THE QUANTUM TIMES

APS TOPICAL GROUP ON QUANTUM INFORMATION, CONCEPTS, AND COMPUTATION

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Quantum Information and Quantum Foundations

I sense a new interest in quantum foundations among people working in quantum information. There are at least two motives for this. First is the recognition that the ideas one finds in the standard textbooks are not quite what we need for quantum information. Understanding the time development of systems that are constantly interacting with experimental probes and the environment requires more than cross sections and perturbation theory. Second is the desire to use quantum information theory to tackle and, hopefully, resolve the well-known conceptual difficulties of Copenhagen – I use it as a convenient albeit inaccurate abbreviation for what one finds in current textbooks – quantum mechanics.

I think both motives are valid. But I also worry that instead of cleaning up the conceptual mess of quantum foundations, we may simply end up by importing it into quantum information, building a new structure on top of old, flawed ideas, and confusing not only ourselves but also the computer scientists, electrical engineers, mathematicians, and others now interested in our discipline. I already see signs that this is going on, and I am concerned.

As someone who has worked for many years in quantum foundations, let me admit that the field deserves some of the bad reputation it has acquired in the broader physics community. There has been lots of work but not all that much progress in resolving the central issues, most of which date back to the good old days of the 1920s or 30s. Disagreement is more common than agreement among the practitioners. Sometimes it seems more like academic philosophy – where some critics think we belong – than like physics. Despite this I believe there are useful lessons to be learned from previous work in quantum foundations. Even the failures can teach us something, and there have been some interesting ideas that are worth further development. Perhaps the first and most obvious lesson is that the foundational problems are not trivial. Do not let the failures of Einstein, Feynman, Schrödinger and Wigner discourage you from attempting your own attack on these matters, but do expect to have to give them sustained, serious thought.

One of the few points of widespread agreement in quantum foundations is that *measurement*, despite its presence in every textbook, is a most unsatisfactory foundation for interpreting quantum mechanics. Everyone thinks the Copenhagen approach results in a nasty unsolved “measurement problem," even if there is little agreement on what to do about it. No doubt the textbook approach assigns correct probabilities to measurement *outcomes* (the “pointer positions" in the archaic terminology of a discipline that predates the computer age). But what does the pointer

(continued on next page)

Changes afoot…

There are a few subtle (and perhaps a few not-so-subtle) changes that mark their appearance with this issue. The first and hopefully most aesthetically obvious is that I have endeavored to make some changes to fonts for headings and in the masthead. My hope is that it not only looks more professional but is a bit easier on the eyes.

Another change that should be fairly obvious from the start is that we have essentially settled into a quarterly schedule here at *The Times*, and thus have opted to drop the specific month in favor of the ‘season.’ As such, this is the Spring 2007 issue (my apologies to readers from the Southern Hemisphere – I had to draw the line somewhere and the equator seemed a good place to do it). Very roughly we expect to put out an issue toward the end of each ‘season’ which is really no different than we’ve been doing: May, July or August, November, and February.

You will notice that once again we have a section for letters. I am hoping that each issue contains a robust letters section so please write to me (e-mail is preferred). Specific information on submissions can be found on the last page of the newsletter. In addition, a section of short news items makes a permanent return (well, at least until we change our minds).

-Ian T. Durham, Editor
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position tell us about the microscopic system that was (supposedly) being measured? I call this the first measurement problem, and will return to it later. The second measurement problem has to do with finding a fully *quantum mechanical* description of a real measurement process carried out in the laboratory using equipment made of atoms that (presumably) follow quantum laws. There are compelling arguments that a consistent quantum description of real measurements is impossible within the Copenhagen framework of wavefunction collapse [1]. Yes, POVMs have been considered, and no, they do not help. To my mind the failure to solve the second problem is particularly serious, as it indicates a basic inconsistency in the textbook approach. The hope that things can somehow be salvaged using a genuinely classical apparatus fades with each advance in creating more and more exotic entangled states in the laboratory. So I ask – and it is a serious question – do we really want to construct the edifice of quantum information theory with *measurement* as one of the axioms? And if not, what are the alternatives?

There is at least one idea coming out of quantum information theory that I think could be helpful in quantum foundations: the notion that a wavefunction can represent information, rather than physical reality [2]. While this does not by itself solve the measurement problem, it could be helpful in disposing of a somewhat different conceptual mess: the nonlocality ghost. It is widely believed that when Alice makes a measurement over here on her half of an entangled state there is an instantaneous, superluminal, nonlocal influence that somehow changes Bob's half, no matter how far away. There are theorems showing that the nonlocality ghost cannot transmit information, which is to say that it can never manifest itself in experiments. The only thing it is capable of doing is causing confusion, and for this reason it needs to be permanently laid to rest, especially as it has given rise to the notion that quantum mechanics is incompatible with special relativity.

Can we deal with this problem using the notion of wavefunction-as-information? I think so. To see how, consider the classical analog in which Charlie places a red slip of paper in one opaque envelope, a green slip in another, and after mixing them up mails one envelope to Alice in Atlanta and the other to Bob in Boston. If Alice opens her envelope and sees a red slip she can instantly conclude, as she knows the protocol, that the slip in Bob's envelope is green, independent of whether he has opened or ever will open his envelope. No nonlocal influences are needed. It is simply a matter of statistical correlation, and obviously does not conflict with relativity.

The quantum case can be worked out in a similar way. Alice and Bob share an entangled singlet state $|\psi_0\rangle = (|00\rangle - |11\rangle)/\sqrt{2}$ of two spin-half particles (qubits). Alice measures S_z for her particle, and if the pointer points up, concludes that S_z was +1/2, corresponding to the state $|0\rangle$ just before the measurement took place. From this and the information provided by $|\psi_0\rangle$ she can infer that $S_z = -1/2$ for Bob's particle. This is a correct inference whether or not Bob carries out a measurement on his particle, as long as he does nothing to perturb its spin. If we understand the wavefunction as somehow representing *information*, there is no danger of falling into the nonlocality trap and supposing that Alice's measurement has an instantaneous influence on Bob's particle. Instead, her measurement provides her with information about the state of her particle before the measurement, and hence with information about the correlated state of Bob's particle. In this respect the quantum case is no different from its classical analog. But in what sense does $|\psi_0\rangle$ represent *information*? I use the term *pre-probability* in Sec. 9.4 of my book [3] (hereafter referred to as CQT). That is, $|\psi_0\rangle$, while not itself a probability, can be used to calculate probabilities, in particular the joint probability distribution of S_z values for Alice's and for Bob's particles, respectively. This is the counterpart of the joint probability for colors of the two slips of paper used in the classical analog discussed above. Thus information, in the broad sense of statistical correlation, is playing a similar role in both cases.

