. H. Freeman, 1976, p 206. In spare moments, as a youngster, I used write computer code to create the illusion of conversing with an intelligent machine, inspired by Weizenbaum's controversial *'Eliza'* program.

[37] See, for example, *An Anthropologist on Mars; Seven Paradoxical Tales*, by Oliver Sacks, Knopf, 1995

[38] Ibid., p 241.

Another commentary on the source of creativity comes from Paul Churchland of MIT. He and his wife, Patricia, have spent their lives trying to understand how brains make minds, and their publications consistently emphasize *computational* processes. He writes[39]

Scientific creativity is the capacity for the novel deployment and extension of existing activational prototypes in the face of novel or problematic phenomena, by means of vector completion and the recurrent manipulation of one's own neuronal populations.

This is the most academic and technical explanation we've encountered so far, and it needs a little unraveling. Paul Churchland's bland "computational" view of the brain[40] is surely only a provisionally appropriate view of this awesomely complex and enigmatic organ. He explains:

We are all capable of recurrent manipulation of our cognitive response to a continuing input. The unusually creative people among us are simply those who are unusually skilled at such recurrent manipulation, *who are compelled to engage in it by a strong sense of delight or entertainment*, who are sufficiently learned to have a large repertoire of powerful prototypes whose novel redeployments are worth exploring in the first place (here the matured and slightly older brain will have an advantage), and who are sufficiently critical to be able to distinguish between a merely strained metaphor on the one hand, and a *genuinely systematic and enabling insight* on the other. [My emphases]

The delight of creative thought is massive. The inventive mind is always at play, a "time-wasting" pursuit we are taught must be put aside when we grow up[41]. (The word *work* occurs nearly 200 times in this essay; might I suggest that when its letters are simply rearranged to spell *play*, the key to the innovative life is revealed?).

But what does Churchland mean by the phrase *"recurrent manipulation of our cognitive response to a continuing input"?* I think what he's saying is that we are prone to fall back on familiar representational prototypes when confronted with nonstandard possibilities, and, by pushing these around in our internal representational space, we can eventually recognize them for what they are, or what they *might be* (like seeing the line- drawing of a Necker cube pop from one projection to another), or at least bring some sort of classification to bear on these novel possibilities. But he seems to believe these classifications are latent and dormant: "These possibilities – these many candidate prototypes –were *already there* in the theorist's hierarchy of partitions".

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[39] In *The Engine of Reason, The Seat of the Soul*, by Paul M. Churchland, MIT Press, 1996, page 279

[40] See also Churchland's *The Computational Mind.*

[41] In *The Soul's Code* by James Hillman, he presents his idea of 'growing down' to our life's calling.

Here again is the tacit suggestion that creativity is the outcome of *orderly, deterministic processes*, even though these processes may occur in a sporadic, poorly supervised or subconscious way. It asserts that the *recognition* of the novel idea occurs only after we have insistently subjected the patterns of latent possibilities to repeated examination and transformation, until they are finally forced to fit into a familiar mold and the idea becomes recognizable – the "vector completion" to which Churchland alludes.

Some contemporary philosophers, including Roger Penrose and Fritjop Capra, strenuously reject the notion of a "computational mind" and deny outright this *strictly reductionist* view of human thought processes. Thus, Penrose[42] writes that consciousness *"is beyond the physics we know"*, and calls for some new science. They hold that we need to appeal to "something more" to explain the miracle of mind and the fountain-head of creativity, a whole new set of physical principles. They may be right, but I don't think so. We surely have to acknowledge the role of *indeterminism*, which is a key aspect of ordinary physics and which I strongly believe affects our minds with equal force.

But, at last, I found a believer*!* The Berlin-based artist Carsten Nicolai views an affinity to the perfect realization of a programmed life as leading to sterility, not development. For him, *errors are the fruitful part of events;* if the observer can attain awareness of *the value of an error*, he can profit from the unforeseen and unexpected. William Shockley wrote about a "creative-failure methodology" in his (highly-colored) 1973 recollections of the invention of the transistor. However, we must not confuse "error" with "indeterminism". The former entails some misapplication of rigor, an oversight of some sort, an incomplete model of the reality. The latter is a purely stochastic process – genuine *"neural noise"* – that causes a logical train of thought to jump the rails and go in another direction. This is a very different matter to the making of mistakes.

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[42] *Consciousness Involves Non-Computable Ingredient*, by Roger Penrose, p. 242, found in *The Third Culture*, a series of philosophical essays assembled by John Brockman, Touchstone Books, 1996

These various explanations of the wellsprings of creativity clearly deserve our careful consideration, but I am convinced that they do not get right down to the root causes. Apart from a lifetime of influences a thorough grasp of one's domain, and perhaps a "high IQ", what other special factors might explain why some people have more *creative sparkle* than others? Might there be a *physical source* of these sparks? Ultimately, there must be. So what might it be? We are aware that there is a mysterious and sometimes frustrating *fluctuation* in our creative energy over time, out of one's control. Fitful periods of unmanageable torrents of originality are followed by long and miserable interludes of stark emptiness. This must be surely be one clue. I offer a hypothesis, which seems to be validated by experience.

Studies of creativity, such as those of Csikszentmihalyi, are based on observations of *behavior*, which is a very-high-level phenomenon, of course. Both he and I have noted that creative individuals are motivated by *a chronic dissatisfaction with the status quo – a restlessness; a certain vague but insistent sense of something lacking; a kind of yearning.* However, having a quizzical, analytical mind is clearly not enough to explain *the felicitous spontaneity* of the creative moment.

Surely, it is more than just a curious fact that creative insights are invariably unexpected, mercurial, and elusive. This is also a significant and important clue. We further note that exceptional creativity and eccentricity (an elevated degree of apparent irrationality and stubborn independence – even "pig-headedness") are bed-fellows[43]. We should be seeking a *deeper physical* explanation all these clues, to be understood not in terms of the macro-science of behavioral psychology, but rather, one stemming from the micro-behavior of the smallest elements of mind: Neurons. *There is a strong case for proposing that an unusually lively imagination involves a stochastic component*.

Cerebral electrochemistry must be implicated in all our thinking and being, so is it too far-fetched to suggest that these profound, elusive, creative flashes have a *thermodynamic* basis? Even what we call *free-will* has a random component. Consider the evidence: However sublime, the mind's "analog program" runs on the complex physical substratum of the brain. Since this fantastic machine is operating at a temperature of 37°C (310K), it is necessarily awash with the energy[44] of thermal noise, which is continually affecting the integrity of electrochemical nerve-impulse transmission, and thus affecting the numerous, more parallel, processes

[43] Indeed, there is a thin line between creativity and madness: witness the lives of great artists and composers; Van Gogh and Robert Schumann come quickly to mind. It is no exaggeration to state that the pressure to conform to the accepted norms in human societies works to suppress creativity. This same risk exists in many corporate cultures.

[44] We can readily quantify this energy: it is kT, where k is the Boltzmann constant and T is the temperature of any physical body. For the brain, kT amounts to 4.28 10^{-21} eV. Expressed as a *voltage* kT/q, this is 26.7 mV. Now, this may seem like a small energy fluctuation, but in fact it looms large at the highly sensitive neuronal cell membrane. Much more will be said about this in a follow-up essay, in preparation.

occurring in higher decision-making groups of neurons. The detailed local neural decisions, then the high-level cortical activity, and ultimately the nature of human *Thought* and *Being*, must all be subject, to some degree, to indeterminism. Almost certainly, we can assert that there are neural errors by the millions each second*!* How very fortunate for us*!*

One doesn't need to be an expert in neurobiology to make this assertion. Thermal noise is a basic aspect of physics, being universally present in any system above absolute zero of temperature[45]. It is well known that individual neurons, and large aggregations of them are subject to statistical fluctuations in their states, and that their spiky outputs continuously exhibit a random character[46]. Electroencephalographs show more noise than systematic signals. To some extent, of course, this is an artifact of the equipment, and the difficulty of detecting deep brain activity at the scalp. But that is a secondary factor; even direct measurements of neuronal impulses show the same randomness.

Much of the signal degradation that might otherwise be caused by sensory and motor noise is greatly diminished by the use of massive parallelism, in part, we may safely assume, precisely to defeat the thermal gremlin. In addition to this fundamentally stochastic aspect of behavior arising from their finite temperature, every neuronal cluster exhibits *chaotic* behavior, in the formal mathematical sense[47].

