Non-Markovianity in Open Quantum Systems

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1 Overview of the Field

Open systems are subject to the uncontrollable effects of their surrounding environments. As opposed to isolated systems' evolutions, open systems' evolutions are not unitary, but include dissipative components that result from environmental fluctuations. The character of these fluctuations dictates the type of dynamics that the open system will undergo. In their simplest form, environmental fluctuations are merely brief deviations from equilibrium values, and the open system typically loses energy and coherence via a unidirectional flow towards the environment. This is the behavior typically observed in atomic relaxation and in the loss of optical coherence in the presence of the radiation field [13].

The type of master equation or dynamical map that describes open system dynamics in these situations is called *Markovian*, or memoryless. The latter name evokes the lack of any black-flow of information from the environment into the system. When derived *ab initio*, a Markovian evolution typically evinces a clear separation of two time scales: (i) the time scale of the system evolution that results from the coupling to the environment and (ii) the much shorter environmental correlation time. This phenomenology was formulated rigorously in the context of the weak-coupling framework by Davies [12]. Subsequent work by Lindblad [25] and by Gorini, Kossakowsi, and Sudarshan [18] provided a neat mathematical result identifying conditions sufficient for the dynamical generator of open-system dynamics to be completely positive and trace preserving (CPTP). The Davies master equations emerge now as resulting from the canonical structure of the generator of quantum dynamical (Markovian) semigroups. These seminal works can be regarded as the first attempts to formalize the concept of the absence of memory (Markovianity) in quantum evolution. Dynamics that cannot be expressed in this manner would be classified as non-Markovian. In recent years—and perhaps motivated by the community's increasing ability to control, probe, and manipulate quantum systems embedded in soft or solid-state environments—it became timely to fully characterize memory effects in the quantum domain. The aim is to develop comprehensive quantum theory of memory. Rather than resorting to microscopic derivations that may change from platform to platform, the aim is to develop a general mathematical framework for quantum non-Markovianity.

This is the general context of the BIRS workshop, whose main goal has been to bridge two promising approaches to the definition and characterization of non-Markovianity in the quantum realm. The first approach introduces definitions of Markovianity and associated non-Marvovianity measures based upon the structure of CPTP quantum dynamical maps. This includes the definition of Markovianity in terms of CP divisibility

[32] and definitions in terms of distance measures that provide contractions for CP maps, like the celebrated trace distance measure [7]. Interestingly, these two definitions are not equivalent [33].

The second approach to quantum non Markovianity aims to extend the theory of classical stochastic processes to the quantum domain. Rather than two-time properties of CPTP generators, the key figure of merit is the multi-time statistics resulting from probing the system at intermediate times. The validity of the quantum regression expression for joint probability distributions provides one possible definition of Markovianity in this setting [36, 28]. A unifying formalism may be facilitated by the recently introduced concept of process tensors [27]. This general description of quantum processes naturally includes the possibility of interrogating the system at multiple times and provides an operational condition for quantum Markov processes, together with associated measures of non-Markovianity [29].

The BIRS workshop brought in researchers exploring these different approaches to non-Markovianity theoretically. We also invited researchers working experimentally and whose observations cannot be explained within the canonical Markovian framework. Our intentions were to foster exchanges and to foment further explorations of the different mechanisms by which memory manifests in the quantum realm and the most general framework able to encompass them.

2 Emergent, Emerging Threads

In multiple cases, several talks addressed closely related subjects from different perspectives. The progression of related talks built up toward what the group recognized as an opportunity for future research. We highlight two such progressions here, one focused on the Kolmogorov consistency condition and one focused on experiments.

