CHIST-ERA Proposal Template

Project Acronym

FIQST

Project Full Title

Foundational Structures for Quantum Information Science and Technology

Addressed Call Topic: QIFT   Duration: 36 months

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1a. Summary of the project *(publishable abstract, max. ½ page):*

We aim to consolidate the activity of an established interdisciplinary team which under the FET Open STREP format has been very successful not only in realizing the highly ambitious goals of the 'Foundational structures for quantum information and communication' (QICS) STREP [1], but also in opening up completely new unexpected avenues of QIFT research, "exploiting the powerful synergies that emerged among the different disciplines involved" (from reviews). Here we aim to explore these new avenues and synergies, as well as tackling those pressing QIFT-challenges that require an established cohesive highly multidisciplinary team like ours to guarantee success.

The point of departure for our joint endeavor is that *the contours of the QIFT-revolution are still not at all well-understood*; very basic questions such as "What are the true origins of quantum computational algorithmic speed-up?" and "What are the limits of quantum computation?" have remained to be answered. Our team approaches these challenges by unveiling *foundational structures* and devising *high-level methods*; such a passage will be even more crucial as architectures start to become more elaborate classical-quantum hybrids with non-trivial concurrency, and will ultimately also help us in our quest for a convincing *general model for quantum computation*.

An additional important paradigm here will be to study QIFT not in isolation but in relation to other disciplines. One key challenge will be the *understanding of matter* (both few and many body systems) in information theoretic terms and by means of their computational capabilities; in turns, this may yield new resources, and novel information processing tasks, computational architectures and components. Another challenge involves the interaction of quantum information with *space-time topologies and geometries*, including relativistic quantum information, quantum cellular automata and topological quantum computing; in short, the structural interaction of the two cornerstones of modern physics. A third and probably the most radical research strand addresses *simulation*, in part through *automation*, and other *cross-fertilisation with key areas of computer science*, e.g. information retrieval and natural language processing.

1b. Relevance to the topic addressed in the call *(max. ¼ page):*

Our endeavor clearly meets the main goals of the CHIST-ERA, 'to reinforce transnational collaboration in challenging multidisciplinary research in the area of Information and Communication Sciences and Technologies (ICT) with the potential to lead to significant breakthroughs', as witnessed by the outstanding reviews for the QICS STREP, "... being at the forefront of the state-of-the-art of international activities in the area". It obviously matches the FET Open objectives, having been ranked 2nd out of the initially submitted 487 proposals in a FET Open call. More specifically, we on-the-nose address the 1st target of the CHIST-ERA/QIFT call (new fundamental understandings, new methods, new computation paradigms, ...), and as recognized by the referees of the QICS STREP proposal, "*The proposed work could drive a major change in the experimental realization of quantum computers. ..., it will greatly speed-up the understanding and the technological development of quantum information processing, significantly enhancing Europe's capabilities in these areas*", it also addresses the 2nd target via the study of models of quantum computation like QCAs, MBQC, and TQC, which open new perspectives in terms of scalability. With respect to expected impact, the QICS team represents the state-of-the-art for this call's objectives 1 and 5.

2. Objectives of the project, expected results *(max. 2 pages):*

We wish to gain a deeper insight into what quantum computation (QC) is in general, its foundational structure, scope and limits, in the light of the recent development of several alternative formats for QC such as *Quantum Cellular Automata* (QCA), *Measurement-Based Quantum Computation* (MBQC) or *Topological Quantum Computing* (TQC). In other words, We seek to answer fundamental questions on the nature of Quantum Information (QI) and quantum computation (QC), which should provide a deeper understanding of the quantum informatics endeavor as a whole. To this end, we will explore the axiomatic boundaries of QC, study QC resources and control structures, and aim to identify the essential ingredients responsible for quantum algorithmic speed-up, with the ultimate aim of developing a convincing general model for QC.

In FIQST we wish to establish cross-fertilisation with three close neighbors of QIFT:

- *the structure of matter* (few and many body systems, including condensed matter physics, statistical physics and QFT),
- *space-time structure* (including non-locality and other causality related features, and quantum information processing in space-time), and
- *modern computer science* (including complexity issues in simulation, diagrammatic and other high-level structures and methods, automated reasoning techniques, and current application areas such as information retrieval and natural language processing tasks (cf. Google)).

These interactions will, in turns, help us understand the foundational structures of QIFT. For example, by clearly exposing the limits of classical simulation (which are still not at all well understood), we get closer to understanding what truly characterizes proper quantum computation. It will be these three interactions with other disciplines that shape the work package structure. These are by no means isolated: we expect that high-level diagrammatic and corresponding techniques may importantly help in the study of matrix product states and tensor network states more generally. Conversely, a better understanding of matter states as computational resources may help efficient implementation of search-related problems in information retrieval tasks.

The project builds upon a high-profile, balanced interdisciplinary consortium of physicists, logicians, mathematicians, computer scientists, at word-leading centers of academic excellence, Oxford (Oxf), Cambridge (Cam) and University College London (UCL) in UK, Hannover (Han) in Germany, Innsbruck (Inn) in Austria, Madrid (Mad) in Spain and a French CNRS/CEA/UJF-cluster (Gre & Par), with proven collaborative strength [1]. We are united by common methods and languages, along the following strands of research:

Models of QC. The experimental developments have indicated that the most likely candidate architectures for a QC-device may end up being very different from those on had in mind at the beginning of the QIFT-activity. This has been anticipated, and in fact partly impulsed by the members of our team, who have envisioned, formalized and promoted original ways in which to conceive quantum computing, such as MBQC [52, Briegel (Inn), Browne UCL)], QCAs [53, Werner (Han)], TQC [50, Simon (Oxf)]. Models of computation are simply rigorous mathematical definitions of what quantum computers are. Yet, each of them captures a different aspect of the inner nature of QC. For example, MBQC has proved incredibly useful for studying 'secure multi-party quantum computation' [48, inv. Markham (Par)], whereas QCA have revealed fundamental facts about 'causality in quantum information' [11, Arrighi (Gre), Nesme (Han), Werner (Han)]. The identification of foundational structures and the development of corresponding high-level methods as part of the QICS effort [1] has for example enabled the translations of algorithms and protocols between these models [35, Duncan (Oxf), Perdrix (Gre)], which brings us to the two other key strands of QICS research.

Foundational structures. A deeper analysis of the fundamental concepts of QIFT must go hand-in-hand with a sharper elucidation of its mathematical presentations, and axiomatic and logical structures. Perhaps a striking example, and product of the QICS endeavor, is that it was realized that high-level formal structures that encompass the information flows in QIFT-protocols and architectures can be captured with full mathematical rigor within 'graphical calculi' [7, 23, 22, Abramsky, Coecke (Oxf), Duncan (Oxf)]. These can be roughly seen as theories of equivalence upon quantum circuits and other computational models. Rewriting quantum circuits in such an elegant fashion leads to proofs of otherwise counter-intuitive protocols and phenomena, formal links with established algebraic structures, graphical representations of states. Corresponding programming languages, type logics and algebraic descriptions then arise via representation results for graphical calculi as certain kinds of categorie, cf. the Curry-Howard-Lambek correspondence. The axiomatic-logical foundation moreover enables logical automation via a purely graphical interface; prototype software has meanwhile been produced, named `quantomatic` [2, inv. Duncan, Merry, Kissinger (Oxf)].

High-level methods. Models and structures provide the key ingredients to describe and specify QIFT-systems. But the analysis, i.e. the verification that the systems fulfill their specifications, is yet another challenge that requires powerful formalisms for abstracting the required properties, and general algorithms to decide whether these have been met. For example, the development of secure distributed quantum communication schemes will involve an interplay between classical and quantum components, distributed agents, and all the subtle concepts pertaining to information security. Our team has imported methods from classical computer science for such purposes, and has been most successful at developing methodologies specific to the quantum setting, such as the notion of 'flow' [18, Browne (UCL), Kashefi, Mehdi, Perdrix (Gre)].

While this consortium can rely upon a socle of many joint achievements, given that "QICS has achieved significant results in all its major areas of investigation" (from reviews), in the context of this project these must be seen as points of departure. Already half-way through the QICS project, "clear synergies have emerged, in the form of results that connect different thematic strands, for example measurement-based quantum computing and non-locality [10, Anders, Browne (UCL)], or non-locality and category theory [24, inv. Coecke, Edwards (Oxf)], whereas other seem promising for the future, such as the use of diagrammatic methods for the characterization of resource states" [23, 35, 25], and, "interesting results opened up the project in unexpected directions, for example towards condensed matter physics [34, 58, Van Den Nest (while at Inn), Dür, Briegel (Inn), Martin Delgado (Mad)]". The review also identified new fundamental results in QCA research with respect to our understanding of quantum space-time [11], and important progress on simulation of quantum circuits [42, Jozsa (Cam) and Miyake (while at Inn)]. The final review emphasized the great potential of automating quantum computations when modeled in terms of discrete graphical calculi [2], and the unexpected spin-off in other disciplines, such as natural language progressing.

Each of these research avenues which were (at least in part) initiated by the QICS project now represent the cutting-edge of theoretical QIFT research, which brings us back to the above discussed WP structure. Together with the interdisciplinary approach of our team, which focuses on fundamental structures, high-level methods, this interaction with other disciplines, makes the research both adventurous and unique in kind.

Concretely, the WPs are:

WP1 Few/many body systems as QI-resources, with interdisciplinary applications

WP2 Quantum computation in space-time: the grid and beyond

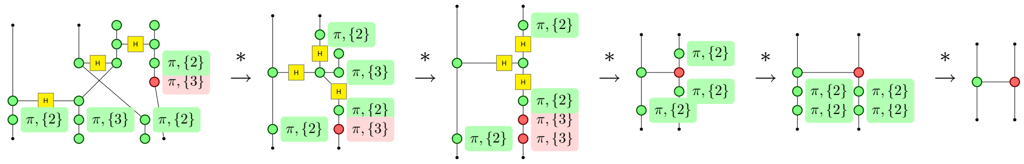
WP3 Quantum computation in space-time: axiomatic and topological aspects

WP4 Simulation, automation, and links with other CS areas

In §3 we provide background and the state-of-the-art to each of these. In the first part §4 we give more detailed descriptions of each of these WPs, moving towards concrete tasks, which themselves are described in the corresponding table.

