The Quantum Times

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Newsletter of the Topical Group
on Quantum Information

American Physical Society

The Q Times and Time's A

Nathan Argaman

The purpose of this letter is to point out that, all too often, Time's Arrow serves as a hidden assumption in discussions of locality and Bell's theorem, in particular those appearing in *The Quantum Times*. Not that it is a bad assumption to make – sending signals into the past is not a viable idea (the grandfather paradox). However, quantum correlations do not allow signaling, and the causal arrow of time may well be due to the entropy being low in the past, therefore being applicable only in the macroscopic realm. Its strict applicability in the microscopic context, which is ostensibly time-reversal symmetric, is a physical assumption, not a mathematical rule.

A century ago, violations of local causality were simply considered illogical – it was taken for granted that natural systems cannot exhibit any actions at a distance or into the past, i.e., anything like telepathy or foresight. However, the mathematical descriptions used in physics were not all constrained in this way. For example, the Lagrangian formulation of classical mechanics typically uses initial and final positions as free variables – it is time-symmetric – and so the *initial* velocity depends on the *final* position in a manner which, at the mathematical level, is retro-causal! The causal arrow of time may be restored by treating the initial conditions as free variables – after all, these can be experimentally controlled at will – and taking the final position to depend on these. A second example is given by the gravitational force, which according to Newton's laws acts at a distance. General relativity replaced this with a field, with disturbances propagating at the finite speed of light.

In the mid nineteen-twenties, Quantum Mechanics (QM) joined the list of non-local descriptions – wavefunctions of several particles are defined in configuration space, rather than physical space, and wavefunction collapse is non-local even for a single particle. It was natural to expect future developments to produce an equivalent mathematical description conforming not only with the arrow of time, but also with the principle of locality. There are additional issues with QM – the measurement problem, and the exponential complexity of the description when systems of many particles are considered – which may also evoke expectations for future developments.

In 1935, the EPR paper raised another issue with QM– "completeness" – based on a suggested condition for identifying "elements of physical reality," which involved "making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it," i.e., made "without disturbing the [first] system." Again, local causality was taken for granted, whereas "elements of reality" and "completeness" were concepts which required formulation.

Bohr's reply [1] to EPR is of interest here. He considered a setup in which the two "systems" were not two particles, but a particle and a much heavier "diaphragm," which could be treated either as part of the quantum-mechanical composite system or as part of a classical measurement apparatus. The arrangement was such that, after

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the particle had ceased to interact with the diaphragm, "… we are … still left with a *free choice* whether we wish to know the momentum of the particle or its initial position …" (italics in original), a choice exercised by making different measurements on the diaphragm. Bohr thus emphasized that the description of QM is retro-causal in this case, but hastened to add that this free choice only affects "… *the possible types of predictions regarding the future behavior of the system*" (italics in original). He rejected the EPR criterion for elements of reality, concluding that QM was just fine. In view of the spectacular success of QM, one could hardly argue with this conclusion.

It was properly understood only in the sixties – Bell's theorem – that no physical or mathematical description conforming with the principles of local causality can ever reproduce the results of QM. Note that the issues of completeness and of realism do not play a role here. Bell introduced a general mathematical notation, referring to two systems (or particles) which are initially prepared in an entangled state but at a later time are separated by a large distance and subject to separate measurements. The two measurements are described by parameters a and b, and the initial preparation by a parameter c. These parameters are external free variables, controllable by experimentalists. The results of the measurements are described by variables A and B, respectively. The goal of a physical theory, or of a mathematical description, is to predict the probabilities of the various experimental results, i.e., to provide $P(A,B|a,b,c)$. All the variables used by the theory to describe the "state" of the two systems between the time of preparation and the time of measurement are collectively denoted by λ. Locally causal theories must conform with two principles:

(i) Arrow of time – the state λ can depend only on the parameter belonging to its past, c [this dependence may be specified by providing either a function $\lambda(c)$ or, more generally, a probability distribution $P(\lambda|c)$].

(ii) Separability – the results for each of the two measurements must be independent of the particulars of the other [again, the description must specify either values, $A(a, \lambda)$ and $B(b, \lambda)$ or distributions, $P(A| a, \lambda)$ and $P(B| b, \lambda)$].