2.1 Kolmogorov consistency condition

Four talks referred to the Kolmogorov consistency condition, defined as follows. Consider a classical random variable x that evolves in discrete time, across the instants $t_{1,2,\ldots,f}$. The variable has a joint probability $p(x_0, t_0; x_1, t_1; \ldots; x_f, t_f)$ of assuming the value x_0, then x_1, etc. Suppose that the time-t_j event is skipped. The associated joint distribution, p', follows from summing p over x_j:

$$p'(x_0, t_0; x_1, t_1; \ldots; x_{j-1}, t_{j-1}; x_{j+1}, t_{j+1}; \ldots x_f, t_f) = \sum_{x_j} p(x_0, t_0; x_1, t_1; \ldots; x_f, t_f).$$

This equation is the Kolmogorov consistency condition, an axiom of probability theory. Classical variables obey the equation.

Consider obtaining the sequence $\{x_j\}$ by measuring a quantum system repeatedly. The joint probability distribution over the sequence can violate the Kolmogorov consistency condition. The reason is measurement disturbance: A measurement at t_{j-1} alters the quantum state, affecting the measurement at t_j.

Philipp Strasberg and Andrea Smirne defined classicality of a joint probability distribution as adherence to the Kolmogorov consistency condition. Violations of the condition underlie violations of Leggett-Garg inequalities [24]—Bell-like bounds for correlations across time, rather than across space—as Smirne and Yunger Halpern noted. Rivas pointed out that a closed quantum system can violate the consistency condition despite resembling its classical analogue in being divisible.

Yunger Halpern showed that, if a distribution violates the consistency condition, it equals a linear combination of Kirkwood-Dirac quasiprobabilities (KDQs). For more information about KDQs, see the relevant talk synopsis. This perspective, rooted in experience with KDQs in information scrambling and metrology, contrasted with the other three speakers' perspective, which was rooted in non-Markovianity. How we can leverage known properties of KDQs in non-Markovianity studies was identified as an open question.

2.2 Experiments

Many of the talks were (appropriately for BIRS) abstract and mathematical. However, a few reported on experiments. Kade Head-Marsden discussed an experiment close to the abstract: a five-qubit quantum simulation performed on the IBM Quantum Experience [20]. The simulation was precisely of an open quantum

system. Similarly, Nicole Yunger Halpern discussed the testing of an entropic uncertainty relation dependent on a weak value [30]. Weak values can be measured via weak measurements, which refrain from disturbing a quantum system much and so help alleviate the measurement-disturbance concerns mentioned in Sec. 2.1. Farther afield, Gabriela Schlau-Cohen discussed the engineering of DNA-origami scaffolds that served as environments to influence exciton transport [19]. Avikar Periwal presented recent experimental progress on engineering entangled states of several atoms using photons in a cavity. His work opens up a new means of performing measurement-based quantum computation [9]. Such developments helped bridge the workshop's mathematical and physics contributions. Furthermore, the experimental talks provided inspiration for testing and applying more of the theoretical results in the lab.

3 Presentation Highlights

Participants presented 24 talks at the workshop. Below are synopses, listed in chronological order of delivery.

Philipp Strasberg (Universitat Autonoma de Barcelona) discussed the foundations of stochastic thermodynamics. Much of our world appears classical, Markovian, and detailed-balanced; but how do these properties emerge from microscopic dynamics? Strasberg offered justifications in the setting of an isolated quantum many-body system [37]. Part serves as the system of interest, and the rest serves as an effective bath. The argument hinged on the eigenstate thermalization hypothesis, an ansatz about the form of the elements of matrices that represent typical local observables relative to the energy eigenbasis. Closely related is the repeated-randomness assumption: The principle of maximum entropy describes a system's state accurately at multiple stages of a thermodynamic system's evolution. Van Kampen believed the repeated-randomness assumption to be reasonable under certain assumptions (if the system is nonintegrable, the observable being monitored is coarse, and the observable is "slow") but had difficulty proving it [38].

