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UNIVERSITY OF SOUTHERN CALIFORNIA

JUNE 2021

FINAL TECHNICAL REPORT

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14. ABSTRACT

In this project we developed novel methods for the implementations of quantum mechanical primitives resilient to noise and spurious interactions with the environment. In particular, on the one hand we designed quantum networks which exploit dissipation in order to compute any Boolean formula. On the other hand, we exploited a novel classification of non-Hermitian, dissipative, topological insulators, to exponentially increase the coherence time of working qubits. We constructed novel measures of quantum coherence and coherence generating power, and showed that they can be obtained through known observables such as the dynamical conductivity. On a more basic level we elucidated the mechanism responsible for quantum thermalization. We showed that the so called Eigenstate Thermalization Hypothesis (ETH), is not only necessary but also sufficient for thermalization. We also showed that the ETH is also implicitly assumed in classical statistical mechanics where it roughly corresponds to the statements that the energy shell is very small compared to the mean energy. As a result, we showed that both classical and quantum statistical mechanics can be formulated according to the same principle, the justification of which, however, is entirely quantum.

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SUMMARY

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INTRODUCTION

Noise is a pervasive and unavoidable feature of any aspect of physical reality. This is especially true for the quantum realm, and is essentially the reason why quantum effects are generally hard to observe, and what makes quantum computing such a challenge. Quantum error correction is what allows, at least in principle, to run a quantum algorithm on a circuit model architecture in presence of noise. Noise resilience is achieved by trading qubit resources and the overhead is so high to be currently prohibitive. The analogous of quantum error correction for the quantum annealing paradigm of quantum computation is instead completely lacking. This shortcoming is at the same time room for opportunity. In most, though not all, situations the effect of unwanted interactions with the environment is simply that of triggering a positive temperature on the system, and noise, in this context, becomes synonym with temperature. The purpose of this project was that of mitigating the effects of noise/temperature for the purpose of enacting quantum information primitives. A possible strategy being that of exploiting dissipation itself for this purpose. At the same time this requires characterization of quantum coherence or lack thereof. Another strategy that we pursued is to use the resilience offered by topological protection. A related, basic science question that we addressed, is understanding how quantum systems reach thermal equilibrium.

METHODS, ASSUMPTIONS, AND PROCEDURES

A theoretically ideal annealing architecture, is described by the Schrödinger equation with a time dependent Hamiltonian. The theoretical justification behind the adiabatic approach is given by the adiabatic theorem [1,2]. In presence of unwanted interactions with external degrees of freedom, we model the dynamics of the system described by density matrix ρ, with a Lindblad master equation, which can be written as

$$\dot{\rho} = -i[H, \rho] + \sum_i L_i \rho L_i^* - \frac{1}{2}\{L_i^* L_i, \rho\}, \tag{1}$$

where H is the system Hamiltonian and the L_i's are the Lindblad jump operators.

We proved the analogous of the adiabatic theorem in this context in [3]. However, as we argued in [4], obtaining a quantum speed-up following the adiabatic approach in presence of realistic noise is unlikely for more than 10-20 qubits.

With this in mind we devised dynamical approaches resilient to dissipation, to perform quantum information tasks. We followed two different strategies. In one we used dissipation itself, while in the other we used the protection offered by topology generalized to the dissipative case. In the first case dissipation itself becomes the resource that ultimately allows to perform quantum informational tasks. In a series of papers, we have previously shown that it is possible to perform quantum information tasks even in the limit of very strong dissipation. The mathematical result that makes this possible is the following projection theorem (proven in [5])

$$\left\|\left(e^{T\mathcal{L}} - e^{T\mathcal{K}_{eff}}\right)\mathcal{P}_0\right\| = O\left(\frac{\tau_R}{T}\right) \tag{2}$$