In the background I hear someone shouting, "How dare you claim that Alice's measurement revealed the value S_z had *before* the measurement was made. That just isn't good quantum mechanics!" Well, it certainly is not good Copenhagen (i.e., textbook) quantum mechanics, which is indeed very difficult to merge with a notion of the wavefunction as information. But it is good physics if we assume that Alice is a competent experimentalist who knows how to construct a piece of apparatus which will measure the *z* component of angular momentum of a particle. Do you think those folks are crazy who take results of their particle detectors and extrapolate the tracks backwards to a point where – so they claim – a collision occurred between an electron and a positron? Let me suggest, at the risk of losing some friends, that the problem is not with the way experimentalists think about real measurements. What is wrong is a textbook approach that invokes measurements, but then cannot tell you the connection between the outcome and the measured property.

If we can talk (in consistent quantum terms) about the S_z that Alice's apparatus has just measured, we are equally free to talk about *z* for Bob's particle before he measures it, or whether or not he measures it. It is important to notice that $|\psi_0\rangle$ provides information (in terms of probabilities) about Bob's particle, and only indirectly about the outcome of some future measurement. A wavefunction provides information about what it is about, not about what it is *not* about. If you want to discuss in quantum terms the outcome of a future measurement, the discussion should include the wavefunction describing the apparatus. This can be done; see Chs. 17 and 18 of CQT for a consistent analysis in fully quantum terms of how a (properly constructed) quantum apparatus functions the way experimentalists think it should. If Bob is a good experimentalist using the right equipment, he will learn from looking at the pointer the value of S_z for his particle before the measurement took place, something Alice already knows if she has measured her particle. What if Alice decides to measure S_x instead of S_z? In this case the same pre-probability $|\psi_0\rangle$ can be used to calculate a new set of probabilities in the same fashion as before. See Chs. 23 and 24 of CQT for details and an explicit demonstration that neither the choice nor the outcome of Alice's measurement has the slightest effect upon Bob's particle. This yields a very short proof that the nonlocality ghost cannot transmit information: it does not exist.

Why don't textbooks talk about properties of quantum systems? Why introduce measurements, which our students immediately (and correctly) recognize as a very odd way to do physics? The same reason your parents insisted you be home by nine in the evening: to keep you out of trouble. Quantum foundations research has uncovered all sorts of dangerous logical paradoxes hiding like alligators in the conceptual swamp underneath the Copenhagen interpretation of quantum theory. To avoid falling prey to them, stay safely on the classical, macroscopic side of the measurement process: look at the pointer, and don't ask what it means.

Logical paradoxes arise through faulty reasoning, and they are easily avoided by not reasoning: Shut up and calculate! A better approach is to replace faulty reasoning with sound reasoning. But what constitutes sound quantum reasoning? Here quantum foundations provides a useful idea. In 1936 Birkhoff and von Neumann [4] proposed that quantum reasoning would work better by modifying the rules of propositional logic. Now some folks treat any suggestion that rules of logic be changed as a frontal assault on Rational Thought, a grave threat to all of Western Civilization. If you feel that way, I suggest you take a look at this paper, written by two of the great mathematicians of the 20th century. Reading it is not easy, but getting the general drift is not difficult. Irrational it surely is not. While the Birkhoff and von Neumann proposal has not (yet) caused the collapse of Western Civilization, it has also not (yet) solved the conceptual difficulties of quantum mechanics, despite a lot of effort in the quantum foundations community. This failure may simply reflect the fact that we physicists are not smart enough to make full use of radical new ideas. Perhaps in a few decades the artificial intelligence of robots, which some of my colleagues assure me will soon exceed that of human beings, can do a better job. (And if that doesn't suffice, how about artificial *quantum* intelligence?)

In the meantime it is worth considering a much less radical proposal by Omnès and me (see CQT) which allows one to talk in a consistent way about at least some aspects of the microscopic quantum world without falling into paradoxes. The basic idea is quite simple. Consider a spin-half particle whose properties, such as $S_z = +1/2$ or $S_x = +1/2$, correspond to one-dimensional subspaces or rays in the two-dimensional Hilbert space; each ray corresponds to a point on the surface of the familiar Bloch sphere. In classical physics whenever *A* and *B* are two properties of some physical system, the conjunction *A* AND *B* makes sense, though it may be something that is never true; e.g., *A* = "energy less than 5 J" and *B* = "energy more than 10 J." But consider the quantum conjunction

$$S_x = +1/2 \text{ AND } S_z = +1/2 \qquad (1)$$

What does it mean? It surely cannot correspond to some property of the particle, for every property is associated with a ray, and every ray (every point on the Bloch sphere) has the meaning $S_w = +1/2$ for some direction *w* in space, so there is none left over to represent (1). If, on the other hand, you assume that (1) is always false (so its negation is always true) you will soon be in logical difficulties (Sec. 4 of CQT) if you follow the usual rules – this is what Birkhoff and von Neumann were concerned about. For these reasons, among others, Omnès and I consider (1) to be *meaningless*, in the precise sense that Hilbert space quantum mechanics assigns it no meaning. The rules of sound quantum reasoning, according to us, require the use of meaningful statements, which means, in particular, avoiding combinations, made using AND or OR, of *incompatible* propositions, those for which the corresponding operators do not commute. This is an example of what we call the *single framework* rule. In some sense it is just the logical counterpart of the well-known result in quantum theory that when A and B are operators representing physical quantities, the same is not true of AB unless it is equal to BA.

Though the single framework rule seems restrictive, it is much less so than Copenhagen. We can talk about what a measurement measures, i.e., what the pointer position is telling us. Wavefunctions can provide information about microscopic quantum properties, not just about outcomes of future measurements. On the other hand, the single framework restrictions are very effective in getting rid of the alligators. They quickly starve when you stop feeding them meaningless quantum nonsense. A number of paradoxes are studied in Chs. 19 to 25 of CQT, and in every case the supposed inconsistency arises from some violation of the single framework rule, i.e., from faulty quantum reasoning.

To summarize, I think quantum information will advance more rapidly with fewer difficulties, and be much more accessible to people coming to the subject from outside physics, if we replace the internally inconsistent and confusing measurement framework of current quantum textbooks with something better. A more extensive discussion of what I think is better will be found in [5]. If you can do even better than that, so much the better. I would be delighted to see courses in standard quantum mechanics taught from an information theory perspective provided measurements are put in their proper place: processes to which the same quantum laws apply as to everything else, and not unanalyzable axioms as in the Copenhagen tradition. Finally, the wavefunction as information is a good idea if we make it clear that it provides information about whatever the wavefunction is about, not (primarily, at least) about the outcomes of a future measurement that may or may not take place.

–Robert B. Griffiths
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References

[1] The essential difficulties are discussed in E.P. Wigner, Am. J. Phys. **31**, 6 (1963). For a thorough analysis, see P. Mittelstaedt, *The Interpretation of Quantum Mechanics and the Measurement Process* (Cambridge University Press, Cambridge, 1998).

[2] C.M. Caves, C.A. Fuchs and R. Schack, J. Math. Phys. **43**, 4537-4559 (2002); quant-ph/0104088.

[3] (CQT) R.B. Griffiths, *Consistent Quantum Theory* (Cambridge University Press, 2002) and http://quantum.phys.cmu.edu.

[4] G. Birkhoff and J. von Neumann, Annals of Math. **37**, 823 (1936); *John von Neumann Collected Works*, edited by A. H. Taub (Macmillan, New York, 1962), Vol. IV, p. 105.