Erik Gauger (Heriot-Watt University) talked about modelling non-Markovian dynamics with process tensors. He presented an overview of (analytic and numerical) approaches and equations used in the theory of open quantum systems, as well as what they can deliver. He focused then on the method of matrix product operators, which are process tensors suitable for analyzing complex hybrid systems [10]. The method is mainly numerical. Gauger considered an optically driven GaAs quantum dot, modeled by a driven excitonic two-level system which is linearly coupled to a bath of oscillators. Under a weak laser intensity, the dynamics show non-Markovian features. To set up a theoretical approach allowing for the treatment of such systems, Gauger presented the process-tensor method (used also in Gregory White's talk), based on breaking the evolution into small time steps. He then explained the automatic-compression-of-the-environment (ACE) technique. He illustrated the power and versatility of the method by comparing its predictions with explicit dynamics for (i) a resonant-level model and (ii) one or two quantum dots coupled to two environments.

Andrea Smirne (University of Milan) addressed the question "How can we tell whether a quantum process can be implemented classically?" [28]. That is, consider receiving joint probability distribution

$$p(x_0, t_0; x_1, t_1; \ldots; x_f, t_f)$$

over a time series of data. Can any classical process give rise to that distribution? Smirne defined classicality as the distribution's obeying the Kolmogorov consistency condition. He then connected nonclassicality with coherence [36]. His main result provided a necessary and sufficient condition for the guiding question's answer to be affirmative: Suppose that an observable is nondegenerate, its statistics are Markovian, and a system's initial state is diagonal with respect to the observable's eigenbasis. Classicality of the observable's statistics is equivalent to the dynamics's not generating and detecting coherence.

Nicholas Anto-Sztrikacs (University of Toronto) introduced an effective Hamiltonian for a system S coupled strongly to an environment [2]. Conceptually, one incorporates some degrees of freedom from outside S into the system of interest. Mathematically, one uses a reaction-coordinate map, followed by

a polaron transformation. One then truncates the reaction-coordinate Hamiltonian, under an assumption (if the reaction-coordinate frequency is the problem's greatest energy scale). Anto-Sztrikacs illustrated this framework with applications to a spin-boson model and an autonomous quantum refrigerator.

Marlon Brenes (University of Toronto) talked about fluctuations and charge statistics in mesoscale conductors. He began with a model where a central system is coupled to two reservoirs. Then, he introduced the notion of stochastic accumulated charge (integrated over time from an initial to a final instant) and the average current. The noise is defined as the time derivative of the variance of the stochastic accumulated charge. The accumulated charge is additive in time, but its variance is not. In order to be able to treat the strongly coupled regime, Brenes introduced a map effectively introducing several fermionic modes, each one coupled to its own reservoir. This is a mesoscopic reservoir. He then discussed the full counting statistics. He addressed the expressions for currents and noise in Gaussian systems. Brenes reported on results obtained in [6], where an analysis of the current and noise was carried out numerically in strongly driven systems.

Nicole Yunger Halpern (National Institute of Standards and Technology) provided a tutorial about Kirkwood–Dirac quasiprobabilities (KDQs). Quasiprobabilities are quantum generalizations of probabilities, able to break some of Kolmogorov's axioms for probability theory. The best-known quasiprobability—the Wigner function—famously assumes negative values, signaling quantum behaviors under specific circumstances. KDQs can assume not only negative, but also nonreal values, which quantify measurement disturbance [14]. The distribution's complex nature, suitability for continuous and discrete systems, measurability, and other properties underlie KDQs' recent infiltration of diverse subfield of quantum physics. Yunger Halpern presented a few applications to quantum information scrambling [40, 41, 1], metrology [3, 26], quantum Shannon theory [42], and quantum foundations [4]. Two scheduled talks had implicitly featured KDQs, as would a later talk, so the tutorial introduced them explicitly.