Bell proved that no such mathematical description can reproduce the results of QM.

This transformed the situation. The principles involved were considered so unshakeable that it was necessary to perform experiments to verify that the predictions of QM hold under the relevant circumstances. Such experiments have been performed with increasing sophistication since the early eighties. Again and again, the predictions of QM are confirmed. Feynman, in his 1982 keynote speech presaging quantum computation [2] reviewed this situation, concluding with: "It's interesting to try to discuss the possibilities … [including] the possibility of … things being affected not just by the past, but also by the future ..."

Unfortunately, most present-day discussions ignore this possibility, and continue to take principle (i) for granted, even when considering violations of principle (ii). There are several apparent reasons (but no justification) for this. For example, Bohmian mechanics, which served as a part of Bell's motivation, and succeeds in reproducing the results of QM while avoiding the measurement problem, conforms with the causal arrow of time. In fact, this arrow is so strongly ingrained in our thinking, that even when the possibility that $P(\lambda|a,b,c) \neq P(\lambda|c)$ is considered, it is most often associated with a breakdown of the framework rather than a violation of the arrow of time. Indeed, if a and b were not free variables, but were to depend, together with λ, on common causes in the past, then one could use $P(\lambda|a,b,c)$ as a legitimate expression of the pertinent conditional probability. Such a denial of the ostensible fact that experimentalists exercise free will when selecting the settings of instruments has been called "superdeterminism" by Bell. It is difficult, if not impossible, to come up with a reasonable alternative framework – one not involving conspiracies – which would allow this.

One could expect articles in *The Quantum Times* to be concordant with Feynman's conclusion, but even he was not able to reform our conception of the arrow of time. Let me mention two examples. The first involves two adjacent items of the News section of an earlier issue (Vol. 5 No. 3), entitled "Testing realism" and "Testing freedom of measurement." Readers are informed that locality means that "objects are only affected by their immediate surroundings," and that realism means that "things exist regardless of whether or not we observe them." In fact, what is implied, of course, is that the properties of things *at the present* are independent of which, if any, measurements or experiments on these things will be made *in the future*.

The second example concerns Matt Leifer's contribution to the latest issue. He reviews recent progress on characterization of the types of possible theories which may reproduce QM: How much information must be included in the "state" λ? In particular, is it possible for λ not to include all the information required to reconstruct the wavefunction of the QM description, ψ? In other words, can one value of λ be associated with more than one value of ψ? The research reviewed by Leifer is based on taking the arrow of time, principle (i), for granted, and the results are rather discouraging. For example, it is concluded that specification of λ entails specification of ψ, justifying the ψ-ontic interpretation, and ruling out the ψ-epistemic interpretation, in which ψ is taken to represent one's knowledge regarding the state of the system.

What happens if one considers retro-causal mathematical descriptions, not constrained by principle (i)? Of course, the answers to essentially the same questions may then be different. In fact, principle (i) is extremely restrictive, and its removal uncovers a vast array of possibilities. It is not difficult to come up with mathematical

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toy-model descriptions which are appropriate for specific cases, including the particular non-local correlations studied by Bell [3] (in this case, the separability principle (ii) holds, but it does not imply locality because the information is passed from one location to the other through the retro-causal state λ; in order not to allow retro-causal signaling, the information in this state must remain "hidden," i.e., be inaccessible to measurements which would amplify it into the macroscopic domain). The door is now open to a host of additional interesting questions, e.g., is it possible to find a retro-causal mathematical description which, like Bohmian mechanics, would be free of the measurement problem? Such questions remain largely unexplored [4].

Bell's theorem is often discussed in a relativistic framework – the a and b measurements are taken to be space-like separated – with the implication that it describes a significant tension between the two pillars of twentieth-century physics: QM and relativity. In fact, it rests on a third pillar as well: the causal arrow of time. It is only when this third pillar is included in the second (after all, improper Lorentz transformations were deemed "improper" for a reason), i.e., the "tension with relativity" is replaced with "tension with relativistic causality," that such a representation becomes valid. On the other hand, one may alternatively interpret the success of the theory of relativity as a recommendation of the "block universe" point of view, in which past and future, at least on the microscopic level of description, are considered to be as similar to each other as left and right are. Within this line of reasoning, relativity becomes another motivation, in addition to Bell's theorem, for dropping the requirement of the causal arrow of time.

