Physics from Computer Science

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Where sciences interact. We are, respectively, a computer scientist interested in the logic and semantics of computation, and a physicist interested in the foundations of quantum mechanics. Currently we are pursuing what we consider to be a very fruitful collaboration as members of the same Computer Science department. How has this come about? It flows naturally from the fact that we are working in a field of computer science where physical theory starts to play a key role, that is, *natural computation*, with, of course, *quantum computation* as a special case. At this workshop there will be many advocates of this program present, and we are honoured to be part of that community. But there is more. Our joint research is *both* research on semantics for distributed computing with non-von Neumann architectures, *and* on the axiomatic foundations of physical theories. This dual character of our work comes without any compromise, and proves to be very fruitful.

Computational architectures as toy models for physics. Computer science has *something more to offer to the other sciences than the computer*. Indeed, on the topic of mathematical and logical understanding of fundamental transdisciplinary scientific concepts such as interaction, concurrency and causality, synchrony and asynchrony, compositional modelling and reasoning, open systems, qualitative versus quantitative reasoning, operational methodologies, continuous versus discrete, hybrid systems etc. computer science is far ahead of many other sciences, due to the challenges arising from the amazing rapidity of the technology change and development it is constantly being confronted with. One could even claim that computer scientists (maybe without realizing it) constitute an avant-garde for the physical sciences in terms of providing fresh paradigms.

In our own recent work, we recast the standard mathematical framework of quantum mechanics (which is essentially due to John von Neumann [1]) in terms of categorical semantics [2], essentially using formal tools which were developed in Computer Science for analyzing linearity and resource sensitivity, and also the geometry of interacting components. Similar work by colleagues involves recasting the description of relativistic space-time using models originally developed for the domain-theoretic semantics of computation [3].

Closing the circle: high-level methods for quantum computing and physical computing in general. But of course this is not a one-way street. Physical theories inspired by computational theories are much better tailored for computer science applications as compared to their low-level counterparts. For example, the current tools available for developing quantum algorithms and protocols are deficient on two main levels. Firstly, they are too low-level. Quantum algorithms are currently mainly described using the 'network model' corresponding to circuits in classical computation. One finds a plethora of ad hoc calculations with 'bras' and 'kets', normalizing constants, matrices etc. The arguments for the benefits of a high-level, conceptual approach to designing, programming and reasoning about quantum computational systems are just as compelling as for classical computation. At a more fundamental level, the von Neumann formalism is actually insufficiently comprehensive for informatic purposes. In describing a protocol such as quantum teleportation, or any quantum process in which the outcome of a measurement is used to determine subsequent actions, the von Neumann formalism does not capture the flow of information from the classical or macroscopic level, where the results of measurements of the quantum-mechanical system are recorded, back to the quantum level. This flow, and the accompanying use of 'classical information', which plays a key role in protocols such as teleportation, must therefore be handled informally. As quantum protocols and computations grow more elaborate and complex, this point is likely to prove of increasing importance. Our work yields a semantics and logic which is appropriate for developing high-level tools for quantum computation and information. It provides a candidate solution for

$$\frac{\textbf{?}}{\textbf{von Neumann quantum formalism}} \simeq \frac{\textbf{high-level language}}{\textbf{low-level language}}\,.$$

The current scene. Computer scientists are lecturing at top theoretical physics institutes [4], while relativity is being discussed at bastions of computer science [5, 6]. Computer scientists even get invited to workshops on the Holy Grail of physics, quantum gravity [7]. Elsewhere, a tropical cocktail of the sciences is being mixed [8, 9]. High-level methods for quantum computing and information are now discussed at an annual workshop which will take place for the third time this summer [10]. The Oxford University Computing Laboratory [11] hosts a weekly multidisciplinary seminar [12].

In short, a critical mass is beginning to form, as part of the larger community engaged with the Grand Challenge on Non-Standard Computation. The start of something big, or a flash in the pan? There is only one way to find out . . .

References

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