This means that even when exposed to primary stimuli that are *fully deterministic*, the response is *not fully predictable*, due to the numerous, recursive, nonlinear feedback paths, as well as to minute variations in the initial conditions, in the threshold levels, and in the input amplitudes. This intrinsically high sensitivity to input conditions, characteristic of all chaotic systems, combined with thermal noise provides all the needed circumstances for a solitary neuron, or an avalanching cluster of such, to generate an output without any "reason", at the highest level of interpretation; or to produce its decision output prematurely, which might whimsically be interpreted as meaning "before the full evidence for a rational judgment is in", at the behavioral level. We subconsciously cope with *non-thermal indeterminism* all the time, for example, in our everyday experimental approach to interpreting speech – a hypothesis-

[45] We are perhaps disinclined to think of ourselves in such terms, but the fact is unavoidable. (It brings new meaning to the expression 'cool-headed' to describe one whose thinking processes are less prone to miscalculation*!*) Viewed as an electrochemical entity, the neuron could be said to exhibit the ionic noise of a chemical reaction; but this too has a thermal basis. Gordon Shepherd's *Neurobiology* (3rd Edition, 1994, Oxford University Press) is a good source of ideas about neural systems and thought. An emergent view of information-processing in the brain suggests that *specific molecular codes* are also used for symbol representation. See, for example, *Information in the Brain*, by Ira Black, MIT Press, 1994, which I recommend for its excellent clarity and exciting ideas.

[46] A computer's logic gates would have precisely the same 'problem' if we chose to use much smaller signal levels to represent internal data. Thus, if the voltage swings in say, current-mode logic (CML) cells were reduced by a factor of ten, from a typical amplitude of about 10kT/q to kT/q or a little lower, what we describe (for convenience) as the 'decisions' of the gates would in become less definite (more 'fuzzy') and in a potentially chaotic way, arising from the residual nonlinearity of the gate and a new sensitivity to a wider field of 'maybe' states.. It is noteworthy that neurons make their decisions on signals of about one-fifth of kT/q (5mV) and the 'bit-error-rate' in a single neuron is actually very high. It is only the fact that that we have such a huge number of neurons that processing can be accurate enough to be called "logical".

[47] Mannfred Schroeder's *Fractals, Chaos, Power Laws*, W. H. Freeman, 1991 may be a useful reference about chaos theory.

and-test process[48]. Thus, when we hear sentence beginning "The good, the bad and the.. " we'll have already completed the sentence by supplying the missing word before it is uttered, probably close to the start of the sentence. A very similar thing happens in music: we know (as a general rule) that the end of a phrase must be "grammatically correct", so we can confidently predict it, in the majority of classical music.

This proclivity[49], which could be called *"contextual confabulation"*, is developed from infancy, and It points to the extent to which we are willing, at the conscious level, *to take a chance* on predicting the conclusion of a sentence, or a musical phrase, based on the context of the discussion, our familiarity with common phrases, and the expectation that the closing words will obey the grammar of the opening of a meaningful expression. It's not just the specific *words* (notes, harmonies) that impinge on us, as the auditory inputs arrive; rather, we are evaluating the kaleidoscopic *ideas and images* for which these are merely tokens. Instinctively and compulsively, we rapidly explore our internal data bases, scanning for matching ideas, and are constantly *predicting the most probable meaning* of the speaker's words or the composer's tune. Similar use of hypothesis-and-test and confabulation occurs in recognizing objects in the visual field, but probably much less so in processing "non-intellectual" taste and olfactory inputs. We are quite accustomed to freely throwing around guesses, sometimes making huge, improbable leaps, occasionally to be surprised by what *actually is said* at the end of a sentence[50] or by the image that is finally revealed to us.

We're also ready to admit that something of this sort occurs in our private thinking, too, although we don't factor this kind of behavior into our deliberations about how internal thinking processes may occur. Small clusters of neurons are even more prone to *the risks of guessing* than are vast cortical agglomerations of them. So, what is a "guess" at the neuronal level? I suggest it is *the heightened susceptibility to trigger an output event when "data" having an essentially deterministic genesis is momentarily corrupted by the thermal noise that perturbs all our analog grey cells*.

In dreaming, these signals (which only loosely correspond to reliable data sources) are less ordered and are not generated in real time, directly from our senses. We are also temporarily freed from our inhibitions. *Thinking in a creative way is much like dreaming.* We set aside convention and the sparks begin to fly. When a noise-events occurs, an avalanche of sympathetic responses arises in scores of coupled neurons (which are also noisy). We can readily imagine this leading to a situation where the overall state of this micro-mind-unit gravitates towards a

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[48] See *When Will HAL Understand What We Are Saying?*, the chapter by Ray Kurzweil in *HAL's Legacy: 2001's Computer as Dream and Reality*, edited by David Stork, MIT Press, 1997, page 132. It is well-known that Kurzweil's ideas do not represent the mainstream. A more authoritative reading can be found in *Speech-Understanding Systems: Final Report of a Study Group*, edited by Allen Newell, North Holland Publishing Co. 1973.

[49] Who has not encountered those annoying people who compulsively complete your every sentence, presumably as a way of indicating that they understand your most difficult thoughts, even before the words are out of your mouth*!*

[50] Joke-telling depends on an exploitation of the *unexpected*, the *unlikely* denouement, particularly evident in puns.

new 'strange attractor', one of an untold number of possible stable states (energy minima) into which a system of even low complexity (perhaps only a few hundred neurons) might briefly relax; only to be rushed onward toward another attractor ("solution") by the next fluctuation of its many parallel inputs.

This notion is reasonable. Indeed, I am convinced that such processes will someday be identified as the root source of our dreams and moments of inspiration. This new knowledge may come from further advances in positron emission tomography (PET) techniques. But for now, this is nothing more than a hypothesis worthy of some consideration. Nevertheless, let's give this notion some further space within which to expand a little, and, putting aside for the moment any possible relevance to *creativity*, consider …

How Neural Noise May Shape Perception

The massive parallelism of organic neuronal information-processing structures guarantees that they are *inherently tolerant of neural noise*. For example, in the lateral geniculate nucleus (LGN) – an olive-sized region nestling in the core of the brain, and responsible for the processing of optical data from the retina[51] – there are believed to be some 100 billion (10^{11}) synaptic branches[52], all scurrying at once to dutifully perform their one, common task – to allow us to see, in living color and three dimensions.

Consequently, this system is tolerant of a lot of single-fiber noise before significant degradation of the information content occurs. If these were electronic, parallel analog signal paths, we can calculate that, statistically, such noise effects will be reduced by a factor of about 300,000. That is, the *use of many parallel noisy channels carrying information that is highly correlated element-to-element reduces the probability of decision errors (here meaning the degradation of visual perception) to negligible proportions*.

Because of this high degree of fault-tolerance (which, in cognitive science circles, is referred to as *functional persistence*) we are totally unaware of any "noise-induced errors" which, almost certainly, are continually being generated within the LGN. Taking just the signals along one pathway, and guessing that as few as 0.1% of the channels are making errors due to noisy thresholding, while noting that the delay time through this structure is about 10ms, there could be a staggering 10 billion faults per second (0.001×10^{11}/10ms) – and we don't notice a thing*!*

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[51] A great deal of pre-processing is performed in the feature-extraction layers of the retina itself. Curiously, these are located on the *front* surface of the retina, through which light passes before encountering the rods and cones. Artificial retinas based on fully-analog neural networks (FANNs) mimic these feature-seeking processes, but there's nothing yet in the electronics domain like the higher-order processes that occur in the LGN. See *Analog VLSI and Neural Systems,* by Carver Mead, Addison-Wesley Publishing Co, Reading, MA, 1989. I had the distinct pleasure of reviewing the first draft MS of this seminal work.

[52] Paul M. Churchland, 1996, op. cit, page 10.

Such is the case for this specialized organ optimized for processing parallel visual data. But what can we say about the noise mechanisms in the cortex? It seems unlikely that there will be a lower *density* of errors due to thermal noise in any one part of the brain over another, since the whole brain is the same, closely-controlled temperature; and the detailed structure of all neurons is very similar, even allowing for the variations needed for specialization. So the question arises: While massive noise in the LGN may generate nothing more than a rare imperceptible flicker or transient aberration in our field of view, *what might such noise do when it occurs in those sensitive areas of the brain where the signal path is significantly more serial, involving hugely fewer neurons?* Undoubtedly, areas of this sort are implicated in our thought processes, and these in turn are often receptive to 'novelty' – that is, to the *unexpected,* especially in creative minds, which seem to be keenly primed and especially eager to respond to anything a bit odd or unusual. Wouldn't all this neural flickering then appear to have some 'meaning'? Might it not be possible for such noise to occasionally steer *the whole course of one's thinking* toward a totally new direction? I have no doubt about it.