3. Background and present state of the art in the field *(max. 2 pages):*

Entanglement is key to the speed-up of QC algorithms, and states such as the GHZ-state or graph states are key resources for QIFT-tasks. Given their important role, it is almost shocking that we have so little structural insight in the space of multipartite states. Even in the case of four qubits, there is an infinite family of states with radically different behaviors [60], and hence a vast potential for application — but whose structure we simply do not understand, yet. The notion of quantum discord has recently challenged our whole conception of 'the quantumness of entanglement' [38, 29, Vedral (Oxf) et al.], even for two qubits! MBQC, an important quantum computational model, draws its computational power from entanglement structure. Within QICS [1] MBQC has become an interdisciplinary field of research, connecting quantum computation to entanglement theory, graph theory, topological order, and statistical physics [48, 58, 16]; high-level CS methods-enabled easy translation to the circuit model [35].



Taken together, the theme of few/many body systems, and corresponding graphical methods, form a concerted approach towards a better understanding of *states* as the key resources for QIFT-tasks. This is the focus of our 1st WP.

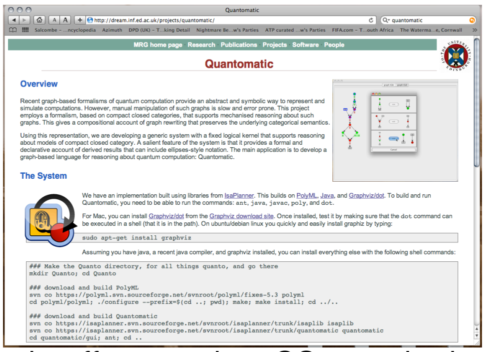
But recently, the study of entanglement as the fundamental resource has infanted a new promising route: that of the study of causality. Questions of causality are prompt to arise in models of QC which make explicit a notion of space and time, e.g. QCA, MBQC, and these must be regarded as privileged mathematical settings in which to confront those issues, with already an impressive track record; in terms of properties such as localizability [11], or applications like Blind Quantum computing [13, 17, Arrighi, Kashefi (Gre), Fitzsimons (Oxf) et al.]. From the outset localization aspects, usually in the simple form of the Alice/Bob-split in the separated labs scenario, have played a key role in quantum information theory. The main theme of the second WP is to take localization really as localization in space-time, in highly distributed systems composed of many equal constituents. This unites three branches of quantum theory: from the computational point of view we just gave a description of QCAs. Condensed matter physicists will see this as a description of quantum spin systems, the prime class of models for understanding magnetism. Finally, field theorists will see here the basic locality assumption of relativistic theory. Technically, the main distinctions here are that while QCAs have a discrete time dynamics, spin systems are Hamiltonian models evolving in continuous time, which implies that localization is respected only approximately, within so-called Lieb-Robinson bounds. In contrast, propagation is strictly within the light cone for field theory, however, the spatial variables are continuous and the system locally has infinitely many degrees of freedom, unless on imposes energy bounds. In order to gain insights by transfer of results between these structures, the mutual approximation relations have to be analyzed.

One important overall question that arises here: What is the foundational structure of causality? Standard results by Zeeman [62] and Malament [47] show that (almost) the entire space-time structure can be reconstructed from the causal ordering of space-time points. These results have motivated partial orders as a foundational structure for understanding space-time. However, questions of causality go beyond the study of states, and shift our focus towards more general processes and dynamics in quantum theory. While the experimenter can prepare arbitrary states, he cannot 'realize' arbitrary effects, since this would inevitably lead to faster-than-light signaling. In fact, one can show that a non-signaling two party process may provide a perfect channel under time-reversal [26]. All this undermines partial orders as providing 'the entire story' on causality. The situation is akin to logic [45]: the passage from truth-structure to proof-structure involved 'thickening' partial orders into full-blown categories. Recently, it was shown that a geometrical space-time picture of the partition function of the Levin-Wen models can be described as doubles (two copies with opposite chiralities) of underlying Anyon theories of TQC [20, Simon (Oxf) et al.] (which is also naturally modeled in category theoretic terms), which brings us back within the realm of WP1.

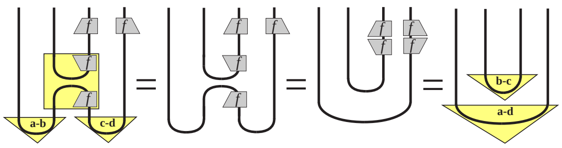
These more axiomatic, high-level viewpoints on the interaction of quantum information with space-time, geometry, and topology constitute the focus of WP3.

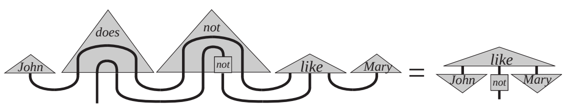
One of the most urgent open issues in QIFT is to understand the relationship between classical and quantum computational complexity and the power of quantum computational models relative to classical computation. One approach to exploring these issues is to study the set of quantum computations (in various models) that can be classically efficiently simulated. Recent work has made significant progress [41, 33, inv. Jozsa (Cam), Kraus (Ins)] and it has also been shown that there would be surprising consequences for classical complexity if some very simple classes of quantum computations could be simulated [15, 5, 4, inv. Jozsa (Cam), Bremner (Han)].

The computational complexity oriented approach towards simulation can be complemented by the algebraic methods of domain theory [8]. Scott and Ershow developed domain theory for the study of denotational semantics and the purposes of characterizing the computability of partial functions. Later it was show that quantum states and their entropic properties can be characterized by domain theory [27, Coecke (Oxf), Martin (while at Oxf)], and that quantum computation more generally can be placed into a domain theoretic framework [43, 54, Kashefi (Gre), Selinger (while at Oxf)].



On the forefront of automation of reasoning is the `quantomatic` software, a (semi-)automated theory exploration tool, developed within QICS [1]. We expect that in the initial phase of this project this software will become powerful enough to become a key research tool for WP1, and also for aspects of WP2. Interestingly enough, the `quantomatic` software is also at the forefront of *automated theory exploration*, a fascinating new area in artificial reasoning, hence a spin-off of QIFT-research in another area of computer science (CS). Another maybe even more surprising spin-off to another CS-area is the fact that the high-level diagrammatic methods for quantum reasoning have recently been applied to computing meaning of languages from meaning of words [28, Coecke, Sadrzadeh (Oxf), Clark (Cam)], a result which immediately has been adopted by leading members of the Natural Language Processing community, a branch of CS concerned with the automatic analysis, generation and understanding of natural language text. It suffices to look at the following diagrams representing entanglement swapping and the flow of meaning within sentences to see a striking structural similarity [28, 22]:





Key to both these spin-offs are graphical languages, where topology becomes a form of reasoning. Recent progress on computing ground states has meanwhile also relied on graphical representations, were our graphical methods may also play an important computational role, which brings us again back to WP1.

Simulation, automation and cross-fertilization with areas of CS, as well as adaptation of CS-methods to the quantum realm (category theory, domain theory) and high-level methods (algorithms in graph theory, interference analysis), are the focus of WP4.

4. Work packages, milestones, and work plan *(max. 3 pages + 1 table per work package):*

Work package 1. We want to better understand the *structure of multipartite entanglement* (T1.1). The vast space of qualitatively very distinct states will lead to many novel applications, and in particular, to a generalized MBQC paradigm. An important step has been made which provides a graphical understanding of states well beyond graph states [25]; by 'composing' GHZ and W states one generates a huge family of qualitatively distinct multipartite states, i.e. which live within distinct SLOCC classes. In addition, we want to obtain a high-level understanding of how the technical notion entanglement relates to computational properties of resource states (T1.2). For example, *discord* [38, 51, 29] can exist even without entanglement and has recently been argued to be responsible for the exponential quantum speed-up in some algorithms.

We want to further explore the interdisciplinary of MBQC, develop a better understanding of the power and implications of quantum computation, and identify novel applications for quantum simulation (T1.3). For example, there now is a fruitful mapping from MBQC to fundamental models in statistical physics whereby the partition function is expressed as the quantum mechanical overlap between a highly entangled resource state and a product state, which can be interpreted as the probability amplitude of a measurement pattern on the one-way quantum computer [34, 58, 46]. By exploiting the universality and transformation properties symmetries of the resource state, we were able to establish hitherto unknown completeness results for a class of statistical models, including elementary lattice gauge theories [31, 32], and develop quantum algorithms for the evaluation of partition functions. Thanks to the generality of the concepts of statistical physics, it seems likely that similar mappings can be established to other fields of science.

In a similar vein, condensed matter physics has recently witnessed tremendous progress, spurred by developments in quantum information theory, in understanding the properties of physical states of strongly interacting many particle quantum systems. The physics of low-dimensional systems turns out to be well captured by variational classes known as matrix product states (MPS), projected entangled-pair states, and the multi-scale entanglement renormalisation ansatz. Very recently a continuum generalisation of the MPS variational class, termed continuous MPSs (cMPS), have been developed which promise to afford, via the variational principle, new insights into the behaviour of strongly interacting QFT. We will pursue this track of research (T1.4), and we will also explore applications of T1.1 in condensed matter physics (T1.5).

Work package 2 and 3. The subject of *quantum computation in space-time* will be approached from a variety of mathematical settings, some whose causal structure approaches that of physical space, Haag's algebraic QFT [36] (AQFT) and QCAs in WP2, and other in which the causal structure is more abstract, 'causal categories', generalized probabilistic theories, MBQC and TQC in WP3. The cornerstone of AQFT is the interplay between relativistic causality and locality of quantum observables. However, the operational aspects, and the compositionality of space-time localized operations are usually not discussed. We will develop the theory to the point that localized operations can be considered as computational steps, which are automatically parallelized when their localization regions are causally disjoint.

The connection between QFT and quantum information theory hinges on the possibility for bounding the number of states in a finite region, when the energy is also bounded. In QFT this is discussed as "nuclearity" [19], and first results in this direction have been obtained [49]. We will pursue this in T2.1.

Under such a finite density of information hypothesis, one is tempted go as far as dividing up space into identical cubes. QCAs are arrays of cells, each of which contains a quantum system described by some finite dimensional Hilbert space. The cells evolve in discrete time steps according to a global evolution, which itself arises from the application of a local transition function, synchronously and homogeneously across space. They are the subject of T2.2, T2.3, T3.4, along the following strands.

Indeed, QCAs constitute a privileged model for discussing causality in QIFT. Moreover, a very promising candidate for the experimental realizations of QCA are optical lattices. However, due to experimental imperfections, the global evolution may no longer be homogeneous in space. In fact, a good model is to assume that the actual evolution consists of two parts, the ideal implementation of the algorithm and a small random perturbation, which depends on the lattice site. Similar error models have been studied in the context of single particle systems [9] and exhibit a breakdown of long-distance information flow (Anderson Localization). The analogues for systems of very many particles have neither been explored rigorously nor heuristically. We will do so here.