where $\mathcal{L} = \mathcal{L}_0 + h_1$ is the total Liouvillian, $\mathcal{L}_0$ is a *strong* dissipative term, $h_1 = -i[H, \cdot]$ where H is the, *weak,* system Hamiltonian, $\mathcal{P}_0$ is the projector onto the steady state space of $\mathcal{L}_0$, finally $\mathcal{K}_{eff} = \mathcal{P}_0 h_1 \mathcal{P}_0$, $\tau_R = \left\|{\mathcal{L}_0}^{-1}\right\|$ is the relaxation time of $\mathcal{L}_0$, and the total evolution time T is $T = 1/\|h_1\|$. The interesting fact is that $\mathcal{K}_{eff}$ generates always a purely *coherent* quantum evolution. The content of Eq. (1) is that, when $\tau_R \ll T$, i.e. dissipation is much stronger than the coherent term, the total evolution, looked from the steady space of $\mathcal{L}_0$, is close to the unitary generated by $\mathcal{K}_{eff}$. Remarkably this result holds true even in case h_1 is purely dissipative. In practice h_1 may contain unwanted and unknown dissipative terms itself but this method will always generate a unitary transformation. Using higher order generalization of Eq. (1) we have shown in [6,7] that it is possible to engineer any possible Lindbladian. In other words, when for example for symmetry reason $\mathcal{K}_{eff} = 0$, one has the analogous of Eq. (1) with $\mathcal{K}_{eff}$ replaced by a suitable Lindbladian. One may think to obtain a Lindbladian master equation directly by coupling the system with an environment and then using the standard Born-Markov approximation. The point is that the latter (Markov) involves uncontrolled approximation, whereas (1) and its generalization have uniformly controlled error. Physically this means that, if a system is well described by a Lindbladian master equation, it can be used as a resource to implement other Lindbladians by coupling the system with external degrees of freedom.

In our approach to compute Boolean formulas, we assume we can prepare a four-local Lindbladian.

Topology is another promising and well known approach to protect quantum information [8]. Our idea is to use edge modes of topological 1D chain as long-lived qubits. However, to be more realistic we will explicitly include the effect of dissipation and disorder. In order to do that we will need a generalization of topological invariants to the dissipative setting, as put forth in [9].

In common situations the interaction of the system with the environment results in the system acquiring a positive temperature. Since, in general, quantum features are destroyed with increasing temperature, it is important to understand the interplay between temperature and quantumness, a question that we addressed in publication (d). Moreover, whereas the emergence of thermalization in classical mechanics can be understood on the hand of Boltzmann's ergodic hypothesis, it is currently not known what is the underlying mechanism that leads to thermalization in the quantum world. This question was addressed and partly resolved in publication (d).

RESULTS AND DISCUSSIONS

In publication (a) we showed that a 4-local dissipative Lindbladian can be used to compute 3-CNF (conjunctive normal forms with clauses of three variables) and so in principle any Boolean formula can be computed in this way. A single clause corresponds to the basic element in the left panel of Figure 1, while an entire 3-CNF is illustrated in the right panel. The blue dot is an ancilla qubit while the yellow dots act as register. For a clause $C = x \vee y \vee z$, the corresponding Lindblad jump operator reads

$$L = \Pi \otimes \sigma^{-}, \tag{3}$$

where $\Pi = |\bar{x}, \bar{y}, \bar{z}\rangle\langle\bar{x}, \bar{y}, \bar{z}|$. For example if $C = x \vee \bar{y} \vee z$, then $\Pi = |0,1,0\rangle\langle 0,1,0|$. If there are N clauses the total Lindblad operator reads

$$\mathcal{L} = \sum_{i=1}^{N} L_i \cdot L_i^{*} - \frac{1}{2}\{L_i^{*} L_i, \cdot\}. \tag{4}$$

Evolving an initial fiducial state with such a network one can evaluate the CNF in a time $t = O\left(n + \log\left({}^{N}/_{\epsilon}\right)\right)$, where n is the total number of registers and ϵ the error made in measuring the ancilla qubits. Moreover, under evolution with the above Lindbladian, the Hilbert space is partitioned into sectors according to dechoerence free subspaces associated with the dissipative dynamics. These sectors provide a natural and consistent way to classify quantum data (i.e. quantum states). Indeed, the attractive fixed points of the network allow one to learn the sector(s) for which some particular quantum state is associated. This structure can also be used to dissipatively prepare quantum states (e.g. entangled states).