In the fully-awake state, millions of such microcosms of noisy mental activity might conspire to generate the rudimentary precursor of a notion or insight. A heartbeat later, this fragment gets presented to our consciousness for our "consideration". Right away – ever vigilant in seeking purpose and relevance – we humans interpret this moment as one of those *felicitous, inexplicable, and very welcome revelations*. When this happens in an everyday context (such as choosing what to select from a lunch menu) we simply view it as a matter of free will – which we undoubtedly have; but when it happens while contemplating some hard problem and culminates in that euphoric, amusing *"A-ha!"* moment, we refer to this cerebral sparkling as 'Creativity', and we gleefully call its progeny Today's Startling New Idea, with immense satisfaction and juvenile delight. We might even get up and do a little dance, or rush to share the idea with a colleague.

But back to dreaming: During sleep, neural noise almost certainly plays a big part in shaping and storing the numerous sensory impressions of each day. Combined with the memories of a lifetime, and night-time changes in brain chemistry, these undergo a bizarre metamorphosis. We don't expect our dreams to 'make sense', or have anything but a *private meaning*. We don't even question the role that randomness clearly plays in this context. Yet something in human nature resists acknowledging *the role of chaos and randomness in our waking life*. We prefer to claim that our creations are planned, purposeful and deliberate: that we're *smart!*

Not all creative thinking is like that. Cerebral sparkling is clearly not enough. There's more to champagne than bubbles. Many new ideas come only from systematic study: by thinking hard about the deficiencies of extant techniques, by considering the fundaments, by stoically hacking away at mountains of details. This is a process marked by occasional oases of pleasure as each new vantage point is reached and Churchland's 'representational vectors' finally snap into focus, and map to a familiar prototype.

Without a large 'data-base' (whether the *knowledge* found in our head, or *information* in the professional journals, the industry's trade magazines, textbooks and notebooks, or found in some remote corner of cyberspace) and without a well-honed awareness of *the parade of opportunities* that daily marches before the eyes of our imagination – in other words, without *a prepared and receptive mind* – all those cerebral fireworks would just fizzle and silently expire, time after time, achieving nothing. However, by temporarily allowing these sparks full rein to control the immediate outcome, by suspending judgment and by allowing full interaction with the far corners of our data-bases, the creative process can be allowed that fragile chance to flourish[53].

I believe this "cortical noise" hypothesis is consistent with our experience. Most of us will be able to recall occasions when a promising new idea had *absolutely no precursors.* It just "appeared out of the blue", very much *an accident of thought*, We then wonder "Hmm*!* whatever made me think of *that!?*" Manifestly, this open door of the imagination is needed in the arts, just as much as in engineering. Those who think we are poles apart can only see the poles.

An excellent example of how a prolonged period of deep thought had to await the flash of insight came to my attention while listening, for the first time, to Anthony Payne's magnificent 'elaboration' of Sir Edward Elgar's Third Symphony[54]. This music was left in sketch formed when he died in 1934, and his family did not want the work completed, in compliance with his request that no-one should "tinker with it". Payne had nevertheless obtained some 130 facsimile pages from the British Library, and was immediately impressed by its creative content.

Although these sketches were quite fragmentary, he had spent a great deal of time between 1993 and 1995, thinking in Elgar's shoes, weaving the movements together principally *for his own satisfaction*, but with the hope that it might someday be heard. At one time there was a prospect that the trustees would allow a "workshop performance" in a BBC studio; but at the last minute they objected. Payne was of course deeply disappointed at the prospect of being forced to abandon this project, especially because he was convinced of the *strength* and *integrity* of Elgar's symphonic statements. Later, he recorded a BBC talk about the reconstruc-

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[53] We can liken our internal data-bases (really, the knowledge gained through a lifetime of experience) to a dry forest: it is replete with potential energy, stored up through a lifetime of sun-bathing: the chance lightning stroke that ignites the trees (the cerebral spark) will be much more likely to succeed if there is a stiff breeze blowing (the opportunity gradient). Analogies of this sort are not proofs of anything; this one simply helps us to see that a minor trigger very commonly leads to a major outcome. That's precisely how the felicitous insight leads to Invention.

[54] This astonishing work poured from the creative courage of a 77-year old man, and was only recently made accessible by the equally creative dedication of Anthony Payne. It had its premier performance in 1997. I recommend you run to your nearest Tower Records and acquire a copy of the definitive performance by the BBC Symphony Orchestra, conducted by the ever ebullient Andrew Davis (recently knighted by the Queen). Listen to it ten times in succession. If, after that intensive exposure, you're not still completely in awe and even more stirred by the magnificence of this noble music, it's probably because either you're (a) not British or (b) too young to have savored the unique, piquant mellowness of pre-1914 England.

tion of the work, explaining the magnitude of the challenge, and the impossibility of completing it to satisfaction. This is how he relates what happened after he gave the talk:

Next day, when taking a final look at the sketches prior to packing them away for good, I quite suddenly discovered the key to completing the first movement – the very thing I had just said was impossible in my radio talk. *The idea struck me with the force of a lightning bolt*. I realized that four pages of faintly outlined fragments I had previously discounted were in fact intended for the development section. Plunging in at the deep end I completed the development and the related coda in a couple of weeks. [My emphasis]

In Payne's mind, all the ideas needed for completion were already present, being mulled over by some subconscious agent working on his behalf. But it needed something more[55] for him to "discover the key", which a creative person would recognize and describe in the same familiar terms: *"The idea struck me with the force of a lightning bolt"*, he said. That's not the methodical, analytical planner and painstaking researcher talking*!* Payne also said: "It seemed I was being impelled by forces greater than myself", which is, of course, the essence of inspiration. Another inspired composer, Richard Strauss, echoed this same thought, and clue to creativity [56] :

Out of the musical ideas which – God knows how – have been readying themselves within me …. a song can appear in the twinkling of an eye…"

We have ample evidence of the two crucial components of the creative moment: not only is it essential to possess *knowledge deeply sounded down*, but this must await a *purely stochastic trigger* to make but a momentary connection. Such an explanation is fully consonant with what we've learned about the unpredictability of our thermally-vibrant physical universe, of which we are each just a part. Every object in this universe, including our brain, is randomized by its temperature at some scale of behavior. This is certainly true at the atomic and molecular level[57]; and in small electronic devices such as sub-micron transistors where a relatively small number of electrons are implicated in the signal representation, thermal noise – fundamental kT uncertainty – plays a major role in limiting accuracy. So it's not much of a stretch to presume that it occurs in similarly-sized neurons.

It is noteworthy that literally-minded people (with "robust brains", that are somehow less susceptible to noise?) are invariably dull and boringly predictable. Likewise, corporations that are controlled by rigid, predetermined, rules and an addiction to spread sheets to analyze and control every last detail, are also very unhappy places for the irrepressible idea-dynamo. The *more enlightened corporations make ample allowance for disorder*, and even a little inspired chaos here and there. Deepak Chopra recently said that "creativity requires disorder and ambiguity", which, in the terms of modern physics, means indeterminism and uncertainty.

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[55] The witty musicologist Peter Schickele teasingly calls this "that certain *je ne sais pas quoi!*".

[56] Notes to a recording of Strauss lieder, performed by Birgit Remmert and Jan Schultsz, Harmonia Mundi.

[57] Although not at the quantum level, which is a noise-free province. Incidentally, I have little patience with authors who spout 'quantum philosophy', and the notion forwarded by Penrose and others that the mystery of mind can only be explained in terms of such misappropriated concepts as quantum gravity and non-locality in the space-time continuum.

Insight: Spontaneous and Certain

These sporadic, uninvited creative flashes (which, echoing the Greeks, could be called *inspiration*, but which are usually called *insight* in psychological studies), have surely been a universal aspect of the moment of invention throughout history, whether in music, literature, the visual arts, in mathematics, science, technology, or any other intellectual pursuit. An endless litany of examples is superfluous, but the fact remains that they are there, for the finding. Here's an experience in the life of Henri Poincaré[58] :

> The incidents of travel had made me forget my mathematical work. Having reached Coutances, we entered an omnibus to go some place or other. …. When I put my foot on the step, the idea came to me, *without anything in my former thoughts* seeming to have paved the way for it, that the transformations I had used to define the Fuchsian functions were identical with those of non-Euclidean geometry. *I did not verify the idea*; I should not have had time, as upon taking my seat in the omnibus, I went on with a conversation already commenced, but I felt *a perfect certainty*. On my return to Caen, for convenience sake, I verified the result *at my leisure*. [My emphases]

This account perfectly demonstrates further aspects of the hypothesis. The *spontaneity* of the insight is again present, but Poincaré's *conscious* thoughts were elsewhere: it was not the result of an alert and deliberate stream of thought, a kind of calculation. What really strikes home, here, is his mention of the assurance of *certainty-without-proof*. The most pleasurable recollections in the life of an inventor or composer are those moments when an idea for, say, some new circuit topology or musical motif, presents itself from "God knows where", and it immediately feels like a *beautiful and elegant solution* – an escape from a prior mind-block, holding forth promises to assuredly break through previously-impenetrable barriers. I can recall frequently having "perfect certainty" that it's the right solution and, even though intensely excited by it, felt that *I could comfortably afford to wait to verify its viability*, set it aside, and "at my leisure" derive an analysis or conduct simulation studies.

