Participatory Universe, Austerity and Circuit Design

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Introduction

The ultimate challenges for computer designers today should not be limited to building machines to approach human intelligence, but also to pursuing the deeper knowledge of what a computer really means. New breakthroughs are likely to happen at the boundaries between universality in information processing and its physical representation in the universe and life.

As early as 1981, John Archibald Wheeler presented a series of lectures at University of Science and Technology of China and discussed much of the idea later known as “it from bit” [1]. From a physics student listening to him then to a computer circuit designer now, I am wondering about a more practical question, how to build such a machine or “universe” that its laws will be decided or contributed later by its participants?

“It from Bit” and Computer Design

What is the concept of “it from bit”? John A. Wheeler once described his thesis in one sentence, “Otherwise stated, all things physical, all its, must in the end submit to an information-theoretic description [2].”

He also explained how this could happen, at a symposium dedicated to IBM scientist Rolf Landauer’s 60th birthday in 1987, “the coming explosion of life opens the door, however, to an all-encompassing role for observer-participancy: to build, in time to come, no minor part of what we call its past—our past, present, and future—but this whole vast world”. [3]

Much of these ideas were discussed by John A. Wheeler when he presented a series of three lectures at University of Science and Technology of China in 1981. I attended all his lectures as an undergraduate physics student.

Time is passing fast and most of my professional career has been in the semiconductor industry; as a circuit designer working for IBM, I used to be responsible for the mixed signal functional verification (that is, in both digital and analog modes) of one of fastest chips used in Xbox. Over the years, I cannot help but wondering about a question, how could we designers in the computer industry help to build a prototype of Wheeler’s dream machine or “our universe” that its laws will be decided later by its participants? In my view, such a machine should help us to understand the deeper meaning and potentials of computers. Regardless whether "it from bit" or "bit from it" is the better answer, building a machine on the observer-participancy principle is a challenge for computer designers. In computer design, we are interested in multiple levels such as devices, circuits, micro-architecture, architecture, and algorithms. What are laws at these levels? Perhaps the most fundamental question was actually asked by Wheeler, "how come 'one world' out of the registrations of many observer-participants?" [2]

Wheeler's USTC Lectures in 1981

In 1980s, University of Science and Technology of China (USTC) was an attractive place for scientists around the world to present their original works. John A. Wheeler visited the university in the fall of 1981 and gave a series of three lengthy lectures. The titles of his lectures were "The inconceivable quantum world", "After the end of time", and "Boundary of a boundary: a principle for physical laws". These lectures were specially prepared for his China visit, with the second one completed during his 3-day boating trip on Yangtze River. USTC astrophysicist Fang Lizhi was Wheeler's host and his translator. Each sentence of Wheeler's lectures was delivered twice, once in English by him and once in Chinese by Professor Fang. A collection of these lectures was published in Chinese [1] and referenced in his papers later [3].

John A. Wheeler presented his lectures with amazing clarity. I have redrawn a few symbols that he used in his lectures and they are shown here in Figure 1. In his first lecture, Wheeler opened up his talk by saying that he came to China with two pairs of eyes and two pairs of ears; one set was his, the other set was of Neils Bohr, who visited China in 1937. Attributing to Neils Bohr's revelation, Wheeler used Yin-Yang symbol (Figure 1A) for an illustration of Bohr's principle of complementarity.

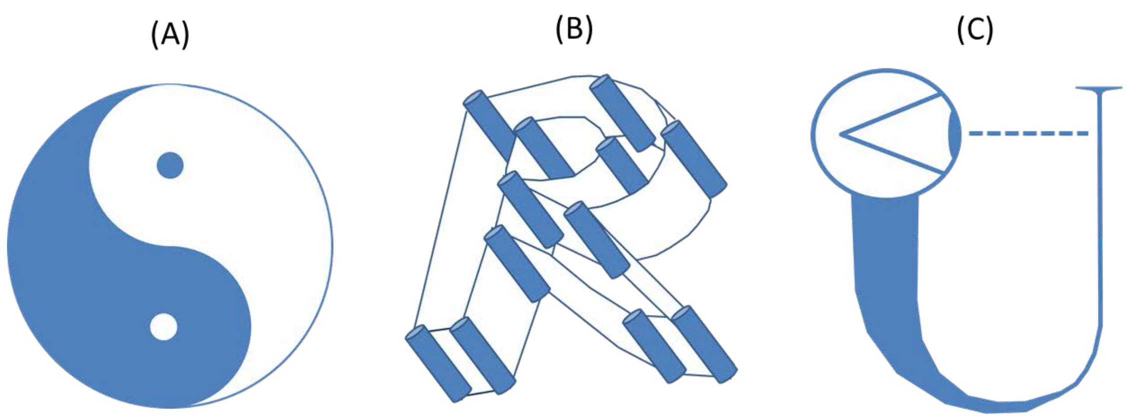

Figure 1. Key symbols for Wheeler's idea. (A) Yin-Yang symbol. (B) Letter "R". (C) Letter "U".