Quantum simulation will be one of most important uses of quantum computers for society. In fact we can forecast that quantum simulation will have huge, unsuspected impacts in quantum chemistry, biochemistry or nanotechnologies, for instance in terms of the synthesis of specific-purpose molecules. But whilst QC may have the computational power to simulate any quantum system, this does not mean that we sure know how to encode the continuous-time and space, isotropic, sometimes complex behaviour of elementary physical elements (wave equations of particles, spin systems, etc.) into the more discrete-data discrete-time framework of quantum computation. This issue of encoding is non-trivial, but has largely been solved for the one-dimensional case, largely using QCA as a mathematical framework in which to model the system under interest. However the simulation will only be up to a certain accuracy, which we must learn to evaluate. Moreover in the more-than-one-dimensional case we are confronted with more fundamental problems, such as the question whether QCA are capable of simulation isotropic phenomena at all. In order to circumvent this last problem, one could consider QCA on a discrete graph instead of a grid, of possibly varying connectivity. The achievement in [11] is a step in this direction; in the continuous-time picture the question was addressed within QG [44, 37]. We will do so here too.

The time-symmetry of causal structure in relativity is due to the fact that the space of solutions (i.e. spacetimes) to Einstein's equations is closed under reversal of time-orientation [61]. In contrast the constraint of no-signaling on a probabilistic theory [14] is time-asymmetric. One can produce examples, even of classical (hence non-signaling) processes, for which a time-reversed perspective provides perfect signaling ability [12, 26]. While partial orders have been proposed as fundamental descriptions of causality [57], motivated by representation results in GR by Zeeman and Malament [62, 47], this view cannot be retained when probabilities are involved. The very definition of causality in a probabilistic setting is much harder than it seems, and has been discussed recently both in Physics [39], and in computational biology [59], in the context of understanding for instance causal relations between genes. This points out the need for a foundational structure of causality adequate for more general probabilistic theories including quantum theory, and as a basis for a high-level approach to relativistic quantum information, in the spirit of the existing high-level QI-approaches [7, 22]. Causality also arises in MBQC in the dependency between some of the measurements: it represents a the fundamental limitation on the parallelization of the local measurements in MBQC; this was captured by the notion of *flow* [30], intuitively guaranteeing that information can "flow" from input to output unharmed. We will perform a set of tasks, aiming at a better understanding of causality in each of these areas (T3.2, T3.3).

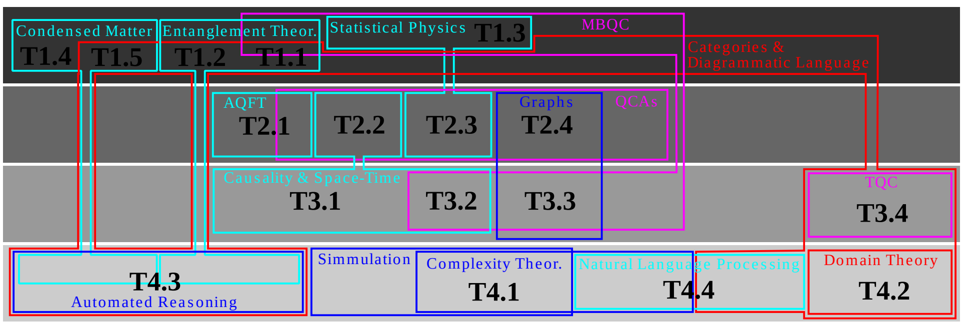
In the fractional quantum Hall effect, strongly-interacting electrons give rise to an effective theory of weakly-interacting 'quasiparticles'. Their charge can be a fraction of that of an electron, and in many cases they are expected to exhibit topological behavior, hence TQC. Current approaches are often haphazard, involving identification of seemingly-arbitrary two-dimensional subspaces of compound quasiparticle systems, identifying these as the computational qubits, and then investigating the effect of the braiding on these subspaces. Although much has been achieved, this is a 'low-level' approach. We intend to device high-level methods for TQC, in analogy to [7, 22] (T3.4).

Work package 4. The preliminary results on simulation discussed above [41, 33, 15, 5, 4] indicate the high fertility of this area; future progress has the potential for significant impact in physics, especially in the study of complex condensed matter systems and the computational complexity of determining their key properties. Additionally, going beyond pure simulation questions, a further novel approach to the above issues is to consider hybrid classical-quantum complexity classes based on computational models (generalising MBQC) that involve quantum computation assisted by classical computation, but crucially the latter is now not viewed as a special case, but as a separate resource [40]. Such models would provide a novel framework for studying the extent to which classical and quantum computing power can be "inter-converted", perhaps with a view to minimising the quantum part. In order to address this problem, we need to address how different models of quantum computation can potentially give rise to alternate notions of simulability. In Task T4.1 we study the extent to which classical computers can efficiently simulate quantum computational models.

We will also complement this computational complexity oriented approach towards the simulation with a novel algebraic one. Recently Selinger has initiated a new approach [54] to Quantum Domains as a description of progressive information, allowing computation on incomplete data. Computations are realized by completely positive maps, which are monotone in "information progression order". However, this monotonicity is not sufficient for implementation by a realizable quantum automaton, and the precise constraints arising from quantum theory are still to be explored. In Task T3.2 we will develop domain theoretic methods for current problems in QIFT.

The `quantomatic` software was initially developed to reason in terms of the diagrammatic language for a pair of complementary observables and phases [23], which, for example, has been successful in studying MBQC [35]. To cope with the challenges of WP1 the software needs to be adjusted to languages specifically crafted to deal with multipartite entanglement, such as the one of [25]. To understand the power of the automation we need to study 'completeness' of these languages too, that is, which class statements in Hilbert space quantum theory can be discovered via automation. One such theorem already exists, due to Selinger [55], for the case of the dagger compact language of [7]. We want to push the scope of automation also further in the area of automated theory exploration: a benchmark here for the software to discover a (1) new, (2) interesting, (3) non-trivial statement about quantum theory. Tasks T3.3 addresses automation and corresponding completeness questions.

Language processing tasks. Search is key to the Natural Language Processing (NLP) tasks (cf. Google). On the other hand search is also one the of the key achievements of QIFT. One of the key open problems of NLP is to obtain a model for how the meaning of words transform into meaning of sentences, and for this purpose the above discussed diagrammatic model of [28] is very promising. One might expect that the great structural similarity of QIFT and NLP in high-level diagrammatic terms may lead to quantum algorithms that may be particularly suited for NLP tasks, beyond Grover's algorithm, taking into account grammatical structure. This is the subject of task T3.4.



An attempt to depict interconnectedness of WPs (gray), tasks, computational models (magenta), key structures (red), high-level methods (blue), and theories involved (cyan).

<table>
<tr><td>WP 1</td><td colspan="6">Few/many body systems as QI-resources, with interdisciplinary applications</td><td colspan="2">month 1 – month 36</td></tr>
<tr><td colspan="9">Contribution of project partners</td></tr>
<tr><td colspan="2">Partner number</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td></td><td></td></tr>
<tr><td colspan="2">Person.month per partner</td><td>18</td><td>30</td><td>34</td><td>31</td><td>6</td><td></td><td></td></tr>
<tr><td colspan="9">Aim of the WP. This work package focuses on few and many body systems, in view of interdisciplinary applications. There will be strong interaction with WP2 and WP3, in terms of models of quantum gravity, and will also draw from the automated reasoning methods developed in WP4.</td></tr>
<tr><td colspan="9">Tasks</td></tr>
<tr><td>T1.1</td><td colspan="8">Entanglement structure & generalized MBQC (months 1 – 36: Oxf; Inn, UCL, Gre).
We want to obtain an increased understanding of how the ‘GHZ-dots’ and ‘W-dots’ in the graphical language of [25] precisely interact. A sufficiently strong calculus will enable automated reasoning techniques, as in T4.3. This understanding should contribute to a generalization of MBQC resource states.</td></tr>
<tr><td>T1.2</td><td colspan="8">Quantum discord and applications to other areas (months 1 – 18: Oxf; Gre, Han).
The concept needs to be understood in more detail in many qubit systems. The standard techniques used in entanglement analysis will here be applied to discord and we intend to investigate if indeed quantum discord can prove to be useful in various protocols involving quantum metrology and information processing. We also intend to obtain a high-level understanding of discord.</td></tr>
<tr><td>T1.3</td><td colspan="8">Applications of MBQC in other areas (months 1 – 36: Inn; Mad, Han, Ox).
We will try to establish mappings from MBQC other fields of science, for example to neural networks, which represent the paradigm of information processing in biological systems, and to discrete models of quantum gravity. We expect not only structural insight and a transfer of concepts and methods, but also the development of new quantum algorithms.</td></tr>
<tr><td>T1.4</td><td colspan="8">Continuous matrix product states (months 1 – 24: Han; Oxf, Mad).
The purpose of this workpackage is to extend the cornerstone application of the variational principle within the MPS class, the density matrix renormalisation group (DMRG) to the continuum setting of cMPS. This would allow the direct consideration of quantum fluctuations in continuum theories pertaining to, e.g., dilute Bose-Einstein condensates and BCS theory. Such corrections are difficult, if not impossible, to obtain using extant quantum Monte-Carlo methods.</td></tr>
<tr><td>T1.5</td><td colspan="8">Diagrammatic methods for condensed matter physics (months 19 – 36: Oxf; Han).
Within the same domain recently informal diagrammatic methods have become very useful, mainly in work by Verstaete, Cirac et al. We wish to investigate how the diagrammatic language of T1.1 may have useful more systematic applications to establish properties of MPS.</td></tr>
<tr><td colspan="9">Deliverable, month of delivery, title</td></tr>
<tr><td>D1.1</td><td>12</td><td colspan="7">A graphical calculus for multipartite entanglement</td></tr>
<tr><td>D1.2</td><td>24</td><td colspan="7">Generalized graph states for generalized MBQC</td></tr>
<tr><td>D1.3</td><td>12</td><td colspan="7">A high-level understanding and applications of discord</td></tr>
<tr><td>D1.4</td><td>24</td><td colspan="7">Generalization of completeness result to other statistical physics models.</td></tr>
<tr><td>D1.5</td><td>36</td><td colspan="7">Quantum algorithms for the evaluation of partition functions.</td></tr>
<tr><td>D1.6</td><td>36</td><td colspan="7">ground-state properties of strongly interacting QFTs within the cMPS class</td></tr>
<tr><td>D1.7</td><td>12</td><td colspan="7">Diagrammatic methods for condensed matter physics.</td></tr>
</table>

WP 2	Quantum computation in space-time: the grid and beyond						month 1 – month 36	
Contribution of project partners								
Partner number		1	2	3	4	5		
Person.month per partner		4	70	10	30	0		

Aim of the WP. This work package focuses on QIFT processing in discretized space-time, causality and dynamics; opening connections with other areas of theoretical physics such as QFT or Quantum Gravity. It builds upon our understanding of resources from WP1; for example, T1.3 and T2.1, are related.

