# 2000-Plus 63 - Way Beyond Silicon?

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2063? That's 53 years from now. How old is the transistor?

Ever since the era of big vacuum tubes began near the turn of the $19^{th}$ century, the relentless march of electronics technology has been in step with *smaller, smaller, and smaller*. Sure, go ahead and substitute "faster-cheaper" if you like clichés, but those two are by-products of "smaller". Smaller means more chips per wafer, per batch, and that usually delivers cheaper. And smaller devices enable shorter connections with shorter delays and such, to deliver data faster. Of course, the *smaller, faster, cheaper* marching tune plays mostly to the IC audience and not so much to discretes; vacuum electronics and single transistors.

The tech-savvy business-oriented denizens of the semiconductor world sum it up in Moore's Law that we might shorten to *"More for your money - evermore"*. But the semiconductor debate of this decade orbits around Moore's Law and voices increasing concern that we're about to hit a "brick wall of science" – the sad end of "evermore". That brought some to rally for a bold move to venture beyond Moore -- "More than Moore". But many are still hoping that Nanotech (whatever that is – 25 definitions and counting) will come to the rescue and ease us back into the comfort zone of "smaller evermore" and maybe back to nostalgic Mooresville. Maybe so, maybe not! And maybe it just doesn't matter. But is the "smaller" track the wrong gauge for tomorrow? Have we been succeeding with the same half-century-old (actually, it's older) stratagem for too long?

If we zoom out and view things from low earth orbit, it looks like we've been using just about the same basic blue print, albeit, with very clever evolutions, for so long that it's cast in stone (Si). But wait, haven't we been talking about Beyond Silicon for a while? Sure, we could swap out one element for another. In fact, that was done a long time ago when silicon (Si) replaced germanium (Ge). So, yes, maybe we can swap carbon (C) for silicon, sit back and look at all the cute "organic" renditions from graphene to "Bucky Balls". [Is nanotech mostly an art form?] Now, is this revolutionary, or what? Or is it just one more logical step in our semiconductor evolution? Aren't we still talking about gates and conductors, "off" and "on", 0's and 1's?

We have embraced semiconductor materials and binary designs for a lifetime, and although alternatives have been suggested (multiple-state instead of binary, quantum vs. ohmic, etc.), most of the industry is drumming the same march with an occasional new instrument with a few new notes and nodes. So will it be semiconductors using binary-state devices for another half-century?

What about photonics, you say? Isn't swapping photons for electrons a real deal? Could be, and the photonic computer is still a glimmer of light on the event horizon. Photonics has certainly become the dominant technology for long distance communications (long-haul fiber), but computing and data storage isn't working well just yet. But the photonic computer is a grand idea and these capable multiple-wavelength photons have advantages over our beloved electrons (OK, there's still electron spin state R&D), but also disadvantages that make this work very challenging. And while the photonic computer would have differences compared to the electronic type, there would still be semiconductors and wafers and conductors (light pipes) -- probably more similarities than differences. So how far beyond the beyond should we go as we march into the future?

From time to time, visionaries and serious thinkers, including sci-fi writers, have drawn parallels between computers and the human brain. Some would even merge the two while others would use DNA and biology to grow circuits. But what if we used the human brain as the blue print for the next computer design? Call it bioinspired or biomimicry if you need a term. Would the bioinspired computer be that different? Let’s look and see how far beyond silicon we can travel inside the brain.

First, the differences in brain materials, architecture, data transport, switching mechanisms, steady states, power sources, “manufacturing” and software are incredible. In fact, it’s mostly differences. Obviously, the brain materials are organic (carbon-based), but that’s the smallest difference. Organic transistors have been known for decades, OLEDs are doing well and carbon nanotubes and simpler graphene show promise for transistors. What about the architecture? Indeed, the basic interconnect concept is way, way different. First, the brain is true 3D and not at all like semiconductors that are more like 2.5D with anisotropic structuring; different X-Y and Y-plane layout and processing. And then look at the data/information transport system. Is it computer-like with electrical conductors, digital gates, electron-enabled memory and electrons-only messengers? Nope!

Also, the human species uses plenty of distributed computing. Most may be aware that there’s computing (filtering, signal conditioning, regulating) happening beyond the brain. The ganglia, spinal cord and peripheral nerves make up a very complex and powerful integrated sensing, information-processing and control system. You might be surprised to learn that even the heart has a brain with about 40,000 neurons; it “learns”, adjusts and “talks” to the mainframe brain using the nervous system, chemicals, and electromagnetic fields, but that’s a whole other story.

Now back to the human “mainframe” and the information transfer. Electrons and electrical current are involved so it might seem that biomimicry has a chance. But the electron is just one messenger. Most life forms use chemical messengers both internally and externally. Our brains use a combination of electrical and chemical signaling, but also electromagnetic fields and even magnetism – and some say there’s more. We might try to simplify brain data transfer by calling it electrochemical, but there’s also a mechanical element especially for memory and learning. Our future bioinspired computer plan is starting to look a bit complicated and we’ll need conductors, insulators, chemical sensors, chemical generators (MEMS?), variable filters, electromagnetic devices (RF?) and maybe magnetometers. Now let’s move onto the basic gate equivalent, or switching structure.

