Putting Memory Into Circuit Elements: Memristors, Memcapacitors, and Meminductors

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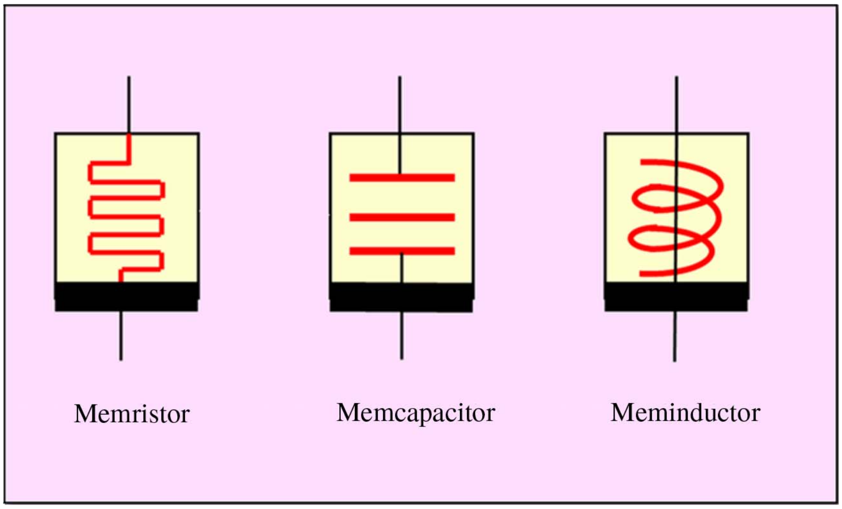

Fig. 1. ***Symbols of the three circuit elements defined by the authors. These devices are generally asymmetric.***

When studying circuit theory, we learn that there are three fundamental circuit elements: the resistor, the capacitor, and the inductor. The first element determines the relation between current and voltage, the second between charge and voltage, and the third between current and magnetic flux (or the time integral of the voltage). These passive two-terminal devices are basic building blocks of modern electronics and are therefore ubiquitous in circuits. However, we are also taught that they do not store information. Even if the state of one of the above elements changes, the information about the new state will be lost once we turn off the power source and wait some time. This point may seem irrelevant, but it is instead fundamentally crucial: storing information without the need of a power source would represent a paradigm change in electronics. For instance, we would need many less active elements (like transistors) to perform any type of computation or processing.

This state of affairs has changed completely by the introduction in 1971 of the concept of *memristor* (short for memory-resistor) by Chua [1], [9], who noticed that fundamental circuit theories miss an element determining the relation between magnetic flux and charge. Equivalently, the memristor relates the current to the voltage [1], [9] but, unlike its traditional counterpart, its resistance, upon turning off the power source, depends on the integral of its entire past current waveform. In other words, it has memory of past states through which the system has evolved. The concept has remained mainly theoretical until last year, when interest has resurfaced due to the realization of such a device by a group at Hewlett-Packard using titanium dioxide thin films [2], [10]. In this device, the resistance changes according to the voltage applied to the system, via the migration of atomic

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defects, which consist in the absence of some oxygen atoms (oxygen vacancies) in certain regions of the film. Due to this effect, when the power source is turned off, the oxygen vacancies do not easily migrate back to their original position, and the system maintains its new resistance state.

Early this year, the authors took an extra step and generalized the concept of memory devices to capacitors and inductors, thus defining two new memdevices: *memcapacitor* and *meminductor* [3] (see Fig. 1 for the symbols we have introduced for these elements). In these devices, the capacitance and inductance, respectively, depend on the state and history of the system. In addition, all these elements show *pinched* hysteretic loops in the two constitutive variables that define them: current–voltage for the memristor, charge–voltage for the memcapacitor, and current–flux for the meminductor. However, there is a significant difference between these new devices and the memristor: unlike the latter, a meminductor and a memcapacitor can store energy. A detailed analysis of these new devices and their properties is given in [3], which will appear in a forthcoming issue of this PROCEEDINGS.

It is important to note that, like for the memristor, devices already exist that operate like memcapacitors [4] and meminductors [5] even though they have not been categorized as such. In these instances, other mechanisms are at play, such as a finite charging/discharging time of nanocrystals embedded in a capacitor [4] (memcapacitor) or magnetic properties of a material inside a coil [5] (meminductor). Our work puts all these findings in a much more general framework.

There is no doubt that, in the future, many other systems that behave as memristors, memcapacitors, or meminductors are bound to be found. In fact, it should not come as a surprise that with continuous miniaturization of devices down to the nanometer scale, these concepts will be the norm rather than the exception. A simple reason for this is that, at the nanoscale, the dynamical properties of electrons and ions strongly depend on the history of the system, at least within certain time scales [6]. Therefore, many devices at these length scales retain partial memory of the electron and ion dynamics.

A natural question is now: what are these devices useful for? Clearly, combined with the already known memristor, such elements open up new and unexplored functionalities in electronics, in addition to the obvious nonvolatile memory application. In particular, it is worth stressing that they store information in a continuous fashion. (According to the values of the control parameter, these elements acquire a continuous set of resistances, capacitances, or inductances, within certain bounds.) This implies that they store *analog* information and, therefore, can be useful not only for conventional (digital) low-power computation and storage but also for analog circuits and analog computation.

This leads us to arguably one of the most fascinating applications of these memory devices in the realm of simulating and understanding biological processes and neuromorphic circuits, namely, circuits that mimic the function and operation of biological systems. For instance, the potassium and sodium channel conductances in the classic nerve membrane model [7], for which Hodgkin and Huxley won their Nobel prize, can both be identified as memristive. Last year, Di Ventra and Pershin have applied the notion of memristors to understand the adaptive behavior of unicellular organisms, such as amoebas, by introducing the concept of *learning circuits*, namely, *LC* circuits with memristive elements, which can recognize input waveform patterns and thus adapt to the incoming signal [8]. It is then quite natural to imagine that more complex combinations of these devices may help us understand adaptive and spontaneous behavior, or even learning, and thus the origin of the workings of the human brain and possibly of many other mechanisms in living organisms.

In summary, the memdevices we have defined open up a whole new world of possibilities in electronics and provide us with new tools to study old scientific problems from a new perspective. Due to their recent introduction, it is difficult to say what new applications will be found and which course the field will take from here. Irrespective, we believe the time is ripe for new and exciting innovations in electronics and hope our work will motivate more experimental and theoretical investigations in this direction. ■

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