Ángel Rivas (Universidad Complutense de Madrid) described the difficulties of defining quantum divisibility. Divisibility helps us answer the question "To predict what will happen next, how far back into the past must we look?" Consider a classical random variable x that evolves in discrete time, across the instants $t_{1,2,\ldots,f}$. What is the joint probability $p(x_0, t_0; x_1, t_1; \ldots; x_f, t_f)$ that x assumes the value x_0, then x_1, etc.? If x is Markovian, then the joint probability factorizes in terms of the initial probability $p(x_0, t_0)$ and conditional probabilities:

$$p(x_0, t_0; x_1, t_1; \ldots; x_f, t_f) = p(x_f, t_f | x_{f-1}, t_{f-1}) \ \ldots \ p(x_1, t_1 | x_0, t_0)\, p(x_0, t_0).$$

In a quantum analogue, we ask about the probability that measurements of a quantum system yield the outcomes $x_0, x_1, \ldots, x_f$. If the system is closed, a unitary operator evolves the system between times t_{j-1} and t_j, and the quantum Markov condition implies divisibility. If the system is open, it evolves under a completely positive trace-preserving (CPTP) map. If the map decomposes as a tensor product of positive maps, the dynamics are called *P-divisible*, and one can approximately follow the logic in the closed-system case. Otherwise, P-divisibility must be replaced. Rivas discussed multiple alternatives, including k-positive-divisibility and CP-divisibility [8].

Dominique Spehner (Universidad de Concepción) presented on the Bures geodesic as a non-Markovian physical evolution. He defined the Bures distance between states of a finite quantum system, then reviewed basic facts about metrics and geodesics in Riemannian geometry. Also, he introduced the geodesic as a smooth curve joining two states and minimizing the length locally. Spehner illustrated this in detail on the case of a qubit using the Bloch sphere. He showed in particular that if two density matrices commute then there are infinitely many geodesics linking them. Geodesics find applications in quantum metrology where they can be used to estimate unknown parameters of quantum channels, and they are important in applications to quantum control in order to steer optimally an initial state to a target state. Spehner then showed the following main result. Given a geodesic starting from a given system density matrix, one can always find a Hamiltonian acting on the purification space of the state (a system–ancilla complex) which implements the geodesic as the physical (Schrödinger) evolution of the enlarged system–ancilla complex. This means that geodesics correspond to the physical evolution

of the system coupled to an ancilla. Furthermore, if the geodesic passes through a pure state, then the initial system–ancilla state is of a product form. Spehner then analyzed which geodesics lead to the "most" non-Markovian evolutions. He showed that for the qubit case, one can numerically maximize the non-Markovianity.

Stefano Marcantoni (SISSA Trieste) spoke about the mitigation of irreversibility under non-Markovian thermalizing dynamics. He started by defining the notion of stochastic entropy production via two processes: (i) a two-point-measurement (TPM) protocol that yields a joint probability of two measurements and (ii) another TPM protocol, obtained by using the time-reversed dynamics. The stochastic entropy production is then defined as the logarithm of the ratio of the two joint probability distributions. Marcantoni considered dynamics given by Kraus operators satisfying some (nonequilibrium-potential) property and a class of observables. The expressions for the stochastic entropy production and its average value simplify considerably and can be related to relative entropies between final and initial and fixed-point states. Marcantoni proceeded to study the effect of non-Markovianity. He took a model of a qubit dynamics given by a time-dependent Lindbladian, where the non-Markovianity can be tuned by altering the time-dependent jump rates. This model satisfies the assumptions leading to a simpler form of the stochastic entropy production as discussed previously. The point now was to find regimes in which the entropy production *decreases* in time and so does the average of the variance. Marcantoni showed that this is indeed the case when the dynamics is not P-divisible [17]. In this sense, non-Markovianity mitigates irreversibility.