[5] R.B. Griffiths, “Quantum Mechanics Without Measurements,” quant-ph/0612065.

Bits, Bytes, & Qubits

QUANTUM NEWS AND NOTES

$|0\rangle$ **Theodore Harold “Ted” Maiman, 1927 – 2007.** As we began assembling this issue of *The Quantum Times*, word came that Ted Maiman, creator of the world’s first working laser, passed away on May 5 at his home in Vancouver, British Columbia from complications due to cancer. A native of Los Angeles, he received his undergraduate degree from the University of Colorado in 1949 before moving on to Stanford where he received his master’s in 1951 and his doctorate in 1955. Ted then moved on to Hughes Research Laboratories (now HRL – see page 9) where a laser he built, based on a synthetic ruby crystal that was grown by Ralph Hutcheson, first became operational on May 16, 1960. This capped nearly a decade of work by the likes of Willis Lamb, Alfred Kastler, Charles Townes, Arthur Schawlow, and Gordon Gould, who first coined the acronym LASER (Light Amplification by Stimulated Emission of Radiation) in a conference paper in 1959. Gould also fought a protracted legal battle with Maiman, Hughes, Bell Labs, and the US Patent and Trade Office that lasted into the 1980s. Maiman left

Hughes soon after building his laser to work at Quantatron, whose laser assets were purchased in 1962 by Union Carbide in order to form the Korad corporation with Maiman as head. Selling his stake in Korad to Union Carbide in 1968, Maiman founded his own company. He was twice nominated for the Nobel Prize in Physics for his work on the laser, won the Wolf Prize in Physics in 1983, was awarded the APS' Oliver E. Buckley Prize in condensed matter physics in 1966, received the 1987 Japan Prize, and was a member of both the National Academy of Sciences and the National Academy of Engineering. Look for a short history of the now ubiquitous and indispensable laser to appear in the next issue of *The Quantum Times*.

$\langle 1|0\rangle$ **John Backus, 1925-2007**. Who among us over the age of 30 (maybe even younger?), whether engineer, physicist, or mathematician (and most *certainly* computer scientist), hasn't been exposed to Fortran at some point in our careers? Sadly, the man who developed the formerly ubiquitous programming language passed away in March at the age of 82 at his home in Oregon. In its obituary in March, *The New York Times* referred to Fortran as "the first successful higher-level language." Despite flunking out of the University of Virginia and then being drafted in 1943, Backus went on to earn a master's degree in mathematics at Columbia in 1950 (thanks in part to high scores on his Army aptitude tests). It was in New York that he landed a job at IBM when he wandered into corporate headquarters and a tour guide asked him what he was studying. In addition to Fortran, Backus co-developed with Peter Naur a notation for describing the structure of programming languages, somewhat akin to grammar for spoken languages.

$\langle 1|0\rangle$ **Loophole closed.** Toshiba announced in late February that they were able to close a loophole in practical quantum key distribution (QKD) systems. Previously, the weak laser diode that was used to create the photons used to distribute the keys would sometimes produce pulses that contained multiple photons, making it possible for an eavesdropper to siphon off one of these extra photons, thereby obtaining at least a portion of the key. While guaranteeing single photon pulses is not feasible, fooling the eavesdropper is, and this is what the new Toshiba system does. In essence it produces weaker decoy pulses that enables the transmitter (Alice) to detect the siphoning by the eavesdropper (Eve). This is because the decoy pulses are weaker on average and thus will rarely contain two or more photons. Toshiba has reportedly demonstrated a one-hundred-fold increase in the rate at which keys could be securely transmitted over a 25 km-long fiber to 5.5 kbits/sec. The work was actually part of an EU initiative to build a secure communication network based on QKD.

$\langle 1|0\rangle$ **Call for nominations.** The 2007 Quantum Information Processing and Communication (QIPC) Young Investigator's Award, sponsored by Qurope (QIPC in Europe), is accepting nominations. The award will be presented to an outstanding young researcher in the field during the QIPC conference, in Barcelona, in October 2007. The award consists of a diploma and a lump sum of 3000€. Eligible researchers must be less than 35 years old on the 1st of October 2007. Nominations, including self-nominations, should be submitted to L. Theussl (theussl@nbi.dk), the QUROPE Administrative Officer, by 31 July 2007. The nominations should include a short CV of the candidate, a letter containing a one page summary of the candidate's achievements, a list of key publications, and at least two letters of endorsement. The letter should be prepared in pdf-format. Candidates are encouraged to also submit an oral presentation at the QIPC conference in Barcelona in autumn 2007. Additional information can be found on the Qurope website at http://www.qurope.net.

$\langle 1|0\rangle$ **Deutsch's algorithm via cluster states.** A joint project of Queen's University in Belfast and the University of Vienna has successfully created a quantum computer using highly entangled multi-partite quantum states known as cluster states which is more practical and efficient than the standard logic-gate approach that is similar to classical computing networks. Deutsch's algorithm is a specific case of the more general Deutsch-Josza algorithm used to solve what is known as Deutsch's problem which very roughly involves querying a register about the result of some calculated function.

$\langle 1|0 \rangle$ **2007 Gödel Prize recipients announced.** The 2007 Gödel Prize, awarded for "outstanding journal articles in theoretical computer science" by the European Association for Theoretical Computer Science (EATCS), has been awarded to Alexander A. Razborov and Steven Rudich for their paper entitled "Natural Proofs," that appeared in the *Journal of Computer and System Sciences* in 1997 and was first presented in 1994 at the Twenty-sixth Annual ACM Symposium on Theory of Computing in Montréal. In short, their paper provides fairly strong evidence that no *natural proof* exists that separates P and NP computing problems since, if such a proof *did* exist, it would violate the conjecture that pseudorandom number generators exist. Briefly, P and NP refer to computing problems that can be solved quickly on a classical computer (P problems) and problems whose solutions can be quickly *checked* on a classical computer (NP problems). One of the most important unresolved questions in theoretical computer science is whether P and NP are identical or not. More information on the award and the winning paper can be found on the EATCS website at http://www.eatcs.org. A brief but accessible discussion of the role quantum computing may play in these sorts of problems can be found on pages 40-42 of *Quantum Computation and Quantum Information* by Michael A. Nielsen and Isaac L. Chuang (a book I am sure most readers are well-acquainted with).

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THE LIGHTER SIDE

My kids in APS shirts – oh, if you only knew…

Conference Announcement

QUANTUM ERROR CORRECTION

Quantum error correction of decoherence and faulty control operations forms the backbone of all of quantum information processing. In spite of remarkable progress on this front ever since the discovery of quantum error correcting codes a decade ago, there remain important open problems in both theory and applications to real physical systems. In short, a theory of quantum error correction that is at the same time comprehensive and realistically applicable has not yet been discovered and thus remains a very active area of research.

The First International Conference on Quantum Error Correction, hosted by the USC Center for Quantum Information Science & Technology (CQIST) and organized by Daniel Lidar (Chair), Todd Brun, and Paolo Zanardi, will bring together a wide group of experts to discuss all aspects of decoherence control and fault tolerance. At this point in time the subject is mostly theoretical, but the conference will include talks surveying the latest experimental progress, and will seek to promote an interaction between theoreticians and experimentalists.

