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The Gears of Genius

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THE MIRACLE

The *Square and Compass* is a tiny pub – well, actually, the *only* pub – in the sleepy village of Worth Matravers, nestled high on the chalk cliffs along the Dorset coast, looking out over the English channel toward France. *The Coastal Hikers' Guide* says of this pub: “Fantastic place; geese running around; roaring log fires; best scenery in the world; the friendliest people; completely unspoiled; a gem”. Whenever I make a trip back there, the salty ocean spray, borne up on summer zephyrs, feels just as it did on my face during an earlier time, when electronics and I were both very young.

One evening in 1940, this pub - called "The Sine and Costin" by the TRE boys - was packed to capacity. Its rustic tranquility had been shattered by an influx of high-spirited workers from a secret research lab (TRE) nearby. They had good reason to be in a celebratory mood. Earlier in the day, Philip Dee, one of the engineers at this top-secret development site, and on war-time loan from the Cavendish Labs of Cambridge University, received an ordinary-looking package from Birmingham University. Its contents would have made an alert espionage agent crave for possession, had he known it contained two precious samples of a unique and radically different sort of microwave oscillator tube: an invention destined to sharpen the eyesight of the older Chain Home UHF radar stations scattered all around this coast during WW2, and radically shift the dynamics of this grim war **[1]**.

Dee was filled with a mixture of awe, elation and anticipation tinged with concern as he carefully extricated one of these strange, awkward devices, sprouting metal pipes for cooling and vacuum pull-down, a rigid coaxial line for its output, and connections for DC power. What he held was quite unlike any other tube. For one thing, it didn't have a visible glass envelope, so the inner structure couldn't be seen; and it needed a powerful magnet, as well as hundreds of volts at several amps, to do its special thing. In essence, it was little more than an elaboration of the diode, the earliest and the simplest of all electron tubes; but that magnet introduced a thrilling twist!

The boffins up north had waxed ecstatic about its miraculous properties; fitting, since Britain needed a miracle. France had already fallen, and the bombing raids all across England were intense. Dee may have wondered “How can yet another type of valve change the outcome of this endless conflict?”. He could not have foreseen, nor even could Robert Watson-Watt, credited as the ‘father’ of radar (he was later knighted for this work; his first, pre-magnetron system dreams on in the British Museum, **Figure 1**) how such a naively simple device could not only win a war, but that it would guide his seafaring through the darkest storm; that it would become a key to forecasting the weather and mapping the earth's terrain and resources; that it would one day cook our dinner in minutes rather than hours.

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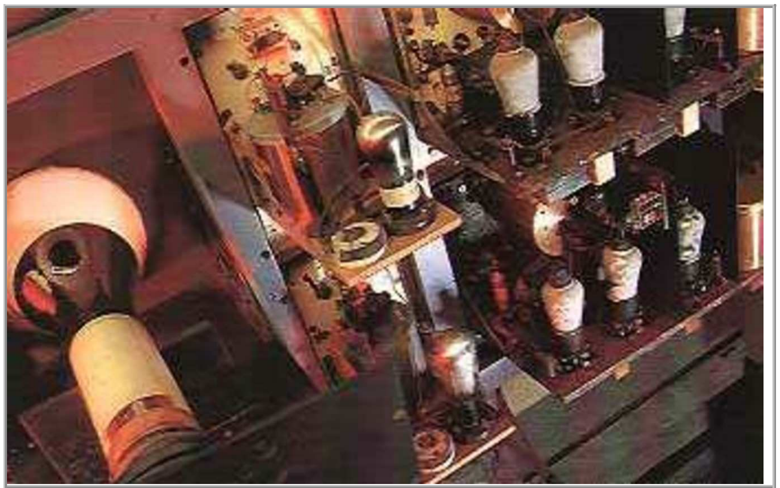


Figure 1. Sir Robert Watson-Watt’s baby, dreaming contentedly in the British Science Museum.

It was even less foreseeable that its cousins, the klystron family, harnessing swarms of electronsin a game of electromagnetic give-and-take called *bunching*, would one day be used by the score to accelerate particles almost to light speed in colliders, revealing layer upon layer of the complexity of matter as they hurtle, blind and thoughtless, head-to-head; and in an instant annihilate each other, leaving just assorted fragments; much as do people in war.

It was beyond imagination’s reach that another ingenious device, the traveling-wave tube, would be used to deliver movies produced and directed by lonely robots roving Mars; or conveniently supplying us with colorful coffee-table close-ups of Saturn’s rings and Jupiter’s moons; capturing visions of the awesome ever-humbling immensity of space through Hubble’s eyes; or mailing the occasional postcard of some small, ignoble potato-objects boiling aimlessly in our star’s asteroid belt, harboring inclinations to wipe out life on Earth, while a small radar silently measures our space-craft’s closing distance, as we test our propositions to land on them, prod and poke them, and report back on the stuff they’re made of.

These amazing electron tubes *profoundly changed the face of civilization*, fully as much as would a later remarkable electronic innovation. No, this was not the *accidental discovery* of minority-carrier conduction. In my own design experience, the debut of discrete commercial transistors (BJTs) only *modified* the paradigms of design and manufacture; just as, later, gluing together four or five components into an awkward, one-off, and rudimentary hybrid proved little and changed nothing. Rather, it would be a *truly revolutionary* invention: Jean Hoerni’s planar process **[2]**.

But for now, in 1940, the only vision that mattered was that of a new hawk-eyed radar; and this primitive new device **(Figure 2a)** held that promise. The basic form of its internal structure can be seen more clearly in a dismantled RAF magnetron from a later time (**Figure 2b**). We can imagine the excitement felt by Dee as he attached the heavy magnet to the steel flanges, with its focusing poles carefully aligned to the upper and lower ends of the rod-like cathode, thus creating an intense magnetic flux along its radial axis of symmetry. When pumped down to Birmingham’s specified vacuum, he started the flow of cooling water, then applied the low voltage to heat the cathode, and made sure the anode was well-grounded. Finally, with trepidation, he applied the supply-voltage to the cathode; at first, perhaps only a hundred volts.

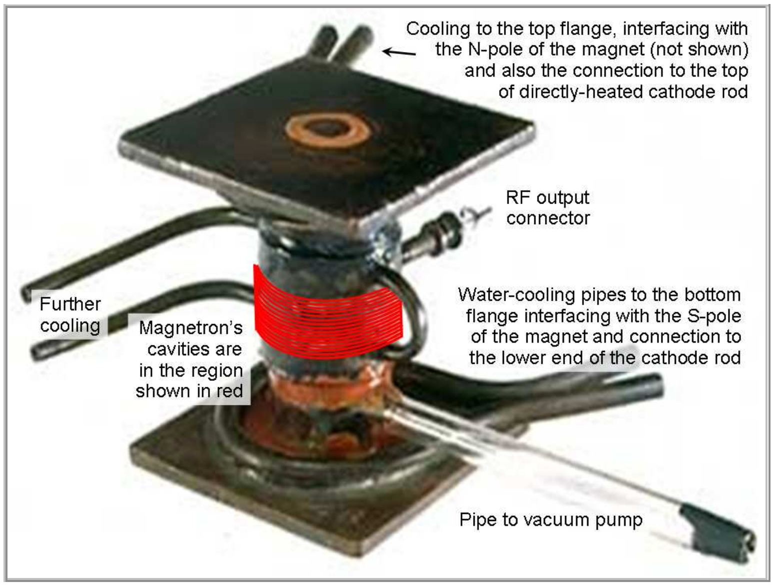
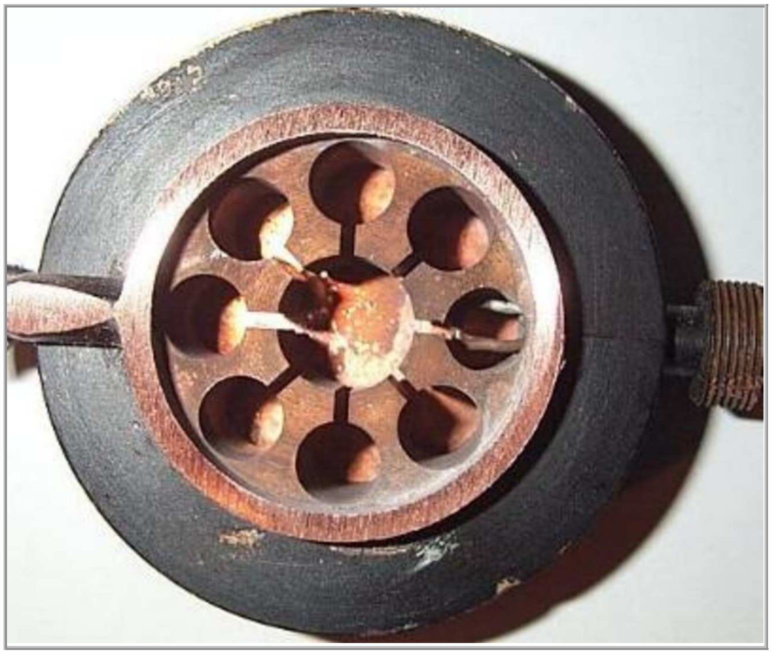


Figure 2. (a) The cavity magnetron of Randall and Boot (now also in the British Science Museum) minus its magnet. (b) A production magnetron disassembled to reveal the resonator cavities in the anode block.



As Dee inched up the supply voltage it seemed nothing remarkable was happening, except the cooling water was becoming very hot. Then, at a critical voltage, he saw the magnetron burst into oscillation. Or rather, he noticed that the RF test load, a bank of five or six 100-W house lamps, began to glow. By the end of the day, using the full accelerating voltage recommended by its inventors, Randall and Boot, the microwave output was lighting up the laboratory like the sun, while the cooling water retreated to a much less threatening temperature. The cavity magnetron *really worked!*

The anode, a thick annulus of solid copper in which six cylindrical cavities had been milled, accelerated electrons radially outward from the cathode as in any ordinary diode. In the absence of a magnetic field these electrons would have hurtled directly to the anode, where they could only turn their energy (momentum) into useless heat (**Figure 3a**). But a magnetron is no ordinary diode: its magnet forces the electrons to follow a *strongly curved* path; and by adjusting the magnetic and electric fields, they can be made to arrive at the anode's inner wall traveling in an almost *circular* path, now carrying their high energy in a powerful, swirling electron tornado (**Figure 3b**).

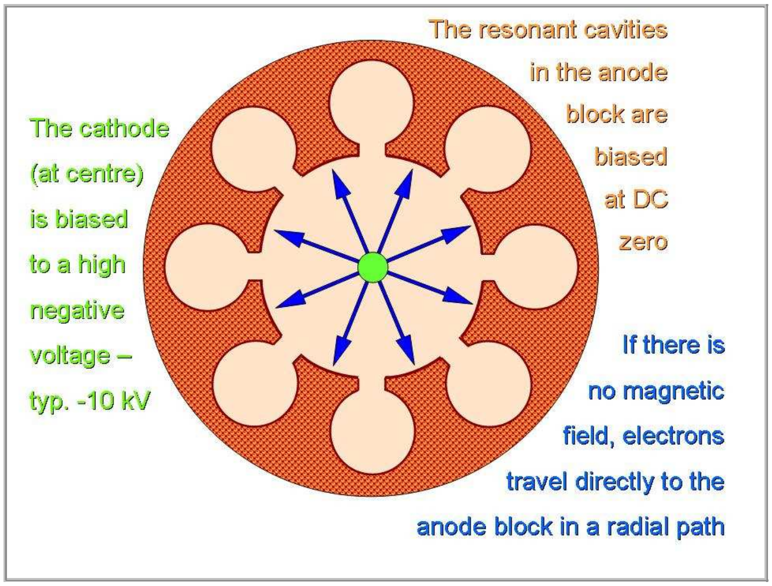
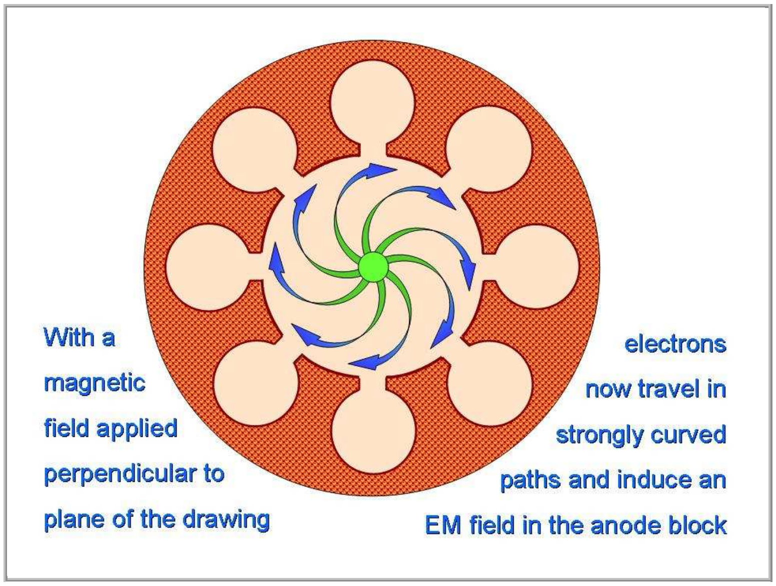


Figure 3. Electro flow in an 8-Cavity magnetron (a) without, and (b) with magnetic field applied.