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[58] *The Psychology of Invention in the Mathematical Field*, by Jacques Hadamard, quoted in *The Emperor's New Mind: Concerning Computers, Minds and the Laws of Physics*, by Roger Penrose, Oxford University Press, 1989, p. 419. This is essential reading for the curious mind. Penrose argues there are facets of human thought and imagination that can *never* be replicated by a machine. I'm not sure how one can assert that with *certainty*, in, say, the world of 3,000 AD, and I'm sure that people like Marvin Minsky of MIT and Andy Clark of the University of Sussex would strongly disagree. But my expectations of the silicon companions I introduce later are much less modest than a total emulation of all human imagination. They don't have to do that to be immensely more interesting and useful than the computers of today.

The satisfaction that accompanies the peculiar and outrageous sense of *certainty-without-proof* concerning the sudden creative insight must be very common. But why do we have that reaction? What prompts us to have this (often exaggerated) sense of 'rightness' and 'beauty'? Penrose[59] discusses the role of *aesthetics* in creativity. Mentioning in passing that this is a matter generally discussed only in connection with the arts, he notes that it was Dirac's *sense of beauty* that led to divination of his famous equation, with its curious 'fermionic' property[60]. In discussing the relevance of aesthetic criteria to the sciences, Penrose says:

It could be argued that in mathematics and the sciences, such criteria are merely incidental, the criterion of *truth* being paramount. However, it seems to be impossible to separate one from the other when one considers the issues of inspiration and insight. My impression is that the strong conviction of the *validity* of a flash of inspiration (not 100 per cent reliable, I should add, but at least far more reliable than just chance) is very closely bound up with its aesthetic qualities. A beautiful idea has a much greater chance of being a correct idea than an ugly one.
[Original emphases]

Similar sentiments about the intrinsic "beauty-plus-rightness" of scientific ideas have been often expressed by others[61]. Penrose goes on to cite Hadamard (1945, p. 31):

It is clear that no significant discovery or invention can take place without the *will* of finding. But with Poincaré, we see something else, the intervention of the sense of beauty playing its part as an indispensable *means* of finding. We have reached the double conclusion: that invention is choice; that this choice is imperatively governed by the sense of scientific beauty. [Original emphases]

Since the conscious part of invention involves *choice*, it requires the application of broad experience and must be shaped by selectivity. In the interplay between invention and innovation, the former attribute is internal and purely *cerebral*, while the latter involves the generation of some publicly-accessible result (a symphony, a painting, a major theory, a new drug, a novel integrated-circuit architecture) and the expenditure of significant – often massive – amounts of *physical energy*.

Much has been written about the matter of insight: it has become a separate field of study, with its own journals and international conventions. A recent compilation of works in this domain[62] makes many interesting observations, and is recommended reading. In one of the essays in this collection[63] Sternberg and Lubart use the analogy of financial investment, and argue that creative insight requires a specific attitude in addition to cognitive abilities, which is not dissimilar to that needed in taking risks in investment decisions:

This attitude is one of searching for the unexpected, the novel and even for what others might label as bizarre. The creatively insightful person seeks the paths that others avoid or even fear; he .. is willing to take risks and stray from the

[59] Ibid., p. 421.
[60] Ibid., p. 264
[61] See, for example, *Beauty and Revolution in Science,* by James w. McAllister, 1996
[62] *The Nature of Insight,* edited by Robert J. Sternberg and Janet E. Davidson, MIT Press, 1996.
[63] Ibid., p 535: *An Investment Perspective on Creative Insight,* by Robert J. Sternberg and Todd I. Lubart

conventional. Drawing on concepts from the world of financial investment, we call this attitude for insight a willingness to buy low and sell high.

Here again we note the critical importance of *anticipation*, although it is more obvious in playing the Market. But the implication is that by closely studying trends in one's field it is possible to identify *approaches that others have not yet seen*.

The mystery associated with the genesis of insight is one and the same as that which accompanies the closely-related process of human creativity; both may reasonably be attributed to physical indeterminism. It is hard to understand why this notion should be unpopular (as I have found it is) even while the underlying thermal mechanisms are so undeniably present, and are even measurable in studies of neural activity.

CHAPTER 6 THE STOCHASTIC HYPOTHESIS CHALLENGED

I am aware that, without having explored every corner and crevice of the vast canvas of art and invention, I am placing a strong emphasis on my hypothesis that random events are invariably an *essential precursor* of original creative thought. Perhaps an ulterior reason for this emphasis is that I strongly suspect it will also be essential, some day, to eliciting rudiments of creative behavior *from machines*, an interesting and maybe even useful step forward[64].

However, in 'trying out' this notion on colleagues, and friends in academia, I have encountered a lot of misunderstanding. Maybe this is because it seems to point to the nihilistic conclusion that "Well, if creativity involves little more than a reliance on haphazard events, then there's not much we can do about helping either ourselves or anybody else, is there?". This appeal to randomness seems to be especially distasteful to some highly-esteemed philosophers. Roger Penrose's essay on this subject was mentioned earlier. He further states:

What I'm claiming is that whatever is happening is different from our present understanding of physics, and *is not just random*. It is non-computational, and that is something entirely different.

I hope it's obvious that *I am not saying that creativity is "just random"* – undirected and unconnected with the current realties simmering in one's subconscious. That would be an extreme, even desperate, position to adopt, in seeking to explain something as sublime, as complex and as all-embracing as the mental processes leading to invention, and then onward to productive innovation.

Nevertheless, it is hard to understand the distinction Penrose is attempting to make here: a process that is non-computational is often a stochastic process; and it's indisputable that *chance* – which, for the physicist, is frequently traceable to the thermal energy kT – *has* played an enormous role in the development of the universe and all life on earth, and continues to do so. Why should it be any less significant in the domain of thought? The notable 20th-century philosopher Karl Popper addresses this topic, and at first seems to be edgy on this point, writing[65] :

If determinism is true, then the whole world is a perfectly running flawless clock, including all clouds, all organisms, all animals, and all men. If, on the other hand, Peirce's [Charles Sanders Peirce, American mathematician and physicist – BG] or Heisenberg's or some other form of indeterminism is true, then sheer *chance* plays a major role in our physical world. *But is chance really more satisfactory than determinism* ... To say that the black marks made on white paper which I produced in preparation for this lecture were just the result of *chance* is hardly more satisfactory than to say they were physically predetermined. [Popper's original emphases]

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[64] Note that I am not suggesting here that "free-thinking" machines will be – or will need to be – conscious, sentient beings in order to emulate creativity in certain closely-channeled and deliberately-limited ways. Already, we are quite familiar with machines that "make suggestions" for us.

[65] Under the heading *Indeterminism Is Not Enough*, see p. 261 of the essay *Indeterminism And Human Freedom*, in the collection of essays *Popper Selections*, edited by David Miller, Princeton University Press, 1985.

The introduction of Heisenberg's ideas of indeterminism appear to be out of place in a discussion of such a high-level, macroscopic phenomena as "the whole world". But note the telling use of the expression "*just* the result of chance..". Would it not be fairer to say "in some small but indispensable measure the result of chance..."? That, I suggest, is a more moderate and realistic view of what is actually going on. Here, I must disagree with these words of the famous old-time philosopher, John Hume

As objects must be conjoin'd or not.... 'tis impossible to admit of any medium betwixt chance and an absolute necessity

Why so? Why need there be such a simple, binary divide? Popper later touches on the idea of quantum jumps in connection with "snap decisions", saying:

I admit that the quantum-jump model may be a model for such snap decisions; and I even admit that it is conceivable that something like the amplification of a quantum jump may actually happen in our brain if we make a snap decision. But are snap decisions really so very interesting? Are they characteristic of human behaviour - of *rational* human behaviour? I do not think so, and I do not think we shall get much further with quantum jumps. They are just the kind of examples which seem to lend support to the thesis of Hume and Schlick that perfect chance is the only alternative to perfect determinism. [Original emphasis]

Then, just as we're beginning to believe that Popper is negatively polarized on this matter, and it seems to be agreeing with the bimodal, excluded-middle of Hume, the sunshine of reason and moderation finally breaks through the clouds:

What we need for understanding rational human behaviour - and, indeed, animal behaviour - is something *intermediate in character between perfect chance and perfect determinism*.... Hume's and Schlick's ontological thesis that there cannot exist anything between chance and determinism seems to me not only highly dogmatic (not to say doctrinaire) but clearly absurd.... [My emphasis]

I was pleased to find this in Karl Popper's writings. He comes to my rescue, so to speak, in suggesting that human behaviour – and that must surely include human creativity – is *partially* the consequence of determinism and *partially* a manifestation of randomness. We might even need to say that invention is *largely* the outcome of experience (determinism) but nonetheless dependent on the crucial intervention of stochastic mechanisms, to disturb the sheer predictability of pure determinism. *I have not the slightest doubt that further scientific work in this arena will eventually demonstrate that a significant fraction of creative thought has a stochastic genesis.*

It seems that to acknowledge the contribution of an element of randomness is offensive to those who need to believe that something as noble as the creative impulse can never be explained in mechanistic terms. Yet we are surrounded by striking parallels in nature. Thus, for example, in the intercell copying of DNA by RNA transferase, random errors occur. The reason may be thermal noise – the systems stochastic energy kT – or it may be an ionizing particle from deep within Alpha Centuri, or the father's luminous watch. It is precisely this unpredictability that makes each of us a unique different entity.

