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Emergent properties of bio-inspired hardware

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State-of-the-art electronic design allows the integration of complex electronic systems comprising thousands of high-level functions on a single chip. This has become possible and feasible because of the combination of semiconductor technology providing atomic-scale devices, allowing very large scale of integration (VLSI) of billions of transistors, and electronic design automation (EDA) tools that can handle their useful application and integration by following a strictly hierarchical design methodology breaking down a system into blocks, sub-blocks or cells. This results in many layers of abstraction within a system that makes it implementable and verifiable, hence, explainable which is usually desired. However, while many layers of abstraction maximise the likelihood of a system to function correctly (because it can be verified and debugged) this can prevent a design from making full use of the capabilities of a process technology.

Moreover this places electronic systems, in the way they are currently designed, at opposite ends of the scale from emergence as—by design—they can be understood from a purely reductionist point of view. The fundamental component of an electronic system, the transistor, is known and the design hierarchy is constructed bottom-up. Starting at the top level, this hierarchy can be traversed in the opposite direction and each block can be understood and explained by looking at the components it is made of. The whole methodology has been developed to avoid unforeseen behaviours and therefore there appears to be no room for emergence.

However, the ever-increasing transistor density and design complexity makes modern systems brittle. As we start to meet fundamental device scaling limits when touching the atomic scale, design challenges arise including the thermal/power constrained Dark Silicon and other deep sub-micron silicon fabrication issues such as intrinsic variability and electrical wear out (ageing). This gives VLSI designers a large number of pessimistic design constraints that must be met to avoid faults and guarantee a certain lifetime of a device. Despite that, the yield (percentage of chips on a silicon wafer that operate according to specification) continues to decline.

This gives rise to the idea of biologically-inspired hardware, which is indeed capable of emergent behaviours or features. Of course the challenge here is to adopt and implement these concepts while achieving a "next-generation" kind of electronic system which is considered at least as useful and trustworthy as its "classical" counterpart—plus additional features. Considering this, the question may be asked whether it is acceptable or useful to speak of emergence at all in the context of bio-inspired hardware, given that the bio-inspired parts also need to be designed using a VLSI methodology and must be comprehensible.

The concept of "emergence" is usually taken to relate to something like an unexplained or unexplainable appearance of an entity or property which is not further reducible to known interactions of other components (non-reductionist, holistic) [1]. Although this is quite vague and short of a definition, a variety of phenomena, including biological dynamics, chemical interactions and various mental phenomena, are labelled as "emergent". Accordingly, a wide range of definitions of "emergence" can be found in the literature and are, thus, generally, almost useless. For example, it is not useful to conceive of emergence in terms of "unpredictable" when trying to model the behaviour of an ant colony.

A useful definition of "emergence" when thinking in terms of engineering and computer science is found in [2], [3]. There, any property or entity within a particular *context* is called "emergent", if it is a property or entity which cannot be further explained in that *context*. A distinction is made between a "strong" concept of emergence, which implies an inability to reduce explanations to simpler concepts, and "weak" emergence, which implies that complex systems posses properties which are not possessed by their parts, but that those properties are explicable in terms of those parts. Hence, when an (electronic) system, comprised of a set (hierarchy) of interacting entities, gives rise to properties which cannot be analysed into components within some context, then for the purpose of that particular causal relationship and that particular context, that system is a singular, irreducible entity, and those properties are emergent. For example, when observing ants by looking at the behaviour of the entire colony rather than the individuals, the colony can indeed be regarded as a singular entity.

Based on this discussion and definition of "emergence", it can now be suggested that drawing inspiration from structure and behaviour of biological systems can bring new, useful behaviours to electronic systems which are explainable and verifiable at some lower level, but which can indeed be regarded as "emergent" properties, e.g. in the context of the entire system.

In this case, the emergent property sought to establish is system-level fault tolerance, the inspiration from biology are social insects (ant colonies), and the hardware system is a many-core computing architecture where application tasks and data need to be allocated transferred and organised. The model of processing elements communicating amongst each other via a network on chip (NoC) provides a conceptual link with many scalable biological models.

Based on this, a self-optimising and adaptive, yet fundamentally scalable, design approach for many-core systems based on the emergent behaviours of social-insect colonies are developed. Experiments aim to capture the relevant decision processes made by each member of the colony to exhibit such high-level behaviours and embed these decision engines within the routers of the many-core system. Results with the bespoke 128-core Centurion platform suggest that there is potential for the social insect model as a distributed, embedded intelligence within a many-core system and with the relevant knobs and monitors, such as clock frequency and temperature, to close the loop for emergent autonomous adaptation and fault tolerance [4], [5].

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