Randall's theory predicted the cavities needed a diameter of ~1.2 cm to produce a 9.5-cm oscillation (*f*» 3.2GHz). They act like *micro-wave whistles*: arriving electrons give up some of their energy as they *blow across* their open gaps, resulting in strong EM-fields in these high-Q resonators that interact with the constantly-refreshed supply of high-energy electrons, further reinforcing the RF power. This extraordinary behavior must have astonished Dee, as rather ordinary DC volts and amps were being converted *directly to pure microwave power*, and gushing out of its coupler like water off a roof during a tropical downpour. Great ingenuity had been poured into previous wondrous tubes, but nothing before the cavity magnetron had provided such power at these high frequencies – orders of magnitude greater than any previous source – and with unprecedented efficiency.

By pulsing the cathode supply at a moderate rate, very narrow pulses of enormous peak power could be generated. Soon, radars would be using magnetrons operating at 16 kV and an I_{PK} of 8 A, thus accepting 128 kW peak DC power, of which more than 50 kW was directly converted to RF. These extremely-short microwave pulses would resolve far smaller targets than possible with primitive UHF radars. At a stroke the magnetron transformed radar in a way comparable to converting a pair of opera glasses into a space telescope. It was this prospect of super-accurate radar that had created such high hopes at TRE that summer evening in 1940, and provided an excuse for all the rowdy celebrations over at the pub.

A FEARFUL PROXIMITY

That same evening, barely far enough away to be insulated from the jubilance over at the *Square and Compass*, Frederick Arthur Gilbert, a serious and sensitive man, and an accomplished classical pianist, was diligently practicing a Beethoven sonata. A toddler, his third birthday just days before, squeezed alongside him on the black piano bench. He was doing his bit to contribute to the unfolding invention, exploring the cackling potential of the top octaves: *What If?* this key? *How About?* this black one? All the while his father's playing was weaving a complex tapestry of enigmatic infinite loops in this boy's head, creating a painful confusion: *What is* music?

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Two days later the piano, so recently joyful, was in mourning. The latest round of bombs that were intended to destroy the older UHF radar station at Ventnor, on the Isle of Wight, or perhaps put an end to the magnetron work at TRE, missed their target. Instead, they hit our home town. I was the top-octave augmenter: the last of his four children. By all the normal rules of nature, my mid-forties mother should have been excused from further childbearing. *Surprise!* On June 5, 1937, two days after the death of Sir James Barrie, the author of *Peter Pan*, I showed up.

So my father named me Barrie, celebrating the creator of this imaginary character, wishing the same for me: that I might never need to grow up, and be forced to develop my life in what was at the time threatening to become the foreign occupation of England. He didn't live to witness that dark prospect vanquished, or to play real duets with me, sharing our mutual joy of music-making like the chromatic soul-mates we doubtless would have been, perhaps striving to guide his new son to make a mark on the world stage as a concert performer. *What If?*

Largely because of radar, and the developments at TRE, a few miles from me, the War would eventually be won by the Allied forces. But in those dark years, I was fatherless and my mother was obliged to raise me and my siblings with zero income. Among our few assets was the piano. Not being musical, she soon sold it, to pay for necessities. So at a stroke I lost both my teacher and the beloved instrument that had once sung for my chubby fingers, as I added joyfully to the fluid sonorities miraculously emerging from my father's hands. My sole inheritance was a stack of sheet music. Some were his own hand-written compositions, but most were the works of the great composers, liberally annotated in the garish purple of the day's 'indelible' ink: *'Legato here'; 'Careful - sudden key-change'; 'Marked fff, but don't wake Barrie.'*

A month after my father's death, Aug. 12, 1940, a secret event took place that was nonetheless so relevant to my life that it might as well have been advertised in the *Swanage Times* or the *Bournemouth Daily Echo*. One of those primitive magnetrons bounced a tentative pulse off the walls of the Norman church at St. Aldhelm's Head, on the Dorset coast. Satisfied with this general test, and perhaps as a way to do some calibration, Dee's team turned the keen vision of their contraption toward a passing cyclist and later, a small aircraft miles out to sea. It was the first time a magnetron had been used in a radar system; and the first time an aircraft had been tracked by radar. While this constructive work was being pursued, three of the early-warning stations in Kent were again under attack; and a fourth, the one at Ventnor, was briefly put out of action later in the afternoon. More bombings of these stations were expected.

Inexplicably, Field Marshall Goering believed that these towers were of no great significance, and he redirected the bombing raids to inland targets, such as Coventry cathedral. The *Enigma* code had recently been cracked (with the help of the *first programmable digital computer*, 'Colussus,' designed by Tommy Flowers, whom I've had the pleasure of meeting) so Winston Churchill knew about this particular air-raid, but he couldn't tip his hand and reveal this knowledge. Many have said that if more attacks *had* been ordered, and those radar defenses were destroyed, the Battle of Britain would have been lost within one month. Instead, by July of 1941, the miraculous magnetron was doing its thing in Navy radar stations, and shortly thereafter, in RAF aircraft. Earlier, in great secrecy, samples had been shown to a group at MIT, and the US soon began to make their own magnetrons. By the time they showed up to aid Europe, their military craft were also equipped with radar.

A DEARTH OF MENTORS

|In his autobiography **[3]** the anthropologist Oliver Sacks tells of a favorite uncle who encouraged his curiosity about the world around him during his childhood in the 1930's. This fellow, who owned a company that made light bulbs ("We once used osmium for filaments", he said), spent a lot of time with his young nephew, reveling in the magical properties of basic chemicals, especially crystals and metals. His admiration for one particular metal led Sacks to name this influential mentor Uncle Tungsten. At a recent MIT event (H*2*.O), where Sacks happened to be the keynote speaker, we talked about early-life influences, and the enjoyment of our experiments in physics and chemistry. The closeness of our learning trajectories was remarkable, but the similarities ended there. Sacks was fortunate in having a highly attentive and supportive extended family of intellectuals and professionals, all of significant means. I had only my overburdened mother, freshly widowed by the insanity of war, and she was constantly broke. As the youngest of her four children, I wore ill-fitting hand-me-downs and repeatedly re-darned socks (a lost art in the consumerist West).

So when asked *"Who was your most influential mentor?"*, I'm embarrassed (since many seem well-prepared – even eager – to amplify this theme) in having to reply that I can't recall there being anyone of that sort. I was a lone wolf-cub, befriended only by a hyperactive urge to experiment with everything. Without a father or an Uncle Tungsten, my childhood inspiration came largely from mile-long treks to the nearest library, where I found such deeply inspiring works as Robert Millikan's account of his painstaking experiments for determining the mass-to-charge ratio of the electron, and "*Principles and Practices of Radar*," by Penrose and Boulding.

Even before I could read, and for many years after my father died, I browsed the enigmatic pages of his stack of music, my only link to him, trying to make sense of their strange yet familiar symbols. Neither my mother nor my older siblings could help. So I became a loner, guided by my imagination, in the company of enigma, perplexity and hypotheticals. I began to formulate probing questions. *What If?* we had not lived so dangerously close to these radar stations, and TRE? *What If?* my father had lived? I felt sure my life should be devoted to music, in some performing capacity, and at an early age, I resolved to earn enough to purchase my own piano. I eventually did, at 18, paying by installments, and taught myself to play. Ironically, this playful instrument was made in Germany. I still have it, but I've since augmented my arsenal with two grand pianos (decked out as *Disklaviers)*, and a farm of synthesizers, computers and perversely expensive audio equipment.

The magnetron was powerless to avert the appalling loss of life that occurred in London later in 1940, particularly during the incendiary bombings of the night of December 29. Not many years later, it was to be my good fortune to be inspired by the war's inventions. It was through *radar*, as much as anything else, that I got tangled up in electronics. *Radar became my inspiring mentor.* The linkage between its brilliant developments, during my childhood, and the numerous neat notions of my own during adult life are readily discernable. Thus, my explanation of how a magnetron works will seem familiar when I later describe a semiconductor device, invented at Tektronix in 1969, to which it bears an uncanny resemblance.

Such strong connections between creative events throughout one's life are surely commonplace; they are an aspect of what may be called the *continuity-of-concepts* principle – the fact that most of us have but a few seminal ideas, forged at an early age, from which we wring every ounce of utility. Sadly, few of today's young circuit designers, having acquired most of their knowledge from studies during school and university years, will have had the opportunity to be exposed to such a rich and varied set of formative experiences as were enjoyed by people of my age. The rare exceptions are the *practical experimenters*, tinkerers, who nowadays build robots with microprocessors for brains, using analog ICs for augmenting the acuity of their sensors and the precision of power-control for their actuators.

TRANSFORMING LOSS TO ADVANTAGE

But I've also learned, from conversations with people having a similar childhood, that inventive aptitudes often arise from the *transformative power of loss* – the shock of, say, no longer having the companionship of a parent during the critical formative years, for whatever reason; and is even aided by the *severely limited resources* associated with poverty. Hiro Moriyasu, a co-worker of mine at Tektronix, was a prolific inventor. This friend died in July, 2005. His obituary states that in 1974 *"[he created] one of the first personal computers, the Tektronix 4051, which caused IBM to take an earlier model off the market".* As a boy, Moriyasu-san lived in Kure City, Hiroshima Prefecture, until the shameful day the US dropped the world's first atomic bomb, surely mankind's most hideous perversion of technology. It appears he hid in a farm truck during this terrible assault on the nearby community, and witnessed the incredible devastation first-hand. Because of this tragedy, he was raised by monks as an orphan. Luckily for Tektronix, he eventually became a first-class engineer.

Yet, it's not so very surprising that creativity may arise in adult life when the infant mind is faced with the *perplexing meaningless* of great loss. Forced to accept *enigma* as a normal and constant aspect of life, and limited by a *paucity of mean*s, the child develops *pragmatism* and *flexibility*. Lacking help in making sense of non-linguistic *symbolic representations*, he acquiresintellectual resourcefulness and independence of spirit. Without the safe ingredients of a normal childhood, the young mind does not simply make *adjustments*, to restore a *neutral* outlook: it may over-compensate. It somehow manages to extract *strength from loss*, and gains the confidence to go it alone, fiercely vowing to be independent and copy no-one.

I find no reference to these ideas of *early loss*, *deprivation* or *limited means* in any of the scores of works in my own library concerned with creativity, nor certain other ideas about the wellsprings of invention; and although that's another story, here's a tiny hint. Cortical neurons are undoubtedly susceptible to electrochemical *noise*. What we call thinking is a stream of controlled processes disturbed by stochastic mechanisms. Significant departures from deterministic, logical thinking caused by such neural noise may be more meaningful to a mind familiar with – and even comfortable with – perplexity, enigma and the dialectic, than one developed during a highly-structured and well-provided childhood.

GROWING UP LEAN

By about 6 years old, I was making model airplanes from strips of wood salvaged from packing-cases, begged from the local grocer. One served as the fuselage; a second, nailed cross-wise, was the wing; and there may have been a tail of sorts. Later, I built many flying, floating and rolling machines; and I was also beginning to discover, through my own *What If?* experiments, how switches, lamps and batteries behaved when wired in various combinations. I made a game in which questions on one board were wired to their answers on another; completing the circuit through a wire placed on corresponding pads illuminated a lamp.