All of this having been said, there is of course every justification for researchers to continue to analyze models in which the state λ depends only on the past. Those who do so should merely mention the causal arrow of time when discussing the physical principles they rely on. In contrast, those who choose to broaden their horizons by studying retro-causal mathematical descriptions of quantum phenomena will be embarking on an adventure into essentially uncharted territory.

Nathan Argaman *is a condensed-matter theorist at the Nuclear Research Center – Negev, Israel. He has four children, a gorgeous girlfriend, and a cat. Editor's note: as we have not measured it, we can offer no information regarding the cat's present state. Nevertheless, it shall henceforth be referred to as "Argaman's cat."*

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2. R. P. Feynman, "Simulating Physics with Computers," Int. J. Theor. Phys. **21**, 467-88 (1982).
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4. There are in fact a number of works discussing the arrow of time in the context of QM, but the majority are not posed within Bell's framework. See Ref. 3 for details.

About Q+

Q+ is a series of online seminars that take place in Google+ hangouts. You can watch the seminars live on any computer with an internet connection, or after the fact on YouTube.

To watch the seminars live, go to http://gplus.to/qplus at the appointed hour. You do not need a Google account to watch, but you do need one if you would like to be able to participate in the question and answer session at the end of the talk.

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Upcoming seminars

All times are British Summer Time

Tuesday, April 24, 2 PM - 3 PM
Jonathan Oppenheim
Fundamental limitations for quantum and nano thermodynamics

Tuesday, May 8, 2 PM - 3 PM
Vlatko Vedral
Title to be announced

We also encourage you to suggest speakers for future talks by adding them to the spreadsheet at http://bit.ly/qplussuggestions.

Who Needs Hidden Variables?

Robert B. Griffiths

Allow me to make some comments on Matt Leifer's "PBR, EPR, and all that jazz" in the fourth quarter 2011 issue of *The Quantum Times* (Vol. 6, No. 3). In it he explains that work by Pusey et al. [1] provides an important "no go" result for hidden variable interpretations of quantum mechanics, and no doubt he is correct. What surprises me is that hidden variables continue to be taken seriously despite the serious deficiencies (several mentioned in Leifer's article) in this approach to understanding quantum mechanics, given the existence of an alternative which seems, at least to me, much more satisfactory.

By *hidden variables* I mean mathematical objects used in addition to, or perhaps as a replacement for, the Hilbert space of standard quantum mechanics as found in textbooks. (Maybe "hidden" is a bad term, but by now everyone uses it.) The best-known hidden variable theory is that of de Broglie and Bohm (dBB) [2]. In addition to a wave function in the standard Hilbert space it employs particle coordinates which constitute the additional variables. The dBB theory contains instantaneous nonlocal influences, action-at-a-distance, which make it hard if not impossible to reconcile it with special relativity. Bell's work has shown that this problem is unlikely to be unique to dBB; one can expect similar nonlocality troubles in other hidden variable theories. In addition dBB is computationally complex in that one first has to solve the time-dependent Schrödinger equation and then *in addition* the differential equations for the motion of the particles.

Much hidden variables research seems motivated by the hope of using them to solve the quantum measurement problem. There are actually two measurement problems. The first is Schrödinger's cat: there are circumstances in which integrating Schrödinger's time-dependent equation for everything, including the measuring apparatus, results in a wave function in which, in the quaint language of quantum foundations, the apparatus pointer indicating the measurement outcome is in a superposition of different positions, contrary to the observations of experimental physicists. A hidden variable telling us the actual pointer position could get rid of this difficulty, and dBB claims to do just that. But there is an alternative approach, which was introduced by Born in the same year (1926) as Schrödinger's time-dependent equation: it tells us that instead of using the wave function to describe the universe, it can be used to *calculate probabilities*. Probabilities of what? From the modern perspective these are probabilities of *quantum properties*, represented, as we learned from von Neumann [3], by (closed) subspaces of the quantum Hilbert space, or the corresponding projectors. A collection of projectors summing to the identity operator (a decomposition of the identity) corresponds to a set of mutually exclusive quantum properties, one and only one of which obtains in a particular situation, thus a sample space in the language of probability theory. Projectors can be used to represent macroscopic properties of a measurement apparatus as well as the microscopic properties of the particles that it measures. Thus by selecting a suitable collection of macroscopic quantum properties (pointer positions) and applying the Born rule one disposes of the first measurement problem without any need to invoke hidden variables.