With the letter "R" (Figure 1B), Wheeler expressed his world view that the reality ("R") was made of a few iron columns or pillars of experimental observations, and filled with the imaginations and theories in between. With the letter “U” (Figure 1C), Wheeler described the participatory universe (“U”) as a circuit of feedback loop, where the observers’ participation now (and more in the future) would contribute to the creation of our universe at the beginning of time.

Austerity, Law without Laws

A fundamental question about the concept of the participatory universe was raised by Wheeler, “how come one world out of many observer-participants?” [4]

Wheeler suggested a possible answer in his USTC lectures: there is no predetermined physics. Every law in physics could come from no laws, in a sense similar to the second law of thermodynamics. As an illustration of the second law, he used a graph to show that the molecules distribute themselves between two regions in proportion to the volumes of those two regions.

“Every heat engineer knows he can design his heat engine reliably and accurately on the foundation of the second law. Run alongside one of the molecules, however, and ask it what it thinks of the second law. It will laugh at us. It never heard of the second law. It does what it wants. All the same, a collection of billions upon billions of such molecules obeys the second law with all the accuracy one could want. Is it possible that every law of physics, pushed to the extreme, will be found to have the character of the second law of thermodynamics, be statistical and approximate, not mathematically perfect and precise? Is physics in the end 'law without law,' the very epitome of austerity?” [1, 3]

Thoughts on the Links to the Computer Designs

Now let me discuss a few things from the viewpoint of a circuit designer.

A paradigm shift in semiconductor industry and information technology at the present time is presenting a unique opportunity to rethink about the relationship between physics and computer engineering. The future of information technology seems to require closer collaboration between physicists, chemists, material scientists, system architects, and integrated circuit designers. Looking from a designer’s perspective, Wheeler thesis “it from bit” leads to an obvious question, how to build such a machine or “universe” that its laws will be decided or contributed later by its participants? The term “participants” could mean computer users or processor nodes in parallel systems.

Reversible computing is another link between physics and information theory. Rolf Landauer said [5], “Information handling is limited by the laws of physics and the number of parts available in the universe; the laws of physics are, in turn, limited by the range of information processing available." Landauer's Principle, on the entropy cost of any logically irreversible manipulation of information, leads to Charles Bennett's information theoretical treatment on why the second law of thermodynamics cannot be violated by Maxwell's demon. [6]

Participants' Freedom and Circuit Design

Performance, power and variability should be simultaneously addressed and optimized for an integrated circuit in the advanced technology regimes [7]. A massively parallel system today may have tens of thousands of processor nodes [8]. If each processor nodes could be made with field programmable logic circuits, then one could realize an evolutionary machine where each node may have its own rules of preferences developed over time. Genetic algorithms may also be used for optimization. Are there any top level laws of such machines? Will they emerge over time? If every participant (for example, every processor node) wants its own optimization according to its own utility function, there will be an overall architectural impact.

From a view of circuit design, and by a little analogy to economics, Figure 2 shows two simplified circuit architectures. Figure 2A is a flat architecture, where each participant (p) has equal access to an information market or exchange (X). This may be viewed a basic free market model, where its participants are treated fairly. For a system with many participants, a wiring density limit seems to exist near X, so that some wires near X have to be shared. This leads to an access time inequality that can be fairly compensated near each participant p locally. If space-time is discrete, the wiring density limit is likely to exist in a broader sense of physics.