My curiosity soon embraced chemistry, initially using utensils and common reagents from the kitchen; and electrochemistry, using batteries borrowed from our rented radio-set. (Not having street electricity at that time, we used only gas-lights and candles, and the house was heated in winter by a small coal fire in one room. Often, as I got ready for school, the bathroom window would be coated with ice. I wondered: *Why?* do the layers on the *inside* surfacemake beautiful fern-like patterns?).

One day, I wondered: *What If?* I place a pair of wires into this salt solution and connect them to the 120-V "HT" battery. Watching my jam-jar at an incautious proximity, I observed the reluctantly-electrified liquid was generating a greenish slime and a cloud of gas. I had discovered chlorine. Incidentally, I repeated this "experiment" when at last we had street electricity, this time using sturdy copper plates wired directly (!) into a 240-V AC outlet. Luckily, the salt solution must not have been very strong, because it didn't explode. But the liquid boiled almost instantly, and green gas proliferated. *What If?* I smell this stuff, I asked. So I placed my nose close to the fuming haze of lethal gas. This was just one of many times during the next few years that I almost killed myself, by letting *curiosity* lead to *reckless disregard* for the punch behind a power outlet, or for the internal energy stressing the bonds in certain nervously-bound substances. It is not wise to idly seek answers to the *What If?* question using live ammunition!

At about 8, using the metal girders, plates, pulleys and gears of my growing Meccano set, I built bridges, Ferris wheels, tractors, robots and steam locomotives. None ever came from How-To books or magazines. It was an unspoken (and unbroken) rule that the things I made had to be entirely the product of my imagination. For example, a new model boat might have begun as a solid bar of balsa wood. As I cut into it and removed pieces, a form began to appear. Soon, the form would take over, and from that point onward, the knife was at the command of the model: I merely watched.

For better or worse, this stubborn independence has remained with me throughout my life. Even today, solitude, a fresh pad of inviting paper, a fine-tipped pen and feline companionship better suit my temperament than life in the madding crowd.

A novel IC product often starts with ideas of the *How About?* sort. I deliberately leave the details unstated: all options remain open. Working with the elements, I gently persuade the product into adopting a certain shape: the broad outline of its function, and essential aspects of performance. At some point, a serviceable structure appears; but I give it considerable latitude to guide me. I allow it to *breathe*; to talk to me. I listen for signs of distress welling up from deep within its physics-bound heart, and attend to them right away. We work as a team, the structure and I, in this fluid and congenial fashion, always prepared to take big chances and make major changes as unexpected ideas for elaboration and refinement come along.

As the structure reveals its own primal shape, I'll often allow this to remain its form, even if different from my original vision. Each IC of the hundreds I have designed was shaped by forces deeper and richer than a *one-dimensional list of objectives*, even though these might have been subliminal guideposts. What finally emerges, in the best cases, is a well-balanced child of many such forces: a product well-trained, disciplined in the primary tasks it has to faithfully execute during its life on a circuit board, as learned by one deeply involved with issues of *usefulness and suitability*, not by the dictates of an inflexible and heartless *Product Definition*.

RADIO AND TV EXPERIMENTS

By 9, electronics had become my daily diet. I experimented with dozens of circuits, trying out new forms, blithely unaware of all the prior work. Replicating something found in a magazine was no fun at all. A sufficient few of these *How About?* circuits actually performed a useful function! This was how I discovered regeneration in a short-wave radio. I was too young to have the knowledge or the patience to perform a pen and paper analysis *before* picking up a soldering iron. Initially, these circuits used ancient components that were screwed down on to a thick wooden board, usually with another, thinner board forming a front panel for mounting switches, pots, lights and binding-posts. These *really were* 'breadboards' **(Figure 4a)**.

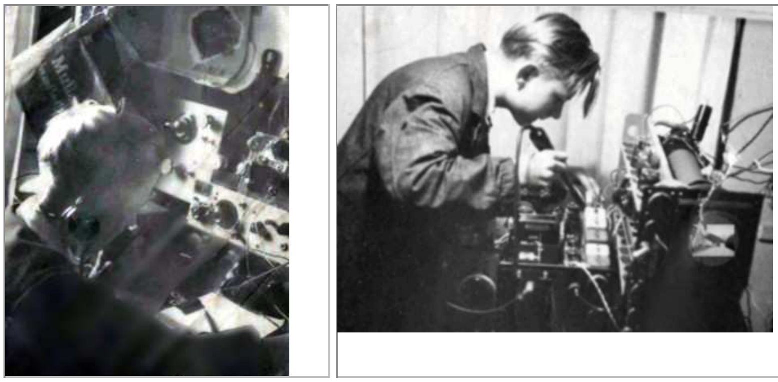


Figure 4. In my natural habitat, the Happylab, about 1946; (b) Later, still there, probably at midnight, doing something gross to one of several home-brew TV receivers, 1951. My elder brother took these pix.

In a vivid recollection from 1946, I was experimenting with a simple amplifier, at one end of our table, at the other end of which my mother was ironing clothes on thick, grey blankets, using two smoothing irons alternately heated on the coal fire. Its two stages were identical, each comprising a triode with a resistive load from its anode to +120V. A capacitor from this first stage coupled the signal to the grid of the second-stage triode (**Figure 5a**). My headphones were connected to the second-stage anode through a capacitor. Touching my finer to the input reusulted in a hum, emanating from the neighbors' AC supplies, mixed with the demodulation of the strongest of the AM radio signals. I later found it was more exciting to connect its input to the telephone wires on an outside wall of our house. We had no phone. The unused wires just hung alongside other lines. But *they* frequently *were* active, and their inductively-coupled conversations were quite clear; and often interesting!)

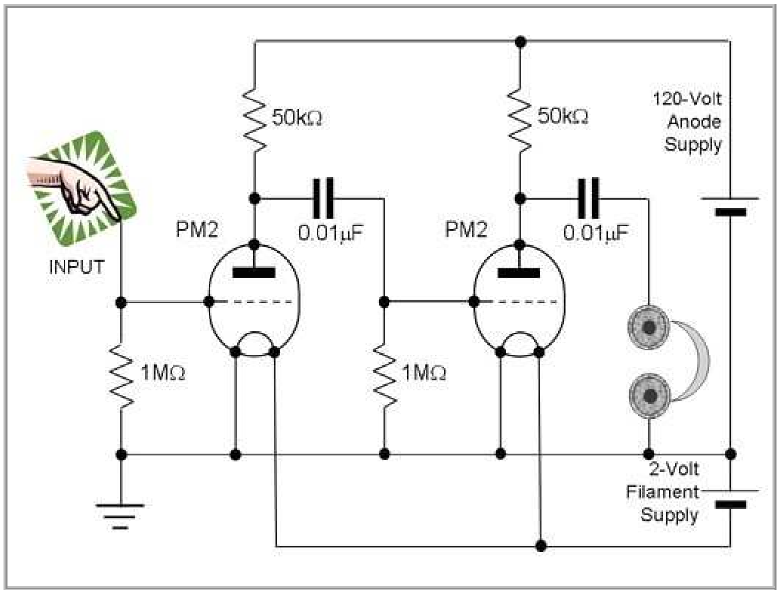
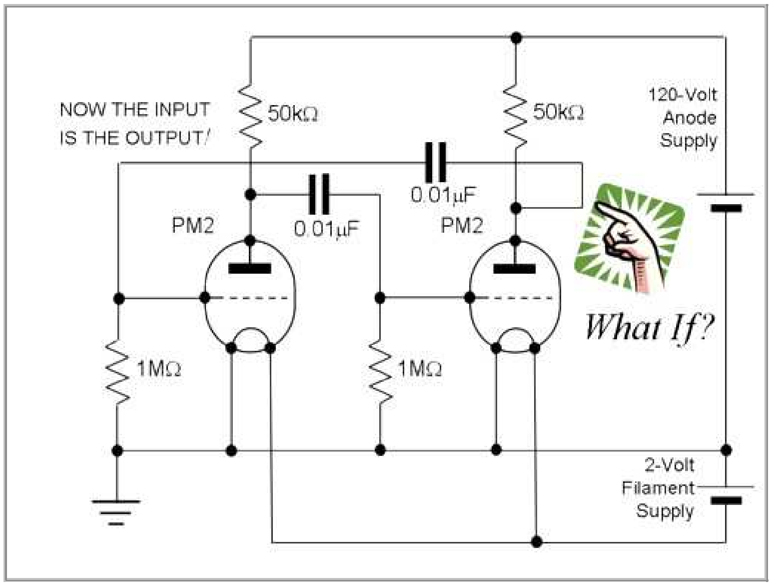


Figure 5. "Inventing" the classical multivibrator. (a) Starting with this two-stage amplifier, I asked *What If?* the output is connected back to the input. (b) Lacking a 'scope, I learned the circuit was oscillating only because of the radio interference it generated, the anode voltages being rich in harmonics.



On this occasion,with questions of the *What If?* and *How About?* sort sizzling in my head, I connected the output of this amplifier back to its input (**Figure 5b**). Immediately, the music on the family radio was hashed by fizzing whistles. Tuning over the frequency span of that receiver, I noticed "my" whistles came and went. More careful note-taking revealed that these squeals were spaced at regular frequencies and appeared to form low-integer ratios. I accidentally discovered two things that day: a basic type of *cross-coupled relaxation oscillator*; and its ability to generate not just *one frequency* but many, in perfect ratios!

Later checking books in the library, I found a similar circuit. In another of these books, I came across something wonderful called the *Fourier transform,* and realized that this might be pretty useful, as it explained the ratios in my scribbled notes about that experiment. About two years later, I designed my own multi-band superhet receiver **(Figure 6)** learning entirely (although often painfully) by doing. Below decks,it was a terrible “rat’s nest”; but it worked remarkably well!

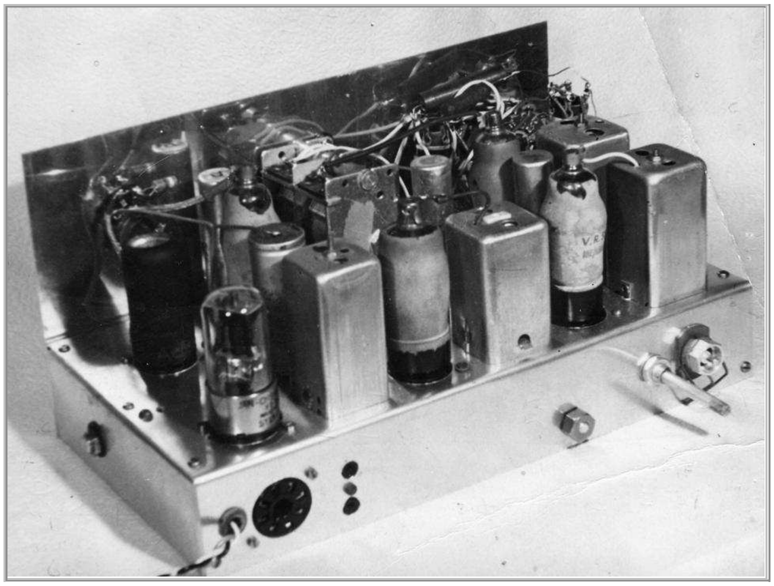
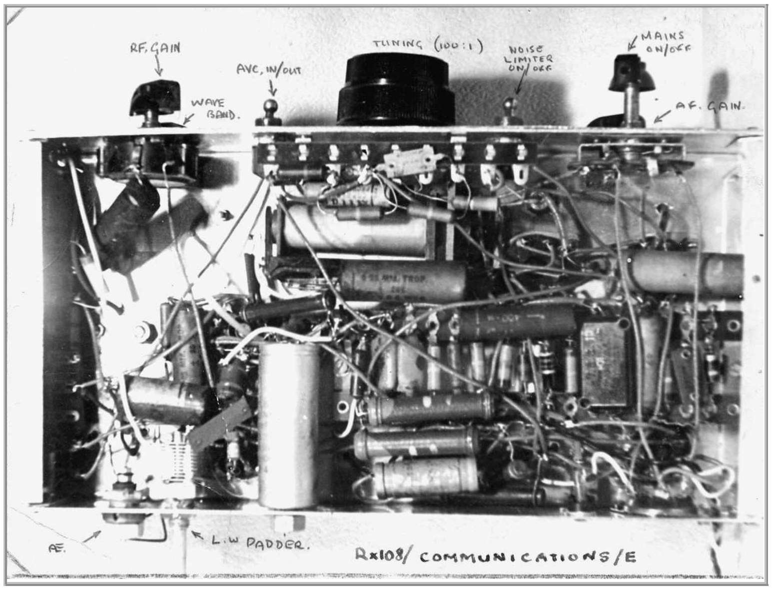


Figure 6. (a) The top-side of my first six-valve superhet and (b) the underbelly – not a pretty sight!



