Cyclical progress in design and technology

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Abstract— Progress in engineering systems is the result of the combined improvements of technology and design methods. It is often a cyclic process, stimulated by success and failure. When the innovation loop stalls in producing effective progress, a change in paradigm is needed. Many examples populate the history of science and engineering, as well as of mankind.

Keywords—Emerging technologies SiNW, EDA, digital design, quantum computing, medical implants.

I. INTRODUCTION

Progress in electronic circuit and system design is due to both the advancement of CMOS nano-electronic technology and the improvement of *electronic design automation* (EDA) methods and tools. The circular interaction of technology and design methods has created a stream of opportunities and challenges [1]. Crossbreeding fabrication and design technologies is a major progress enabler.

II. EMERGING TECHNOLOGIES

As downscaling CMOS technology is getting increasingly harder, the search for alternatives has led us to several alternatives [2]. Rather that foreseeing a replacement of silicon and CMOS, these technologies can support *hardware accelerators* and *application-specific units* for some part of the computation. The search for smart applications of post-CMOS technologies is driven by the fact that diverse technologies can be more efficient than standard CMOS in solving some parts of the computation, e.g., by means of *in memory computing*. In particular, the problem of matrix-vector multiplication can be solved natively on a memory array, by storing the matrix entries into the memory and by using an analog or digital readout. Such memories can be *non-volatile* and realized through *back end of line* (BEOL) steps on top of other CMOS circuits, thus providing both area savings as well as shorter and faster interconnect [3].

The circular exploration of emerging technologies and devices and their related design tools can be exemplified by the following experience. About a decade ago, it became clear that the roadmap for CMOS would lead to 3-D devices, such as FINFETs, *silicon nano wires* (SiNW) and *nano sheets* [4]. The fabrication of SiNW with undoped channels enables both type of carriers to flow (i.e., ambipolar conduction), which may be disruptive if not controlled. By creating devices with an additional *polarity gate* that affects the silicon-metal contact Schottky junctions, it is possible to suppress selectively a type of carrier and to realize electrically-controllable N or P devices [5]. The use of such *controlled-polarity devices*, enabled us to create new transistor configurations. For example, compact 2- and 3-input XORs as well as *majority* functions can be realized with fewer transistors than in CMOS.

With such logic gates, a disruptive innovation step was to create tools that use the majority gate abstraction, possibly complemented by inverters and/or XOR gates [6]. Logic synthesis tools using the *majority paradigm* have been shown to be applicable to both emerging (e.g., controlled polarity SiNW) and established (e.g., CMOS) technologies. In the latter case, comparisons on standard benchmarks could show a significant improvement on delay (e.g., 15%) in both academic and commercial settings [6]. The most interesting outcome is that an emerging technology has spurred interest into new models, algorithms and tools which eventually showed an improvement on an established one, such as CMOS. The next challenge is whether the majority paradigm can enable other emerging technologies. The answer is positive, and for example some *superconducting* [7] and optical technologie*s* benefit from this approach, as the underlying devices have native models based on the majority operation.

The broad impact of combining research for advancing technology and EDA is well recognized. The term *system-technology co-optimization* (STCO) is often related to designing transistors that will deliver realistic performances in a system. It is a predictive approach, as transistors are used in systems much after their structure and parameters are determined. We are now at an inflection point, as it is not clear whether further downscaling beyond the 3-nano node will correlate to silicon area scaling, even though delay and energy reduction are expected. EDA will be the compass to steer among the choices of further downscaling silicon devices, for embracing emerging technologies or more likely for achieving balanced heterogeneous solutions leveraging specificities of various devices and circuits.

III. QUANTUM COMPUTING

Our insatiable appetite for computing power will be hardly satisfied by classical computing even with an evolution of technology. Thus, a disruptive change of the rules of the game is required, as promised by q*uantum computing* (QC). A QC can be seen as an accelerator booster connected to a host through an interface, that processes the information in a revolutionary way. QC can be embodied by various emerging technologies (e.g., superconducting electronics, quantum dots, …). The use of quantum properties of materials to compute, such as *superposition* and *entanglement*, enables computational speed-up at the price of challenging hardware manufacturing and more complex design methods. Current QC implementations require supercooled environments or high vacuum, thus making the realization and interfacing of QC hardware expensive and complex. Moreover, design has to satisfy specific constraints, such as *reversibility* and *no cloning*.