Tasks

T2.1	*Causality structure, nuclearity and localized operations in algebraic QFT (month 1 – month 36: Han; Gre, Inn).* Based on the nuclearity condition of algebraic QFT, we will explore how figures of merit for information/communication theoretic tasks depend on the energy bounds. In particular we will study the entanglement properties of states associated to two spacelike separated regions e.g. maximal values of correlation expressions, via Bell inequalities (Han, Inn). We will explore the computational implications of nuclearity, such as simulability questions and the connection to QCAs (Han, Gre).
T2.2	*Dynamical effects in QCAs (month 1 – month 36: Han; Gre, Inn).* We will study, within the QCA model, whether information of energy can be transported faster due to quantum effects (Gre, Inn). But we will also study models where, due to spatial fluctuations, the global evolution of the QCA is no longer homogeneous in space. Here the question we want to address is the opposite: under which circumstances localization effects occur i.e. whether the deterministic global rule is “suppressed” by the random perturbation (Han).
T2.3	*Approximation of continuous space and time dynamics by QCAs (month 1 – month 36: Gre; Han).* Physical spin systems run in Hamiltonian (i.e., continuous time) dynamics. For the simulation of such systems by a QCA, as well as for the study of information flow in these systems it is important to develop precise bounds for the accuracy of the approximation of Hamiltonian systems by QCAs. This involves higher order Trotter expansions and improved Lieb-Robinson estimates (Han). Related to this problem is the accuracy to which a QCA may model the isotropic dynamics of a particle in 2D continuous space (Gre).
T2.4	*Cayley connectivity-varying QCA. (month 12 – month 36: Gre; Par).* Considerations in previous task will lead us to consider QCA on graphs instead of grids, as in [11] but with a time-varying connectivity. This is also of strong interest in Quantum Gravity [44, 37], but quite challenging: causality imposes a constraint on the dynamics, but now the dynamics feedbacks and changes the causality constraint. A cautious route is via Cayley graphs, i.e. regular graphs generated by a finite group.

Deliverable, month of delivery, title

D2.1.1	12	Energy dependent bounds on the maximal value of correlation expressions
D2.1.2	36	Computational implications of the nuclearity condition
D2.2.1	12	Eigenvalue distributions of disordered QCAs
D2.2.2	24	Faster signalling and transport in QCAs
D2.2.3	36	Dynamical localization for disordered QCAs
D2.3.1	12	Norm approximation of almost local automorphisms by local ones
D2.3.2	36	(An)isotropy in QCAs
D2.4.1	24	Cayley connectivity-varying QCAs

WP 3	**Quantum computation in space-time: axiomatic and topological aspects**						month 1 – month 36	
Contribution of project partners								
Partner number	1	2	3	4	5			
Person.month per partner	14	50	30	40	0			

Aim of the WP. This work package focuses on the causal and topological structures that underly QIFT processing. It draws upon WP2, either seeking to generalize and axiomatize (e.g. compare T2.1 and T3.1) or to explore other models of QC, establishing connections with WP1 and WP4 (e.g. compare T1.3, T3.3, T4.3).

Tasks

T3.1	*The foundational structure of causality (month 1 – month 24: Oxf; Gre, Han, Inn, Mad).* We aim to device a foundational structure of causality adequate for general probabilistic theories including quantum theory, contributing towards a high-level approach to relativistic quantum information. We will extend some already existing relational models that capture several essential features of these theories cf. [24, 6] (Oxf), and focus upon the state-effect symmetry: how it may arise from superimposed principles, e.g. a trade-off between states and effects [56], whether it helps in characterizing the Cirelson bound [21]. The connection will be made with Stochastic Einstein Locality and the axiomatization of Probabilistic Cellular Automata (Gre, Han).
T3.2	*Non-locality (month 1 – month 36: UCL; Oxf, Gre).* Connections between non-locality and computation have recently been exposed by us (UCL) and many open questions remain. The non-locality which arises under simulated adaptive measurements will (in connection with task T.3.3) be investigated and the role of MBQC flow in multipartite non-local correlations established. We shall distinguish non-local correlations which provide a speed up in MBQC from those which always remain efficiently classically simulatable.
T3.3	*From flow to causality in MBQC. (month 1 – month 36: Gre; UCL, Par).* We will look at how to use the causality embodied by our current flow conditions to give practical security and verification proofs in several multi-party computation protocols. But we will also investigate the possibility of strengthening our current flow conditions into a 'local flow' for the sake of underlying finer causal structures, such as entanglement. We will see how these results combine with a known automated rewriting system that converts MBQC into quantum circuits, hopefully leading to hands-on algorithms for the above two properties.
T3.4	*High-level descriptions for topological QC (month 12 – month 36: Oxf; Han).* We will pursue a high-level approach to topological QC, by modelling them within the formalism modular tensor categories. Bases for measurement of quasiparticles will become commutative dagger-Frobenius algebra structures, and complementary bases will become a pair of such basis structures which interact via a bialgebra relation. A body of existing work will then to come into play, which uses these structures to implement standard algorithms, and also will help in finding novel areas for applying the TQC-model.

Deliverable, month of delivery, title

D3.1.1	12	Causal category theory as a foundation for causality
D3.1.2	36	An axiomatization of causality in a probabilistic setting
D3.2.1	12	Multi-party non-local boxes play games
D3.3.1	24	Multi-party measurement based computation
D3.3.2	24	The flow of causality and entanglement
D3.4.1	24	High-level structures for Topological quantum computing

WP 4	Simulation, automation, and links with other CS areas						month 1 – month 36	
Contribution of project partners								
Partner number		1	2	3	4	5		
Person.month per partner		24	24	10	7	51		

Aim of the WP. This work package applies computer science methods to problems in QIFT, QIFT methods to CS problems, and hybrids of these. The developed methods will be key to several other work packages, and some of the tasks in other work packages will fed in here. For example, T1.1 and T4.3, are strongly intertwined.

Tasks

T4.1	*Classical simulation and complexity (month 1 – month 36: Cam; Han, UCL, Inn).* In this task we study the extent to which classical computers can efficiently simulate quantum computational models. We will examine if quantum circuits can be used to define decision languages and sampling problems that have markedly different classical simulation traits. We will also seek to formulate hybrid classical-quantum complexity classes and explore their relationship to existing classes, and to the study of complex many body systems. We will characterize classical simulation properties of classes of quantum computations in various models, including both cases that can be classically simulated, and cases for which there is evidence of hardness of simulation (D4.1). We will formulate hybrid classical-quantum computational models (as a generalisation of MBQC) and analyse their implications for existing algorithms and complexity classes (D4.2).
T4.2	*Generalized approximation theories (month 13 – month 36: Han; Oxf).* Complementing the approach to simulation in T4.1 will study quantum channels, and more generally quantum computations from an algebraic perspective by employing the methods of domain theory. Paramount to this, is the need for a general domain theoretic description of quantum operations that allows for recursion. In particular, we will establish under what conditions monotonicity, resp. continuity under a Scott topology can allow for well defined quantum channels. Further to this we will establish a fixed-point theorem for quantum computations in this setting.
T4.3	*Automating quantum reasoning (month 1 – month 24: Oxf; Gre, Inn).* We will adapt the `quantomatic` software to reasoning about multipartite entangled states, in particular by exploring the space of diagrammatic presentations of representatives of SLOCC-classes of T1.1. We will search for states in that vast space which may have particularly interesting novel QIFT applications. A benchmark is to discover a (1) new, (2) interesting, (3) non-trivial statement about quantum theory purely by artificial means (D3.5).
T4.4	*Algorithms for language processing (month 17 – month 36: Oxf; Cam).* We will exploit structural similarities of high-level description of informations flow in quantum systems and in language to craft quantum algorithms for language processing tasks, such as grammatically structured search of meaning based concepts (e.g. similarity, sentiment, domain of application etc.).

Deliverable, month of delivery, title

D4.1	12	Classical simulation properties of classes of quantum computations
D4.2	24	Hybrid classical-quantum computational models
D4.3	24	Implementability conditions for superoperators on Q-domains
D4.4	36	Fixed-point analysis of quantum computations using domain theory
D4.5	36	Automated exploration of multipartite quantum behaviors
D4.6	36	An automatically generated result in QIFT
D4.7	24	Quantum algorithms for natural language processing tasks

Work package overview: Person-months per WP and partner

project-partner	WP1	WP2	WP3	WP4	total
1	18	4	14	24	60
2	30	70	50	24	174
3	34	10	30	10	84
4	31	30	26	7	94
5	6	0	0	51	57
total	120	114	120	116	423

Milestones

No of Milestone	Delivery month	WP involved	Title
M1	18	1,4	Automated reasoning for general multipartite states
M2	36	1,2,3	A confluent rewrite system for multipartite entanglement
M3	24	1	A high-level axiomatization of quantum discord
M4	24	1,3	An MBQC QC model of non-locality and multipartite states
M5	24	1,2	Local, synchronous graph-rewriting in the quantum setting
M6	36	2	Simulating continuous quantum dynamics in discrete time and space
M7	24	3	A high-level framework to reason about causality
M8	18	3	Purely monoidal categorical semantics for TQC
M9	30	4	An automatically generated QIFT-result (benchmark: should be publishable in a good QIFT journal without mentioning its artificial origin)
M10	18	4	An application of QIFT to natural language processing

5.1. Partner 1	
Dr. B. Coecke	University of Oxford (FIQST coordinator)
Dr. D. E. Browne	University College London

Expertise. Oxford University is one of the pioneers of QIFT, and currently includes many department with large QIFT groups. The 'young' Quantum Group at the computing Laboratory, headed by Abramsky and Coecke includes 32 members, and is a multidisciplinary group, including mathematicians, physicists, computer scientists and linguists. Abramsky-Coecke pioneered categorical and diagrammatic methods in QIFT in a 2004 IEEE-LiCS paper, the 1st paper on QIFT to ever have been accepted by this prestigious conference.