A list of many of the topics that will be considered can be found on the conference website, http://qserver.usc.edu/qec07/, that also contains full details of the conference itself. In brief, the conference will take place during the week of Dec. 17, 2007. It will start with a series of tutorial lectures by Dave Bacon (Washington), Daniel Gottesman (Perimeter Institute), Raymond Laflamme (Waterloo), and Lorenza Viola (Dartmouth). It will feature keynote talks by David Cory (MIT), John Preskill (CalTech), Peter Shor (MIT), and David Wineland (NIST).

Registration is now open and the number of spots is limited, so hurry!

–Daniel Lidar
Departments of Electrical Engineering and Chemistry
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Editorial Entropy

RANDOM THOUGHTS & UPDATES

From the classroom to Denver and back

In our last issue I wrote an editorial that touched on some pedagogical issues and noted that I was teaching a course in quantum mechanics this semester. The course caused me to think extensively not just about *how* best to teach it but *what* to teach since it has been my opinion since graduate school that the "old" way of teaching (including some of the topics) was outdated. Luckily this first batch of students were receptive and flexible, helping me feel out a more modern approach appropriate for undergraduates.

I had numerous conversations at the March Meeting in Denver about these and related issues that were both useful and enlightening, and I intend to continue to facilitate such discussions, hopefully leading to some concrete accomplishments potentially including web-based resources for teachers of quantum mechanics. I will include a more detailed update in a future issue, but other ideas being pursued include a workshop or conference dedicated to discussing these issues (an idea that first surfaced during my interview of Bill Wootters last summer for *The Times*) and, potentially by spring of 2009 (and despite the fact that some of my colleagues disagree with me on the need for this), a new textbook that transforms the actual *pedagogy* while being open-ended enough to suit a variety of teaching styles, topics, etc.

Hey, I needed to put *something* here…

In the November 2006 issue, in a rather silly article, I noted that my father – a retired high school English teacher – might qualify as having an Erdös-Bacon number. My father's Erdös number was never in question (see the November issue), but since Bacon numbers require acting in a *film* and not onstage, there was some question. But, apparently, he really did appear in an independent (though never-released) film with his former student David Moreland (who was in *Donnie Darko* among other things) and so his Erdös-Bacon number is at *least* as legitimate as Hank Aaron's (the Erdös portion of which was "earned" by signing the same baseball as Erdös).

Quantum Communication

LETTERS TO THE EDITOR

Further comments on our name

As one of the original organizers of GQI, I think it would be a big mistake to change the name so as to only include quantum information. When we sent around the petition for people to sign, we advertised ourselves as an inclusive organization, for people working on all fundamental aspects of quantum mechanics, since there was no place else in the APS for such people to go. There are people in the group who are working on all sorts of fascinating topics that basically have nothing to do with information. For example, there are many people working on the various interpretations of the theory, on using down conversion to perform experiments on the uncertainty principle, teleportation, entanglement swapping, the AB effect, etc. There are people interested in entanglement as such, such as Werner and GHZ states, entropy of entanglement, purity of entanglement, and entanglement as a resource exclusive of its use as an information resource. There are experiments in mesoscopic physics, such as the diffraction of large molecules. There are all kinds of questions in BEC and gravity that impinge on quantum concepts. And of course there are people who work on all aspects of Bell-type theorems.

In short, quantum information is just one facet of a very big field, and to consider it as our only source of strength is sort of like the tail wagging the dog. Right now it is a very hot topic. and lots of people are working in it. But it has also led to new ways to analyze quantum theory and it may very well lead to new insights that have little relevance to information as such, as we perceive it today. Personally, I would like to see more people enter the group, so that someday we might even aim for divisional status. That way we can raise much more money for our own awards, and recommend more of our own people for APS fellowships, and have more influence in the physics community, etc. It makes no sense to drive people out of the group because they perceive us as not being relevant to their research. It is also a breach of trust to the people who originally signed the petition.

I think we should bury the issue. It isn't even fruitful to talk about it. It's only divisive.

Sincerely,

Dan Greenberger, CCNY
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Back to Baltimore

QUANTUM-RELATED ACRONYMS GATHER

CLEO, QELS, and PhAST meeting report

The joint CLEO, QELS, and PhAST conferences were held 6-11 May 2007 in Baltimore, Maryland. Conference-goers were favored by warm, sunny weather all week, allowing pleasant reprieves from the over-air-conditioned Baltimore Convention Center when a few moments could be spared between talks.

This year's Quantum Electronics and Laser Science (QELS) conference offered up an astounding array of experimental and theoretical topics, ranging from new technologies based on quantum devices to deeper conceptual issues in quantum information theory. Faced with the impossible task of giving a comprehensive description of the many talks presented, I will instead provide a "sample platter" based on my own interests. In no way should this be construed as an endorsement for the talks I have included – or, more importantly, as a judgment against those I have omitted – rather, the selection process may be considered representative only of my own capricious nature. [*Editor's note*: Capricious nature of author not verified.] For more detailed information, visit the conference website at http://www.cleoconference.org.

Jeff Kimble (CalTech) kicked off Monday's Cavity QED sessions by conjecturing on the use of quantum networks to distribute specially prepared quantum states, and the eventual realization of a "quantum software" industry. In his hour-long tutorial, he provided an extensive overview of recent advances in quantum network technologies, from measurement-induced entanglement to reversible state transfer between light and atoms. In the Integrated Nanophotonics session, Luke Bissell (Inst. of Optics) gave a fascinating description of a room-temperature single-photon source based on a quantum dot submerged in a liquid crystal. During Quantum Key Distribution, Hideo Kosaka (Tohoku/CREST-JST) discussed the demonstration of the coherent transfer of photonic qubits to an electron spin for use in semi-conductor quantum repeaters while Taehyun Kim (MIT) described the experimental realization of an entangling probe attack on the BB84 protocol. At Quantum Dots, Eric Gansen described the photon-number-resolving capabilities of a quantum dot photodetector.

In the evening, Alan Heeger (UCSB) gave a CLEO plenary speech on the use of Bucky Balls and semiconducting polymers in the production of cheap plastic solar cells. He illustrated the significance of this discovery by showing off a working prototype with roughly the thickness and flexibility of a sheet of glossy paper.

In Tuesday's sessions on Entanglement and Squeezing, Ben Brown (JQI/NIST) described an atom-interferometer based on number-squeezed states in an optical lattice. Dzmitry Matsukevich (Georgia Tech) outlined recent progress towards the realization of quantum repeaters based on quantum ensembles, and described the entanglement of atomic qubits separated by more than five meters. During the Cold Atoms session, Tanya Zelevinsky (JILA/Colorado) described experiments on coherent manipulation and precision measurement of ultracold atoms in optical lattices. Kurt Gibble (Penn State) asked what the difference between a photon's momentum and an atom's recoil should be, and surprised many members of the audience with the revelation that they are not the same! Interestingly enough, an atom absorbing a photon from a laser receives a smaller momentum kick than (naively) expected, due to the Gaussian profile of the beam.