I enjoyed many windfalls. A lady for whom my mother house-cleaned had also lost her husband in the war, and he had left a bonanza of 4- and 5-pin tubes, audio transformers, 3-inch long resistors that clipped into holders, fixed and variable capacitors, and other basic components, most still in their original rust-spotted cartons; and scores of spools of enameled copper wire, of assorted gauges, and green-silk-wrapped multi-strand “Litz” wire.

Another mecca was a radio repair shop, run by a certain Mr. Sparks (I assumed that was his real name). He allowed me to rummage in a back room, a storehouse of beautiful old telephones and crystal sets in walnut cases, with bright brass screw-terminals (I still have one – a *GEC Marconiphone*) and two- or three-tube “wireless sets”, with fat tuning coils whose sturdy turns were held in place by heavy coatings of shellac, sporting ebony panels and overly-precise protractor dials. Inside one was an odd-looking rotating spherical coil, which I was told was a “goniometer.” Of course, I bought as many of these treasures as I could afford.

Only a few years after the terrible attacks on Britain (and the equally terrifying attacks on Germany's heartland), a glut of government-surplus stuff appeared on the market. Among my many treasures from that time were 'rotary converters' (small motor/generators sets), electromechanical servo systems, IFF receivers and many strange, exotic tubes. But it was the radar displays that were my greatest inspiration. **(Figure 7)**. One, an Indicator Unit 62A, included a 15-cm CRT and a feast of tubes; cannibalizing it and parts from a surplus UHF receiver, I built a TV receiver. Another provided the 9-cm CRT which became the heart of my first oscilloscope. I immodestly note that both of these were entirely of my own design. Building something was as much an adventure in learning as the provision of a new tool for my HappyLab.

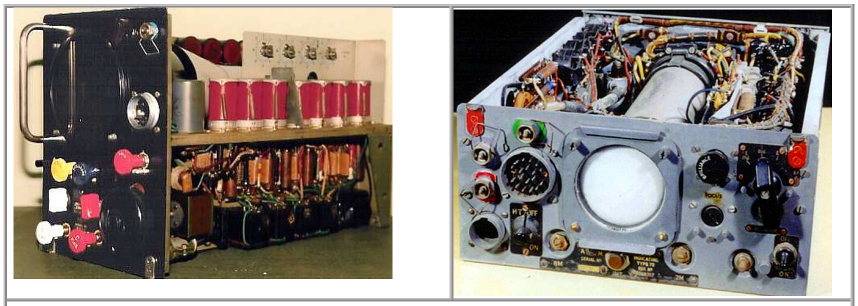


Figure 7. "Some radar 'Indicator Units' purchased as WW2-surplus equipment.

Oscilloscopes were to become a special fascination for me, traceable to my exposure to these wondrous and enigmatic radar indicator units, and I designed several as a kid, experience that was to later prove invaluable in industry. However, until we got electricity in our house, I had to carry the heavy steel chassis of my first TV receiver on the saddle of my old bicycle, which I pushed to the home of a school-friend who lived about 2 km away. Their house *did* have power, and I painstakingly tested my awkward contraption on their kitchen table. The first time it was plugged in, a spot of about 2 cm in diameter appeared at roughly the centre of the screen. A propitious start, I thought; and back it went on to the bicycle. Over the course of numerous journeys, the spot became smaller and turned into a horizontal line; the line eventually turned into a raster. One day, after another long walk to Mark Dore's house, the raster finally revealed a snowy picture. It was upside down.

EARLY "WORKING" YEARS

At age 17, I started my first job, at SRDE (the Signals Research and Development Establishment, Christchurch), as an "Assistant, scientific" in a group developing speech-encryption for narrow-band transmission. There I handled my first transistor, a frail point-contact type costing the Government an arm and a leg. It was one of three technologies being considered to replace the ECC81 double-triodes used in scores of shift-registers. The other two were trigger-tube or ferroresonant flip-flops. In the end, none prevailed, and the next generation of encoding systems would use miniature wire-ended vacuum tubes. This was fascinating and entertaining work. I recall building an 8-bit A/D converter using a special CRT with an encoded target.

But as a rookie in the job-market (to use today's jargon) I was naïve about the full scope of the charter at SRDE; and when, after a few months, it became clear that some very sinister military systems were also being developed there, I immediately left. Later, on trial as a pacifist, I was directed to work for two years in the local hospital, in lieu of military training. I provided general patient care in a ward for the elderly and the terminally sick. Many nights I would hold the hand of a dying patient and the next morning prepare him for the morgue. But electronics kept popping to the surface. I made a sensor that clipped on to the glass drip-window of an infusion set, and the associated circuitry, to display the drip rate on Dekatron counter tubes, and developed other sensors and displays to show vital signs. These simple aids could not be bought; medical electronics was yet to become a business; and the rotating plasma domain in the Dekatron was to become an important bridge between the magnetron and my carrier domain magnetron, described later.

At the end of the two years of mandatory service, my affection for the patients, staff and the hospital environment led me to request a transfer to their surgical operating rooms. The work was not always charming: more than once I carried a warm freshly-amputated leg to the incinerator. But during these two further years I developed electronic devices of a less trivial kind for use in surgery. And, incredible as it must seem, I was eventually entrusted to monitor patients under anesthesia, maintaining their critical parameters and the gas-flow rates, whenever a major emergency led to a shortage of doctors; eventually even inducing anesthesia with Pentothal and Flaxedil (a powerful muscle-paralyzing agent). At other times, scrubbed-up and gowned, the surgeons allowed me to carry out minor steps in almost every kind of surgery. Today, of course, any hint of such of thing would be, appropriately, a litigious *cause célèbre.*

Dragging myself from hospital life with teary-eyed reluctance in 1958, and back in full-time work as an electron-director, I found myself at the part-time airplane company Vickers-Armstrong, I designed triply-redundant PID systems using early germanium PNP transistors, for controlling the insertion depth of the critical moderator rods in an experimental nuclear reactor at the Atomic Energy Research Establishment, located at Winfrith Heath, close to the same chalk cliffs where the magnetron had caused such excitement 18 years earlier. AERE's charter was the development of reactors for power generation, of the kind later used widely in Britain to provide electricity.

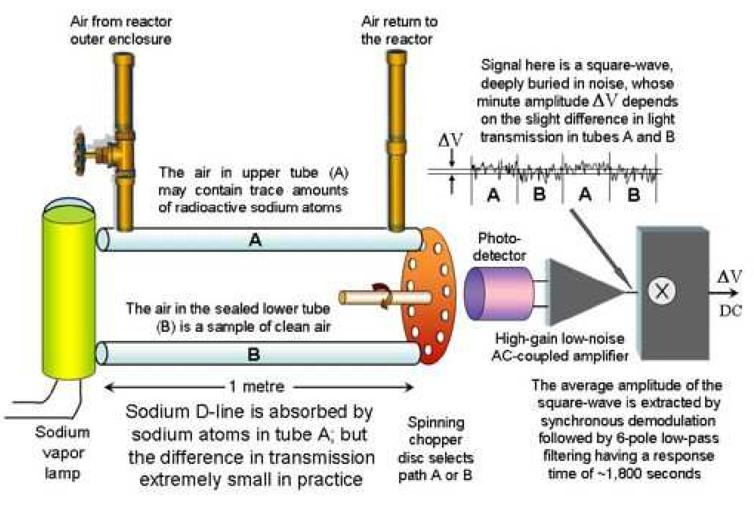


Figure 8. My leak detector monitored the status of a sodium-cooled nuclear reactor.

Seeing the need for a device that could detect trace amounts of leaking sodium, I proposed a detector system that chopped light between an air sample in a tube from the reactor housing and a second tube filled with outside air **(Figure 8)**. Using synchronous demodulation and averaging over a very long interval (many minutes), I figured this scheme should be able to detect trace amounts of sodium vapor. No-one at Vickers showed any enthusiasm for the idea, so I built it. A need was recognized, and the solution provided, *before being requested*, which I believe to be the hallmark of the serious inventor. Whether or not this is a tenable position in these tiresome days of what is called "market-driven innovation", this has always been my personal mantra, and was to become an attitude I would encourage my team to adopt, and known as 'inciting to mutiny' at the Analog Devices NW Labs in Beaverton. Incidentally, this was the second-only remote design site of ADI, established in 1979, the first being that archetypical one in England from 1972-77 – a risky step that Ray Stata described in a 1985 article in Forbes Magazine **[4]**.

A MAJOR EPIPHANY

After moving to Mullard, in 1959, I saw a Tektronix oscilloscope for the first time**.** Its ergonomics, its precision and ease of use inspired me to design an entirely new dual-channel *sampling plus real-time* oscilloscope along the same lines. I was never asked to do this, but I believed it would surely be needed soon to provide ‘millimicrosecond’measurement capabilities (the ’scopes of the day were limited to a bandwidth of about ‘10 Mc/s’ with poor geometry, spot-size and almost no time- and voltage-calibration) while at the same time providing a good demonstration what these things called ‘transistors’ could do, first, by publishing all of its circuitry in full detail in open papers, then using it to develop faster devices and circuits.

The L362 was a crude yet trail-blazing sampling ’scope, based on a design by Chaplin and Owens from the Royal Radar Establishment that had been commercialized by Mullard. One is visible on the left of Figure 9a. When it was learned that these oscilloscopes were failing by the phalanx in the field, my personal rationale to build it finally came along, and no-one was saying “No!” (nor even “Yes, *good* idea!”). The failures were due to the stresses caused by avalanche operation of its germanium alloy-junction PNP transistors. Being familiar with this mode of transistor operation, I was given the job of “finding a quick fix”. Instead, I designed a radically new kind of oscilloscope, closely mimicking the appearance of the Tektronix 545 scope, as a sort of homage, but also to exploit familiarity and ease of operation **(Figure 9b)**.

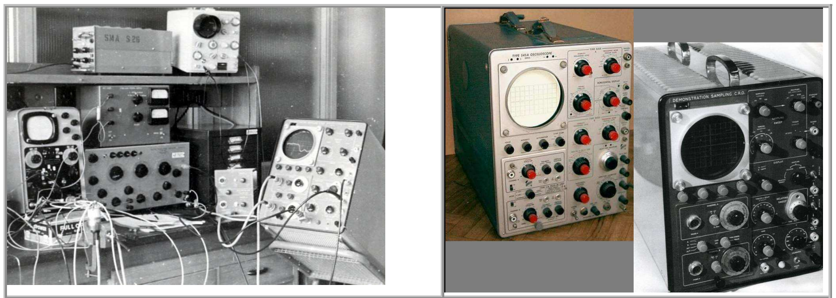


Figure 9. (a) The L362 oscilloscope (on the left) and my own sampling oscilloscope (on the right); a second plug-in can be seen. (b) Shows its similarity to the superb Tektronix 545 oscilloscope.

It was a rare occasion when I felt comfortable about emulating a masterwork. Its designers evidently had an exceptional understanding of the importance of ergonomics in crafting the human interface – the “front panel.” The presentation of each of the functions (which were literally at one’s fingertips, just behind each knob) were very clear; the use of color to identify these functions; the way in which this ’scope faithfully and precisely executed its promised behavior – all these were exemplary, and quite unprecedented. My interpretation of this was that the folks at Tektronix had *a deep empathy for the needs of the customer*. This was a powerful object lesson in itself, although it resonated fiercely with my own passion to put electronics at the service of people.

Whether designing systems, instruments or ICs, it is our job as creative engineers to make customers’ lives a little easier, and *their* work more enjoyable. (In doing that, our lives will be enriched, too). A project must start with such questions as: *What Must Be?* (that is, what are the *external* requirements and constraints that put bounds on the project?); *What If?* I put myself into their shoes: how would *I* like this new product to work? *How About?* adding [some feature] to make it more useful? In this *empathic approach to design*, one constantly alternates between the customer’s perspective – looking *into* the shop window – and one’s *outward* view from the back-room workshops of novelty.