Dr. B. Coecke is University Lecturer in Quantum Computer Science and EPSRC Advanced Research Fellow. He gave 120 invited talks, holds EPSRC, ONR, Leverhulme, JTF and FQXi grants, and organized many conferences and schools. He coordinated the FP6 STREP QICS.

(1) — & R. Duncan (2008) *Interacting quantum observables*. In: Proc. 35th ICALP, LNCS. 0906.4725 - (2) — & A. Kissinger (2010) *The compositional structure of multipartite quantum entanglement*. In: Proc. 37th ICALP, LNCS. 1002.2540 - (3) — (2010) *Quantum picturalism*. Cont. Phys. **51**. 0908.1787 - (4) —, M. Sadrzadeh & S. Clark (2010) *Mathematical foundations for a compositional distributional model of meaning*. Linguistic Analysis **36**. 1003.4394 - (5) —, ed. (2010) *New Structures for Physics*. Springer.

Dr. D. E. Browne co-pioneered measurement-based quantum computing. He was instrumental in breaching the departmental barriers while at Oxford, being active in physics, materials as well as in computer science.

(1) E.T. Campbell & — (2010) *Bound states for magic state distillation in fault-tolerant quantum computation*. PRL **104**. - (2) H.J. Briegel, — , W. Dür, R. Raussendorf & M. Van den Nest (2009) *Measurement-based quantum computation*. Nature Physics **51**. - (3) J. Anders & — (2009) *Computational power of correlations*. PRL **102**.

Prof S. Abramsky FRS is Christopher Strachey Professor of Computing and one of the world's most prominent theoretical computer scientists.

(1) — (2010) *Coalgebras, Chu spaces and representations of physical systems*. Proc. LiCS 2010. 0910.3959 - (2) — (2010) *No-cloning in categorical quantum mechanics*. In: Semantic Techniques in Quantum Computation, CUP. - (3) — & B. Coecke (2009) *Categorical Quantum Mechanics*. In Handbook of Quantum Logic and Quantum Structures. Elsevier.

Prof S. Simon is Professor of Physics in the Condensed Matter Theory Group. He is a world-expert in topological quantum computing.

(1) C. Nayak, —, A. Stern, M. Freedman & S. Das Sarma (2008) *Non-abelian anyons and topological quantum computation*. Rev. Mod. Phys. **80**. - (2) F. Burnell & — (2010) *Space-time geometry of topological phases*. Ann. Phys. **325**. - (3) L. Hormozi, N. E. Bonesteel & — (2009) Topological quantum computing with Read-Rezayi states. PRL **103**.

Prof V. Vedral is Professor of Quantum Information Science, pioneered methods in entanglement theory, and is a leading figure in the QIFT community.

(1) B. Dakic, — & C Brukner (2010) *Necessary and sufficient condition for nonzero quantum discord*. PRL **105** - (2) — (2008) *Quantifying entanglement in macroscopic systems*. Nature **453**. - (3) L. Amico, R. Fazio, A. Osterloh & — (2008) *Entanglement in many-body systems*. Rev. Mod. Phys. **80**.

Role in project. The Oxford team brings in expertise in categorical and diagrammatic methods, and high-level computer science methods more generally, expertise in automation, in natural language processing, in entanglement theory, topological quantum computing, quantum non-locality, measurement-based quantum computing and quantum foundations; in each of these areas it has a world-expert in the team. Each of these scientists is surrounded by many brilliant postdocs.

5.2. Partner 2	
Dr. S. Perdrix	Université de Grenoble
Dr. D. Markham	Telecom ParisTech
Dr. A. Grinbaum	CEA-Saclay/DSM

Expertise. The French node is a joint research effort of seven permanent researchers over three sites: University of Grenoble, Telecom ParisTech, and CEA-Saclay. This group benefits from its strong interdisciplinary, including physicists, computer scientists, and philosophers. Almost all of this young group were active in the QICS project, where solid collaborations were formed as witnessed by several joint publications.

Dr. P. Arrighi is assistant professor. He is a world-expert in quantum cellular automata (1,2). He is coordinating the ANR project CausaQ.
Dr. D. Markham is a CNRS reseacher. He is an expert on multipartite entanglement and its uses for QIP. Of physics background he now works regularly with computer scientists to this end (7,9).
Dr. S. Perdrix is a CNRS researcher. He is an expert on graph states and measurement-based model. He is also contributing to the categorical axiomatisation of quantum mechanics (3,4,5,7,8,10).
Dr. M. Mhalla is a CNRS researcher. He worked on algorithms and complextity of graph problems (Best Paper award at ICALP'04). He contributes to the development of the graph state uses in the measurement-based model (7,8,10).
Dr. A. Grinbaum is a researcher at CEA-Saclay. He contributes to information-theoretic reconstructions of quantum mechanics (6).
Dr. F. Prost is associate professor. He developed formal tools for reasoning about entanglement in quantum programs (11).
Dr. E. Kashefi is CNRS researcher, on leave at University of Edinburgh. She is a world-expert in measurement-based quantum computation (4,7,8).

(1) **PA**, Renan Fargetton, Zizhu Wang *Intrinsically universal one-dimensional quantum cellular automata in two flavours*, Fundam. Informaticae, $\mathbf{21}(2)$, 197-230, (2009). Pre-print arXiv:/0704.3961.
(2) **PA**, Vincent Nesme and Reinhard Werner. Unitarity plus causality implies localizability, QIP 2010 and J. of Computer and Systems Sciences. arXiv:0711.3975.
(3) B. Coecke, **SP**. Environment and Classical Channels in Categorical Quantum Mechanics. CSL'10 LNCS.
(4) V. Danos, **EK**, P. Panangaden and **SP**. Extended Measurement Calculus. Chapter of Semantic Techniques in Quantum Computation.Cambridge University Press, 2009.
(5) R. Duncan, **SP**. Rewriting Measurement-Based Quantum Computations with Generalised Flow. ICALP'10 LNCS.
(6) **AG**. Who is the quantum observer?, in Oxford Questions on Quantum Physics and the Nature of Reality, Oxford University Press, to appear.
(7) **EK**, **DM**, **MM** and **SP**, Information Flow in Secret Sharing Protocols. EPTCS (2009).
(8) D. E. Browne, **EK**, **MM**, and **SP** Generalized Flow and Determinism in Measurement-based Quantum Computation. New J.Phys. (9),p. 250, (2007)
(9) **DM**, A. Miyake and S. Virmani, Entanglement and local information access for graph states. New J. Phys. 9, 194 (2007).
(10) **MM** and **SP**. Finding Optimal Flows Efficiently ICALP08, LNCS 5125, (2008)
(11) **FP** Reasoning about Entanglement and Separability in Quantum Higher-Order Function. UC09 LNCS.

Role in project. The French node is composed of leading figures in MBQC, pioneering works on graph states, on measurement-calculus, and on high level methods. They are also expert in quantum cellular automata, theory of entanglement, and foundation of Physics. In each of these areas, these scientists brings with them teams of brilliant students and postdocs.

5.3. Partner 3	
Prof. H. J. Briegel	Universität Innsbruck
Prof. M.-A. Martin Delgado	Universidad Complutense

Expertise: The University of Innsbruck is the second largest University in Austria, with about 20.000 students, offering Bachelor, Masters and PhD studies in all major fields of Science and Humanities. The two identified priority areas of the university are Quantum Physics and Molecular Biology. The Quantum Information and Computation Group is headed by Prof. Hans Briegel and comprises currently 19 researchers, including 3 senior scientists (project leaders), 5 postdocs, 8 PhD students, and 2 Master students.

Prof. H. J. Briegel is Professor of Theoretical Physics at the University of Innsbruck and a Scientific Director at the Institute for Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences. Together with his collaborators and students and, he co-proposed several key concepts in QIC in the past, among them the quantum repeater and the one-way quantum computer, and the notion of graph states as an entanglement resource.

(1) —, D. Browne, W. Dür, R. Raussendorf, M. van den Nest, Measurement-based quantum computation, Nature Physics 5, 19, (2009); (2) G. De las Cuevas, W. Dür, —, M. A. Martin-Delgado, Unifying all classical spin models in a Lattice Gauge Theory, PRL 102, 230502, (2009); (3) J. Cai, W. Dür, M. van den Nest, A. Miyake, —, Quantum computation in correlation space and extremal entanglement, PRL 103, 050503, (2009); R. Hübener, M. van den Nest, W. Dür, —, Classical spin systems and the quantum stabilizer formalism: general mappings and applications, J. Math. Phys. 50, 083303, (2009); J. Cai, G. G. Guerreschi, —, Quantum control and entanglement in a chemical compass, PRL 104, 220502, (2010).

Prof. M.-A. Martin-Delgado has abroad expertise in the area of condensed matter physics, statistical mechanics, and quantum information theory. He is an expert on topological codes and topological quantum computing, and has made pioneering contributions to relativistic protocols of quantum information. He is a frequent visitor at IQOQI and a long-term collaborator on various projects with the Innsbruck group.

(1) H. Bombin, —, Topological computation without braiding, PRL 98, 160502 (2007); (2) L. Lamata, —, E. Solano, Relativity and Lorentz invariance of entanglement distillability, PRL 97, 250502 (2006); (3) H. Bombin, —, Family of non-Abelian Kitaev models on a lattice: Topological condensation and confinement , Phys. Rev. B 78, 115421 (2008). (4) G. De las Cuevas, W. Dür, H. J. Briegel, —, Unifying all classical spin models in a Lattice Gauge Theory, PRL 102, 230502, (2009); (5) G. De las Cuevas, W. Dür, H. J. Briegel, —, Mapping all classical spin models to a lattice gauge theory, New. J. Phys. 12, 043014, (2010).

Dr. W. Dür is senior scientist at the Institute of Theoretical Physics and has made a number of highly significant contributions to the field of QIC. He is an expert on the theory of multipartite entanglement and has co-authored many papers on graph states, measurement-based quantum computation, and applications.

(1) G. De las Cuevas, —, H. J. Briegel, M. A. Martin-Delgado, Unifying all classical spin models in a Lattice Gauge Theory, PRL 102, 230502, (2009); (2) J. Cai, —, M. van den Nest, A. Miyake, H. J. Briegel, Quantum computation in correlation space and extremal entanglement, PRL 103, 050503, (2009); (3) R. Hübener, V. Nebendahl, —, Concatenated tensor network states, New J. Phys. 025004, (2010).