Wednesday morning, CLEO plenary speaker William Phillips (JQI/NIST) provided a beautiful explanation of how photons can be made to carry orbital angular momentum, and provided several examples of the demonstration of this phenomenon in the lab. QELS plenary speaker Sir John Pendry (Imperial) gave the QELS plenary on the realization of negative-index metamaterials and recent experimental progress in the field.

During Wednesday's Symposium on Degenerate Fermi gases, Hrvoje Buljan (Zagreb) discussed experimental realizations of Bose gases confined to one dimension in the Tonks-Girardeau (i.e., "faux fermionic") regime, and recent advances in solving these systems numerically. Later, during the Entanglement session, Carlton Caves (New Mexico) described methods for reaching the Heisenberg measurement limit for different experimental setups, then provided a general proof of the limit, independent of the experimental realization.

Thursday was a busy day for quantum information. The Quantum Information session began with Patricia Lee (JQI/NIST) speaking on the experimental implementation of a square-root SWAP gate in a double-well optical lattice. This was followed by my own talk on a proposal to use a double well potential to prepare entangled atoms for use in a loophole-free Bell inequality test. Eugene Polzik (NBI/Copenhagen) spoke about experimentally teleporting the quantum state of a pulse of light onto that of an atomic ensemble at room temperature.

During Quantum Communication, David Fattal (HP Labs) spoke on a proposal to use a micropillar cavity coupled to a waveguide for a quantum repeater system with high operating efficiency, despite realistic imperfections. Christian Bonato (BU/Padova) discussed the use of Earth-to-satellite links for global quantum communication networks and considered compensation systems for imperfections in the satellite pointing mechanism. In Quantum Computing, Manny Knill (NIST) gave an overview of the status of quantum computing with special attention paid to tolerable error thresholds. He took a balanced position on the question of what an acceptable error threshold should be, warning against both overly optimistic and pessimistic predictions. Interestingly enough, he also expressed skepticism about verifications of two-qubit gates that rely on tomographies, claiming he wasn't satisfied that anyone had demonstrated a two-qubit gate yet! Julio Gea-Banacloche (Arkansas) gave an interesting talk on the limitations encountered when "recycling" the electromagnetic fields for quantum gates, explaining how error probabilities scale worse than one would superficially expect as the number of reuses increases.

Post-deadline QELS sessions ran Thursday evening from 8:00pm to 10:00pm, including such topics as high sensitivity magnetometry using an alkali vapour cell, a CNOT gate using linear optics in the telecom band, a fibre-based entangled photon source, and slow-to-fast light switching in a quantum well semiconductor, just to name a few.

Friday's session on the Dynamics of Dots, Wires and Tubes included interesting talks on spin relaxation times in dots by Evegy Zibik (Sheffield) and Yasuaka Masumoto (Tsukuba), as well an intriguing presentation by Dawei Wang (Queen's [Canada]) on the advantages of solving the semiconductor Bloch equations in the exciton basis. Shortly after, I was lured away to the session on Miscellaneous Nonlinear Optics for a talk by Bahram Jalali (UCLA) on "Energy Harvesting in Silicon Photonics," in which he described the use of nonlinear effects in silicon to obtain a two-photon photovoltaic effect. By this point, my brain was full and could fit no more, and so a very busy week of Quantum Electronics and Laser Science came to a close.

–Nathan Babcock
Institute for Quantum Information Science
University of Calgary

Quantum Mechanics in Denver

2007 APS March Meeting Visits Mile-High City

Stockyards, Steak, and Stuff

I'd been to Denver before but, oddly, never downtown. My impression – both first and last – was that it (and some of the nearby neighborhoods) reminded me quite a bit of the downtown and nearby areas of my hometown of Buffalo (minus the big lake). This is not necessarily a bad thing (before you inundate me with e-mails, you should know Buffalonians are a notoriously loyal breed that borders on the obsessive). In any case, it was a pleasant surprise in some senses including a distinct lack of the bland ubiquity that seems to define most places these days. It had a somewhat gritty feel to it and was less populated in the evenings than I expected. One might think that the smell of the stockyards wafting down 14th Street would entice me to order a non-meat product for dinner, but, alas, the bison meatloaf just looked too good to pass up.

Of course, none of this has anything to do with physics but part of the fun of any conference is spending a little time in the host city. Though there were no karaoke stories to tell as far as I know (see the November 2006 issue if you don't get the reference), the culinary aspects of the trip were generally excellent (with the exception of the meal that gave me food poisoning the night before I was to chair an 8 AM session). But there was hardly enough time to do much cavorting, with the various dinner meetings and receptions taking up most evenings (though I'm still kicking myself for not sending back that RSVP to the IOPP reception since they gave out nifty, programmable digital ID tags – my kids would have loved them).

Perhaps the most notable of these for a variety of reasons was the business meeting of the GQI, held on Tuesday evening (March 6). The evening included honoring GQI members recently elected as APS Fellows, financial and membership updates, continued discussion of the group name, and general merriment (including, of course, food and drink). Further discussions took place the following evening at the Executive Committee meeting where planning for next year's meeting in New Orleans already began.

Along those lines, GQI sponsors a full slate of sessions, sometimes even sponsoring more than one session during a single time-slot. It is a testament to the rapid growth of the group as well as the field as a whole. However, it makes it an even greater challenge to summarize each and every session. With the specter of simultaneous sessions an even greater possibility as the group grows, the need for multiple contributors becomes more pressing. This year the focus of these summaries is weighted heavily toward sessions I personally attended and took an interest in with the exception of one (many thanks to Sergio Boixo of the University of New Mexico and LANL for his contribution). I am hoping additional contributors will volunteer next year in order to broaden our coverage to include all the sessions while also providing a greater diversity of viewpoint.

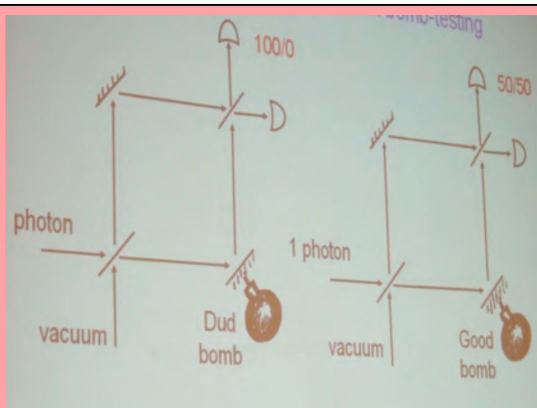
In addition to the session summaries provided here, brief contributions from our two student paper award winners are included. As someone who teaches undergraduates I was excited to see one win one of the awards.

Monday, March 5

The GQI-sponsored portion of the conference began early Monday morning with the focus session **Quantum-Limited Measurements** that featured an invited talk given by JM Geremia (New Mexico) on the role entanglement plays in metrology and in quantum parameter estimation as a means of achieving the fundamental limits of uncertainty dictated by quantum mechanics. In particular he discussed a recent proposal for improving such measurements by making use of multi-body quantum interactions. The idea of using such multi-system interactions was expanded on later in the session by the aforementioned Steve Flammia in conjunction with Geremia, Sergio Boixo, and Carl Caves (all at New Mexico with Boixo also at LANL). Specifically, they developed generalized bounds for quantum single-parameter problems where the coupling to this parameter is described by these multi-system interactions.