The design of this oscilloscope (and later in life, of ICs) came out of that philosophy. To begin with, I decided it should *look* like a 545 with the same familiar arrangement of controls and functions, allowing the user to immediately apply his knowledge about a similar instrument of this sort and feel comfortably expert. Thus, often the customer was, and is, myself, whether designing an instrument or a novel-function IC. Later, Solartron made a hundred copies of a sampling add-on unit I designed (described in the references) to functionally and visually complement one of their low-cost 30-MHz 'scopes (top-centre, Figure 8a).

Just as fine art and great music projects a sense of effortless simplicity while concealing its complex root resources and techniques, my deceptively familiar-looking oscilloscope was a *very* different machine inside. It used the same Tektronix CRT and other parts, from the high-voltage-supply rectifier to their unique ceramic component mounting strips and control knobs; and it needed the help of a handful of ‘valves,’ for example, as high-input-Z cathode followers and CRT plate drivers. But beyond that, it was *fully transistorized.* One may wonder how I pulled this off, in 1959-61 since those early devices were pretty slow. But this is precisely the beauty of the sampling technique: in a single step, it can transform gigahertz phenomena into benign audio-bandwidth signals **[5]**. It is a sort of magic, a modern *léger de main.*

In the ‘Delaying’ mode, it operated as a conventional (real-time) scope: just as in the Tektronix 545, this slower ‘B’ timebase could be used to precisely delay a trigger to start the fast ‘A’ timebase, whose time-range was shown by a gating bright-up. When the ‘Delayed’ mode was selected (or using the ‘A’ timebase alone) this clever machine seamlessly converted to a dual-channel 700-MHz *sampling* oscilloscope, having the novel benefit of *high-impedance probes* (all early instruments used 50-Ω inputs). These probes included the sampling gate proper and the crucial “strobe pulse” generator, using a special transistor, the ASZ23, I had developed with the process people at Mullard, to operate reliably in the stressful, high-energy avalanche mode.

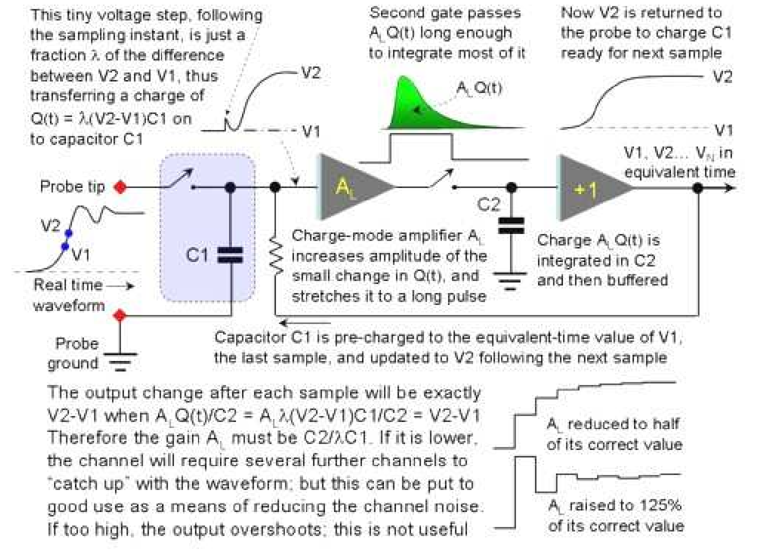


Figure 10. Sampling-scope processor using predictive feedback, novel in its day.

For the first time in a sampling oscilloscope, to my knowledge, a closed-loop system was used to ensure *near-perfect linearity*. In this scheme (**Figure 10**) the previously-acquired sampled voltage is fed right back to the load side of the sampling gate – *one step from the probe tip* – thus predicting the next output of this gate and allowing it to operate simply as an *error-detector,* affording a near-exact unity closed-loop gain. You could compare this to the operation of an op-amp connected as a unity-gain voltage-follower, though with a more complicated forward-gain path. It is also called a ‘slide-back’ scheme, a reference to Kirchoff’s practical implementation of Hunter Christie’s clever technique for measuring a voltage to state-of-the-art accuracy **[6]**. It allowed these probes to make multi-digit voltage measurements at the node being investigated, at any time-point on the waveform, and display these on an external DVM. Alternatively, the sampling channel could as easily be used simply as an accurate DC "preamplifier" whus avoiding the loading effects of a typical multimeter's high input capacitance. It occurred to me at the time that it would be wonderful if this digital data could be actually presented right on the CRT – an idea that later saw fulfillment at Tektronix.

Early in this development, I discovered that by lowering the gain of the loop amplifier (A_L), and exploiting the *high correlation* between adjacent samples in a periodic-stationary signal (such as a stable-frequency sine-wave or pulse-train), the noise on a displayed waveform could be greatly reduced, at the risk of some time-smearing. As has often been the case, the theory came later (and it is simple). So I exploited this, as a user-adjustable function, for each channel independently. Later called “smoothing”, it became a standard feature of progressive-time samplers for averaging a wave vector. An ingenious advance, the random sampler, later invented by Frye and Zimmerman at Tektronix, no longer required the user to provide a *pre-trigger* in advance of the waveform segment of interest. This was a great step forward. However, the random locations of the sampling instants preclude the benefits of such smoothing.

I was understandably proud of these advances in oscilloscope design, much ahead of their time. Looking back almost 50 years, I wonder where I found the energy to do it, single-handedly, but for the invaluable help of an excellent mechanical engineer whose name I confess to have forgotten. (I recall he preferred the mature Mahler's 9th to my preference, at the time, of the spooky *nachtmusik* of the 7th.) Its two, matched, high-bandwidth channels with high-impedance probes, using the robust ASZ23 avalanche transistor for strobe-pulse generation **[7]** the feedback sampling loop **[8]** the low-jitter timebase for real-time sweeps and precise trigger delay,and its linear nanosecond-scale timebase for equivalent-time modes **[9]** – all required entirely new approaches. All of its circuits were nonexistent transistor topologies in the 1960's, and they had to be implemented using the low-frequency alloy-junction transistors of the time.

The Monsterscope had other tricks up its sleeve. Simply by pressing a button, an accurate, *multi-color, plain paper* copy of the waveforms appeared effortlessly on an analog XY plotter. This was yet another novel, and obviously valuable, operational feature stemming from the time-translation process (comparable to the benefits of frequency-translation in a superhet receiver). However, it led me to stumble on an exceptionally powerful noise-reduction technique **[10]**.

This was an unintentional benefit of the tiny analog computer (using the same old PNP transistors!) which I had initially incorporated for the following pragmatic reason. Conventionally, the *equivalent-time* sampling instant progresses at a *constant horizontal rate* across the waveform tracked by the X-location on either the CRT or the plotting table. A abrupt change, such as the edge of a pulse, would cause the |*dV/dt* of the time-transformed output to rise. But very rapid changes could not be tracked by the analog plotter's Y-axis servo, which first would be slew-rate limited and then severly overshoot, causing the plotted waveform to be seriously distorted. The problem could be averted by using an extremely slow horizontal progression; but this was an unsatisfactory way to cope with a few rare regions of rapid change.

The "analog computer" (**Figure 11**, updated here with NPN transistors) *subtracted a current proportional to |dV/dt|* from the fixed current which charged the capacitor in the plotting-specific time-base, which determined both the equivalent-time sampling instant and the plotter's X-position. At a pulse edge, the *|dV/dt|* reduced the charging current, slowing the progression of the sampling instant. Consequently, the |*dV/dt*| dropped. The *self-adjusting* dynamics of this control system resulted in the pen moving at a constant *scalar speed*, whether strolling across 'flatter' regions of the waveform or *climbing straight up near-vertical edges*. The reconstructed waveform geometry was completely free of the usual aberrations due to a plotter's mechanical inertia. Another amazing bit of *léger de main,* which could equally be applied to the CRT display.

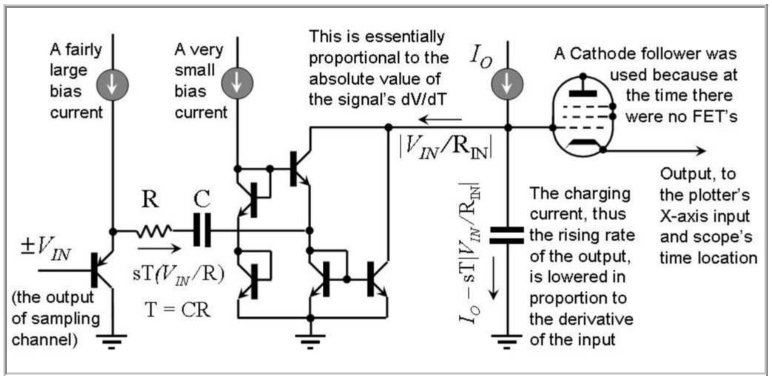


Figure 11. This simple analog computer ensures high-resolution in plotter-generated hard-copy.

Here's where some more magic made a welcome appearance. This speed-stabilizing process *incidentally* resulted in the transformed waveform being *trapezoidal in real time.* (Think about it). The glacial slope ofthis *intermediate representation* of the waveform allowed heavy averaging to be applied with no smearing of rapid pulse edges on the reconstruction; indeed, without being noticeable at all. **Figure 12** – an actual CRT photo and pen-plot, extracted from [10] – illustrates the routine way in which this little analog computer exhibited mischievous disregard for the tyrannical rule of noise and averaging statistics. The nonlinearaveraging of this *rate-adaptive* filter provides a far higher degree of noise reduction, over a given time interval, than is possible by linear filtering. To my knowledge, this neat technique hasn't been used since, although modern embodiments and applications would be straightforward.

For example, in a conventional spectrum analyzer, where the band of frequencies of interest is progressively scanned at a constant rate, the representation of signal power shows many sudden sharp peaks. These often limit the permissible minimum IF and video bandwidths, unless an inordinately slow scan can be tolerated. But these are benefits one may need to invoke: very low receiver bandwidths raise the resolution acuity for tiny, narrow-band signals nestling alongside much larger "interferers", as well as reducing the noise bandwidth. A technique such as just described could be very useful. Likewise, when vector data is pre-stored in RAM, the rate of withdrawal can be controlled, and DSP can perform the discrete-time differentiation of the signal.

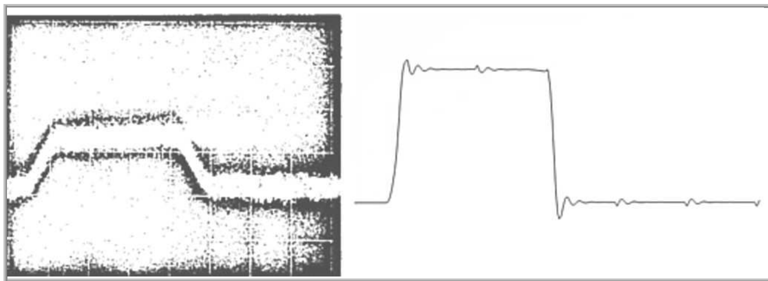


Figure 12. Pulse details buried in a noisy screen display are clearly revealed using rate-adaptive scanning.

HIGH JINX at TEKTRONIX

Monsterscope had introduced several breakthrough in sampling scope design, and it became my *open sesame* to jobs in the US. In 1964, with a plane ticket to Hewlett Packard in Loveland, CO already in my hand, I switched preferences to Tektronix in Beaverton, OR (at a 10% lower salary) after an eleventh-hour phone-call from their VP Lang Hedrick. I joined a group designing sampling scopes (what else?), directed by the energetic Norm Winningstad. However, I was soon invited by Wim Velsink to join a new team to develop an exciting family of laboratory oscilloscopes. This team included a clever youngster named Les Larson, with whom I enjoyed a close collaboration for many years.

Out of this "New Generation" project came the acclaimed 7000-series: an ambitious design, with many advances in structure, function and implementation. The first product would accept four plug-in units. Numerous new plug-ins were to be designed. Of special note were John Addis' exquisite low-noise differential amplifier with selectable HP and LP filters, and the ultra-compact dual time-bases and sampling-scope units (the latter using two of the available slots) designed by George Frye, Al Zimmerman, and Gene Cowen. It was to be permissible for any plug-in to be placed in any slot, in any combination; the 7000 had to infallibly operate as "expected". (Thus, one could swap the vertical plug-in and the time-base if one's head happened to be oriented 180° to the horizontal).