At the same time this gets rid of one of the conceptual difficulties mentioned by Leifer: wave function collapse. If one is using the wave function to calculate probabilities (in my terminology, Ch. 9 of [4] a "pre-probability") there is no similar difficulty: the probability about what is happening at some distant location can change instantly when it is conditioned on something nearby, and no magic is needed to account for this. Thus the Schrödinger wave function regarded as pre-probability forms a plausible part of an epistemic approach to quantum interpretation.

But what about ontic or realistic interpretations of quantum mechanics? This leads to the second measurement problem: how are the pointer positions related to some property the measured system had *before* the measurement took place? Its solution is fundamentally the same as the first. In an apparatus constructed by a competent experimentalist the pointer positions (macroscopic quantum subspaces) are designed to be correlated with properties (microscopic quantum subspaces) possessed by the measured system, typically some particle, just before the measurement. The careful experimentalist checks the apparatus by sending in particles which he has prepared with one of the to-be-measured properties and checking that the pointer later points in the right direction. The appropriate theory is Hilbert space quantum mechanics. By contrast the dBB hidden variable approach can yield what (most) quantum physicists would regard as the wrong answer: under some circumstances a detector constructed to detect a particle passing through it can be triggered by one passing some distance away (see [5] for references). And suppose the experimentalist prepares a particle in a superposition of states corresponding to different measurement outcomes. Treat this quantum superposition as a pre-probability that assigns probabilities to the different physical properties that the apparatus was designed to measure. Given a competently constructed apparatus, the probabilities of these different properties of the particle that is about to be measured will be reflected in the probabilities of the later measurement outcomes.

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What happens to quantum weirdness when Hilbert space properties are employed and hidden variables excluded? Some of it simply goes away. Instantaneous action at a distance disappears when quantum mechanics is applied in a consistent way, using probabilities, to the measuring apparatus as well as the particles. Objective properties of an isolated individual system do not change when something is done to another noninteracting system. That is a result based on an analysis using Hilbert space quantum mechanics [6], and, not surprisingly, it contradicts the Bell inequalities, which are based on (classical) hidden variables.

The weirdness that remains in the Hilbert space approach arises from the non-commutation of operators, the main point at which it differs from classical physics. Two quantum properties are said to be incompatible if the projector representing one of them does not commute with the projector representing the other, and one cannot ascribe both to the same system at the same time. For example the properties $S_z = +1/2$ and $S_x = +1/2$ for a spin half particle. Textbooks tell us that one cannot measure both S_x and S_z simultaneously on the same particle, and they are correct. What they ought to (but unfortunately fail to) say is that this is so because there is nothing there to be measured. There is no room in the Hilbert space for the conjunction of these two properties, and even the best experimentalist cannot measure what is not there!

One of the motivations for looking for hidden variable theories seems, to me, to be the desire to somehow escape the weirdness of non-commutation. Thus far there is little if anything positive to show for all the effort expended in this direction. One can applaud PBR's driving another nail into the hidden variables coffin, and Leifer's interesting exposition [7] of their ideas. But rather than all the discussion about what is wrong with hidden variables, wouldn't the time be better spent on something known to work and amply confirmed by experiment: Hilbert space quantum mechanics?

The reader who is skeptical that the quantum Hilbert space can be used in a consistent way to obtain the results mentioned above may wish to look at some of the following [4, 8, 9], listed in order of increasing brevity.