Gerardo Paz Silva (Griffith University) reported about open quantum system control. The control is modeled by time-dependent conrol terms in the system-bath (SB) Hamiltonian. In the interaction picture, this results in time-dependent bath operators. Paz Silva explained that, in this setting, only bath correlations matter, and those can be inferred by system-only measurements (noise spectroscopy). He highlighted that, for Markovian noise (produced by the bath), typical control tasks—such as decoherence suppression—cannot be implemented, while, for non-Markovian noise, they can. Paz Silva presented an iterative procedure to represent the reduced-system dynamics, based on the $B+$ decomposition [31]. In this decomposition, any full SB density matrix is written as a sum of product operators, in which the bath factors are positive operators (but not the system factors, for entangled SB states). Paz Silva then set up a hierarchy of equations governing the evolution of the correlation functions of the bath. Using this correlation information, he developed a "controlled Born approximation," where the bath correlation functions (up to a given order) are approximately constant in time, rather than the bath state's being constant, as in the usual Born approximation. Paz Silva illustrated the accuracy of the approximation by comparing it to the exact solution for an explicitly solvable spin-boson model.

Gniewomir Sarbicki (Nicolaus Copernicus University) talked about the optimization of entanglement witnesses. Starting from the Bell inequalities and explaining the Bell experiment detecting nonclassical behaviour, Sarbicki explained the concept of entanglement witnesses—observables which are positive on separable states but not positive overall. Sarbicki explained that such a witness exists for any entangled state, and gave explicit examples for two qubits. He then addressed the optimality of witnesses: How many entangled states can a given witness detect? Graphically, he explained this by a diagram depicting the witness by a line separating the areas of entangled from separable state—the closer the witness lies to the boundary of the two classes of states, the more effective it is. Optimality means that no other witness detects more states than the given one. Sarbicki discussed this explicitly, again for the case of two qubits. Using the concept of spanning subspaces, he presented the "spanning criterion," a sufficient but unnecessary condition for optimality of entanglement witnesses. Sarbicki then showed that using information given by the spanning criterion, non-optimal witnesses can be transformed into optimal ones. He then discussed the realignment criterion for the separability of a density matrix and showed how the latter produces a family of (non-optimal) entanglement witnesses [34].

Alain Joye (Université Grenoble-Alpes) presented results about the time-dependent Wigner–Weisskopf model, where an atom intearacts with a radiation field. A single excitation, initially located on the atom, is eventually emitted into the radiation field. Joye presented recent rigorous results on this model, based on based on the recent work [22], where the atom-field dynamics contains adiabatically varying (slowly

in time) Hamiltonian and interaction terms. In particular, Joye analyzed the dynamics of the atom and of the radiation field in the adiabatic and small coupling approximations, in various regimes. He focussed on describing the radiative decay of the atom, but mentioned that analyzing the properties of the emitted excitation (photon) has also been done in this work. Joye's results are as follows: (a) In the weak coupling regime (coupling to reservoir very small compared to adiabatic time scale), the atom evolves purely according to its adiabatic, uncoupled dynamics (no emission) and the effect of the field is negligible. Joye further divided this case into two distinct sub-cases, depending on the the relative size of the two quantities. In the regime (b) where the atom-field interaction strength is of the order of the adiabatic parameter, Joye showed that the probability for the atom to be de-excited into the ground state is not 100%. In the strong-coupling regime (c), where the interaction exceeds the adiabatic parameter, the atom will lose its excitation exponentially quickly, with 100% certainty, within the time span considered. Joye then proceeded to discuss the Markovianity of the atomic dynamics. The generator of the approximating dynamics they found is given by a time-dependent Lindbladian.

Massimo Palma (University of Palermo) spoke about reservoir computing [21]. Reservoir computing involves a neural network that has input, reservoir, and output layers. Only the weights connecting the reservoir to the output are optimized through training. The reservoir's weights are random and fixed. The reservoir remembers the recent past but not the distant past, its present state depending only on the present input. Reservoir computing has applications to classification and to processes extended in time, such as speech recognition; only after listening to a considerable portion of a speech can one understand it. Palma discussed classical and quantum reservoir computing, proposing an implementation of the latter: A (bosonic) squeezed state could form the input, while a fermionic reservoir would experience loss and pumping. The reservoir computer would report whether the input is entangled.