The brain comes with some hardwiring but it’s also dynamically programmable – and its busy wiring and rewiring all the time and this is the essence of learning/memory. While we can program some ICs (memory cells don’t count here), like EPROMs and various programmable gate arrays, that isn’t dynamic – it’s not happening as the IC runs nor is it self-programming like the brain. While we can probably figure out how to handle dynamic self-programming, it certainly is complicating our future bioinspired computer.

We need to zoom in even further and ask how electro-chemical-mechanical-enabled data transfer takes place. And by the way, since we have all kinds of sensors requiring vastly different bandwidths, the transfer mechanisms and pathways can be different. The eyes, our dual vision sensors, use a big chunk of the bandwidth, but there’s a direct connection to the brain to handle the big data load, apparently without multiplexing. The eyes aren't taking snap shots so it’s more like video streaming, but in stereo - two eyes to give 3D and then there's peripheral vision. Best guess is that there might be about a gigapixel *in the blink of an eye* – and that's a huge amount of rapid data transfer and processing no matter how it's counted.

We need to move down to "gate equivalent" and that's the neuron and it's much more than an "off"/"on" switch. The brain has about 100-billion neurons as the primary structure for computing and memory storage. Neurons are orders of magnitude more complicated than our gate-wire computer design. Neurons have a cell body with a DNA-containing nucleus (just one strand of DNA has the equivalent of over 1-million pages of code), an axon that is a long, cable-like projection from the cell that carries the electrochemical data, and dendrites - nerve endings. And there are many types of neurons designed for different tasks. The axion is probably the closest analogy to the IC conductor and can have myelin insulator covering (myelinated neurons). But most of the brain neurons don't need the myelinated cover and this makes them even more analogous to silicon ICs. We might look at the dendrites as connector ends that can link up with multiple cells to program, transmit, and share data – and its in 3D. The figure below is my imperfect attempt to compare the semiconductor computer to the brain.

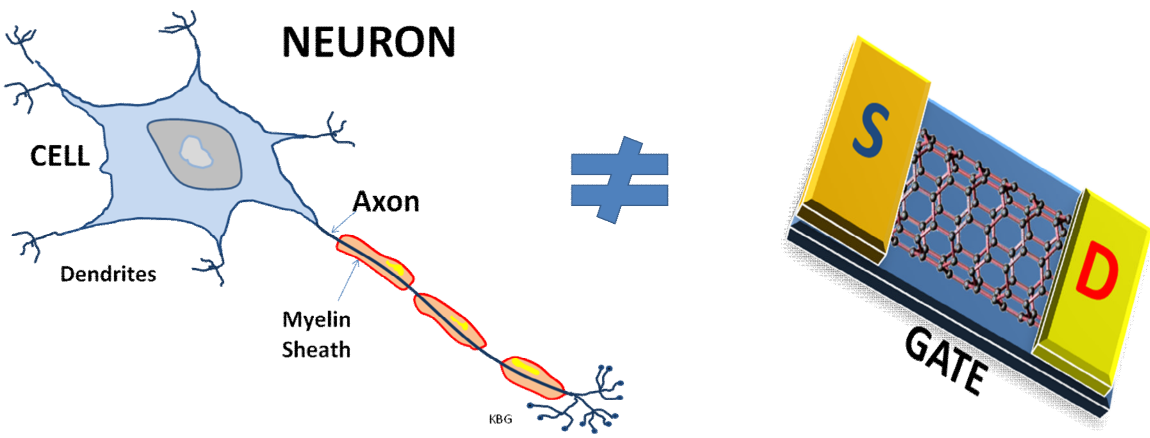


**Figure 1 – Do They Compute?**

It's looking like the semiconductor computer and the human variety are entirely different machines and their capacities and tasks have limited overlap. The human system shows extraordinary creativity – those leaps of imagination that brought us computers in the first place. The brain can generate a plethora of emotions (for better or for worse) and make moral judgments, but it has imperfect data storage (memory) and slow number crunching capability (excepting a few savants). Well, what should we expect with vastly different materials, architectures, switches, memory mechanisms, data transfer media, and so much else? So, our good old digital semiconductor binary computer model is probably the right one for a long time to come. We probably can't mimic the human brain that we still don't understand. The human brain is an exceedingly complex entity using chemical-electronic-mechanical-electromagnetic-magnetic mechanisms with an ever-changing structure and it needs much more than electricity to keep running. The human computer has given us the amazing creativity to invent, design and economically craft amazing silicon-based machines. So let's continue to evolve these semicon marvels and celebrate human ingenuity derived from organic brains. Happy semiconducting in the future.