Furthermore, its back-plane/router (largely Les Larson's work, with some involvement on my part) needed to support very high vertical and horizontal bandwidths, since the more-upgradeable plug-ins were expected to get faster as the years went by. The 7000-series had to last forever! Needless to say, these grand objectives made even the *physical* design of the back-plane – the mechanical interfaces to the plug-ins, the choice of connector types and the fixed set of pin assignments extremely challenging – quite apart from how the signals were supposed to be routed to all the right places! And all this would, for the first time, make near-exclusive use of Tektronix ASICs.

These instruments would also extend the practice – first used in the Tektronix 576 Semiconductor Curve Tracer – of showing the major operating conditions, set up by the control knobs, in the same area as the waveforms. Hiro Moriyasu wanted to use bundles of coherent fibres, illuminated in each plug-in unit by passing light through characters printed on plastic discs attached to the mechanical control shafts. As these were rotated, new characters would be projected through coherent optical connectors at the plug-in/mainframe interface, then through more fibre bundles up to an area to the right of the CRT display. (You will find the 5-mm-diameter holes in the plastic molding at the rear of these plug-ins where Hiro's fibre bundles were expected to go; an indication of how close to production this approach had progressed).

While this scheme needed no extra "fancy electronics", in an already complex design, I felt it would be a mechanical engineer's nightmare, from the registration tolerances at the interfaces, to the snaking of dozens of fibre bundles from the dense plug-in mother-board up to the front panel alongside the CRT. It was also hopelessly inflexible, for an instrument intended to have a long production life. I frankly expressed these and other concerns to Hiro, who was, typically, quietly adamant that his was the best approach.

I already had all the key ideas for a novel, tight-knit set of ICs for a fully electronic 'knob read-out' (KRO) system, that would adventurously exploit the new possibilities opened up by custom analog integration, using Tektronix's new wafer-fab. I built a working demo using *Teledeltos paper* circuits(!) for my all-analog character ROMs (this was long before IC memories) and showed it to the company's president, Howard Vollum. Its strings of alphanumeric characters, written on the *same focal plane* as the waveforms by further time-sharing the one CRT, displayed various operational settings, with independentcontrol of *size, style, position and brightness*. Howard was visibly impressed, and immediately supportive. If Hiro harbored any regrets, when his scheme was ousted by the KRO, he didn't show them.

Howard was an ardent and enthusiastic engineer, deeply involved in the technical life of his engineers, even to the point of sitting down with them over a breakfast at Tom's Pancake House on Canyon Road and actually talking circuits! **(Figure 13)**. What president of a large technology company now has the time to do that? (Answer: Every one of them has exactly as many hours today as did Vollum back then). Rather like the *Square and Compass* was 'the only pub in town' for the TRE folks, Tom's was just about the only restaurant in Beaverton, in the mid-1960's: close to the Tek campus, to the Satellite Motel with its garish flashing 'flying saucer' sign, and the little airstrip where many Tekkies parked their planes. We thought nothing of flying to the coast, 70 miles west, for a change of scenery and a fully-stacked hamburger, of the kind just as easily found at the more proximal Skyline joint, but rarely found anywhere today!

Figure 13. Howard Vollum (right) and I talk shop over at Tom's Pancake House, 1968.

We were all working in new and unfamiliar territories, feeling our way forward by instinct, rather than by reference to maps, and I was now in the hot seat to deliver this synergistically co-integrated system quickly, at low cost. In one unusually productive year, I designed 15 ASICs for this unique knob-readout system. Its most interesting aspects related to the design of the superintegrated character generators: analog ROMs.These evolved in form, becoming more sensible and efficient in their structure over three generations of prototype approaches **[11]**. My decision to use *fully-analog data-coding* also raised a lot of eyebrows and was declared to be unworkable. (Clothed in Teflon criticism-deflectors, it's easy to respond to naysayers with an absent, bemused smile). Two sets of ten-level analog-current sequences would access locations on a 10´10 matrix; about 50 corresponded to characters, the rest were special instructions, such as those related to shifting the interpretation of the data when attenuating probes were added. (I learned recently that when these inscrutable 10-level data codes had to be adapted to a new all-digital scheme for readout, they caused immeasurable grief!).

In those days, the schematics were hand-drawn on pale green engineering pads, and handed directly to the small layout team. After only a few rough sketches, they picked up their "scalpels" (Exacto knives) and began to make cuts on the thin red-plastic film bonded to a stable mylar backing. The maker's name for this material was *Rubylith*, so these masters were called "rubies". About a dozen rubies were needed to define all the photo-layers for Tek's first NPN-only process, having an f_t of 0.6 GHz. After cutting the polygons corresponding to one layer of the final IC (say, transistor emitters) the red film in all these regions had to be manually peeled off, making many clear windows; then each was hung on a large back-lit surface and photographed at x500 reduction. It became the designer's responsibility to check the accuracy of the rubies using a multi-color x100 set of these images, overlaid in the actual sequence of process steps.

In this tedious process, errors were easily missed. For example, the hundreds of 10-µm contact polygons for emitters, as cut regions of film, were only 5 mm square on the ´500 rubies, and often not stripped off. This oversight could easily go unnoticed in examining the 'overlays,' as a missing 1mm opening. An easily-committed error, with disastrous consequences. But in spite of all the labor-intensive steps in going from HB pencil-lines to a complete and accurate set of rubies, then the IC masks and the waiting days in wafer-fab, first silicon invariably worked well enough to be final silicon. On a wall at Tek where Les Larson still works, he proudly displays the schematic of their first production IC, the M001. The 7000-scope took us up to about M059 (a 4-decade superintegrated counter/latch/quad-DAC of mine, for a DVM integral to the readout).

TRANSLINEAR TOMFOOLERY

In my spare time – my *best* times – at Tektronix I developed an extensive new class of *current-mode circuit-cells*, based on what I later named the *Translinear Principle* **[13,14]**, and also vigorously exploited what I called *super-integration.* These included super-compact logic cells, a foretaste of I^2L **[15]**, and an intriguing class of semiconductor devices based on *current domains* – narrow, mobile regions of current injection which can be *physically positioned* on the chip either by magnetic fields or applied voltages, to realize *components* such as solid-state potentiometers and common *functions* such as analog multiplication **[15]**. Many of these inventions were announced in ISSCC papers, and to my surprise, they garnered a clutch of 'Best Paper' awards.

My first ISSCC paper **[16]** was one such. It described some ideas that are especially neat, and was later expanded into a pair of JSSC papers **[17,18]**. I am told these were the first JSCC papers to have been cited at least 100 times; and I've been asked to comment on the impact of this body of inventions. One way to assess their impact is to note that for decades thereafter scarcely an issue of the JSCC went by without at least one reference to one of these papers. Another is the fact that only today I devised yet another unique topology within this tight genre of 'stem cells'. Yet another is to note that, in my office, I have a do-it-yourself crystal-set kit, presented to me on my 60th birthday, on whose cardboard box a friend generously wrote *"The only radio that does not contain a Gilbert Mixer!"* Let's leave it at that; the truth is always more nuanced.

Those early papers only scratched the surface. A much deeper lode was already being mined, even as I wrote them, namely, the *translinear* gold-mine, although I coined that term later, and didn't publicly advocate its use until 1975, in a brief *Electronics Letters* item. The ubiquity of these ideas quickly became evident, and led to scores of other papers, at first by myself, and later by others, including Evert Seevinck (I was his PhD advisor) who added, to my initial twenty or so basic translinear topologies, some ideas about formal synthesis; and with my agreement wrote the first book on the topic **[19]**. Special Issues in many of the Journals, and full Conference sessions, followed.

What was the Big Deal? As much as anything else it was the arrival of '*current-mode'* as an eminently practical and advantageous signal processing paradigm, enabled by the BJT. As ideas go, it was deliciously rebellious, and potentially iconoclastic, while also of immediate value. More recently, I have tried to discourage the lax usage of the term *current mode* in papers, since in practice, good circuit design requires the use of whatever "modes" – and thus the principle state variables – as are appropriate at each stage of the processing chain **[20]**. However, so far, my sage advice seems to have gone unnoticed! One can still find numerous papers with titles like *A Novel Current-Mode Filter*; but no-one is staking claims to *A Novel Voltage-Mode Filter*. Yet both must equally depend on the *interchange* of voltage *and* current states.

The *current-mode paradigm* all started with the *current mirror*, a cell that had no equivalent in vacuum-tube design, mostly because tubes are "depletion-mode" devices. Since a mirror accepts a current and delivers a current, and the voltages associated with the cell are largely incidental, it was the first genuinely useful *current-mode cell.* Its "gain" is also described in current-transfer terms, and in the basic form of the mirror, this is fixed by the ratio of emitter areas, A_2/A_1 **(Figure 14a)**. In fact, it's easy in principle to electrically alter this gain **(Figure 14b)**; but I was curious about another possibility. *What Would Happen If?* I were to set two mirrors side-by-side (**Figure 14c)** then, after *severing the emitter branches* of just the *output* transistors from their roots, I enjoined them *to hold hands, one-to-one?* A marriage made in Imagination!

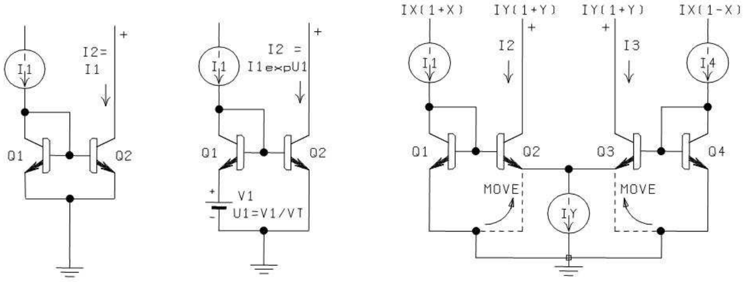


Figure 14. Transformations of the current mirror, leading to a new multiplier form.

My matchmaking efforts fostered a radically different cell concept: a new creature. Two mirrors were transformed into a tightly-knit – indeed, indivisible and enduring – unit of four transistors. Now, the collector currents I_{C1} through I_{C4} were forced to honor and obey the (yet to be codified and ratified) Law of Translinearity: which requires that $I_{C1}.\,I_{C3}$ º $I_{C2}.\,I_{C4}$ under certain trivial and readily-met assumptions. In other words, here was a circuit form that did not process signals as *voltages mixed with currents*, but thrived entirely on a diet of *current-ratios*. Such ratiometric representations were a totally new sort of signal processing-paradigm. And *that* was the Big Appeal.

By casting the inputs I_{C1} and I_{C4} into the *complementary* form shown, using the notion of a *modulation factor X* acting on a fixed bias I_X, and supplying a *tail current* I_Y, we find that *Y*, the modulation factor in the output, is simply identical to *X* , over the full *large-signal range*-1 £ *X*£ +1. This identity doesn't depend on I_X and I_Y, nor the transistor scaling, nor the technology, nor temperature, nor (in moderation) on supply voltages. Even the BJT's finite beta does not impair this identity! Viewed as a novel linear amplifier, the gain is simply the *ratio* I_Y/I_X. No amplifier before (or since!) could claim to be linear *to the extremities* of the signal range that is, from the limit X = -1 *right up to* X = +1. Further, by varying I_Y, we had an elegant, wideband, inherently linear *two-quadrant multiplier.* The extension to four-quadrant operation was easy.

In fact, the actual trajectory of the invention was slightly different. It started with another rudimentary cell, the differential pair – the topology assumed by Q2 and Q3 in Figure 13 (c), once their emitters were joined – which forms a crude *transconductance* multiplier. But this cell is *nonlinear* with respect to what may be called its "X" input, the voltage V_{B2}-V_{B3} (the tail current I_Y being the "Y" input). I asked: *How About?* using a similar nonlinear pair to cancel theinherent *tanh* form of this transconductance. (I refer to this design-think as an appeal to a 'homeopathic cure' – the elimination of a cell pathology by appealing to a mathematically similar one in an inverse mode). The first account also avoids any reference to *intermediate* and merely *incidental* voltages and thus holds true to a pure current-mode theme. And it demonstrates how tiny gene-slips in the chromosomes of an analog topology can strongly impact the near-identical mutant, having critically modified its DNA (Design, Nature, Applications).