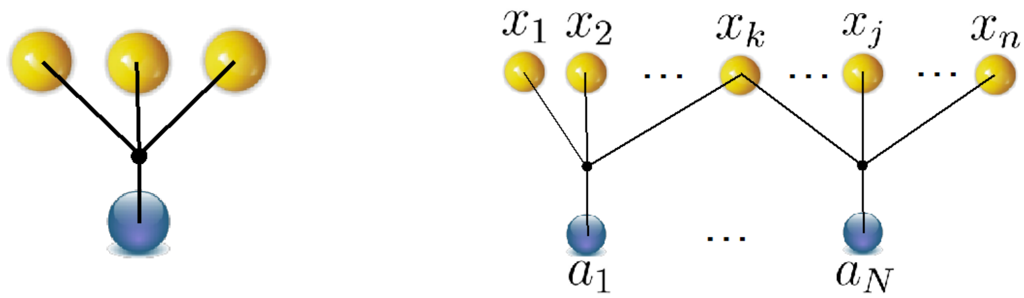

Figure 1 Left panel. Three input qubit (in yellow) coupled dissipatively to an ancilla qubit (blue). Right panel: Dissipative network for computing a 3-CNF with N clauses.

In the above setting, as is customary, one assumes to have perfectly ideal qubits. This is notoriously impossible. We then addressed the question whether it is possible to increase the coherence time of the working qubits. In publication (b) we investigated the capability of topology to achieve this goal. We assumed that the fiducial qubit is part of a dissipative, i.e. imperfect, network of qubits. It is known that one can generalize the classification of topological charge from the unitary, ideal case, to the dissipative, non-ideal case. In [9] this generalization has been carried out to define a dissipative winding number. The idea, generalized to super-operator space, is that a one dimensional, topological, dissipative chain, can support stable edge modes localized at the end of the chain. In turn, in our construction, such stable edge modes would be responsible for exponentially increasing the qubit's coherence time. We then considered networks of qubits and dissipative microwave cavities inspired by cavity QED but also applicable to other experimental platforms. In particular we studied the dissipative, dimer and trimer chains shown in Figure 2. The J_i's are coherent interaction between qubits and cavities, whereas Γ is the dissipation rate of the cavities. We also allowed for quenched disorder on the couplings J_i to account for imperfection in fabrication.

Figure 2 Left (right) panel: dissipative dimer (trimer) chain. Black dots are qubits and open dots are lossy cavities. The couplings J_i are various qubit-cavity interactions.

The results for the clean case are shown in Figure 3 left panel. The coherence's qubit rapidly decays to zero for trivial topology (charge *W*=0). In case of non-trivial topology (charge *W*=1 or 2) the coherence does not decay to zero. For *W*=1 the coherence approaches a finite value corresponding to a stable coherent state. For *W*=2 there are two stable, non-decaying states and the coherence displays Rabi-like oscillations. For the noisy case results are similar for the average coherence (Fig. 3 right panel).