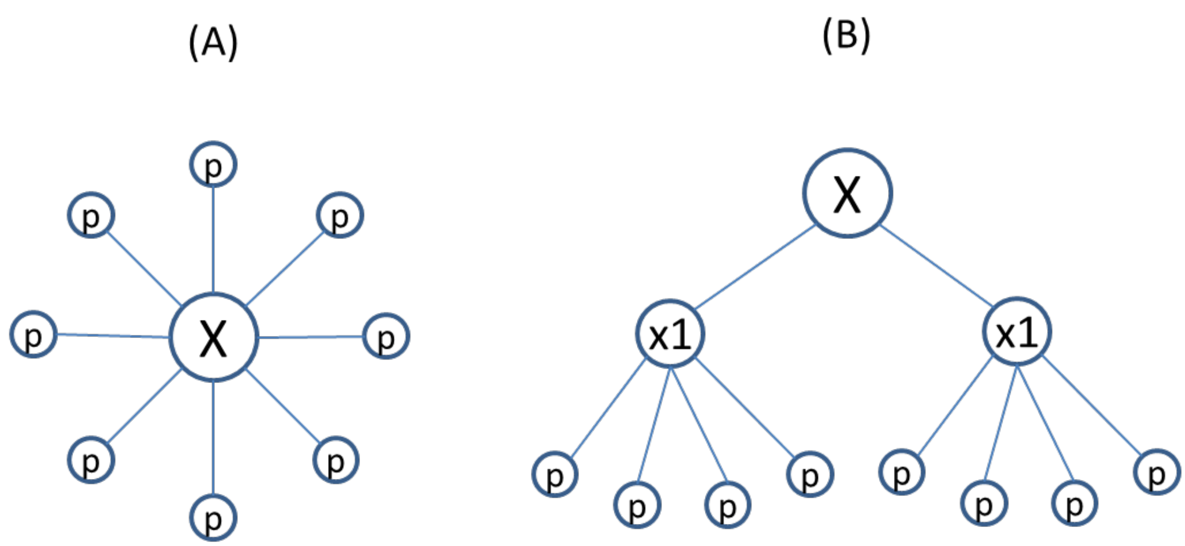

Figure 2. (A) Flat architecture. (B) Hierarchical architecture.

Figure 2B is a hierarchical architecture (shown with 2 levels for simplicity). This may be viewed as a command economy model or planned economy model, if we let X to represent a central planer and x1 to represent lower level bureaucrats. However, if X and x1 are only circuit mechanisms collectively decided by the participants, this hierarchical architecture will not necessarily violate the principle of fair participancy. Such a hierarchical architecture becomes a planned economy without planers, or a command economy without commanders, by analogy to Wheeler's law without laws.

As another example, a design parameter called random access cycle time is a critical parameter in parallel computation in order to have different processor nodes to interact smoothly. Faster random access cycle time of a memory system depends on its building elements and trade-offs with other parameters such as layout area. In destructive-read type random access memory (such as DRAM), conventional operation requires immediate write-back. However, by an architecture called "destructive-read random access memory system buffered with destructive-read memory cache", with negligible cost of layout area, write-back can be avoided so that the random access cycle time can be doubled [9]. In this example, a rather complex set of rules and algorithms on data transfer is resulted from a simple concept of improving the speed of information processing if this improvement must be true for all participants (in this case, the word lines in memory arrays). One interesting by-product is that the proposed system [9] requires no duplicated copy of the information-carrying entity at any time and thus satisfies no-cloning theorem for quantum computation.

Opportunities in Circuit Design

The field of engineering can be felt like a lawless world to people with physics background. Of course, every transistor must follow the law of physics; however, computers are used mainly to perform functions at the system level. From physical devices to system-level functions, many engineering steps must be followed; empirical formulas, patents, and trade secrets are all parts of the process.

Surprisingly, semiconductor industry has been guided very well by Dennard's scaling theory in the past three decades [10]. Robert Dennard and his co-workers in 1974 described a set of rules for scaling transistor device parameters and the expected resultant circuit benefits [11]. Dennard's Scaling Law was an evolutionary roadmap for obtaining simultaneous improvements in transistor density, switching speed and power dissipation, in accordance with Moore's Law [12]. However, semiconductor device scaling has deviated from this evolutionary path in recent years due to fundamental physical limitations. Therefore, while "from physics to functions" has been a traditional driving force based on constant device shrinking, the new paradigm is demanding more innovation of functions from circuit and system designs.

Significant progress with fundamental impact has been rarely resulted from the interaction between physics and circuit design in the past. An exception is Cockcroft–Walton voltage multiplier, which is an electric circuit that generates a high voltage. Physicists John

Cockcroft and Ernest Walton used this circuit design to power their particle accelerator and won the Nobel Prize in 1951. Today, there appears to be greater opportunities for physicists and designers to work together to explore the complex world.

On the functional and system levels of computers in the future, are we going to find more fundamental laws or "laws without laws"? I think these laws will be discovered when we try to build prototype machines behaving like Wheeler's "participatory universe".

At the end of his USTC lectures in 1981, John Archibald Wheeler showed an interesting cartoon that I think was drawn by a famous Chinese cartoonist. In the cartoon, an elementary school student appeared to be studying diligently at her desk. The cartoon had a Chinese text caption stating "focusing your attentions". Wheeler used it to emphasize his final point that we are only at the beginning of physics. He said something like, "Great people will emerge among you. Their discovery will be greater than Einstein and Bohr. Why? Physics is not over. Physics is at its beginning." (The above quote is my translation from Chinese text in [1].)

My question is: what will be the role of circuit design in foundational physics?

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