Whatever is going on in the attic, humans are clearly not logical state-machines, as are computers, and which (we trust, at least for today!) deliver responses to formally structured questions that are determined entirely by their stimuli. Few of our own conclusions are reached dianoetically. There are *emotional* and *aesthetic* elements to invention, including an important place for deep sensitivity to *beauty, form* and *symmetry*, qualities all too easily brushed aside by the literally-minded technocrat. And then there is always that elusive *spark*, our unique creative response to which will depend on our mood, our preparedness, our innate orientation to opportunity, and our eagerness for the new.

Can Machines be Creative?

I find many of the ideas in print about machine intelligence quite silly, particularly those that presume that, in order to be really useful, our silicon companions must rigidly pass the (advanced) Turing test, and act (and even look) more or less like humans. I agree with the view of John Snodgrass[66] who says we need *Intelligence Augmentation, IA*, rather than some vague Artificial Intelligence, AI. We need specialized assistants, not general-purpose human replacements. Still, it is interesting to briefly consider what it would take for a machine to exhibit this thing called creativity[67].

Today, our own creative potential can only be fully realized through the utilization of powerful silicon-based auxiliary minds (let's call them that for now) which help us cope with the prosaic and routine, as well as with the complex and the previously unimaginable, such as the realization of fractal images, and in playing out numerous what-if games involving some kind of modeling and simulation, as in molecular synthesis and circuit design. We need them in much the same way as the ancients needed mechanical levers. Indeed, it is very appropriate to think of computers as *levers for the mind*.

We recognize that they are already playing a powerful *adjunct role* in all manner of creative pursuits, in the arts as well as the sciences. Computers can perform speech recognition, and they can talk back (they have ears and a passably human voice). They can easily be equipped to see images (they have eyes) and can interpret them, classify them and respond to specific forms in useful ways. Some research machines, such as those in Rodney Brooks lab at MIT, have actuators and can reach out and grab things, and some can walk or otherwise change

[66] John Snodgrass and I have enjoyed an Internet debate on this theme. John believes, as I do, that classical AI research has been misguided, in trying to 'make machines that act like people'. He sees the need for more work on 'IA'—Intelligence Augmentation—the concept of having machines do the things that we can't do, or do poorly, while leaving the sensory and creative roles to the human. While the value of strong heuristics and even randomness in extending the resourcefulness of the IA means may be questionable, it seems to me that the step beyond IA – the creative machine – demands this courageous step.

[67] Or, for that matter, "common sense", which Mark Twain has noted is remarkably uncommon, and which Marvin Minsky and his MIT students are still struggling to emulate

their locale[68]. They can play what appear to be difficult games like chess better than the average human, and would pass with flying colors many traditional tests for 'intelligence'.

Turning the question around, we might ask: can a human ever perform as well as a computer in arenas that *they* are specialized in, such as rapid calculation, prodigious feats of memory recall, the ability to search the Internet, or speed an instant message to Beijing? We are in no sense on a *converging* path with computers. Rather, it is clear they have become a powerful complementary asset and exhibit the basic qualities of a *companion*, being reliable and trustworthy in almost every circumstance and unflagging in their availability. But even the most advanced computers are, of course, *lacking in creative sparkle*. Putting aside for the moment the philosophical debate about whether contemporary or future silicon systems might be *capable* of, say, intuition or insight, we must admit that throughout their brief history *we have consistently lacked the courage to allow machines even a modicum of free will*.

Computer geeks are aghast at the suggestion that one ought to build in a bit of indeterminism, the essential component of originality, to our machines. Well, none of us likes the idea of our tools behaving differently or mischievously each time they are given the same task. Even worse is the prospect of HAL, who put the importance of the mission above the value of five human lives aboard the *Discovery*. And this seems to be at the root of the fear of the programmer: to the extent that she is expected to produce reliable code, any unexpected responses are anathema, and usually classified as bugs.

Obviously, that is not what I'm advocating as the objective, although one should note in passing that *some degree of unpredictability is the price we are ultimately going to have to pay, in pursuit of higher levels of machine intelligence, resourcefulness and autonomy* within carefully defined and limited domains. Free will and abject subservience are poles apart.

Consider this: you'd be quite dissatisfied, wouldn't you, with a junior assistant who did *precisely and exactly* what you asked of him. Although perhaps never stated explicitly, you trust that he will 'show some initiative', even a significant degree of independence. It seems inevitable that we will soon have similar *expectations of enterprise* of our knowledge machines. Even without such elaborations, today's inexpensive home computers are already capable of coping with extensive archives of information, accessible within fractions of a second; they excel in tasks like searching and sorting; they rapidly execute millions of calculations, drawing on a vast library of algorithms and procedures, and in their Internet dialogues, they pull strings and tap into relationships that we don't even know about. Given the opportunity, they can act as experts in the dynamics of sub-atomic particles, or transistors, or vaccines, or rivers and oceans and weather and space and stars, and accurately predict outcomes. These machines

[68] Since the original writing, Sony have introduced a number of "intelligent pets', such as the "dog" AIBO (which I saw in their Tokyo showrooms and couldn't resist buying), and their plan is to introduce many more such "creatures" in the future. Space exploration also calls for sentience with mobility.

have access to a far wider base of facts than their owners, and they are almost flawless in using these facts, in executing algorithms and presenting results. But they remain *rule-based*; they don't have our probabilistic sparkle. This tradition in computing, *the total reliance on absolute determinism*, has served us well. Huge technical hurdles remain before we will be equipped to break with this tradition[69]. Devising a machine that combines unruly and emotional human thinking, so prone to error and forgetfulness, with cool-headed, immaculately logical digital computation will remain a future prospect for a while. The step beyond that, to *productive indeterminism*, poses even more daunting challenges.

A man-machine symbiosis of sorts is already transforming the process of industrial innovation, but so far, this has taken a very predictable route. A much stronger symbiosis is going to result with the installation of indeterminism in advanced thinking systems. This bold step will not come simply from further advances in, say, fuzzy logic, which remains deterministic. It is more likely to come from the application of fully-analog neural-network (FANN) cores, whose massive parallelism will be choreographed by digital control paths, and whose cell-level behavior will be modified by small amounts of thermal noise, whose intensity is controlled by a "creativity index". (Routine problems will be solved with the creativity flag set to zero).

This courageous step is destined to radically alter the path of all manner of machine-augmented innovation, with unpredictable consequences. I find this a fascinating prospect, and hope to live to see some elements of it realized. But we currently have little idea how to achieve that kind of goal. Certainly, if we start with the human mind, which weight-for-weight and size-for-size is by far the most complex system in the known universe, and try to copy it, as Ray Kurzweil has several times foolishly and presumptuously suggested[70], we will get nowhere. We're learning that its structure is vastly more complex than ever before realized, and even without reciting all the new terms in neuroanatomy, we can be sure to find only limited parallelism between computers and brains. Creative actions in machines must come from more objective design.

Rules, Tools and Trust

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[69] As noted, this is mainly because we don't *allow* computers to exhibit random responses to a give stimulus (program, data), although it's also true that we have not even begun to address how to *effectively* harness non-determinism in a computer architecture. The nearest we come is to appeal to heuristics in coping with deeply branching problems, as in chess games. Even here, the process is deterministic aided by heuristics. What appears to be needed, as a first step, is a way to perturb a logical process just far enough to generate outcomes which are unexpected though not dramatically erroneous. The second step, which is to know when the computer should be distracted by such an event, and in what way, is much harder.