Among the many other interesting papers presented in that session was one by Aashish Clerk and Dian Wahyu Utami of McGill University that particularly intrigued me given my interest in statistical mechanics. They show, at least theoretically, how one can extract the photon number statistics of a driven, damped oscillator at a finite temperature from the dephasing spectrum of some two-level system that is dispersively coupled to the oscillator (previously only purely thermal or zero-temperature driven cases had been considered). By assessing the fidelity they are able to show how the initial number statistics are represented by the measurement itself.

The midday session was the first of two sessions on **Quantum Foundations (I)** (including my own paper, discussed below, since I usually end up in one of the foundations sessions). Rob Spekkens (Cambridge) kicked things off with an invited talk based on the idea that classical theory plus limited knowledge is *almost* quantum theory. Measurement results, then, are not reality, per sé, but rather "states of knowledge." This is even true for the vacuum state as demonstrated by applying the Elitzur-Vaidman bomb test to his toy theory.



How did Spekkens get this through security?

Matt Leifer (Perimeter Institute) then spoke on certain aspects of de Finetti's theorem which got me thinking tangentially about whether this continuing quest to axiomatize quantum theory runs into a little problem by the name of Gödel. Leifer's work, done in conjunction with Howard Barnum (LANL), Jonathan Barrett (Perimeter Institute), and Alexander Wilce (Susquehanna), builds on a generalized probabilistic theory developed by Barrett that actually includes both the classical and quantum theories as special cases. The Gödel question resurfaced in the very next talk in which Frank Schroeck gave a brief overview of his phase space version of quantum mechanics and discussed the notion of *informational* completeness. He also, curiously, indicated that, based on his results, Shor's theorem would need to be reformulated.

Continuing with the theme of exploring the quantum-classical contrast, Caslav Brukner (Vienna) discussed a new approach to macroscopic realism and classical physics within the bounds of quantum theory. There were two aspects of this that I found interesting, the first being that macrorealism can be violated for large systems by violating the Leggett-Garg inequalities, viewed as the temporal analogue of Bell's inequalities. This occurs when the accuracy with which the measurement is made is unrestricted (i.e. in the limit of increasing accuracy). The second aspect is that, in the opposite situation, when measurements are coarse-grained (i.e. the accuracy is restricted in some way), even Newtonian physics emerges from classical physics. Ultimately this summed up my own personal philosophy on the quantum-classical contrast which is based on the aggregate behavior of probabilities: determinism and irreversibility gradually take form as systems become larger and larger. This was pointed out by Arthur Eddington in the 1920s (a point I spent some time discussing in my doctoral thesis a few years back).

Surprisingly, Chris Fuchs (Bell Labs) did not discuss his Bayesian approach this time round. Rather he discussed the possibility of quasi-orthonormal bases for density operators, emphasizing the need for a good coordinate system to be introduced, though the states of knowledge of the system are technically coordinate free (again, this rings faintly of aspects of Eddington's so-called 'fundamental theory').

Again, following on some of Brukner's ideas, Jeff Tollaksen (George Mason) discussed non-contextuality and the effort to find a time-symmetric reformulation of quantum mechanics (see Sergio Boixo's summary of the second foundations session). This included a presentation of the rather odd 'three-box' paradox which produces a basic failure of the product rule (e.g. $P_A = 1$, $P_B = 1$, but $P_A P_B = 0$).

Time also played a role in Jan-Åke Larsson's (Linköping) talk in more ways that one. In a somewhat humorous bit of timing, the talk began with a Skype call from his wife. Like the true professional that he is he promptly hung up on her (she reportedly has forgiven him) before making the important general observations that 1.) 'theorems,' per sé, can't technically be violated and that 2.) 'loopholes' are really *experimental* problems (take that, you fiendish experimentalists! – oh, that's not what he meant, was it?). He then proceeded to analyze the time-dependence of Bell's inequalities by looking at the timing in the measurements. This provides a way to compare local realist models with non-local realist models. In addition he makes the note that the Clauser-Horne inequalities from 1974 (CH74) are the 'mother-of-all' Bell-type inequalities since they deal more specifically with probabilities. I had a hunch about this a few years ago and even found a funky set theoretic way to relate the CH74 inequalities to the generalized uncertainty principle, but no one took me seriously (note to self: do *not* include picture of clown in next paper).

Several other papers found ways to poke at the ever annoying problem presented by mixed states and highlighted the differences in measurements between mixed and pure states (and one by New Mexico's Matt Elliott discussed a really neat graphical description of Clifford groups with definite pedagogical use). This all led up to the most stunning talk of the entire conference given by some supremely annoying little fellow by the name of Ian Durham (Saint Anselm). Hey! Don't be so quick to agree!

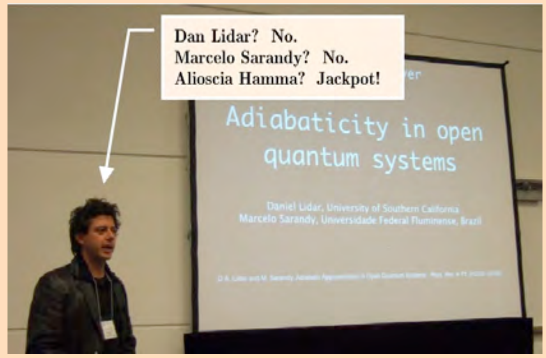
Quite seriously, though, I discussed work (recently revised) in which I derived the Cerf-Adami inequalities from the second law of thermodynamics and the Markovian postulate (which, in itself, is really part of the second law) and showed a link to the uncertainty relation (entirely separate from the set theoretic one I mentioned above – in the revised version I made use of a phase space relation Frank Schroeck showed me to enhance this). Oddly enough, it wasn't until weeks after the conference that I discovered that Caslav Brukner and some collaborators had derived entanglement from the *third* law of thermodynamics. Having chatted with Caslav more than once at the conference, I was surprised he didn't mention it.

The midday session on Monday centered on the topic of **Ion Traps for Scalable Quantum Computing**. Scalability is, of course, one of the primary hurdles in the drive to develop practical quantum computers, both in terms of increasing the number of qubits as well as reducing the size. This session included presentations by MIT's Isaac Chuang and NIST's Dave Wineland, among others. Unfortunately, hunger got the better of me and I missed this session.

Monday closed out with a second session on **Quantum Foundations (II)**, summarized in the box to the right.

Tuesday, March 6

Tuesday morning came bright and early beginning with the first of four focus sessions on **Superconducting Qubits (I)**. This began with an invited talk given by Jay Gambetta (Yale) on the application of continuous-in-time measurement theory to circuit QED in order to obtain a quantum trajectory description of the qubits. Schrödinger would likely have been pleased. Unfortunately, I had a meeting and missed the session.