***Robert Griffiths** is the Otto Stern University Professor of Physics at Carnegie Mellon University and the originator of the consistent histories approach to quantum mechanics. He is a fellow of the APS and a past winner of the APS' Dannie Heineman Prize for Mathematical Physics.*

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Correction

In the announcement of new APS GQI fellows in the previous issue (Vol. 6, No. 3), the citation for Paolo Zanardi was incorrect. The correct citation reads "For his profound theoretical contributions at the interface of quantum information processing and condensed matter physics, in particular his pioneering work on noiseless subspaces, holonomic quantum computation, and the fidelity approach to quantum phase transitions."

Response to Griffiths

Matt Leifer

First of all, I would like to thank Prof. Griffith for his comments. The exchange has reminded me of the series of letters that appeared in *Physics Today* following the publication of an article by Chandralekha Singh, Mario Belloni, and Wolfgang Christian on improving the teaching of undergraduate quantum mechanics (see http://ptonline.aip.org/journals/doc/PHTOAD-ft/vol_60/iss_3/8_1.shtml). In those responses, both Griffiths and Travis Norsen argued that students' understanding of quantum mechanics would be vastly improved if they were taught more about the foundations of quantum theory, and I wholeheartedly agree with that sentiment. The thing is, Griffiths argued vociferously that this should be done by teaching students according to *his* approach, as outlined in his textbook *Consistent Quantum Theory*, whilst Norsen argued that it should be done by teaching students the de Broglie-Bohm theory, i.e. precisely the sort of theory that Griffiths argues strongly against in his response to my article.

I do not want to get into the arguments surrounding the various interpretations of quantum theory here, but only wish to point out that, for every physicist who advocates one particular view, one can find a number of physicists arguing the opposite. By any measure, the foundational problems with quantum theory should be considered unresolved to the satisfaction of the physics community as a whole. In light of this, I think that it is valuable to explore the whole space of possible interpretations, and to rule out possibilities via rigorous theorems, such as the PBR theorem, rather than by more contentious types of argument.

In general, I believe that the most sensible approach to both teaching and research in the foundations of quantum theory is to pay attention to the insights and intuitions that come from all currently viable approaches. This is not to say that I am a pluralist about the interpretation of quantum theory. I think there will ultimately be one true way of understanding the theory and think that the division of the theory into its "practical" part and its "interpretation" is a mistake. Nevertheless, until we finally manage to achieve this understanding, we would be wise to keep our minds open, so long as they are not so open that our brains fall out.

Different interpretations quantum theory provide different insights, which are valuable even if the interpretations themselves turn out to be false. For example, the many-worlds interpretation was a key inspiration for the idea of a quantum computer, as proposed by David Deutsch, even though the idea itself does not require that interpretation. Similarly, the tension between de Broglie-Bohm theory and von Neumann's no-go theorem for hidden variables was the main driving force behind Bell's development of his eponymous inequalities. If you like, you can interpret those inequalities in terms of the ability of Alice and Bob to perform better in certain cooperative games using quantum resources than they could with classical resources without ever mentioning hidden variables, as many quantum information theorists are wont to do. However, it is unlikely that Bell's theorem would ever have been discovered were it not for the foundational context in which it first arose.

What I was trying to argue in my article, is that the PBR theorem might have a similar status. Whilst it is inspired by the question of the status of the quantum state in a hidden variable theory, it may end up telling us something new about the differences between quantum and classical resources in general. We will never gain these new insights if we close off avenues for understanding quantum theory, even if we regard the foundational programs that they are associated with as unlikely to succeed in the long run.

***Matt Leifer** is a postdoc at University College London. He obtained his Ph.D. in quantum information from the University of Bristol in 2004, and has since worked at the Perimeter Institute, the University of Waterloo, and the University of Cambridge. His research is focused on problems at the intersection of quantum foundations and quantum information. See http://mattleifer.info for more details.*

Bits, BYTES, *and Qubits*

QUANTUM NEWS & NOTES

A new method for focusing light

A group at the Max Planck for the Science of Light in Erlangen, Germany led by PhD student Anna Butsch have developed a new theoretical method for focusing light using radiation pressure. Butsch's team examined the behavior of light moving through two strips of glass placed 300 nm apart and fixed at their ends. While the light was focused along the strips, the electromagnetic field "leaked" into the region between them, exerting a small force that either drew them together or pushed them apart. While the effect was quite small - only one or two nanometers of displacement - it was enough to affect the propagation of the light in the strips themselves by varying the effective refractive index across the width of each strip. This, then, focused the light into one or more narrow "tracks."