[70] Other footnotes refer to Kurzweil's publications and his far-out ideas. In revising this essay, I can now point to his chapter in *HAL's Legacy*, in which he proposes (pp. 164-167) slicing a dead brain, layer by layer, to decode its structure and content, or even scanning a live brain with the same objectives, namely, to replicate its function in some other medium. However, he is quite unclear about how the deconstruction and reconstruction mapping work would be carried out (it makes the human genome project look like child's play). This appears to be not so much a bold and daring futuristic vision as a badly misguided attempt at "reverse engineering" – blind copying – in the naïve assumption that a "brain clone" would be somehow helpful, even if possible.

Before leaving this discussion of the tensions that arise between the *rule-based actions* of computers on the one hand, and the inclination to resort to *guessing and hypothesis-and-test* on the part of humans, on the other, it will be useful to consider the place for human rules, and the need for trust, in large corporations pursuing innovation. The work of the creative individual cannot be decoupled from the corporate culture; nevertheless, we hope that it can be encouraged.

In seeking to foster high levels of quality in one's products, there is a conflict between the need for procedures, structure and closure (emphasizing *rules, supervision, control*, and a framework for *analysis* of performance), and the desirability of leaving parts of the organization loosely structured (emphasizing *the empowering potency of tools, freedom and trust*, and a much greater reliance on *synthesis* in attaining goals).

These are difficult undercurrents to reconcile. Those of us who think of ourselves as rational and reliable members of the technical community well know that the best way to solve problems is *certainly not* through the slavish observance of formal structures (rules and analysis), but rather through the independent, skillful application of our tools (high-quality instrumentation, computers, communication media, etc.), in a corporate culture of implicit trust.

Invention requires temporary isolation in a far-seeing place, and adequate time. Generous allowance must be made for one's thoughts to travel aimlessly at for extended periods, away from the project in search of *more general truths*. This is not the sort of thing that well-paid engineers are supposed to do; hence the special need for trust. In that connection the comments by philosopher Jean-François Lyotard[71] are germane:

> In what we call thinking the mind isn't 'directed' but suspended. You don't give it rules. You teach it to receive. You don't clear the ground to build unobstructed: you make a little clearing where the penumbra of an almost-given will be able to enter and modify its contour.

Invention and innovation are stifled in a rule-bound context. They may occur, but they cannot thrive On the other hand, they can be significantly enhanced in a *liberating tool-rich environment*, particularly if some of these tools provide access to vast territories of knowledge and allow one to play countless *'What-if?'* and *'How-about?'* games with this knowledge; time and tools that allow us to imagine *an endless variety of virtual worlds* and navigate freely throughout them.

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[71] J-F Lyotard, *The Inhuman: Reflections on Time*, translated by G. Bennington and R. Bowlby, Stanford University Press, Stanford, 1991, p. 19.

Such circumstances have proven capable of generating profound and *completely unexpected* insights. Thus, the beautiful world of fractal images was unknown to us (and, from a practical point of view, unknowable) without computers; the same can be said of chaos theory, whole-body imaging, much of modern mathematics, mapping the human genome, cataloging the universe, and a lot more.

Imaginative use of computers has become synonymous with both theoretical and applied science, because of their capacity to open our minds to *visualizing new possibilities*. As well as being perceived as "'levers for the mind" they may be seen as *imagination extenders*. They are equally important in the modern arts, both musical and visual.

Some years ago, my daughter, who was at the time Trade Show Coordinator at Silicon Graphics Inc., gave me a stunning demonstration of what can be done with image manipulation, such as 'morphing', and other visualization techniques using their machines, including molecular modeling. The facile transformations of images has since become commonplace, of course, leading one to wonder how else they might be used in the pursuit of innovation.

In *circuit simulation*, we have scarcely begun to scratch the surface in devising ways to visualize circuit behavior. We hardly need to be reminded of how much more useful is a graphical representation compared to a table of numbers. Yet in some ways we're still using little more than fast calculators and generally static output representations, to work our way through complex design processes. Proprietary circuit simulators invariably support numerous useful features not found in public-domain software; these clearly represent an important competitive advantage.

But the ergonomics of the interface remain quite prosaic. Some would argue that this is exactly what you want of a tool: solid determinism based on formal statements and procedures. However, such a position is unimaginative. It seems to assume that a more responsive outer shell would somehow interfere with the internal robustness of the core programs. Yet in many cases, the data are already available to provide help in *a more dynamic, attention-getting* manner.

For example, in using ADICE (the Analog Devices Integrated Circuit Emulator) we can choose to be automatically alerted to situations in which device terminal potentials, branch currents and the like exceed some permissible limit value. But these alerts are not presented on the *on-screen schematic*, to which one's attention is primarily directed. It would be more valuable to see these aberrant conditions dynamically appear and then disappear in circuit elements as, for example, a transient analysis proceeds. In this way, one could see that a certain transistor goes briefly into saturation, or its V_{CE} or its I_C exceeds a safe value, at which point one might choose to stop the run, leaving the guilty transistors lit up on the screen. This *modus operandi* is more likely toward the end of a product development, on large product designs. Design rigor and the pursuit of robustness demands that one conduct literally *thousands of*

investigations at each cell level before stitching them all together: looking for, and eliminating, all manner of sensitivities, through subtle refinements and more optimal choice of parameter values.

Nonetheless, it is not uncommon for a few new mistakes to sneak in at the eleventh hour, when extra vigilance is especially crucial, and where tools of this kind could be especially helpful. Apparently trivial artifacts that appear in the course of circuit studies may be a *"cry from the heart"* – the circuit's valiant attempt to tell us that there's pain in certain parts of its anatomy. I can recall countless occasions when, after chasing such leads and clues, and eventually determining the *root cause* of some otherwise minor manifestation of pathology – *appearing only under extreme and unrealistic conditions of stress* – I subsequently uncovered a significant, and sometimes serious, malaise in one's design, requiring minor to radical surgery.

In the future, I hope we will be able to *experience* circuit simulation in an even more visceral manner. Maybe we will strobe the circuit to freeze, or slow-roll, its dynamic operation, and thereby experience the ebb and flow of voltages and currents, in slow and *more understandable* motion. Perhaps we could visualize the trail of havoc wrought by an ESD event as the discharge rips through the fabric of our circuit. It might help one to *actually hear* the signals at selected nodes, when rendered at appropriate pitches, just as weather satellites and MRI systems render features in artificial, but insight-bearing, color. It might be useful to include speech recognition and even speech responses, to extend the power of these tools.

Of course, such features could easily descend to mere gimmickry. And I know that one of ADI's leading programmers feels that such augmentations as described here are mere "band-aids", that are not worth spending valuable time in providing. I must disagree. The man-machine interface – the *ergonomic design of these tools* – is extremely important. It may not address the fundamental speed or accuracy of the core function in a simulator, but it can profoundly enhance *our relationship with the machine and its messages*. We expect today's workstations to burn up massive amounts of memory and CPU time in doing nothing more mundane than simply refreshing the screen or indexing the hard-disk. In the future[72], we can expect CPUs to run at Gigahertz rates, and to be supported by Gigabytes of RAM and tens or even hundreds of Gigabytes of disc memory. Today, this may seem like an idle pipe dream, but there is no technological reason why it should not be a reality. With such compute-power, it should be possible to do much to improve the nature of the man-machine interface.

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[72] That last paragraph appeared in a revision of this essay in about 1999. Now, ten years later, some of this expectation has been fulfilled; but not much progress has been made in "humanizing" the interfaces into simulators. However, we have only a small team, and they have worked hard at further improvements to the core capabilities, and in providing access to more advanced types of simulator, and in device modeling for very high speed circuits. Nevertheless, I have been able to get some of these "band-aids" installed. For example, an analysis of circuit noise used to print out the contributions of all devices in a number order; now, they are ranked by their magnitude, which is far more useful in design studies, since the most significant sources can now be quickly identified. Other proprietary advances have also been coded and installed.

But will all this extra power be used that way in the looming 21st century? That must always be a matter of priorities, and the history so far suggests that the emphasis in the professional area will remain *"objective-bound"*, while in the public area the emphasis will always be placed on prosaic entertainment value.

Addendum

Since writing this essay, my good friend Kendall Castor-Perry gave me the book called *Behind the Eye* by Donald Mackay (ISBN 0-631-17332-3, Series III Gifford Lectures, University of Glasgow, published by Basil Blackwell Inc. 3 Cambridge Center, MA).

Space and time prevent me reporting Mackay's many valuable ideas; but I will mention that at several points in this book he makes it clear that he fully appreciates the role – and indeed, the *absolute necessity* – of neural noise as a precursor to the New Idea. You might start by reading the section 'Intelligent Behavior' on page 181. I will have a lot more to say about Mackay's material in Part 2 of this essay, yet to be completed. It was of interest to learn that some fifty years ago he published a book entitled *Analogue Computing at Ultra High Speed* (Chapman and Hall, 1962) – which is now in my library.