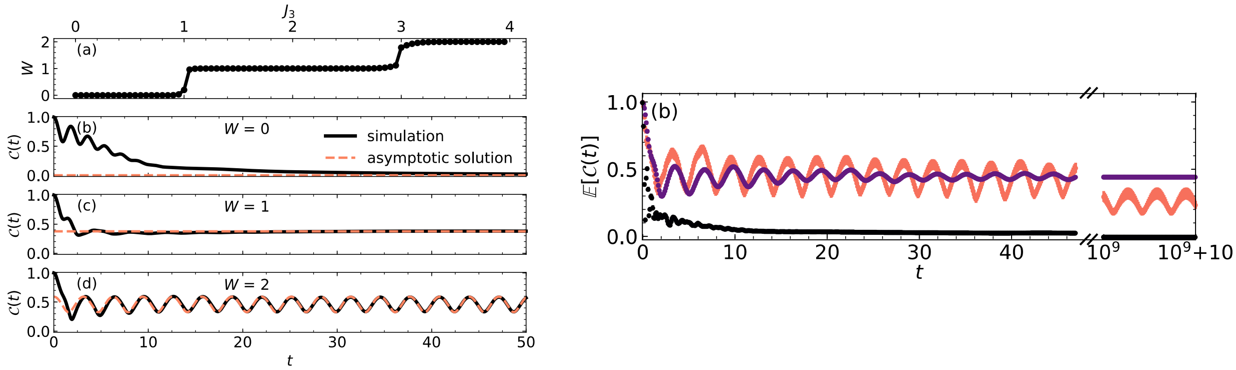

Figure 3 Left panel: Coherence of the clean trimer chain for different topological charges W as a function of time. Right panel: averaged coherence as a function of time for W=0 (black), 1 (purple), 2 (orange).

Interestingly, the introduction of quenched disorder can trigger a peculiar, counterintuitive phenomenon. For certain range of parameters explained in (b), increasing noise has the effect of increasing the topological charge, see Figure 4. In our setting, this means that increasing noise dramatically increases the coherence time, from finite to exponentially large in the number of sites.

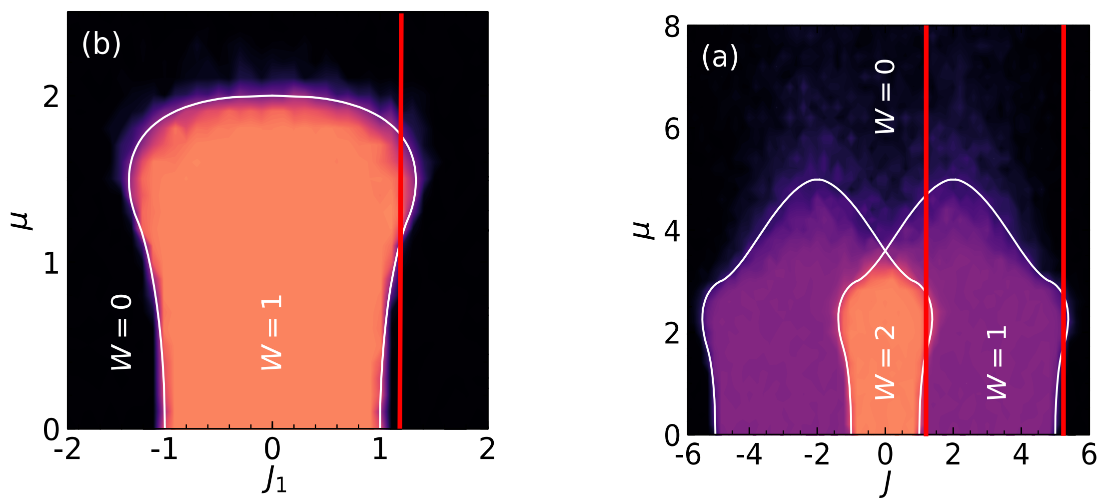

Figure 4 Reentrance phenomenon in a dissipative dimer network (left panel) and trimer network (right panel). Moving along the red lines increasing noise one crosses a region of higher topological charge, i.e. increasing noise makes the system more coherent.

In the other half of the project we concentrated on those particular situations where the effect of unwanted interactions is that of inducing a positive temperature on the system. We wanted to understand how thermalization works in quantum mechanics and what is the interplay between thermalization and quantum coherence.

It is known that classical thermalization can be understood microscopically thanks to Boltzmann ergodic hypothesis: if the orbits are dense in the phase space, the infinite time average can be replaced by phase space average, the latter being the definition of thermalization. In quantum mechanics there is no phase space to begin with. Unitary evolution always brings the state around on a multidimensional torus, and whether such orbits are dense or not has no connections to thermalization. Instead, one possible route to quantum thermalization is the so called Eigenstate Thermalization Hypothesis (ETH) put forward by Deutsch and Srednicki [10, 11] and made popular in [12]. Quoting a recent review on the subject [13] "*While all known examples of thermalizing systems obey ETH, at present it is not clear if ETH is a necessary condition for thermalization*.". Moreover, the concept of ergodicity itself in quantum mechanics is much less clear than in classical mechanics: "*We note that in the context of quantum many-body systems the term ergodicity is defined somewhat differently compared to classical mechanics. Our use of the term is synonymous with thermalization"* [13].