–ITD

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Contributions

Contributions from readers for any and all portions of the newsletter are welcome and encouraged. We are particularly keen to receive

- **op-ed pieces and letters** (the APS is *strongly* encouraging inclusion of such items in unit newsletters)
- **books reviews**
- **review articles**
- **articles describing individual research** that are aimed at a broad audience
- **humor** of a nature appropriate for this publication

Submissions are accepted at any time. They must be in electronic format and may be sent to the editor at idurham@anselm.edu. Acceptable forms for electronic files (other than images) include LaTeX, Word, Pages (iWork), RTF, PDF, and plain text.

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All opinions expressed in *The Quantum Times* are those of the individual authors and do not represent those of the Topical Group on Quantum Information or the American Physical Society in general.

2012 MICHIGAN QUANTUM SUMMER SCHOOL


Michigan summer school days in Ann Arbor

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Registration website:
http://www.umich.edu/~mctp/SciPrgPgs/events/2012/MQSS12/reg.html
Registration deadline: April 16th, 2012

The University of Michigan played an important role in the development of quantum physics by hosting the famous Michigan Summer Schools, which ran from 1928-1942 and featured distinguished guest lecturers including Bohr,Dirac, Fermi, Heisenberg, and Pauli. In recognition of the role of the Michigan Summer Schools, the American Physical Society recently commemorated U-M's Randall Laboratory as a historic site.

In the spirit of the historical Michigan Summer Schools, we continue this tradition with a series of lectures by world leaders in the areas of quantum information and precision measurements which are aimed at graduate students and others that have been exposed to quantum physics at an introductory level. These lectures are intended to introduce students and postdocs getting started in the field of Atomic, Molecular, and Optical (AMO) physics to the foundations of quantum mechanics as related to current frontier research. Short contributed talks by selected participants and poster sessions will be organized for communication on more specific topics in this field. In order to encourage student participation, there is no registration fee and lodging in shared dorm rooms will be provided for accepted applicants. The school will enjoy a relaxed environment in the dynamic college town of Ann Arbor, with great opportunities for interaction between students and lecturers.

For more information, please check the website:
http://www.umich.edu/~mctp/SciPrgPgs/events/2012/MQSS12/index.html

清華大學
Tsinghua University

Event and position announcement

Event: Reception at the 2012 DAMOP meeting by the Center for Quantum Information, Tsinghua University

Time: 6:00 - 9:00 PM, Wednesday, June 6, 2012
Place: Hyatt Regency Orange County, Anaheim, California
Website for registration: http://openings.iiis.tsinghua.edu.cn/DAMOP2012/

Details: The Center for Quantum Information (CQI) of Tsinghua University (http://iiis.tsinghua.edu.cn/en/) is led by the famous computer scientist and the Turing Award laureate, Prof. Andrew Chi-Chih Yao, with the aim to build a world-class research center for Quantum Information Science defined in the broad sense. The CQI adopts the management method of top western institutions and provides excellent support for young researchers.

The CQI and IIIS currently invite applications for Tenure-Track and Research Faculty positions. The interested areas include but are not limited to Quantum Computation, Communication, Network, Cryptography, Quantum Simulation, Metrology, Many-body Physics, Modeling of Complex Systems, Econophysics, Financial Engineering, etc. People with related backgrounds are strongly encouraged to apply. Experimentalists are particularly welcome.

The remuneration package will be very attractive, driven by the market competiveness and the individual qualification. The CQI will support the qualified applicants to apply for the Chinese National Recruitment program the "Youth 1000-Talents" fellowship. Interested applicants should send a detailed curriculum vita with a publication list, a teaching and research statement, names and contact addresses of 3 to 5 people who can provide reference letters, by email to the following address: iiisquantum@mail.tsinghua.edu.cn.

The CQI will host a reception at the 2012 DAMOP meeting to introduce the Institute and its recruitment plan. Dinner will be provided at the reception. Candidates interested in the faculty positions at the CQI will be interviewed during the DAMOP meeting.