An important step in QC design is *quantum compilation,* i.e., the mapping of a quantum algorithm into elementary steps. First, designers need to express the computational objective with executable models, i.e., by quantum computation languages, e.g., IBM's *Qiskit*, Microsoft's *Q#*, Google's *Cirq*. Such models need to be compiled next into *quantum circuits*, that are a common technology-independent abstraction of an equivalent "assembly code" for quantum computers. Quantum circuits express the computation by a sequence of steps, each one represented by a quantum gate. Quantum circuits are often represented by 2-dimensional array diagrams, with rows corresponding to *quantum bits* (qubits) and with columns representing the flow of computation. In general, the number of qubits is limited by the physical design of the hardware substrate, while the number of computational steps is limited by the coherence time. The design of optimal quantum circuits entails the mapping of a model of computation expressed in a QC language into quantum circuits satisfying the technology constraints (i.e., qubits count and coherence time limit) where quantum gates eventually are chosen from a given library, such as Clifford+T. The cost (e.g., execution speed) of each quantum gate depends on the realization technology of choice. Note that there are various technological options, with advantages and disadvantages.

At present, good examples of *noise-intermediate quantum* (NISQ) computers have been realized. These systems assume the unavoidable presence of noise in quantum computation, and solutions are applicable to many modeling problems in physics and chemistry not requiring bit-level precision. Today, quantum error detection and correction are subjects of ongoing research, and current solutions are still onerous in terms of qubit usage to achieve precision. Thus, we are not ready yet to put to practice algorithms, such as Shor's algorithms for factoring, that would heavily impact computer science and security in particular.

The role of EDA in quantum computing design is essential for the exploration of future circuits and architectures. Tools and flows are available for quantum compilation, and in particular for *reversible logic* circuits and mapping [8,9,10]. Nevertheless, the design of QC interfaces and the realization of QC error correction schemes are still not automated. QC has direct applications to EDA, even though most challenges in EDA relate to combinatorial optimization problems that require quantum computers with error correction. Nevertheless, exact solutions to most relevant problems would still require over-polynomial time and space, albeit the computational burden and time may be lower as compared to conventional computing. The application of Grover's algorithm, that speeds up searching quadratically, can find applications in many EDA tools.

Overall, quantum computers can be seen as accelerators that speed up the solution of problems with specific characteristics that can benefit from superposition and entanglement. Present NISQ computers support the analysis of physical phenomena and materials, as they are well geared to study the evolution in time of Hamiltonian models. Such materials can be used then for future generation QCs. This gives us a path for a cyclic evolution of quantum computers with increasingly better performances. To guide this evolution, EDA is key to determine the useful matches between quantum devices and architectures, i.e., determining predictive models of quantum devices to be used in upcoming quantum architectures as well as requirements on material properties, shapes and composition rules to realize effective quantum hardware devices.

IV. COMPUTING AND LIFE

Today the use of computational devices as assistants has become prevalent to improve our working and social skills. Smart terminals (e.g., phones, watches) can be viewed as common enhancers of our mental skills, as for example assistants to memorize information. Medical implants realize a tighter connection between computational platforms and living matter, by using a wide variety of transducers and actuators. For example, pacemakers communicate to the heart via electrical signals and artificial limbs are likewise electrically stimulated. Electronically-controlled drug dispensers (such as insulin pumps) communicate to the body via chemical injection. Some of these systems work in a closed loop, where the information acquired by sensors (e.g., glucose sensors) is processed digitally to control dispensing (e.g., insulin pump). Enormous progress has been achieved in restoring locomotion after spinal cord injury. Understanding and decoding the brain signals is key in providing the appropriate stimulation. Recent results have reported restoring autonomous locomotion in a human subject through the use of a brain implant connected to an epidural electrical stimulator [11]. This fantastic result has shown how computing can bridge two biological subsystems, that were separated by an injury.

Tomorrow's systems may enhance further the merger of computing and life, in the search of extending our capabilities. Thus, we humans, can invent technologies that can be absorbed by us to enhance the human species itself, and lead us to an unprecedented future.

V. CONCLUSIONS

Science and engineering evolved through centuries as a sequence of steps that has accelerated in the present years, involving also biology and benefitting medicine. The combination of computational thinking and design methods with the advancement of materials and technology has been the enabler of progress in this exciting times.

VI. REFERENCES

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