Coarse Graining of Quantum Cellular Automata

(Dated: November 8, 2019)

Supervisor: Giuseppe Di Molfetta (MCF).

Contact details: giuseppe.dimolfetta@lis-lab.fr, 0646497714.

Place: Laboratoire d'Informatique et Systeme (LIS), Natural Computing team (CaNa). Scientific environment: The CaNa research group (Pablo Arrighi, Giuseppe Di Molfetta, Kevin Perrot, Enrico Porreca, Sylvain Sene) seeks to capture at the formal level some of the fundamental paradigms of theoretical physics and biology, via the models and approaches of theoretical computer science and discrete mathematics. The group is located in Luminy, Marseille, France, and benefits from a rich scientific environment with the Cellular Automata experts of I2M (Pierre Guillon, Guillaume Theyssier) and the physicists from CPT (Alberto Verga, Thomas Krajewski, Rovelli group).

Theme and goals Quantum cellular automata are quantization of the classical cellular automata. In this project we are going to employ the definition of QCA recently put forward by [3]. In the proposed model the QCA can be defined over a general graph where in each vertex sits a cell, with each cell composed of subcells defined as finite dimensional quantum systems. The evolution of the QCA is given by local unitaries that act on partitions of the graph, i.e. all quantum cellular automata are reversible. This is in accordance with the expected microscopic fully quantum dynamics. One of the goals of the present project is to use the discrete structure of the QCA as to depart from this description and obtain emergent (possibly stochastic) dynamics.

Typically the suppression of quantum features is described within the theory of open quantum systems [4]: the system of interest is coupled to a large reservoir, and despite of the unitary dynamics for the combined system plus environment, when looking just for the system its quantum properties decay [1].

In this project, however, we will employ a different perspective, and will describe the fading of quantum properties in a closed quantum system. This will be done by describing the system at different scales and in different levels of detail, as if one would zoom out from the microscopic description. By doing so one averages over the possible microscopic descriptions which are compatible with a higher level description, and the quantum features are gradually suppressed. Such a procedure has been recently proposed for general quantum systems [5]. In this project we will develop coarse graining procedures tailored for QCA, *especially in two-particles sector*.

More in detail, inspired by the classical coarse graining procedures [6, 8], we are going to define supercells for the QCA (that might include many unit cells and time steps) and construct effective dynamics for different sizes of the supercell. In the most low-level we have the fully microscopic and reversible quantum dynamics; while for increasing supercell size the quantum features are gradually suppressed and a non-reversible dynamics emerge. With this procedure we can investigate whether a classical dynamics will emerge, or if the quantum fluctuations of the fundamental local observables are sizeable throughout the coarse graining procedure thus not allowing for its classical simulation.

Note that this procedure, together with the continuous limit of the QCA dynamics, can be used to obtain master equations for the system's dynamics. These equations are however for the closed system, and the lost of information comes strictly from the description level – one can imagine that the available "detectors" are not good enough to resolve the more basic level of the dynamics, and as such it only makes sense to speak of a high-level description. We are thus proposing a way to obtain effective, non-unitary, dynamics for closed quantum systems for which a complete description is not available.

Perspectives: Apply the coarse-graining procedure to some QCA, simulating microscopic quantum physical theories (such as QED), to obtain different levels of descriptions for the quantum field theories that QCA themselves are aiming to describe.

The internship will funded as legally required.

Prerequisite: Strong programming skills, strong knowledge of linear algebra, knowledges in quantum information or quantum mechanics is atout but not necessary.

---

[1] M. P. Almeida, F. de Melo, M. Hor-Meyll, A. Salles, S. P. Walborn, P. H. Ribeiro, and L. Davidovich. Environment-induced sudden death of entanglement. *Science*, 316(5824):579, 2007.

[2] Leandro Aolita, Fernando De Melo, and Luiz Davidovich. Open-system dynamics of entanglement: a key issues review. *Reports on Progress in Physics*, 78(4):042001, 2015.

[3] Pablo Arrighi and Jonathan Grattage. Partitioned quantum cellular automata are intrinsically universal. *Natural Computing*, 11:13, 2012.

[4] Heinz-Peter Breuer and Francesco Petruccione. *The Theory of Open Quantum Systems*. Oxford University Press, 2007.

[5] Cristhiano Duarte, Gabriel Dias Carvalho, Nadja K Bernardes, and Fernando de Melo. Emerging dynamics arising from coarse-grained quantum systems. *Phys. Rev. A*, 96(3):032113, 2017.

[6] Navot Israeli and Nigel Goldenfeld. Coarse-graining of cellular automata, emergence, and the predictability of complex systems. *Phys. Rev. E*, 73:026203, Feb 2006.

[7] A. Salles, F. de Melo, M. P. Almeida, M. Hor-Meyll, S. P. Walborn, P.H. S. Ribeiro, and L. Davidovich. Experimental investigation of the dynamics of entanglement: Sudden death, complementarity, and continuous monitoring of the environment. *Phys. Rev. A*, 78(2):022322, 2008.

[8] A. Weeks. *Neutral emergence and coarse graining cellular automata*. PhD thesis, University of York, 2010.