Role in project. The Innsbruck team brings in expertise in the theory of measurement-based quantum computation, multi-party entanglement, quantum communication, classical and quantum simulation of quantum systems, and quantum algorithmic complexity. In all of these areas they have made essential or even pioneering contributions. The team is part of a larger scientific environment at Innsbruck University and IQOQI, which hosts world-class research groups in both experimental and theoretical quantum physics.

Partner 4 Prof. Reinhard Werner	Leibniz Universität Hannover

Expertise. The Hannover node is led by Prof. Reinhard F. Werner and comprises researchers working in the Institut für Theoretische Physik at the Leibniz Universität Hannover. The group currently has three professors, two post-doctoral researchers and ten PhD students. The focus of the Hannover node is mathematically rigorous work on various aspects of quantum information theory. Most notably quantum cellular automata, complex quantum systems, cryptography, computational complexity, and general structural properties.

Prof. R. F. Werner is a professor of theoretical physics at the ITP Hannover. He has been one of the pioneers of quantum information theory, contributing, amongst other things, the distinction between separable and entangled mixed states and groundbreaking work on quantum cellular automata.
(1) A. Ahlbrecht, H. Vogts, A. Werner, — (2010) *Asymptotic evolution of quantum walks with random coin.* arxiv/1009.2019 - (2) D. Gross, V. Nesme, H. Vogts, and — (2010) *Index theory of one dimensional quantum walks and cellular automata.* to appear in Commun.Math.Phys.- (3) A. H. Werner, T. Franz, and — (2009) *Quantum cryptography as a retrodiction problem.* Phys. Rev. Lett. **103** - (4) D. Kretschmann, D. Schlingemann and — (2008) *The information-disturbance tradeoff and the continuity of Stinespring's representation.* IEEE Trans. Inform. Theory **54** - (5) J. Gütschow, S. Uphoff, —, and Z. Zimborás (2010) *Time Asymptotics and Entanglement Generation of Clifford Quantum Celluar Automata.* JMP **51**.

Prof. T. J. Osborne is a professor of theoretical physics at the ITP Hannover and a member of the QUEST cluster of excellence. He has held an EPSRC first grant and a Nuffield foundation grant and was a fellow of the Wissenschaftskolleg zu Berlin for 2009/2010. TJO originated the study of entanglement in complex quantum systems, work which has now attracted over 1000 total citations.
(1) N. de Beaudrap, M. Ohliger, —, and J. Eisert (2010) *Solving frustration-free spin systems* PRL **105** - (2) — (2008) *Approximate Locality for Quantum Systems on Graphs* PRL **101**. - (3) C. M. Dawson, J. Eisert, and —, (2008) *Unifying Variational Methods for Simulating Quantum Many-Body Systems* PRL **100**. (4) M. Cramer, C.M. Dawson, J. Eisert, and — (2008) *Exact Relaxation in a Class of Nonequilibrium Quantum Lattice Systems* PRL **100**. - (5)C. K. Burrell and — (2007) *Bounds on the Speed of Information Propagation in Disordered Quantum Spin Chains* PRL **99**.

Dr. M. J. Bremner is a researcher at the ITP Hannover. His expertise is in quantum simulation and quantum computational complexity and he has made significant contributions to understanding the role that entangling dynamics play in QIFT.
(1) —, C. Mora, and A. Winter (2009) *Are random pure states useful for quantum computation?* PRL **102** - (2) D. Shepherd and — (2009) *Temporally unstructured quantum computation.* Proc. Roy. Soc. (Lond.) A465 - (3) —, R. Jozsa, and D. Shepherd (2010) *Classical simulation of commuting quantum computations implies collapse of the polynomial hierarchy.* Proc. Roy. Soc. (Lond.) (in the press)

Role in Project. The Hannover node chiefly brings expertise in mathematical methods for quantum information science. This group will contribute widely to the consortium, but in particular their expertise in quantum cellular automata, condensed matter physics, quantum non-locality, and computational complexity will play a central role.

5.5. Partner 5 Prof. R. Jozsa	University of Cambridge

Expertise. The Cambridge node comprises researchers from the Centre for Quantum Information and Foundations (CQIF, formerly CQC, based in DAMTP), and from the Computer Laboratory. The node contributes expertise in quantum computing and information theory, quantum foundations, domain theory, and category theory.

Prof. R. Jozsa is Leigh Trapnell Professor of Quantum Physics in DAMTP, Cambridge. He is a former EPSRC Senior Research Fellow and former Royal Society Leverhulme Senior Research Fellow. With Deutsch he first demonstrated that quantum effects may lead to an exponential enhancement in computing power over any classical machine. He is also co-discoverer of the process of quantum teleportation.

(1) —, B. Kraus A. Miyake, and J. Watrous (2009) Matchgate and quantum space-bounded computations are equivalent, Proc. Roy. Soc. (Lond.) A466 p809-830. (2) — and A. Miyake (2008) Matchgates and classical simulation of quantum circuits, Proc. Roy. Soc. (Lond) A464, p3089-3106. (3) — (2008) Embedding classical into quantum computation, Springer LNCS 5393 Beth Festschrift, J. Calmet, W. Geiselmann, J. Mueller-Quade (eds.), p43-49. (4) M. Bremner, — and D. Shepherd (2010) Classical simulation of commuting quantum computations implies collapse of the polynomial hierarchy, Proc. Roy. Soc. (Lond.) (in the press). (5) S. Clark, — and N. Linden (2008) Generalised Clifford groups and simulation of associated quantum circuits, Quant. Inform. Comp. 8 p106-126.

Dr. N. Datta is Lecturer in Mathematics of Pembroke College and an Affiliated Lecturer of the Statistical Laboratory, DPMMS, Cambridge. Her research is principally on various aspects of quantum information theory, especially quantum Shannon theory. (1) F. Buscemi and — (2010), Distilling entanglement from arbitrary resources J. Math. Phys. 51, 102201. (2) — (2009) Max- Relative Entropy of Entanglement, alias Log Robustness, International Journal of Quantum Information, vol 7, no.2, 475-491, 2009. (3) M. Mosonyi and — (2009), Generalized relative entropies and the capacity of classical-quantum channels J. Math. Phys. 50, 072104.

Dr. A. Kent is Reader in Quantum Physics at DAMTP, Cambridge and an Associate Member of Perimeter Institute for Theoretical Physics. His current research interests range from novel quantum cryptographic protocols to new experimental tests of quantum theory.

(1) — (2010) One world versus many: the inadequacy of Everettian accounts of evolution, probability, and scientific confirmation, in "Many Worlds? Everett, Quantum Theory and Reality", Oxford University Press.

Prof. G. Winskel, Professor of Computer Science, pioneered causality in computer science (event structures). He is a world-expert in domain theory, and in mathematical structures in computer science more generally.

(1) Sam Staton and —. On the expressivity of symmetry in event structures. IEEE LICS 2010. (2) David Turner and —. Nominal Domain Theory for Concurrency. CSL 2009. (3) —. Events, Causality and Symmetry. The Computer Journal 2009

Dr. M. Fiore, Reader in Mathematical Foundations of Computer Science at the Computer Laboratory, is a world-expert in domain theory and category theory.

(1) —, N.Gambino, M.Hyland, and G.Winskel. The cartesian closed bicategory of generalised species of structures. In J. London Math. Soc., 77:203-220, 2008. (2) —. Second-order and dependently-sorted abstract syntax. IEEE LICS'08, , 2008. (3) — and O.Mahmoud. Second-order algebraic theories. MFCS 2010, LNCS 6281, pp. 368-380, 2010.

Role in project. The Cambridge node contributes expertise in mainstream aspects of QIFT, including a synergistic complement to novel categorical and diagrammatic methods. We bring particular expertise in quantum complexity, classical simulation studies and measurement based computation, in entanglement theory, in quantum nonlocality and foundations, in domain theory, event structures and category theory.

6. Added value of the proposed collaboration, multidisciplinarity & European dimension

The consortium includes the leading authorities with respect to the proposed research.

These include several of the pioneers of QIFT, and of key sub-areas of QIFT, as well as pioneers and world-leading researchers in the other disciplines involved (See §5). The formation of this consortium follows several years of intense interactions and collaborations, within the framework of the highly successful FET Open STREP Foundational Structures for Quantum Information Science (QICS) [1]; together we pioneered novel unexpected synergies between the distinct disciplines involved, resulting in new QIFT-research strands, and in particular, synergies between QIFT research and other disciplines. In short, this team has a track record of joint groundbreaking research.

Multidisciplinarity. The proposal is highly interdisciplinary, involving researchers of different fields: (i) *Physicists* who are challenging the boundaries of nature's capabilities by studying novel quantum computational models such as measurement based quantum computational schemes and quantum cellular automata, mainly in Hannover, Innsbruck, Oxford-UCL and Paris; (ii) *Logicians* who adopt novel structural tools such as category theory, type systems and formal calculi to cast quantum behaviour, mainly in Oxford-UCL, Cambridge and Grenoble; (iii) *Mathematicians* trying to achieve an understanding of quantum information by providing both qualitative and quantitative accounts on it, mainly in Cambridge, Hannover and Oxford-UCL; (iv) *Computer scientists* who bring in their know-how on high-level methods to cope with complex interactive and distributed situations, mainly in Grenoble, Paris, Oxford-UCL and Cambridge.

Moreover, within the STREP QICS it was our intention that the recruitment and development of the post-docs to be hired would serve to enhance this interdisciplinarity, and produce some outstanding young researchers with a broad set of skills drawing from the many different areas involved in QIFT research. Several of them meanwhile have faculty or permanent research positions, and some are now co-investigators in the current proposal, e.g. both Markham (Par) and Perdrix (Gre) obtained prestigious permanent CNRS positions, hence in part consolidating the QICS research effort.

Extending the scope of QIFT. The goal of the present proposal even involves interaction with areas beyond the traditional QIFT scope, such as in condensed matter physics and statistical physics (WP1, WP2), special and general relativity (WP2, WP3), quantum field theory and quantum gravity (WP1, WP2, WP3), and branches of AI such as automated reasoning, information retrieval and natural language processing (WP4).