During a leave of absence from Tektronix (1970-77) to expose my young family to a taste of life in Europe, and before being 'discovered' by Ray Stata of Analog Devices in 1972, to set up the first ADI remote design center, I took a job as Group Leader at Plessey Research Labs, managing a variety of ambitious projects. One was a holographic memory: a translucent cube of about 25 mm on a side was written by several lasers; we hoped to cram a gigabyte of data into it – unthinkable at that time. To my surprise (and only because the Department Head died of a heart attack) I also briefly managed MOS memory development. As these became faster and denser, the holographic research was eventually eclipsed. Another of my project responsibilities was the development of a new high-speed optical character recognition (OCR) system. Its front-end image processing circuitry used what I called *multi-channel adaptive threshold*. (Today, these circuits would be classified as 'neural networks'). The Plessey 4200 systems that were currently in the field had 160 analog adjustments, each of which needed an expert in the field to align. I insisted that a key objective for the new system (intended for the British Post Office) was that it should have no adjustments. In the end, there *was* one: an iris in front of the camera lens! In reading the addresses on sometimes fuzzy or faintly-typed envelopes at very high throughputs, its recognition accuracy was the highest ever reported.

I also had 'spare time' to design several communications ICs at Plessey. In one, an HF modulator, the distortion generated by the DV_{BE} nonlinearities of a BJT differential pair were sensed as they *re-appeared in a differential cascode* and applied to an auxiliary *gm* cell, which added correction currents in anti-phase at the final output – a technique I named *feedforward correction*. Such 'homeopathic' techniques, first exploited in the earlier "current-mode" cells at Tekronix, addressed both the *signal-dependent nonlinearities* and the much slower time-dependent V_{BE} errors associated with the *power-induced temperature shifts* in these transistors. They provide a good example of the *"continuity of concepts"* themes that permeate one's life.

Incidentally, Plessey were hopelessly unsupportive. They saw fit to ignore the patent disclosure I filed on those thermal correction techniques. And after having had a previously-cleared paper submission to the ISSCC accepted, they refused to pay for travel to the conference and a hotel. So I paid my own way. Apparently shamed by this, they reneged a month after I returned.

Later, back at Tektronix, I shared the thermal-correction concept and later elaborations of the cells with Pat Quinn. It became widely used to avoid the previously serious thermal distortion in vertical (Y-axis) deflection amplifiers, and known as the *CasComp*. Today's BJTs, fabricated on silicon-on-insulator (SOI) processes, exhibit thermal resistances often higher than 10,000°C/W. Extraordinary care is needed to combat the effects of non-isothermal operation – one of the firm promises made by transistors when they first roamed the planet. Translinear cells fare especially badly: for I_C = 1mA and V_{CE} = 1V, the DT could be 10°C; at, say –1.8mV/°C, this translates to a whopping –18mV of DV_{BE}, causing a 2:1 current-ratio error in a TL loop! This concern led me to introduce thermal modeling into our simulator's BJT equations at ADI, about 20 years back, now standard for all processes. It is sobering to watch the consequences of turning the self-heating terms back on again, after briefly being off.

I had developed an excellent rapport with ADI and a great respect Ray Stata – an "engineeer's engineer" like Howard Vollum – while designing the first laser-trimmed IC multiplier (AD534), the first monolithic RMS-DC Converter (AD536/636), and first IC V/F Converter (AD537) **[21, 22, 23]**. But my life-long fascination with oscilloscopes and my regard for Howard remained strong: now my loyalties were in an awkward tension. When the family traveled back to the USA, in 1997, this angst compelled me to return to what I had come to regard as my *alma mater*, Tektronix, where I felt there was unfinished work to flush out of my system. Anyway, I could still "do ICs" there, I reasoned. (My car sports IDO ICS plates).

A LINK TO MAXWELL

A memorable assignment took me back to the lair of Philip Dee (remember him?) – the Cavendish Labs at Cambridge University, to spend time in the company of the world's largest vacuum tube, their 2-Angstrom electron transmission microscope. This monster was nearly a metre in diameter at the viewing ports on the ground floor. From there it rose up through three floors; at the top, the cathode was supplied with 700 kV, donated by a huge transformer and rectifier inside a shielded room.

My thing was to provide the electronics to measure the cathode current. It used a V-F converter I had designed at Analog Devices (the AD537 – the first monolithic V-F, still in the catalog). One of the useful features of this empathy-borne IC was that I'd made sure it could optionally supply large currents to an LED at its square-wave output. The buzzing light then dropped down through the three floors on a thin glass fibre, to the working desks at the anode levelwhere the scientists struggled to see Very Tiny Things through very thick windows, fiddling with "my" cathode current, I suspect, in a struggle to improve the contrast of these images.

Once, my host mischievously defeated the safety interlocks and opened the door to the EHV room while the supply was operational. I felt my hair being tugged forward by the fringing field just outside. With the power off, and the interlocks again grounding everything in sight it was safe for me to enter and work on the cathode-current monitor. But of course, to make my calibration adjustments, the microscope had to be fully operational; so I blissfully toiled in this little room at 700 kV "below sea-level"!

As an invited lecturer at Cambridge University, I was delighted to learn that the classroom in which my talks were to be presented was the very one used by James Clarke Maxwell, while teaching his new mathematical theory of electromagnetism. The musty atmosphere descended on me with the full weight of history. The students' desks were the original ones, with initials and other cryptic symbols carved deeply into the noble dark wood, rising toward the back from the speaker's level, and the long demonstration bench, on which Maxwell rested his palms in an earlier age. Standing there, soaking up the vibes, and dismissing my modern audience to invisibility for a moment, I felt oddly like a distant ancestor, William Gilbert (1544-1603), who wrote *De Magnete, Magneticisique Corporibus* and, bless his wooly socks, coined the word *electricity*. In this venerable setting, I took the opportunity to remind the audience of the work ethic of another great electronics engineer, Michael Faraday **[24]**:

"Faraday never could work from the experiments of others, however clearly described. He knew well that from every experiment there issues a kind of radiation, luminous in different degrees to different minds… And here, for the sake of younger inquirers, if not for the sake of us all, it is worth while to dwell for a moment on a power which Faraday possessed in an extraordinary degree. ***He united vast strength with perfect flexibility***. His momentum was that of a river, which combines weight and directness with the ability to yield to the flexures of its bed. The intentness of his vision in any direction did not apparently diminish his power of perception in other directions; and ***when he attacked a subject,*** expecting results ***he had the faculty of keeping his mind alert, so that results different from those which he expected should not escape him through preoccupation"***. *[emphases mine]*

"MY MAGNETRON"

I started this piece by describing the marvelous magnetron. While at Cambridge, one of my lectures concerned a superintegrated solid-state device which I had devised and fabricated at Tektronix **[25]**, but had not yet tested. It invoked the same intertwining of magnetism and electricity, and because of that, my blithe interlude with the ghosts of Maxwell and Gilbert was especially poignant. In 1970, during the working period back in England, samples of this *carrier-domain magnetometer* (CDM) were supplied to Prof. Greville Bloodworth (University of York) and Prof. Henry Kemhadjian (University of Southampton), and later successfully demonstrated **[26]**. Among several Ph.D. projects spawned by this concept, Martin Manley provided an elaborate mathematical treatment of its temperature-dependent scaling coefficients, and demonstrated a robust compensation ruse. Sadly, he was killed in a car accident far to soon thereafter.

The CDM was unique in two distinctly valuable ways: first, in its ability to convert magnetic field strength *directly to frequency,* by virtue of a *circumferentially-rotating domain;* second, in having an *integrating response,* meaning that in principle *even the weakest H-field* caused a slow, but readily measurable rotation – a very low frequency output. **Figure 15** shows the principle elements of a representative device. A junction-isolated disc of n-type collector is contacted only at its center, '1.' Over it, and grounded only at inner contact '2,' is another disc, a p-type base; just inside its circumference is diffused an n+ ring emitter, contacted uniformly all around its perimeter, thus at an equipotential, being biased by a fixed current. Beyond the p-base edge is a coaxial ring, another p-type diffusion, '4,' also contacted uniformly around its perimeter and biased by a fixed current. This ring acts as the emitter of a *lateral* PNP, whose local base is also the n-type collector for the NPN section, and whose (inside) collector is the edge of the p-disc ‘2’, which simultaneously forms the base for the NPN section. Notice that the only path for the minority carriers (holes) issuing from this LPNP’s emitter is *underneath* the NPN disc-base, where the sub-emitter (‘pinch’) resistance is very high.

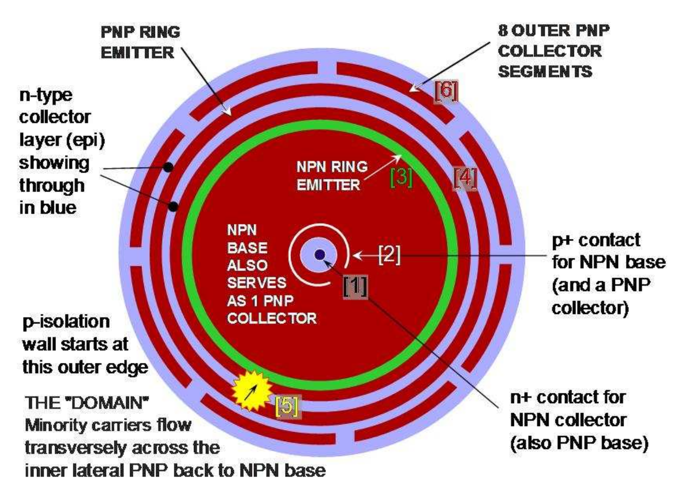


Figure 15. My “magnetron”: a superintegrated carrier-domain magnetometer.

Thus, even small currents from the LPNP in the vicinity of its emission zone can raise the localized NPN V_{BE} thus *raising its emission* exclusively in that zone. Although an elemental PNPN structure exists all around the circumference, *only one* confined region of intense current injection, ‘5’, can be supported. Since the currents I_{EN} and I_{EP} are finite the *spatial feedback* process is bounded (the PNPN loop can’t ‘latch up’); it serves only to force both n- and p-injection into a small angular range. This is the *carrier domain*: a mobile *filament of current* (roughly analogous to an ‘isolated north pole’) of a few microns in length, flowing laterally from the p-ring back to the p-base. In a perfect world, the domain would arise in a totally random location at power-up; in practice, it won’t. Either way, it is thereafter obliged to chase around the circumference under the intoxicating influence of the magnetic field perpendicular to the page, in a tantalizingly-reminiscent fashion as did in ancient times those electrons grazing the anode rim of the new-born magnetron, glowing with self-satisfaction on Dee’s bench.

Just outside the p-emitter, I placed p-type sectors forming *outer* collectors, ‘6’, in a location analogous to the cavities of a magnetron; and while these are not microwave resonators, comparisons to the magnetron are irresistible. After all, this CDM *really is* an RF oscillator, although unlike the magnetron its frequencyis proportional to the H-field strength, fulfilling its lesser destiny as an ‘H-*f* converter. Which is pretty neat; but beyond that, these things are inherently (and uniquely, I’m pretty sure) *integrating* magnetic sensors. Acting as it *should*, a domain will stroll leisurely around this circus-ring at a slow angular velocity even for minuscule fields. The direction of its stately promenade, thus the *field polarity*, can be sensed by the phasing of the current pulses generated by the outer sectors, while its *magnitude* can be ratcheted up in a counter.

Unfortunately (although predictably) my first devices suffered from a malaise I called *‘electrostiction’*. Mask-alignment skews gave the domain the determination to wake up in its ‘home state’. This forced us to go chasing after a few mega-Teslas to overcome its stubborn will, long before MRI-grade superconducting magnets came on the scene. We finally did track down a cast-off from some early NMR work (really!), quietly rusting in a dark corner of the Southampton University campus. This sticking-point was later addressed. I asked *How About?* applying a large *alternating field* having a mean value of zero, exactly as I’d once done in my home-brewed tape-recorder to thwart magnetization hysteresis in the medium. The *net angular* *drift* of the domain due to a small superimposed DC field should now be measurable, using up-down counters to integrate the pulses as it rushes in a CW- then CCW-swirling tornado.

It worked! – thus making the CDM a viable *integrating magsensor* and the only such concept to have been reported. Incidentally, when the magnetic field lies *across* the device, it acts as an electronic compass (and yes, the cosine law bears on the frequency scaling in off-perpendicular cases). I also devised *linear* structures for operation in a field-nulling feedback loop to convert an H-field directly to a proportionate DC current. Although this work was gleefully presented in lectures all over the map, in memos, letters and peer-reviewed papers, none of it was ever patented, largely for lack of time on my part. (Others gladly rushed in to fill that vacuum). The original work has found its way into a 2004 textbook by G.W.A. Drummer of electronic's most noteworthy inventions **[27]**. And, just as the terms *'current-mode'* and *'translinear'* have been rampantly misapplied, it is regrettable that so has '*carrier-domain*', being used in subsequent work on linear-mode (non-integrating) magnetic sensors.

