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White Paper: Computing Models and Architectures for Spatial, Disordered, Heterogeneous, and Dynamic Substrates

In the world of biological, molecular, and nano-scale building blocks, we need a paradigm shift from rigid, top-down engineered, and exogeneously imposed computing architectures to dynamic, network-based, decentralized, adaptive, evolving, self-organizing, developing, and hierarchical complex systems that solve problems efficiently and robustly. Our research aims to develop novel and transformative models, methodologies, and architectures for computing with *spatially extended*, *heterogeneous*, and *disordered* computing substrates that are subjected to dynamic *changes in space* and *functionality* over time. The approach is motivated by the increasing number of novel substrates and the need for non-von-Neumann computing systems. The scientific research question we ask is: ”What are the principles and methodologies to reliably and efficiently solve real-world problems with such systems?” Nature has solved this “design challenge” elegantly by adopting a bottom-up approach, but the computing disciplines do not offer the appropriate foundations and tools with traditional top-down engineered, fixed instruction-based computers.

To address this research challenge, we believe that one needs to the tackle the following inter-related research problems: (1) develop compute models based on emerging devices and new state variables; (2) develop new interaction and communication schemes; (3) develop new architectural principles based on dynamically interacting compute elements; (4) develop adaptive programming paradigms to make the systems robust, efficient, and scalable. To achieve the objectives, we draw inspiration and apply tools from computer science, computer engineering, physics, biology, complex systems science, and cognitive science. The interdisciplinary research will open new applications in the embedded computing field, help the medium- and long-term sustainability of the computing disciplines' technological future, and influence the computing disciplines at large. These new paradigms, in turn, may also give insight into the fundamental principles of growth, self-organization, and adaptation in natural processes. The research is transformative because it provides novel solutions to the challenge of engineering *man-made complex computing systems that we do not fully understand.*

References

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