François Damamet (University of Liège) introduced stochastic Schrödinger equations as alternatives to master equations. To massage a master equation into a useful form, one often invokes several approximations. Candidates include the weak-coupling, Born, Markov, secular, and large-detuning approximations. Yet these approximations are often unjustified. For example, non-Markovianity is crucial to the Dicke model's superradiant phase [11]. Hence Damamet introduced the stochastic Schrödinger equation, in Markovian and non-Markovian flavors. The equation presents a quantum system as undergoing a certain trajectory, conditionally on outcomes of measurements of the bath. The equation is solved via the hierarchy-of-pure-states approach. Applications include the Hubbard–Hostein model.

Kade Head-Marsden (Washington University in St. Louis) discussed quantum simulations of open quantum systems. Suppose that we wish to understand how chromaphores transport excitons so efficiently during photosynthesis. Gabriela Schlau-Cohen proposed an experimental approach (discussed in a later synopsis), but a theorist would run a computation—-ideally, several years from now, a quantum computation. Conventional gate-based quantum computations are on closed systems that ideally evolve unitarily. Simulating open quantum systems requires ancilla qubits that serve as the environment. In 2001, Bacon *et al.* showed how to simulate all possible Markovian dynamics of one qubit [5]. This result cracked open the field, which now includes, for example, a simulation of a five-qubit Jaynes–Cummings system on the IBM Quantum Experience [20]. A key open question is "What is the minimal number of ancilla qubits needed to simulate a desired open evolution?"

Bassano Vacchini (University of Milan & INFN) illustrated that quantum-information-theoretic tools can be used to diagnose non-Markovianity [35]. The tools of interest were measures of distance between quantum states. An open quantum state will tend to evolve away from its initial state, but revivals can signal non-Markovianity. Vacchini discussed desirable properties of distance measures (boundedness, normalization, contractivity, and triangle-like inequalities) and several distance measures (the trace distance; the Rényi divergences, including the Kullback-Leibler divergence; and the quantum Jensen–Shanon divergence).

Gregory White (University of Melbourne) introduced the process tensor as a mathematical tool for representing and characterizing general not-Markovian quantum evolutions [39]. A general quantum system evolves under influences controlled by the experimentalist (via "knobs") and uncontrolled influences (noise). The process tensor separates the two sets of influences. A processor tensor is a

Choi matrix, a quantum state that represents an evolution. This representation offers the advantage of transforming poorly understood temporal correlations into spatial correlations, which are better understood. White explained how to construct a process tensor mathematically and infer it experimentally. The experimental resources required typically scale exponentially with the system size but can scale polynomially under certain assumptions.

Gabriela Schlau-Cohen (MIT) spoke about engineering a bath to influence a system of interest in a desirable way. Her lab sought to understand how plant chromophores operate so efficiently: Upon receiving a photon from the sun, a chromophore can convert the photon into an exciton and transport the exciton with a quantum efficiency of $\approx 85\%$. Schlau-Cohen's team built analogues of chromophores, using DNA origami [19]. The DNA scaffolds served as baths for the exciton systems of interest. Upon tuning a property of the scaffold (such as rigidity), the experimentalists measured the effect on exciton-transport efficiency. These experiments demonstrate the power of the bath to steer an open quantum system.