Quantum Foundations II

The second foundations session started with a talk delivered by Alioscia Hamma (USC), in place of Dan Lidar (USC), on Adiabaticity in Open Quantum Systems. The adiabatic theorem states that an eigenstate of a slowly varying closed Hamiltonian will remain an eigenstate at later times, and is a key ingredient of adiabatic quantum computation. Nevertheless, real quantum systems are open, and, surprisingly, adiabaticity has not been previously studied in this context. For the crudest form of the adiabatic theorem, write the time-dependent Schrödinger equation in the instantaneous diagonal basis, plus a perturbation that updates this basis. If the Hamiltonian changes slowly, the perturbation is negligible, and the eigenspaces remain decoupled. This intuition is carried to the open systems picture by considering the Lindblad operator as a superopertor (matrix). The problem is that eigenspaces of the closed system do not correspond to eigenspaces of the Lindblad superoperator. Furthermore, the superoperator might not even be diagonalizable. The closest structure would be a Jordan block decomposition, and the open adiabatic theorem deals with the decoupling of the Jordan blocks. Another important difference is that the eigenvalues might have imaginary parts, and adiabaticity might brake down even for slowly varying interactions.

David Craig (LeMoyne) talked about the uncertainly principle in the context of the consistent histories approach to standard quantum theory, pioneered by Griffiths, Gell-Mann and Hartle. This approach starts with the observation that probabilities can be assigned to a sequence of measurements results, which can be viewed as a path or history. Once there, the underlying inner

(continued in box on next page)

I was back in time for the two concurrent midday sessions. The first, on **Quantum Computing in AMO Systems**, was co-sponsored by DAMOP. Among the interesting talks in this session was one by Fernando Cucchietti (LANL) who demonstrated how a Loschmidt echo can be used to measure such things as the fidelity of the quantum simulation and even the intensity of some external potential (including gravity). What is a Loschmidt echo you ask? In a sense it is a measure of irreversibility (there it is again!) in quantum systems, or, conversely a measure of the time reversal of the evolution of a quantum system. Mathematically, it takes the following rather elegant form,

$$M(t) = \left|\langle 0 \right| \exp(it(H + \mathbf{S}) \exp(-itH) \left| 0 \rangle\right|^2$$

where **S** is the perturbation and H is the Hamiltonian and specifically looks at the attenuation in some localized density excitation. A nice basic discussion (that includes a nifty picture of a stamp with Loschmidt on it) can be found at http://www.lanais.famaf.unc.edu.ar/loschmidt/.

René Stock, in collaboration with Nathan Babcock (see the QELS article) and our very own Barry Sanders (all of IQIS/Calgary), presented an interesting paper in which they devised entangling operations using Yb and Sr atoms in which certain electron transitions are forbidden thus resulting in low decoherence. They use this scheme to investigate the rapid measurement of clock-state qubits in a Bell-test that manages to avoid the detection loophole for spacelike-separated entangled qubits.

The second midday session was the second focus session on **Superconducting Qubits (II)** and included a series of talks on Cooper-pairs. Notably, Ofer Naaman and José Aumentado (both of NIST) presented work in which they spectroscopically measured narrow-band microwave radiation that was emitted by a single-Cooper-pair transistor (SCPT) electrometer that was biased in its subgap region. It never ceases to amaze me how small a system we can now manipulate (and, yes, I am aware that single-electron tunneling [SETs] transistors have existed since 1987).

A bit later in this session, Matthias Steffen, in collaboration with Frederico Brito, APS GQI Vice-Chair David DiVincenzo, and Roger Koch (all from IBM), presented IBM's tunable flux qubit in both two and three junction versions coupled to a harmonic oscillator. The IBM qubits exhibited three features that the authors consider essential for the development of a scalable quantum computer: that they (the qubits) be tunable, that the coupling itself be tunable, and that the qubit is capable of information storage. Later in the session D-Wave systems was slated to present experimental results for a system of four coupled qubits under adiabatic evolution, but I got hungry again.

The first of two afternoon sessions was the jointly sponsored **DCMP/GQI Prize session** that included presentations by Irfan Siddiqi (Berkeley), Bill Wootters (Williams), Huanqian Loh (Data

(continued from previous page)

product between histories is taken as the primary object. This is often called the decoherence function. Probabilities can be assigned to sets of histories only under certain consistency conditions, which boil down to the orthogonality (or decoherence) between different histories. As one would expect, non-commuting observables generate incompatible histories. Craig proposed to interpret the uncertainty principle as inconsistence among histories. Kicheon Kang (Chonnam University) proposed an experiment for quantum erasure in electronic Mach-Zender interferometers. An electronic MZ is a two-path electron interferometer that works like an optical MZ, with quantum point contacts (QPTs) as beam splitters. Kang proposes to use another QPT for which-path information, and that completes the necessary elements for quantum erasure. Ken Wharton (San Jose State) talked about a Time-Symmetric Quantum Mechanics interpretation, accomplished by applying two consecutive boundary conditions onto solutions of a time-symmetric wave equation. Michael Clover (SAIC) argued about a possible local interpretation of quantum mechanics, but his interpretation of some classical equations was somehow criticized.

Just some brief comments on the other talks. Edward Floyd talked about quantum Young's experiment, nonlocality and trajectories, and showed some nice diagrams with temporal retrograde motion. Joel Maker replaces the general covariance in the Standard Model and gets azimuthal trifolium. Shantilal Goradia (Gravity Research Institute) argued, among many other things, that particles have barcodes. Finally, the much talked about Fourier transforming purple bacteria were also in this session.

-Sergio Boixo
Dept. of Physics and Astronomy, U. New Mexico and Los Alamos National Laboratory

Storage Institute), Hugh Churchill (Harvard), and Fazley Bary Malik (Southern Illinois).

Siddiqi discussed using Josephson bifurcation amplifiers as a means of measuring quantum systems since the inherent non-linearity provides for fast, sensitive detection and the lack of dissipation reduces decoherence problems. So far these amplifiers have been successfully used to read the states of superconducting qubits and future applications potentially include single molecule magnets (how cool is that?).

Wootters, winner of the Prize for Research at an Undergraduate Institution, gave an overview of his work on discrete Wigner functions (see the July 2006 issue of *The Times* for an interview with Bill in which he discusses this work in some depth). This particular discrete Wigner function developed by Wootters and his students (there are other such functions) is particularly well-suited for work in quantum computation and quantum cryptography due to its suitability for binary objects. In these analyses, the Wigner function provides an alternate method for determining probability distributions (as opposed to methods employing state vectors or density operators). While the Wigner function itself can't be interpreted as a probability distribution since it can have negative values, its integral along any axis in phase space *is* the probability distribution of an observable along that axis.

The second of the afternoon sessions was the third focus session on **Superconducting Qubits (III)**, a session I only poked my head into a couple of times. While the second superconducting qubits session focused on Cooper-pairs, this one focused on phase qubits. One talk that did catch my eye in this session was given by a group out of UC Santa Barbara that is working to develop a CHSH Bell-type experiment using Josephson phase qubits. The experiment is unique in that it places high demands on most qubit performance measures (e.g. fidelity, energy relaxation time, decoherence time, etc.). This is a novel approach to Bell-testing which, these days, is most often performed using lasers or atom trapping.

