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Anticipatory Computing

For over 300 years—since Descartes' major elaborations (*Discourse on Method*, 1637 and *Principles of Philosophy*, 1644) and Newton's *Principia* (1687)—science has advanced the understanding of the reactive characteristic of the physical world, expressed in the cause-and-effect sequence. The corresponding reductionist viewpoint states that a machine can represent the functional characteristics of reality, including the functioning of the human being. The assumption of homogeneity is implicit in physics.

Computer programs ("soft machines") are descriptions that capture details of a homogenous reality that has escaped all previous machines. Programs express these details in many ways: from visualizations to intelligence-like inferences, to procedures for automating the execution of complicated yet well-defined tasks (the domain of robotics, for instance). However, in describing the living, regardless of its complexity—from monocell to human being—descriptions based on the deterministic understanding of the world and the corresponding reductionist model fail to capture the defining characteristic of life: the ability to anticipate. The living is infinitely heterogenous and variable.

Arguing from a formal system (the Turing machine, the von Neumann sequential computer, algorithmic or non-algorithmic computation, quantum computation, neural networks, etc.) to reality is quite different from arguing from a characteristic of the living (in particular, brain functioning) to formalism. Libet's readiness potential (i.e., the time before an action, signaled through neurological activity, actually takes place) is an expression of anticipation. It was and continues to be measured/quantified in various cognitive studies and in brain research. The area of inquiry extends from the anticipation of moving stimuli (vision) to synchronization mechanisms, medicine, genetics, motion planning, and design, among others. Inferring from this very rapidly increasing body of data to an integrated understanding of change, and its possible anticipation, assumes that we know how anticipation is defined. Two distinct formal definitions of anticipatory systems originate from Robert Rosen's work:

1) An anticipatory system is a system whose current state depends no only upon a previous state, but also upon a future state.
2) An anticipatory system is a system that contains a model of itself that unfolds in faster than real time.

My own definition deviates a bit from Rosen's:

3) The current state of an anticipatory system depends not only on a previous state, but also upon possible future states.

These definitions can serve as a basis for conceiving, designing and implementing anticipatory computing.

The more constrained a mechanism, the more programmable it is. Reaction can be programmed (though this is not always a trivial task) even without computers. Although there is anticipation of a sort in the airbag and the anti-lock braking system in cars, these remain expressions of pre-defined reactions to extreme situations. In programming reaction, we infer from probabilities (a shock will deploy the airbag, sometimes without justification), always defined after the fact (collisions result in mechanical shock). They capture what different experiences have in common, i.e., the degree of homogeneity. Proactive behavior can to some extent be modeled or simulated. If we want to support proactive behavior, for instance prevention, we need to define a space of possibilities and to deal with variability. We need to make possible interpretations (e.g., a shock that does not require the airbag should be distinguished from a collision). To infer from the combined possibility-probability mapping of the information process describing the dynamics of reality to anticipation means to acknowledge that deterministic and non-deterministic processes are complementary. This is especially relevant to information security (and to security in general) since it is not in the nature of the computer—a homogenous physical entity—to cause security breakdowns, but rather in the nature of those involved in the ever expanding network of human interactions—a heterogenous entity of extreme variability.

Given the nature of computation it is quite possible either

(1) to achieve effective pseudo-anticipation (since only the living authentically anticipates) performance within the forms of computation currently practiced; or
(2) to develop hybrid computational mechanisms that integrate physical and living components with the aim of achieving effective anticipatory properties.
(3)

These are two distinct research themes within the emerging notion of anticipatory computing.

Information Security and Assurance will become an ever more elusive target within the reactive mode of computation, as it is practiced today. Every step towards higher security and assurance only prompts the escalation of the problem that gave rise to such steps in the first place. In order to break this cycle, one has to conceive, design, implement, and deploy anticipatory computing that replaces the reactive model (such as virus detection) with a dynamic stealth ubiquitous proactive process distributed over networks. Anticipatory computation, inspired by anticipation processes in the living, implies a self-repair component. It also involves learning, not only in reaction to a problem, but as a goal-action oriented activity. The human immune system, which is anticipatory in nature, is a good analogy for what has to be done. In some ways, anticipatory processes are reverse-computations. Therefore, an area of anticipatory computing research will involve experiments with reverse computation (limited, of course, by the physical substratum of the computation process, i.e., by the laws of thermodynamics), either through quantum computation implementations or through hybrid computers (with a living component).

Anticipatory computing is indeed a grand challenge. The ALife community could not deliver this kind of solution because it failed to acknowledge the role of anticipation. The current efforts of leading scientists and research centers (e.g., Intel's research in proactive computing, the work of the Department of Energy's Sandia Laboratory) support the claims I made in 1998—anticipation is the new frontier in science—and in 2000—anticipation is the second Cartesian revolution, dedicated to the description of even more complex forms of causality than those associated with determinism and reductionism. Most research, which I wish to acknowledge, is carried out without an understanding of the fundamentals of anticipation. The technical aspects of anticipatory computing extend well beyond the subject of the CRA Grand Challenges conference. It might well be that in addressing information security, we simultaneously address the fundamentals of current computation, intrinsically unsecure. My hope is to create momentum for further investigation of anticipatory computing throughout the computing community. Social expectations, expressed in the notion of trust—itself a matter of anticipation—are such that such research will eventually become mainstream.