Thomas Fay (UC Berkeley) talked about coupled electron-transfer processes and energy-transfer processes in light-harvesting complexes, particularly in photosynthesis. Phenomena such as photoprotection (protecting cells from high intensity light during direct sunlight exposure) cannot be captured by a Lindblad approach. The goal is therefore to develop a more powerful description. Fay explained the difference between excitation energy transfer and electron transfer between a donor (D) and an acceptor (A). The former is mediated by the electrostatic interaction (strength J_{DA}) between D and A and happens at a system–bath (protein scaffold) coupling strengths similar to J_{DA}. In charge-transfer processes, electrons are transferred between D and A. These processes are mediated by orbital overlaps and alter the charge distribution within molecules. Charge-transfer processes are induced by strong coupling to the reservoir, where the interaction energy is much larger than the system transition matrix elements. Fay then modeled an aggregate of three chlorophyll molecules interacting with each other (via charge and electron exchange) and interacting linearly with a (local, harmonic) protein-scaffold bath. Fay used the HEOM (hierarchical-equations-of-motion) method to describe the dynamics, capturing the non-Markovian nature of the processes. A deep HEOM hierarchy was needed, due to the large energy scale of charge transfer process. This makes the method computationally very costly, if not impossible. Fay presented their ideas [15] to solve this dilemma. They introduced a "quencher" system to which the chlorophyll is strongly coupled, as well as a global polarization bath, coupled to both the chlorophyll and the quencher. This represents a subdivision of the total physical bath into different independent parts. They developed a hybrid HEOM method that separates out the strong-coupling charge-transfer process. The excitation energy transfer was treated exactly with conventional HEOM. Then, the charge transport was tackled with perturbation theory (ultrastrong coupling between the chlorophyll and the quencher). The resulting equations of motion were not of Lindblad form. Numerical simulations of the latter showed the accuracy and computational efficiency. Fay explained how the method also works for LHCII processes, which are much more involved. Detailed non-Markovian effects are revealed by this method, which cannot be captured by the Lindblad approach.

Avikar Periwal (Stanford University) reported on optical-cavity platforms where atoms and cavity modes interact nonlocally, creating highly entangled states such as squeezed states [9]. The atomic interactions are experimentally controllable and non-demolition measurements can be performed on the atoms. Periwal explained the experimental setup and the technical difficulties Monika Schleier-Smith's lab had to overcome. He explained how they can detect and measure entanglement and how they can engineer complex new atomic structures. In particular, Periwal explained how to place atoms in the cavity and to control their positions using lasers. Initially put in the ground state, atoms are excited by cavity modes. Entangled states are created via the absorption and emission of photons. Entanglement can be accessed experimentally by a measurement of the degree of squeezing (of certain observables' enhanced or reduced variances). Periwal then explained how they can engineer atomic entangled states that may be used for quantum computing. One of the advantages of the platform is that it allows one to generate entanglement programmatically over sizeable atomic systems. Throughout the talk, Periwal gave illustrations in diagrams, measurement data, photos of instrumentation, and formulae.

Christoph Simon (University of Calgary) continued the biophysical trend, asking whether quantum phenomena affect brains' functioning. The brain contains photons and spins, two platforms that can store and process quantum information under certain conditions. Focusing first on photons, Simon proposed that axons could serve as waveguides and that opsins (light-sensitive proteins) could serve as photodetectors [23]. Spins feature in the radical-pair mechanism, believed to be responsible for avian navigation. Simon posited, however, that the mechanism could have far more biological applications.

Anton Trushechkin (Steklov Mathematical Institute) discussed the exactly solvable model of pure dephasing of a qubit (S) in an oscillator bath (B). For initially uncorrelated SB state and B in thermal equilibrium, the S populations are constant and there is an explicit expression for the decoherence. Trushechkin presented the following results: For the spectral density $J(\omega) \sim \omega^\alpha$ as $\omega \to 0$, the decoherence decays superexponentially for $0 < \alpha < 1$, exponentially for $\alpha = 1$, subexponentially for $1 < \alpha < 2$, as a power for $\alpha = 2$ and for $\alpha > 2$ there is only partial decoherence. Trushechkin then analyzes the validity of the weak coupling, Markovian Davies–van Hove theory for $J(\omega) \sim \omega^2$. On the Davies–van Hove time scale, there is no decay of decoherence, but the exact solution shows that eventually, as $t \to \infty$, decoherence decays (polynomially). This example shows that the weak-coupling limit has to be taken *cum grano salis* and does not apply on all time scales. The *quantum resonance theory*, an extension of the Davies theory and valid for all time scales, holds under the validity of the Fermi Golden Rule Condition (FGRC). The latter is not satisfied in the present model. This analysis shows that one cannot generally draw time-asymptotic information from the Davies theory *unless* the FGRC is satisfied, a "detail" often overlooked in the literature. Trushechkin then addressed the possibility of Markovian embedding, where a non-Markovian system-environment complex can be mapped to a new, enlarged system that interacts in a *Markovian* way with a new reservoir. The reaction-coordinate method is an example of such an embedding. Trushechkin noticed that such an embedding is generally not possible, since it would lead to an exponential decay of observables' expectation values with time. However, the above model shows that power laws or sub- and superperexponential behaviour is also realizable, even at small coupling.