In publication (c), by properly defining ergodicity in quantum mechanics, we have shown that indeed ETH is both sufficient *and* necessary for a quantum system to thermalize, thus solving the question raised in [13]. A well-known equivalent characterization of ergodicity in the classical case is that for any summable function f, and for almost any initial condition,

$$\overline{f(t)} = \langle f \rangle_{\mu} \tag{5}$$

where overline indicates infinite time average and $\langle \cdot \rangle_{\mu}$ is the statistical average with respect to the invariant measure μ. The above means that the time average of an observable *function* f is the constant function almost everywhere. Another equivalent characterization of ergodicity is that for any function f

$$\overline{\langle f(t) f \rangle_{\mu}} = \langle f \rangle_{\mu} \langle f \rangle_{\mu}. \tag{6}$$

It is straightforward to generalize the above to the quantum case. The role of the function f is now played by an operator A, and the statistical average becomes $\langle \cdot \rangle_V \stackrel{\text{def}}{=} Tr(\cdot\, \rho_V)$ where ρ_V is an invariant state. We say now that an observable A is shell ergodic if

$$\overline{\langle A(t) A \rangle_V} = \langle A \rangle_V \langle A \rangle_V \tag{7}$$

We have shown that in quantum mechanics there are similar characterizations of ergodicity as in classical mechanics, namely an observable A is shell ergodic if and only if

$$\overline{A(t)} = \langle A \rangle_V \mathbb{1}, \tag{8}$$

where $\mathbb{1}$ is the identity operator. This is clearly the quantum generalization of Eq. (5), where the identity replaces a constant function. With this machinery we have been able to prove that shell ergodicity is equivalent to thermalization and that ETH is equivalent to shell ergodicity, thus proving the equivalence between ETH and thermalization.

Moreover, we have also shown that the analogous of ETH exist also in classical mechanics and is usually implicitly assumed. In this way we have shown that it is possible to build both classical and quantum statistical mechanics using a unified framework. However, the proper justification of this framework comes from quantum mechanics. This is a basic science result but also of fundamental importance as it settles the long-standing question of how quantum systems approach thermal equilibrium.

Since thermalization is generally detrimental for quantum computation it is important to understand situations which do not lead to thermalization and their relation with quantum features such as quantum coherence. It would be desirable to have experimentally accessible figures of merits able to quantitatively assess a precise quantum feature. In (d) we have studied precisely this complex interplay. A situation which is known to inhibit thermalization is Many-Body Localization (MBL). MBL is the many-body generalization of Anderson localization for which (some) Hamiltonian eigenstates are spatially localized. In such a system transport is strongly suppressed and the dynamics is so slow that thermalization cannot be reached. Intuitively one expects that, for similar reasons, MBL should destroy quantum coherence. In order to make such statements quantitative we have defined proper measures of coherence and of Coherence Generating Power (CGP). The CGP measures the amount of coherence that a given quantum operation, generate on average. In formulae, the CGP of the quantum map $\mathcal{E}$ is

$$\mathrm{CGP}_B(\mathcal{E}) = \mathsf{E}_\rho[C_B(\mathcal{E}(\rho))], \tag{9}$$

where $B = \{|i\rangle\}$ is the preferential basis along which we measure coherence, $C_B(\rho) = \sum_{i\neq j} |\rho_{i,j}|^2$ is the coherence of ρ with respect to basis B, and $\mathsf{E}_\rho[\cdot]$ is the uniform average over the set of incoherent states. We have shown that, not only are the concepts of localization and quantum coherence closely related but that natural indicators of CGP are exactly the same as known indicators of (the lack of) MBL. Indeed, a common indicator of MBL for a Hamiltonian H, is the average return probability (ARP), with respect to the (localized) basis B, is

$$\mathrm{ARP}_B(H) = \frac{1}{d}\sum_{i=1}^{d} \overline{|\langle\iota|e^{-\iota tH}|\iota\rangle|^2}. \tag{10}$$

We have shown that the ARP, is exactly equal to one minus the coherence generating power:

$$\mathrm{ARP}_B(H) = 1 - \mathrm{CGP}_B(W), \tag{11}$$

Where $W = \sum_i |i\rangle\langle\phi_i|$ is the adiabatic intertwiner between basis B, and the Hamiltonian eigenbasis $\{|\phi_i\rangle\}$. There is a similar situation for the differential CGP, the different in CGP created by two nearby close maps. We have found that the differential CGP is exactly equal to the DC dielectric polarizability, a quantity directly accessible in experiments.