As an example, the study of entanglement alone penetrates many distinct areas; it is the key resource of the measurement-based quantum computational model (QICS), which, in turns, has resulted in new applications in statistical physics, on which we elaborate in T1.3, with further applications to quantum gravity; computer science have enabled to craft diagrammatic calculi (QICS) which may enable us to solve important problems in condensed matter physics in T1.5; aspects of this investigation may even by automated by relying on the automated reasoning techniques of T4.3; MBQC also provides a vehicle to study non-locality (T3.2) and causality (T3.3); structural similarities between information flows in entangled states and certain natural language processing tasks may lead to new applications of QIFT in that area. Other key topics of this project such as QCAs and causality also penetrate a variety of areas.

European dimension. The nature of the research is typically European, drawing from the European strength such as logical methods in computer science and novel QC architectures. Originality has always been the cornerstone of European research, which for example resulted in the QIFT enterprise itself, with for example the work by Deutsch (Oxford) and Jozsa (Cambridge). Pursuing highly original research such as the research proposed here will be crucial for Europe to stay at the forefront of QIFT-research both in the short and the long term, in particular by coupling the QIFT activity to the key European research strengths, such as logic in computer science, new QIFT-architectures, and the other areas involved in this highly multidisciplinary project.

7. Description of significant facilities; large equipment available to the consortium

This proposal requires no large equipment. All institutions involved are world-leading research institutions with the relevant infrastructure for performing scientific research.

8. Consortium agreement principles

Overall. The administrative, financial and overall responsibilities are coordinated by Bob Coecke at the Oxford site. The overall scientific coordination and the coordination of the reporting is the responsibility of Pablo Arrighi and Simon Perdrix at the Grenoble site. The organization of events is the responsibility of both of these sites, in consultation with the work package leaders.

Per workpackage. The scientific responsibility of work pages is ensured by the University of Innsbruck and Oxford (Prof. Hans Briegel, Dr. Bob Coecke) for WP1, by University of Hannover (Prof. Reinhard Werner) for WP2, by UCL (Dr. Dan Browne) for WP3 and by the Universities of Cambridge and Oxford together (Prof. Richard Jozsa, Dr. Bob Coecke), i.e. 'Oxbridge', for WP4. Work package leaders are in charge of monitoring and timely reporting the performed research to coordinators, as organized by themes.

Per partner. The consortium is composed of five partners in five countries (UK, France, Austria, Spain, and Germany). The Oxford-UCL (University of Oxford and University College London) partner is coordinated by Dr. Bob Coecke; the French partner is composed of University of Grenoble, Telecom Paristech and CEA-Saclay/DSM, wherefrom it will be coordinated by Dr. Alexei Grinbaum; the Innsbruck-Madrid partner is coordinated by Prof. Hans J. Briegel; the Hannover site is coordinated by Prof. Reinhard Werner; and the Cambridge site is coordinated by Prof. Richard Josza. Partner coordinators are accountable for the local administrative and scientific aspects, and timely reporting of local research results to WP leaders.

Research monitoring. Every six month, there will be a meeting of the work package leaders and site leaders, either via electronic media (e.g. Skype) or at a FIQST event. At this meetings the progress of the research, budget spending, realization of objectives and milestones, potential for more collaboration and interaction, will be monitored. These meetings will be organized by the French and the Oxford site.

9. Link with ongoing projects *(max. ½ page per partner):*

9.1. Partner 1 - Oxford and UCL

US Office of Naval Research (ONR) GRANT Complementary quantum observables and resulting information flows in algorithms and protocols. ∼285 K USD. Participant: Bob Coecke. Dates: 2008-2012. Involvement: 10%. This project aims to further develop the category-theoretic calculus of complementary observables due to Coecke and Duncan, and to automate reasoning within it via the quantomatic software. This calculus is the predecessor of the GHZ/W-calculus due to Coecke and Kissinger that we will study here.

EPSRC GRANT Complexity and Decidability in Unconventional Computational Models. ∼ 174 K GBP. Participant: Bob Coecke. Dates: 2008-2011. This project aims at studying non-standard complexity resources in unconventional computational models, including non-standard quantum computational models. It may contribute other complexity resources to simulation questions here.

EPSRC GRANT Logic of Interaction and Information Flow. ∼ 314 K GBP. Participant: Samson Abramsky. Dates: 2008-2012. High-level methods for studying information flow are developed. These methods may be used here for studying the specific case of quantum information flow.

EPSRC Advanced Research Fellowship of Coecke. ∼ 460 K GBP. Participant: Bob Coecke. Dates: 2007-2011. Faculty duty relief which allows for research only focus.

EPSRC Senior Research Fellowship of Abramsky. ∼ 560 K GBP. Participant: Samson Abramsky. Dates: 2008-2012. Faculty duty relief which allows for research only focus.

Leverhulme Research Fellowship: Bell inequalities and Quantum Computation ∼ 37 K GBP Participant: Dr Dan Browne Dates: 2010- 2012 Involvement: 30% This project aims to further strengthen the connections between Bell inequalities and Quantum computation in a number of directions, including developing new types of inequality in which adaptive measurements are considered and making concrete links between limitations of quantum computation and the limitations of quantum correlations embodied by Tsirelson-type bounds.

9.2. Partner 2 - Grenoble and Paris

ANR Projet FREQUENCY (ANR-09-BLAN-0410-03). ∼400 keuros. Participant: Damian Markham. Dates: 2010-2013. Involvement: 30% 2010-2013. The FREQUENCY is aimed at the development of quantum networks (from integration of QKD into classical networks, to full quantum networks, including entanglement and how it can be used). Dr. Markham's part is on q secret sharing (developing the protocols). In particular it involves overlaps with WP1 as the project works towards new protocols as example of a multiparty protocol, and looking for new uses of entanglement. Certain overlaps with WP2 can occur as well.

Project "Quantum Computation: Theory and Feasibility" in the framework of the CNRS-JST Strategic French-Japanese Cooperative Program on ICT. ∼90 keuros. Participants: Damian Markham, Mehdi Mhalla, Elham Kashefi. Dates: 2008-2011. This project is focused on developing theory and practicability of quantum computation and information. One aspect, worked on by Markham, is on developing the understanding of how multipartite entanglement can be manipulated and use for QIP, which, although different in approach, overlaps with WP1.

ANR JCJC project "CausaQ". ∼277 keuros. Participants: Pablo Arrighi, Simon Perdrix, Mehdi Mhalla. Involvement: Pablo Arrighi 36 p.m (Coordinator), Mehdi Mhalla 24 p.m, Simon Perdrix 24 p.m. CausaQ focuses on causality in quantum information. These are more specific questions that those of FIQST, sometimes outside (MBQC, Multi-party NL-Boxes, Church-Turing thesis in QCA), sometimes within (Representation of entanglement, Further axiomatization of QCA) the scope of QICS II. There will no doubt be cross-fertilization.

PEPS CNRS-INS2I project “GraphIQ”. ∼8 keuros. Participants: Mehdi Mhalla, Simon Perdrix (coordinator). Date: 2010. GraphIQ project brings together researchers in QIT and graph theory for working on the graph state formalism which establishes strong connections between these fields. There are connections with WP1 on the graphical representation of entanglement and with WP3 on the links with other computer science areas (graph theory in that case).

PEPS CNRS-INS2I project “QuAND”. ∼8 keuros. Participants: Pablo Arrighi, Simon Perdrix. Date: 2010. The objectives of the QuAND project is to work on non deterministic aspect of computation emerging from different areas of CS: logics, quantum computing and concurrent programming. The aim is to point out the links between these areas and development common methods and tools.

9.3. Partner 3 - Innsbruck and Madrid

Project “Measurement-based quantum computation in the frame work of FWF-SFB “Foundations and Applications of Quantum Science” ∼ 340keuro. Participants: H. J. Briegel, W. Dür. Dates 1/1/2009 - 31/12/2012. This project investigates a broad range of both fundamental and practical questions relating to MBQC and its implementations. There is a certain overlap with WP1 on the mapping of MBQC to classical spin models, and with WP4 on the classical simulation of quantum many-body systems.

9.4. Partner 4 - Hannover

7th framework STREP “CORNER” contract number 213681. ∼ 180 keuro. Participants: Reinhard Werner + group.

Involvement: Reinhard Werner (node PI). Dates: 2008 - 2011 Work of the Hannover node concerns mostly the notion of quantum memory channels, and the correlations between successive uses of a channel and is as such a much more specialized project than FIQST.

7th framework STREP “COQUIT” contract number 233747. ∼ 204 keuro. Participants: Reinhard Werner + group.

Involvement: Reinhard Werner (node PI). Dates: 2009 - 2012 The idea of this project is to build a theoretical framework around the distinction between hard and easy quantum operations, as seen by different experimental implementations. While there is expected to be some cross-fertilization with this project on issues involving quantum cellular automata, this project is much more focused on issues of implementation of quantum computer technologies than the far reaching foundational issues of the FIQST proposal.

German National programme funded by the Federal Ministry BMBF, managed through DLR “QuOReP” . ∼ 180 keuro . Participants: Reinhard Werner + group.

Involvement: Reinhard Werner (node PI). Dates: (final approval pending) This is specifically targeted to repeaters for quantum communication, especially with quantum optics technology. There is no overlap at all with the current proposal. It is mentioned here only because the funding source is similar to the German node of CHIST-ERA.

DFG project “Forschergruppe 635 – Quantum control and simulation distributed neutral atom systems” ∼ 180 keuro. Participants: 2 PhD students + Reinhard Werner + group.

Involvement: Reinhard Werner. Dates: 2009 - 2012 Forschergruppe 635 (funded by DFG) ”Quantum control and simulation distributed neutral atom systems” Emphasis in this project is on collaboration with experimentalists in the same consortium.

9.5. Partner 5 - Cambridge

EC FP7 grant 255961 QCS - Quantum Computer Science. Sept 2010 for 36 months. Participants: R. Jozsa (8mo’s) N.Datta (3mo’s) A. Kent (3 mo’s). This project is focused on development of quantum computer science, especially new algorithms, communication protocols and mathematical techniques. Main emphasis is operational rather than foundational, so will provide an interesting complement to some aspects of FIQST.

10. Scientific Impact, dissemination and potential exploitation

The information technology of the future. Information Technology will have to confront the challenges of the fundamentally quantum nature of physical embodiments of computing systems. This passage to quantum information technology is both a matter of technological necessity and one of technological opportunity:

(i) As the scale of the miniaturization of IT components reaches the quantum domain, taking quantum phenomena into account will become simply unavoidable;

(ii) The emerging field of QC has exposed new computational potential, including algorithms which endanger currently used cryptographic schemes, whilst on the other hand QI provides the corresponding remedy in the form of quantum cryptographic protocols.