GLANCING BACK

It has been my good fortune to have grown up through the most prolific period of genius in electronic*s*: to have witnessed its major inventions, not as a journalist, but as a *user*, being intimately involved in exploiting them in numerous applications; to have welcomed the arrival of the first, fragile point-contact transistors, not in a newspaper headline, but as an *experimenter*; to have immersed myself in silicon technologies, reaching into their rich treasure trove of possibilities, not by replicating the advances of others, but as a stubborn and fiercely independent *inventor*. Today, much of what is called electronics is block manipulation and re-use. One needs to know little about *electronic fundaments* to design many of today's IT products.

Figure 16. Scots Experimenter/Tinkerer/Inventor (ETI) Baird fiddles with his CRT-based TV receiver (1927).

Understandably (although regrettably), few of today's students of microcircuits have a *visceral awareness* of the electronics of the past century. So here's a micro-history. Perhaps the most ingenious and seminal advance was the invention of the triode tube, by Lee De Forest in 1906. However, we cannot say that *'electronics'* arose at that time. The word was not even coined until 1927, in an obscure professional paper. In that same year, using a primitive 'cathode-ray tube', the Scottish genius John Logie Baird demonstrated the first practical TV system **(Figure 16)**. In 1930, Sam Weber launched the influential periodical *Electronics*. Our journey on Big Maps had begun.

Baird's TV was a profoundly important milepost, by applying tubes to a far *broader scope of functions* than previously found in telegraph, telephone and radio. It, and radar, spawned clever circuits of every imaginable kind for specialized waveform- and pulse-generation: all described for my boyhood pleasure in the biblical *Waveforms* **[28]**, just one of the cornucopia of books in MIT's Radiation Lab series, published after the war (1949). Many of these circuits sported mystical descriptors, while others were weighed down by their names, some of portmanteau proportions (*"Hey Joe! The Phantastron sure beats the Pentode-Miller-Sweep-with-Integral-Suppressor-Grid-Gating!"*). Just as any war has propelled technology, WW2 was the essential engine of advances in electron-beam optics, which would one day become the *open sesame* to creating the ultra-fine spot-size of the magnificent CRT found in thousands of Tektronix 545's; and one more, stealthily hiding in my monster-mutant.

From 1930 onward, technologies for vacuum-tube and electron-optics developed rapidly, to a broad peak around 1950, during which time numerous and diverse types were developed, as the scope of applications grew exponentially. This progress radically expanded peoples' faith in science and technology, and expectations of a coming dream-world, already elevated beyond reasonable hope of consummation. (Even washing machines were hyped as "Designed for the Atomic Age". Nowadays, we have "Digital-Ready" loudspeakers (?), microprocessor-controlled toothbrushes (?) and "Digital-" everything else, including digital war; while Paradise is postponed).

In that same mid-century year, the transistor – the BJT – was gearing up to change the world even more dramatically. It's known as a Bell Labs "invention", but its history is very different. First, it was an *accidental discovery* of bulk conduction, in their fruitless attempt to develop a field-effect device **[29]**, although an upstaged Shockley must be credited with having predicted *minority-carrier transport*. Second, merchant-ship wireless-telegraphers were experimenting with HF oscillators (that is, with circuits that require *power gain*) using two, differently-biased whiskers on a chunk of galena *as early as 1915* **[30]**. Third, the refinement and commercialization of transistor technology – the essential know-how of semiconductor processing, the growing awareness of the yield losses due to particulate matter, the development of protective packaging techniques, and a better understanding of device behavior and the creation of models – emerged incrementally over a period of many years, and was spread over many companies and universities. No-one was the "Father of the BJT."

From 1955 onward, the use of vacuum tubes declined; twenty years later, they were practically obsolete. They now sleep in private museums, such as Prof. Tom Lee's collection of 10,000 (and mine of about 100!). But the accumulated knowledge of managing *electron beams in a vacuum* persisted. It was firmly established during the development of specialized CRTs for radar, television, oscilloscopes, medical-, analytical- and industrial-instrumentation, and countless other information displays; in the design of transmission (TEM) and scanning (SEM) electron microscopes; in complex photon detectors equipped with high-gain secondary-emission multipliers for use in such applications as neutrino detection; in *gas-filled* variants, such as the thyratron, or as gated-rectifiers using *mercury vapor*, in power control devices (roughly doing the same as a CMOS switch in a regulator, but controlling a million times the energy); and in huge triodes for generating the RF power used in industrial induction heating applications (frequently in semiconductor processing); and in other exotic ways. Tube-museum web-sites such as **[31]** and **[32]** offer an inspiring visit.

While few of the small, ordinary tubes remain in use today, specialized types continue to have great practical value, and in fact are still being developed. Viewed as *extended structures* having a plurality of *functionally distinctive sections*, each of these clever inventions is a *System in a Tube* (SiT?). From this modern perspective, they bear a certain relationship to the contemporary analog *System on a Chip* (SoC). Of special relevance in this respect was the development of the *traveling-wave tube* (TWT) and the *klystron*, both of which are RF power amplifiers. The *reflex klystron*, and the ineffective and transitional *split-anode magnetron*, which was soon trumped hands down by the powerful *cavity magnetron* – are RF power oscillators.

These tubes deserve comparison to the SoC because they co-integrate such elements, for example, as *low-loss lumped-element transmission lines* for velocity-matching (as in the TWT, and in the advanced ultra-wide-band CRTs developed at Tektronix) or the *ultra-high-Q resonators* found in magnetrons and klystrons. These modulate, manage and magnify electron flow or direction in novel ways. Formerly, in a vacuum tube, the only way to control this flow was by one or more *grids* (six in the *octode*). However, combinations of two, three or even four independent active devices were developed, some with integrated passive elements; others, such as the "Magic Eye", widely used as a tuning indicator, integrated a vacuum tube with a tiny phosphor screen. A study of Adler's 1946 inscrutably-complicated wave-weaving Phasitron tube **[33]**, once used in FM broadcasting, should convince you of the validity of the 'SiT' notion – if it doesn't leave your head spinning.

THE GEARS OF GENIUS

These experiences form a long chain whose links remain unbroken, and which is still growing in length, sixty years after I became an avid Experimenter/Tinkerer/Inventor –an ETI – in *real* electronics: to wit, the *analog domain*, where circuit concepts and topologies are Diverse, Dimensional, Durable and downright Difficult **[34]**. This chain is an uninterrupted continuum of constantly-developing knowledge, orbiting a nucleus of only a handful of seminal themes. In today's immensely complex world, few can hope to excel as professionals in a broad range of disparate endeavors. Most of us have just one *bag of tricks*. We reach into it numerous times, to again extract inspiration from our expanding museum of ideas; and each time we put an idea back into our bag, it will have become a little smarter, and shine a little brighter the next time it pops out.

I have three, maybe four, seminal themes: my daisy-chains of concepts. The chain *magnetron*-to-*dekatron*-to-*carrier-domain-magnetometer* provides a great example of the *persistence-of-envisioning.* They all involve electrons – sometimes as plasmas – that are persuaded to *bunch in preferred locations* and then *rotate around a circular outer perimeter*, where they do something useful. For the first and third links in this particular chain, the persuasion comes from a magnetic field. In the second, it is discrete plasma transference, instigated by clock pulses, and in *that* regard it bears acloser resemblance to another daisy-chain – the super-integrated string counters of [14]. Indeed, it was my exposure to (and as a user of) the Dekatron counter tube as a kid that inspired the invention of this and subsequent "string" counters (which are extremely efficient in their use of chip area).

I suspect most careers are characterized by such 'continuity phenomena' as the *daisy-chain-of-concepts*, the *persistence-of-envisioning* and the *little-bag-of-tricks.* But these daisy-chains are gregarious: they intertwine. In my experience, many of the resulting cross-connections have led to branching ideas of equally satisfying quality.

As well as these, we also carry around in our head *models* – imagination-maps which give us a sense of *location*, *direction* and *intention*. The topological map of a metro such as Tokyo's will seem arcane to the casual visitor: yet a resident must understand its details, and the lines and stations for daily travel must be committed to memory. However, if we like to explore the roads less traveled, to venture forth to an invigoratingly different place, to risk, to remoteness, to travel up through Tohoku to Hokkaido, then a geographically-faithful map is indispensable.

Absorbing the *key aspects* of the metro map (many lines and stations may need to be ignored, for now) is like acquiring a firm foundation in the *fundaments* of electronics. Numerous equations, criteria, methods, models and minutiae must be assimilated, filed and sorted in one's mind. While many (say, Bessel functions) can be overlooked, for now, all the rest must be distilled down to everyday essentials. *What is the noise-spectral-density of a 50 W resistor at 300 K? What is the value of the electron charge? Why does* V_{BE} *decline linearly over temperature? Can it really fall right down to zero, for practical conditions?* Such issues must be at one's finger-tips, as numerous individual, intellectual knowledge objects: but beyond that, they must be integrated into the instinctive, emotional fabric that *is your core being*. You won't get very far on the metro if you need to consult the map each day as you travel to work, and scrutinize every station-name beyond the window as something perplexingly new.

On the other hand, for most ETIs, a thorough grasp of the *business* of contemporary electronics – as a *phenomenon,* as an *enterprise,* as an *industry,* as a *competitive forum* – comes slowly, and requires us to take some long and lonely journeys on Big Maps. Like this one, articles in the *SSCS Newsletter* describing such journeys – situations encountered in technical, business and emotional places very far from the reader's own familiar landmarks, or the sentimental recollections of someone else's youthful adventures and irrepressible aspirations – serve to refresh us. Informed by these vicarious expeditions, the reader can return to the detailed challenges of daily work with a new perspective, a little better equipped to examine issues under a brighter light.

Younger engineers: you'll find the world is full of naysayers, who should be firmly but politely ignored. Rebut the accepted wisdom, but reserve respect for the wise. *Understand the reason* for my insistent repetition of the power-questions *What Must Be?, How About?*, *Why?* (and *Why Not?*)and rising high above them all, *WHAT IF?*. These are your launch-pads to novelty; they are your gilt-edged Invitation to Mutiny; they're your instruments of invention; they're the primary drive-line gears of genius.

Take big risks. It is to be hoped that all the little histories of a thousand minor past-players such as myself will add up to a powerful testament to *risk-taking*. Without going out on a limb, novelty is unlikely to emerge from one's work. Walk out onto the fragile canopy of thin limbs as often as you dare. You risk a break through, and may be in for a big fall; and what's wrong with that, I want to know. Don't *wait to be told* what to do: do it anyway. Anyway, *never* do as you are told: or rather, do it only when it seems the right and smart thing to do; then go 100% beyond what you were *asked* to do, and 200% beyond what you were *expected* to do, and 300% beyond what you *thought* you could do, rising to the pinnacle of what you *really can* do. Do it soon.

I'm starting to sound suspiciously syrupy, so here's a sobering post-script: In 1966, Sir Robert Alexander Watson-Watt, at age 64, married Dame Katherine Jane Trefusis-Forbes. Jane died five years later, leaving him hopelessly confused in a sea of jumbled memories suffering from what was likely the dreaded Alzheimer's. A few days before Christmas, 1973, unnoticed in a nursing home in Inverness, this Scot, this giant gear of genius, Sir Robert died alone. Buderi, in *The Invention that Changed the World,* called him "a scientist, a kind of philosopher, even a poet; and a bad businessman". Now, *that's* an epitaph to live for.

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[1] R. Buderi, *The Invention that Changed the World*, Simon and Schuster, 1996, p. 88. Much of The information came from this magnificent, meticulously-researched source, which should be on every engineer's bookshelf. Some embellishments of life at TRE are mine, though without compromising substantive facts and dates.

[2] M. Riordan et al., *Crystal Fire: The Birth of the Information Age,* W.W. Norton, Co. 1997, p.262.

[3] O. Sacks, *Uncle Tungsten Memories of a Chemical Boyhood*, Alfred A. Knopf, 2001.

[4] Main, Jeremy, 'A Chipmaker Who Beats the Business Cycle,' *Fortune*, December 23, 1985, pp. 114-20, in which Ray Stata talks about his readiness to invest in Gilbert "wherever he wants to live."

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