The Green Man is not just the name of a pub (or two*!*) in Ireland

CHAPTER 7 MAKING THINGS HAPPEN

While advanced tools for visualization will doubtless be of immense value in the future, imagineering is not the central challenge for the innovator. As useful as modern computers are in their capacity as cerebral levers and auxiliary minds, they are only tools, and, at least for the present, essentially passive agents. *It remains up to we humans to forge real, robust, marketable products out of those infrequent, fragile and evanescent cerebral sparks using whatever tools are available to us*.

This *'reduction to practice'* is the true essence of innovation. Although dependent on a rich flow of new ideas combined with experience and personal insights, *innovation requires a special sort of "know-how"*, that is all about making things happen (it might be called "make-how"). It frequently involves the use of markedly unusual and unexpected methods to achieve its objective: the delivery of a material product which can be replicated by the millions to demanding specifications with high yields, and used by numerous customers.

The precise moment when a new 'art' first bears fruit is especially significant. At its most expressive, it marks the imminent eclipse of all that proceeded it, as did the invention of photography, the telephone, radio and radar, plastics, antibiotics, analog and digital computers, tape and disc recorders; then, at the mid-point of this century, the transistor, with the later seminal development of the planar process for integrated circuit fabrication. The microprocessor and mass-storage devices were not far behind. These all began as brilliant insights – just inventions – realized eventually in reliable quantities only through *the process of innovation*, becoming progressively more reliant on team activities as their complexity and the scale of the development increased. All of them have profoundly changed the nature of human life by the sheer force of their presence and their penetration into every corner of the world.

Innovation is the practical outcome of our insights, and our perceptions and reactions to environment. It is the human response to the opportunities that will always abound in the world. It sees the world in an ever-fresh and bold new light, often requiring that we throw some – if not all – of the rules out the window. It's about being convinced of *the validity and viability of one's singular vision* and a passionate compulsion to continually channel that vision into profitable realities. The pursuit of this paradigm implicitly acknowledges that the next step is largely up to oneself, that it will not come from research conducted elsewhere, nor can one afford to assume that it will always come from one's colleagues or team associates.

I have often advised my teams to regard the Company for whom they work as their "*personal success machine*", noting: "If we each succeed, we all succeed".

Nevertheless, we must recognize the mutual benefit of *sharing our zest* for the novel, and our *responsibility* to do so, whether at the white-board, in technical memoranda, or through e-mail. Furthermore, teaching forces one to think more logically, less instinctively. In so doing, hitherto hidden weaknesses or practical snags in one's innate viewpoint may become apparent. Enthusiasm about one's work is highly contagious.

Innovention – *Invention followed by Innovation* – is an iterative, exploratory journey of discovery, down roads of one's own making, with no maps, and often (more often than we might admit) without even a clear destination. *Dissatisfaction and yearning* appear at every turn. Design revisions occur with clockwork regularity. The focal depth, perspective and center of attention is *constantly in need of readjustment*. The dynamics of "getting it all together" involve numerous nested loops of judgment and restructuring, a process quite unlike the popular image of unidirectional, rule-based technical progress.

Young designers often expect that every step in a design should – and surely will – follow directly and inevitably on the heels of the last. They are surprised to hear me (the "expert") say that I need to go *down dozens of dead ends* before arriving at a juncture that finally promises to take me to where I want to go. Seasoned engineers need to be honest about this when seeking to help the newcomer, who may believe that failing to get it right the first time is a mortal weakness.

Science might be defined as honesty confronting mystery. Although engineers are not practicing science – which is about understanding the unknown – honesty and candor regarding one's work are no less important. Papers published in professional journals are frequently disingenuous when recounting, say, the order in which developments occurred, often suggesting a strictly logical and linear flow of progress, when it's far more likely to have been highly *fractured and convoluted, and even chaotic* at times.

The hiding of inconvenient results in papers offered to the professional journals, such as replacing revelatory plots of *deviations from an ideal* with obfuscating "full-scale" graphs, is an all-too common practice. As one who is called on to review papers for publication in professional journals, I've seen many examples of such "cover-ups". The charitable view would be to assume that, being written by a relatively inexperienced author[73] the lack of rigor and full disclosure in the presentation is probably just due to a poor appreciation of the wider aspects of some circuit's behavior, or the practical requirements it must meet.

[73] Many are student submissions from university "research", encouraged by the overseeing professor, whose reputation may depend strongly on the numerical count of "co-authored" papers; quality is often a secondary consideration.

World-View and Teamwork

We each experience and model the world in a unique and idiosyncratic way. It's easy to forget this, and assume that something that makes perfect sense to oneself will be manifestly clear to all. This is obviously illusory. No one sees the world exactly (or even approximately) as I do, or the way you do. Because the advanced tokens of language – our words – are so commonplace, so ubiquitous, we are tempted to suppose that they have an intrinsic, independent, absolute, universal meaning of their own, whereas of course *they have meaning only by usage and convention* within our private, self-constructed interpretation of the world, which we compulsively presume is the natural, shared view. The ambiguity that arises between individual viewpoints is certainly a little frustrating, but at least *being aware of it* may help us to become better communicators.

I like this passage from Weizenbaum[74]:

> Man is conscious of himself, of others like himself and of a world that is, at least to some extent, malleable. ... His tools, whatever their primary practical function, are necessarily also pedagogical instruments. They are then part of the stuff out of which man fashions his *imaginative reconstruction* of the world. It is within the intellectual and social world he himself creates that the individual prehearses and rehearses countless dramatic enactments of how the world might have been and what it might become. That world is the repository of his subjectivity. Therefore it is the stimulator of his consciousness and finally the constructor of the material world itself. It is this *self-constructed world* that the individual encounters as an apparently external force. But he contains it within himself; what confronts him is *his own model of a universe*, and, since he is a part of it, his model of himself. [My emphases]

Life demands we establish anchor-points in the world beyond our skull. As product developers, the marketplace is such an anchor-point; it is the final arbiter of success or failure for the innovator. Ultimately though, *we have to depend on our internalized model of this world*. While our attention must be focused on the *technical* issues relating to the systems, components and technologies that we and competing companies are concurrently developing to serve a particular market, we must also appreciate the non-technical "soft" factors, such as the *dynamics of our business* and the *psychology of our customers* in depth. Further, we must understand not only the *present* markets, but go well beyond, constantly *anticipating their future needs*.

The innovator can be neither timid nor cock-sure about this challenge. If timid, one might fall into the trap of perceiving the market as a fortress of rationality, around which an impenetrable wall has been built; where for numerous compelling reasons the existing solutions are not just satisfactory, but superior; where all the good ideas in some arena have long ago been figured out in every detail.

Such an apologetic approach to the call of opportunity would be unwise. The truth is that the majority of our customers for advanced components and systems are daily managing to scrape

[74] Ibid., page 17

by, quite often with *barely adequate solutions*. You will hear a lot about pricing; but the truth is that customers are frequently on the lookout for more accurate, more capable, more reliable, more stable, more powerful alternatives. They crave to be advised by their vendors. *In the endless pursuit of Leadership, we cannot afford to let them down.*

In the halls of any corporation with a trail of impressive successes behind it, one may occasionally overhear scornful comments about competitors. This is very dangerous. *The innovative spirit has no place for derision or complacency*. One's attitude to the marketplace and one's competitors needs at all times to be *honest, focused, realistic and balanced.* Contributors to the complex process of innovation should always feel they're individually doing their utmost to enhance the company's competitive edge and reputation, and should be *justifiably* proud of their corporation's achievements.

But it would foolhardy to imagine that any one company, or any individual employee, has an exclusively accurate understanding of what it takes to be successful in any particular field, or enjoys a superior vision of what the future holds. That should certainly be our personal and unspoken goal; however, *a brutally honest recognition of one's own weaknesses is the beginning of strength and wisdom.*

As we stand at the threshold of a new century, anticipating the further evolution of electronics, we feel it will yield even more profound and far-reaching consequences. At this momentous juncture, comparable to the pioneering days of "electricity and magnetism", I am unsure whether to be glad to have witnessed, directly or indirectly, almost the entire history of electronics to date, and able to use that experience as a reliable pointer to the future; or rather, to be envious of the new generation who will apply the enormous potential of what has been achieved so far, and go on to witness the marvels of the post-millennial "knowledge-technologies" to follow.

The prospect that richer, broader and deeper intercultural exchanges will bring about a peaceful new order is tantalizing and uplifting. It is only the sobering awareness of the darker side of human nature, taught us by the miserable lessons of history and the political upheavals and clashes of contemporary ideologies, that forces one to have second thoughts about Utopia.

Heroes and Role Models

As children, we were fascinated by accounts of heroes: titanic figures who leave the world as we know it and enter another arena, seething with conflict and chaos, where they take on primal challenges against impossible odds. Upon returning to the world of mortals, they proceed to communicate their moral message to ordinary people.