As our society becomes more and more reliant on the manipulation of huge amounts of data, novel techniques to deal with them become essential, and again there is an opportunity provided by quantum information technology:

(iii) A multi-purpose algorithmic primitive (Grover's) can reduce virtually any task involving some form of brute force search over n elements, down to a complexity of $\sqrt{n}$.

This is where we stand now, but given, in scientific terms, the relatively recent emergence of quantum information technology, it would be extremely naive to think that there is not much more potential well beyond the currently envisioned targets for actual commercial devices such as quantum computers and quantum cryptography. Discovering these requires highly adventurous, high risk research, in interaction with other disciplines, and by leading figures in all fields, exactly like we propose here.

For example, even in purely theoretical terms, abstracting over actual physical implementation, we still do not understand the limits of QIFT, nor do we have a clear understanding of the limits of (efficient) classical simulation. Entanglement, the key resource of QIFT, is simply not at all understood once we go beyond three systems. Given the number of large applications of the very few well-understood states such as the GHZ-state and graphs-states, e.g. in fault-tolerance for QC, novel QC-models, applications in security, etc., there must be a huge undiscovered potential within the vast space of possible multipartite entangled behaviors. These may go well beyond each of the applications mentioned above. They may also lead to radically new architectures which may could bring actual commercial devices closer to reality.

More precisely, the proposed work has the potential for major scientific impact on the future development of the entire area of QIFT, as it will provide a solid conceptual and mathematical basis for understanding the foundational structures and possible architectures for QIFT. We seek to answer fundamental questions on the nature of QIFT, which should provide a deeper understanding of the QIFT endeavor as a whole. It would yield a substantial enhancement of available methods for all those concerned with the development, exploitation and implementation of QIFT, both in terms of software and physical devices. By greatly expanding the repertoire of tools available to quantum architecture designers, it could shape the QIFT architectures of the future. It could even drive a major change in the experimental realization of quantum computers, since the profound study of new models could indicate architectures that might be implemented many years before the currently proposed schemes. The proposed research could also have a major impact on the exploitation and application of these new QIFT architectures. The high-level methods which we propose to develop would be applicable to a wide range of potential QIFT-systems, and should allow a smooth integration of quantum and classical components, which will surely be essential in realistic applications of QIFT. It will also lead to systematic methods for building-in data-reliability and fault-tolerance — it were considerations on fault-tolerance which originally pointed to the novel QCA or MBQC architectures as compelling candidates for QC, and it is obvious that several other candidates are yet to be discovered.

The science of the future. The QIFT-revolution also has produced a number of methods and paradigms that are highly applicable to other areas of science; this is the sign of of a maturing important branch of science, it's concepts and methods will have applications well beyond its initially envisioned scope.

At the most basic level, our established conceptions about computation, information and logic which have been shattered, since QIFT trashed the wall which isolated information theory and Computer Science (CS) from the Physics implementing it; we have been forced into realizing that the very notion of what an algorithm is fundamentally dependent upon the chosen physical setting. Acknowledging the fact that Physics and CS are deeply intertwined, this project seeks to clarify their relations at the most fundamental level. Our work is to further *understand*, in the sense of identifying and quantifying, the nature of the resources granted to us by Physics (*e.g.* entanglement, interference, dynamics, ...) for the purpose of information processing.

One also needs to produce novel mathematical structures, to model these resources. This means capturing these physical resources in the tightest possible manner through the elaboration of novel logics, categorical structures, models of computation — and the deep mathematical theorems that arise within those. Further, our work is to learn to *reason* about these models. This reasoning may be human, or artificial. As the complexity of interactions that one may want to consider in QIFT-protocols increases, automated reasoning techniques from AI may as well become essential. Meanwhile, the converse is also already happening; the development of the `quantomatic` software has already impacted the research in automated theory exploration.

The current project aims to solidify and expand many more synergies which have started to emerge with other branches of science such as statistical physics, condensed matter physics, quantum field theory, quantum gravity, relativity and causality. It also wants to bring QIFT into areas where it has not been considered yet, such as information retrieval and natural language processing.

Dissemination. Given the very broad scope and areas involved we plan to dissimilate the results in a variety of manners. Besides the traditional scientific means (publications, seminars) we also plan to hold a dedicated conference, and a school at the end of the project. Both events will be filmed and the recordings will be publicized at the Talk Archive of the Quantum Group at Oxford University Computing Laboratory.

All the software that we aim to produce will be made freely available for download in all standard formats (Mac, Unix, Windows); the current prototype version of the `quantomatic` software [2] is already made available for download, as well as other software produced by Quantum Group at Oxford University Computing Laboratory – e.g. the `TikZiT` software [3] interface for generating the diagrams used in the diagrammatic languages that will play a prominent role in this project.

11. Financial plan

11.1. Partner 1 - Oxford and UCL

Part of the oxford budget consists of a budget for overall network activity such as schools, conferences, workshops, admin support for these as well as for overall administrative management. The remainder consists of funding for the research that will take place at Oxford and UCL. This will consist of two postdocs, one for a period of three year (RA1) and one for a period of one year (RA2). RA1 will spend one year at Oxford University Computing Laboratory, one year at UCL, and one year at the Department of Physics at Oxford University; this arrangement will guarantee close collaboration between these sub-sites. RA2 will be required to have strong programming skills and help with the highly software dependent tasks (T1.1, T4.3, T4.4). We do not request funding for PI's and co-PI's. Travel for the UCL partner will be claimed through Oxford.

Overall network budget. The network budget consists of:

- **25 K EUR** for a FIQST Conference, which will not only be restricted to FIQST researchers, but to other researchers with related interests.
- **25 K EUR** for a FIQST School, which will take place at the end of the project to disseminate the results obtained by the network. The entire school will be filmed.
- **18,750 EUR** for a FIQST Workshops, which will be organized whenever the partners feel the need for a concentrated effort on a specific topic.
- **32,261 EUR** for administrative support; this will be someone with ample experience in managing networks at EU level.
- **1 K EUR** for a laptop for the administrative support person.

Personal costs.

- **141,192 EUR** for RA1, year 1–3.
- **45,660 EUR** for RA2, year 1.

Other costs.

- **37.5 K EUR** for travel, i.e. attending conferences, visiting partners.
- **4 K EUR** for 2 laptops, for RA1 and RA2.
- **2.5 K EUR** for recruitment.

The total is obtained at 80 % Full Economic Cost incl. indirect and estate Costs.

11.2. Partner 2 - Grenoble and Paris

Personnel cost. Full workforce cost is justified by the following chart showing involvement in person-months. Permanent staff (person-months):

Name	Year 1	Year 2	Year 3	All years
Alexei Grinbaum	3	3	3	9
Pablo Arrighi	2,4	2,4	2,4	7,2
Damian Markham	3	3	3	9
Mehdi Mhalla	4,8	4,8	4,8	14,4
Simon Perdrix	2,4	2,4	2,4	7,2
Frédéric Prost	2,4	2,4	2,4	7,2
Total	18	18	18	**54**

Existing PhD students who will contribute to the project (person-months):

Name	Year 1	Year 2	Year 3	All years
Mael Pegny	6	1,5	0	7,5
Issam Ibnouhsein	9,6	9,6	9,6	28,8
Jerome Javelle	2,4	4,8	4,8	9,6
Zizhu Wang	9,6	2,4	0	12
Total	27,6	18,3	14,4	**60,3**

Two postdocs will be recruited on the FIQST contract for a duration of $2,5$ years each. (60 person-months in total).

Travel costs. We'll actively participate in the workshops and meetings with other partners. Travel costs for the French side amount to 15000 euros per year.

Small consumables. Purchase of laptops is planned at the beginning of the project. Total cost of small consumables is 6494 euros for the whole duration of the project.

11.3. Partner 3 - Innsbruck

Personnel cost. Full workforce cost is justified by the following chart showing involvement in person-months. Permanent staff (person-months):

Name	Year 1	Year 2	Year 3	All years
Hans Briegel	1	1	1	3
Miguel Angel Martin-Delgado	1	1	1	3
Wolfgang Dür	1	1	0	2
Total	3	3	2	**8**

Postdocs and PhD students who will contribute to the project:

Name	Year 1	Year 2	Year 3	All years
Gemma De las Cuevas (PhD)	4	0	0	4
Ying Xu (Postdoc)	6	12	0	18
Total	10	12	0	**22**

Two postdocs will be recruited on the FIQST contract for a duration of 3 years and 1.5 years, respectively (54 person months in total).

Travel costs. Travel money will be used to participate in meetings with other partners and for presenting results relating to FIQST, e.g at conferences and workshops. Total travel costs amount to 6.500 Euros per year.

11.4. Partner 4 - Hannover

Personnel cost. Person months of permanent staff:

Name	Year 1	Year 2	Year 3	All years
Reinhard Werner	3	3	3	9
Tobias Osborne	1	1	1	3
Michael Bremner	3	0	0	3
Total	7	4	4	**15**

Existing PhD students:

Name	Year 1	Year 2	Year 3	All years
Volkher Scholz	3	0	0	3
Fabian Furrer	2	2	0	4
Total	5	2	0	**7**

One FIQST postdoc and one FIQST PhD student will be recruited, each for 36 months.

Travel costs. 10 000 euro per year for 3 years, for postdoc, PhD student and node members to attend FIQST meetings and conferences.

Small consumables.

- 5000 euro total for computing hardware for the node members.
- 3000 euro total for consumables.
- 1000 euro per year for software licenses.

11.5. Partner 5 - Cambridge

Personnel cost. Person months of permanant staff:

Name	Year 1	Year 2	Year 3	All years
R. Jozsa	3	3	3	9
N. Datta	1	1	1	3
A. Kent	1	1	1	3
Total	5	5	5	**15**

Existing PhD students:

Name	Year 1	Year 2	Year 3	All years
Matthew Lee	2	2	2	6
Total	2	2	2	**6**

One FIQST postdoc will be recruited for 36 months.

Travel costs. 7500 euro for 3 years, for postdoc and node members to attend FIQST meetings and conferences.

Small consumables. 1200 euro for laptop for postdoc.

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[1] FP6 FET Open STREP Foundational Structures in Quantum Computation and Information (QICS); http://users.comlab.ox.ac.uk/bob.coecke/QICS.html.

[2] `quantomatic software`, written by L. Dixon (Edinburgh) and R. Duncan (Oxf) and A. Kissinger (Oxf) and A. Merry (Oxf). dream.inf.ed.ac.uk/projects/quantomatic/.

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