Sergei Filippov (Algorithmiq Ltd, Helsinki) talked about a tensor-network description in Markovian repeated-interaction models. Filippov presented a repeated-interaction model of qubits, a model that allows for an analytic exact form of the dynamics, which exhibit homogenization, dephasing and amplitude damping. He then introduced non-Markovian collision models, arising in particular from situations where the environment ancilla qubits are correlated, which is important, e.g., in quantum optics. Filippov then described the state of such a system using a matrix-product representation. This leads to a tensor-network representation of the repeated-interaction dynamics. He then explained the right-canonical form of matrix-product states and how to use it to obtain a tensor network for the collision model. By changing the point of view and interchanging the horizontal and vertical directions in the tensor network, he obtained a Markovian embedding of the dynamics, the takeaway of a theorem by the speaker [16]. Filippov then illustrated applications where the repeated interaction was with a two-photon wave packet or a photonic cluster state. The effect of the environment correlations on the decoherence of the repeatedly interacting qubit became manifest.

4 Zoom and social-media engagement

Many participants joined the talks via Zoom. Just as the in-person audience posed many, many questions of the speakers, so did the virtual participants, who chimed in via their audio systems. We suggest that future workshops develop a system for ensuring that Zoom participants always state who they are before posing their questions: The in-person audience—not being able to see them—can't identify them by their faces. Such a system could strengthen connections amongst participants with shared interests. One Europe-based virtual participant tried to follow the workshop live but ended up unable to, due to the infeasibility of staying up through the night. However, multiple participants expressed interest in the recordings of the talks. Also, we know of at least two students, based in North America, who virtually dipped into the workshop for talks relevant to their research.

Beyond the electronic-engagement opportunities provided by BIRS, we brought the workshop to social media. Co-organizer Yunger Halpern posted multiple photos from the workshop on Twitter, Facebook, and LinkedIn. Despite gathering no data rigorously, she registered high engagement with the posts, as measured by "likes," comments, etc. Additionally, Yunger Halpern wrote an article about the workshop for *Quantum Frontiers*, the blog of Caltech's Institute for Quantum Information and Matter [43]. Yunger Halpern blogs for *Quantum Frontiers* every month, and the workshop article served as her post for March 2023. The article introduced non-Markovianity, spotlighted Schlau-Cohen's talk, and referred to the previous two BIRS workshops that she had attended (as well as the blog posts she had written about one of them [44, 45]).

5 Participant configuration

The total number of participants was 79, and 24 talks took place. The table below summarizes the percentages of different groups, using the abbreviations UG (undergraduate student) M.Sc. (master's student), Ph.D. (doctoral student), PDF (postdoctoral fellow), ECR (early-career researchers, defined as have worked in faculty positions for ≤ 6 years), and ER (experienced researchers, defined as having worked in faculty positions for > 6 years).

Total Percentages of: 79 registered participants | 24 delivered talks			
	Onsite | Talks	Online | Talks	**Total** | **Talks**
UG, M.Sc., Ph.D.	8 | 14	34 | 0	**42** | **14**
PDF	8 | 18	4 | 0	**12** | **18**
ECR	4 | 4	8 | 0	**12** | **4**
ER	11 | 34	23 | 30	**34** | **64**
Total	**31** | **70**	**69** | **30**	**100** | **100**

The high percentage of the UG, M.Sc. Ph.D. and the PDF groups resulted from the concerted effort of the organizers to involve young researchers and to give them a chance to present their work.

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