These findings allowed us to extend known predictions from condensed matter theory for MBL and conductivity [14] to the field quantum information, and in particular for the ability of maps to generate coherence. The prediction is then that the CGP tends to 1 in the thermodynamic limit in the ergodic phase while it is submaximal (i.e. <1) in the localized phase. Similarly the differential CGP diverges in the thermodynamic limit in the ergodic and subdiffusive phase it converges to a finite value in the MBL phase. In short, known measures of transport/localization turn out to be exactly identical to precise measure of coherence. Since quantum coherence is a necessary ingredient of any quantum computation, this allows to have faithful indicators of coherence that can be directly accessed experimentally thus allowing figures of merit for quantifying the possibility of performing quantum computation.

CONCLUSIONS

In this project we searched for novel methods for enacting quantum information tasks, resilient to noise and spurious interactions with the environment. In order to achieve this goal, we exploited on the one hand, dissipation itself and on the other hand the natural resilience offered by topological protection, extended to the dissipative case. In particular, we developed a dynamical strategy that exploits dissipation to compute any classical Boolean formula. With the same approach it is also possible to classify quantum data, the quantum equivalent of a notorious machine learning task. We have shown how a network of dissipating qubits can be tailored to achieve topological protection of a fiducial qubit, exponentially increasing its coherence time. Since temperature can be seen as a particular form of noise, we have also studied how temperature impacts quantum mechanical tasks, in particular quantum coherence. Finally, on a more basic level, we have studied how thermalization occurs in the quantum realm by settling a recent debate.

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APPENDIX A – Publications and Presentations

(a) Jeffrey Marshall, Lorenzo Campos Venuti, and Paolo Zanardi, "Classifying quantum data by dissipation", *Phys. Rev. A* **99**, 032330 (2019)

(b) Yu Yao, Henning Schlömer, Zhengzhi Ma, Lorenzo Campos Venuti, Stephan Haas, "Topological Protection of Coherence in Noisy Open Quantum Systems", arXiv:2012.05274

(c) Lorenzo Campos Venuti, Lawrence Liu, "Ergodicity, eigenstate thermalization, and the foundations of statistical mechanics in quantum and classical systems", arXiv:1904.02336

(d) Georgios Styliaris, Namit Anand, Lorenzo Campos Venuti, Paolo Zanardi, "Quantum coherence and the localization transition", *Phys. Rev. B* **100**, 224204 (2019)

Conferences and talks

- Lorenzo Campos Venuti, March meeting Boston, March 6, 2019. *Quantum Coherence, phases of matter and many-body localization*
- Lorenzo Campos Venuti, UMass Boston, March 6, 2019. *Ergodicity, eigenstate thermalization, and the foundation of classical and statistical mechanics.*
- Lorenzo Campos Venuti, University of Southern California, April 5, 2019. *Ergodicity, eigenstate thermalization, and the foundation of classical and statistical mechanics.*
- Lorenzo Campos Venuti, Dolomites Conference, Dolomites Italy, July 2019. *Ergodicity, eigenstate thermalization, and the foundation of classical and statistical mechanics.*
- Lorenzo Campos Venuti, University of Bologna, Italy, October 15, 2019. *Ergodicity, eigenstate thermalization, and the foundation of classical and statistical mechanics.*

LIST OF ACRONYMS

ETH – Eigenstate Thermalization Hypothesis

1D – One-dimensional

CNF – Conjunctive Normal Form

QED – Quantum Electrodynamics

MBL – Many Body Localization

CGP – Coherence Generating Power

ARP – Average Return Probability

DC – Direct Current