Joseph Campbell reminds us that this message is always the same: *We each must pursue an inward journey that involves either a painful reconciliation of opposites or the permanent and unresolved accommodation of the dialectic*. As adults, we are obliged to be aware of the necessity of pragmatism, the compromise, the "trade-off". Still, our childhood *belief in magic doors* is exceedingly hard to shake off[75].

Just as for heroes, accounts of the lives of inventors often take on mythic proportions in a surprisingly short period of time. Edison created his own myth. But we should be able salvage something of value, some faint echo of the reality, some glimpse into their personal style and habits, as well as a better understanding of the value of their technical output, seen in retrospect. *How did they think* about their work? *Where did their best insights* come from? - and under what circumstances and when? What sort of hours did they keep? Did they dream a lot? Were the inventors of the past good team players, or awkward and idiosyncratic misfits?

In our field of microelectronic products, the name of one innovator comes to mind: Bob Widlar, who died in 1991. He was a maverick, a non-conformist, with stubborn ideas of his own and a huge ego. Many regard him as a legend. He certainly did some clever things with silicon, and introduced many industry firsts. Thus, Jim Solomon says of him[76]:

He pioneered the three-terminal voltage regulator, on-chip power devices, the bandgap voltage regulator, super-beta transistors and a full bag of interesting circuit and device techniques.

Yet Widlar was decidedly *not* a team player. Those who knew him recall that he was very hard to relate to. Bob Dobkin of LTC (always "Dobbie" to Widlar), who worked alongside him for many years, said: "Widlar knew it all, he *knew* he knew it all, and nobody else knew anything". This arrogance was quite apparent even to those of us who knew him less intimately. Yet Lew Counts, who believes analog designers might beneficially keep Bob's seminal articles ready to hand, generously observes: "Bob was concerned with all aspects of his craft (or art), including 'marketing', in the true sense of understanding the economics and systems applications of his products"[77].

While we may be disappointed to find nothing explicit in these publications about *the motivation* driving the development of his various IC concepts, his overall grasp of the possibilities of the medium and his *market orientation* were undoubtedly a constant and tangible aspect of his work. With this knowledge, he pursued product design with admirable disregard for the thin distillate trickling from his marketing advisors. However, one is bound to wonder whether Widlar would be as outstanding an achiever in a modern corporation as he was at National Semiconductor in the '60's, and what his reaction might be to the contemporary passion for

[75] Searching for new circuit topologies, I expect to find "yellow doors" that open into new worlds of possibility, by defeating some (incorrectly presumed) fundamental limitation, and to my surprise and delight I often succeed.

[76] Tribute in the August 1991 issue of the IEEE *Journal of Solid-State Circuits*, VOL. 26, NO. 8, pp. 1087-1088.

[77] Private communications with Dobkin and Counts.

every new management fad in corporate structures for innovation. *I have no doubt he would have vehemently rebelled against any and all creativity-crushing initiatives.* Widlar's specialized "bag analog of tricks" left a strong impression on certain aspects of analog design, but few young engineers today know much about him.

Among recent inventors in electronics and communications, many are known to us because of just one rather limited idea that carries their name. On the other hand, major inventions passed into everyday use without the originator being widely heard of. What did Amos Dolbear, Ben Thompson and Idvorsky Pupin[78] each invent? The "Darlington" connection of two bipolar transistors is an example of an invention on a very rudimentary scale, scarcely an invention at all, simply one of the numerous ways of using two transistors that any experimenter is bound to try, sooner or later. The Patent Office's test for the elusive quality of "non-obviousness" is barely passed.

In other cases, a basic yet cleverly-contrived cell of a few transistors can suddenly open up many valuable applications and opportunities for useful extensions. In these cases the degree of "non-obviousness" about the principle is apparent, when we first encounter it, and, with a mixture of admiration and envy, gasp: "Now, why didn't I think of that?". The Wilson current mirror and Brokaw's band-gap voltage reference come to mind[79], and I trust it is permissible to include my own analog multiplier cells and other circuit concepts based on the "translinear principle" as such examples.

Today's engineers are the beneficiaries not only of relatively recent innovators; we are also the inheritors of *the spirit of a long lineage of role models*, going way back to the Sumerians (3,000 BCE), through Archimedes (287-212 BCE), da Vinci (1452-1519), Gutenberg (?-1468), Gilbert (1544-1603), Davy (1769-1830), Faraday (1791-1867), Babbage (1791-1871), Morse (1791-1872), von Siemens (1816-1982), Maxwell (1831-1879), Edison (1847-1931), Hertz (1857-1894), Steinmetz (1865-1923), Tesla (1856-1943), Marconi (1874-1937), Wiener (1894-1964), Armstrong (1890-1982) and many, many more fine minds.

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[78] Pupin's book *From Immigrant to Inventor* was the inspiration for many young aspiring inventors in America. AT&T gave Pupin $500,000 for his seminal patents related to the inductive loading of long communications cables.

[79] Naming cells in this way is likely to deter young inventors, who may think that all the good ideas have already been thought of. Names that are more descriptive are preferable in this regard, because they allow the new engineer to see them strictly in terms of their function, and to internalize them as their own possessions. Thus, not "the Brokaw band-gap", but (say) the "emitter-coupled band-gap cell". This is not meant to deflect acknowledgement of the inventor, but to encourage the young engineer to think objectively and functionally, and use the documented cell as a starting point for independent invention.

What might we learn from these legendary figures that could be useful to us today? I see as the most important feature of their lives and work that *they didn't wait to be told to innovate.* Their actions stemmed from a fundamental, deeply personal, almost primal urge to pursue new ideas that *significantly challenged the norms*, and which at their finest were destined to transform the world.

The Sumerians' had the stunning insight that the physical tokens[80] formerly used to keep track of financial transactions could be replaced by *a representation* of these *(the root invention)* in the form of distinctive marks on soft clay tablets, which were later transformed into records of archival quality by exposure to the noonday sun *(the key innovation)*. This was innovention springing from great independence of mind. *Who would have been the "customer" for writing? Who did the market research?* The very thought is laughable. Nonetheless, this was a practically-minded response to a latent and *as-yet unexpressed* communal need.

In just the same way, no one had to tell Gutenberg of the importance of adapting the Asian innovations of movable type and paper to his "modern" world, or how to convert an old wine-press toward this revolutionary use. *He was his own guide, his own marketeer, his own tool-maker, his own prototype-builder and initially his own customer for the manufacturing technology he developed*.

Likewise, no one needed to tell Mike Faraday to go wind a little coil, or Nick Tesla to go wind a ginormous one, or that they should work from dawn 'til dusk (as did Mike, while Nick did the dusk-to-dawn shift). No one told Guggi Marconi how useful it might be if only he could find a way to apply electromagnetic waves to communicate across the Atlantic. *All these guys were pursing their own very private agenda, not carrying out someone's mandate*. They instinctively knew the future value of their *inventive ideas*, and they proceeded to proved this, through *practical innovation*.

Most of us feel – maybe without adequate justification – that we cannot aspire to the greatness of such inventors, particularly in our limited, highly-specific domain of virus-scale electronics. Nevertheless, it is proper – and not immodest, in my view – to *seek to emulate their example*. Their achievements are invariably strongly colored in passing through the long telescope of time. A significant proportion of history's inventors were not giants, nor even prolific; many were pretty similar to you or me.

Just like them, we need to have a *clear conception* of what advances will be useful. We need to always be ready to *propose solutions without first needing to be asked.* We must be *passionately committed* to our vocation, willing to practice *tenacity and resilience* in the face of defeat, *confident of eventual success.* We should expect to spend a high proportion of our energy *pursuing dead-ends,* while at the same time maintaining *a high level of concentration.* We should at all

[80] See *Before Writing; Vol. I, From Counting to Cuneiform*, by Denise Schmandt-Besserat, University of Texas Press, 1992, for an enlightening account of the precursors of writing.

times feel *resourceful, qualified, capable, well-equipped, determined.* We will benefit greatly by devising a continuous supply of *self-imposed challenges as exercises.*

It is out of these deeply personal attitudes – the **"State of the Heart"** – that the best ideas wells forth. Surely it's permissible to feel proud of one's achievements, if they're of proven worth. We all harbor the hope that we will accomplish something of enduring value, and be remembered for it. When I wake up each day, in my senior years, with an abundance of aches and pains, I think: "Wow*!* I'm *still alive!* There's *still time* to change the world*!* Today, I'll make a difference*!*". Although we probably won't change the world in any major way, we can all leave something of value. In Longfellow's words:

Lives of great men all remind us,
We can make our lives sublime,
And, departing, leave behind us
Footprints in the sands of time.