Tuesday closed out with the business meeting, discussed above.

Wednesday, May 7

Highlighting just how many sessions GQI sponsored or co-sponsored this year, Wednesday morning began with yet another pair of concurrent sessions. The first, **Progress in Superconducting Quantum Computing**, was co-sponsored with DCMP and consisted entirely of invited talks. It began with a talk by Frank Wilhelm (IQC/Waterloo) that gave a general overview of the topic, describing the latest achievements to date. He was followed by Travis Hime (Berkeley) speaking on solid-state qubits and SQUIDs, Andrew Houck (Yale) describing the generation and measurement of single photons in circuit QED systems, Matthias Steffen (UCSB/IBM) detailing the use of state tomography to directly measure the entanglement of two superconducting qubits, and Hans Mooij (Delft) discussing the readout method applied to systems of flux qubits. Alas, I only poked my head in a few times in between papers in the other morning session, **Quantum Measurement**.

That particular session got rolling with a paper by New Mexico's Sergio Boixo (see box above) who, in collaboration with Rolando Somma (LANL), described a quantum circuit that estimates operators at the optimal Heisenberg limit. This is achieved using a general unitary operation for multi-parameter estimation when the operator acts on a set of qubits. Achieving the optimal Heisenberg limit essentially means reaching a sensitivity for determining the parameters in the estimation that scales as $1/N$ where N is the number of times the unknown unitary operator is applied. The circuit contains an ancilla (extra qubit) that is initially in a pure state with the system qubits initially in a mixed state. Basically, any unitary transformation on some arbitrary number of qubits can be built from elementary quantum gates (like a Hadamard gate for instance) and measurements are then performed on the ancilla.

Another fascinating paper appeared courtesy of Mark Keller and Neil Zimmerman (both of NIST) working in collaboration with Ali Eichenberger (METAS). They asked the question: is the charge carried by the discrete quanta in single-electron circuits *exactly* e? In order to answer this apparently non-trivial question they actually utilized some good, old-fashioned E&M: they placed a known number of SET charge quanta onto a known capacitor and measured the voltage across it (the capacitor)! Hey, even my introductory physics students would at least get the basic idea (assuming they remember that $C = Q/V$). In any case, as simple as that sounds it did require a Josephson voltage standard (something my intro. students likely would *not* be familiar with). Their results put the equivalence of the SET charge quantum and e at one part in 10^6 which is about 100 times better than any previous result and they expect their results to improve to about 3 parts in 10^7 sometime in the near future which would then provide some potentially useful information on possible corrections to the Josephson constant, K_J =

$2e/h$ (which is the inverse of the magnetic flux quantum, Φ_0).

Later in the session, Constanze Metzger (LMU Munich) described an interesting project designed to realize laser-cooling of macroscopic mechanical resonators. The system described employed passive optical cooling of the Brownian motion of a cantilevered micromirror to cool an 11 pg (yes, that's pico-gram) mass (the mirror itself) which is the smallest mass cooled thusfar.

Toward the end of this session, Alexander Korotkov (UC Riverside) discussed work with Andrew Jordan (Rochester) in which they propose that it is possible to actually *undo* a quantum measurement! This is, of course, a very unique idea since, if you're a Copenhagen adherent (personally, I'm agnostic) you would immediately be suspect since wavefunction collapse is a generally irreversible process. On the other hand, if you adhere to a non-collapse interpretation, perhaps there's nothing surprising here. In any case, Korotkov and Jordan suggested potential experimental realizations of this using quantum dots or superconducting qubits. Personally, I'll be very interested to see the results of any experiments of this type.

The midday session was our fourth **Superconducting Qubits (IV)** session and it began with a series of papers from the Yale contingent discussing their proposal of a new type of superconducting qubit called the "transmon" that consists of a Cooper-pair box shunted by a large capacitance. As interesting as the concept was (and it really did sound interesting), I shuffled off to lunch.

The day closed with a session that bridged a lot of the topics already discussed by considering **Physical Implementations of Qubits**. The first two talks dealt primarily with ion-traps while the third, from the Vienna group (Robert Prevedel, et. al.), presented work on a physical realization of high-speed linear optics quantum computing in which randomly induced measurement errors are *classically* fed forward and then corrected by adapting the *basis* of subsequent measurements. In a sense, this is a physical realization of quantum error-correction where the change in basis for subsequent measurements is, in conjunction with the feed-forward step, the error-correction operation. With current technology, the feed-forward step can be performed in less than 150 ns.

In the next talk, Frank Gaitan (Southern Illinois) presented results of simulations that suggest a particular class of non-adiabatic rapid passage sweeps from NMR should be able to implement a series of quantum gates including the one-qubit Hadamard, phase, and $\pi/8$, and the two-qubit controlled-phase. This was followed by Emily Pritchett (Georgia) presenting a procedure for two-qubit gate realization utilizing a small set of primitive operations whose Makhlin invariants are then compared to that of the target gate (i.e. the set of operations is tweaked until the Makhlin invariants match). Examples included several new CNOT gates. CNOT gates were later analyzed from a slightly different perspective by Gabriel Colburn (Colorado School of Mines). In particular, the feasibility and minimal implementation of these gates from specific model Hamiltonians was discussed.

Thursday, May 8

Well, if you're still with me, you're in for chuckle (or perhaps a cringe). I had to arise rather early to chair one of the morning (i.e. 8 AM) sessions after having been up late with food poisoning! My, life is an adventure, isn't it?

In any case, we again had two concurrent sessions and since I chaired one I could not attend the other, which was the first of two on **Quantum Cryptography and Quantum Communication (I)**. While the papers in my session were generally interesting and of a high caliber, I did miss the chance to hear Anton Zeilinger speak on one of my favorite topics: long-distance, large scale quantum communication! I suppose I am simply jealous that Anton gets to spend time beaming giant lasers over the Canary Islands, but it's an interesting and fun topic nonetheless, particularly when applied to quantum cryptography (it brings out my "inner spy"). The rest of this session consisted of invited talks as well, including the Beller Lectureship Recipient Talk.

The session I was *actually* at that morning, **Quantum Algorithms, Simulation, and Error Correction**, was actually probably just as interesting. In particular, Ari Mizel (Penn State) proved the equivalence of adiabatic quantum computation and the usual circuit model of quantum computation. This work actually relates to the work discussed at the very beginning of the second session on quantum foundations (see box above), which is no surprise considering Dan Lidar (USC) had a hand in both. Ari was followed by Peter Love (Haverford) who gave a really cool talk presenting quantum cellular automata as a means to address questions about quantum dynamics. Specifically Peter discussed a particular unitary class of automata. Cellular automata in general have their origins in game theory and, in particular, in perhaps the first person to get hooked on computer "games," Stanislaw Ulam who was working with John von Neumann at Los Alamos in the 1950s. The basic rules were codified in 1970 by John Conway in what has now become known as the Game of Life. The "game" Ulam was playing (and that Conway codified) involved pattern repetition through replication and von Neumann began to consider what would happen if something (a universal constructor) could be programmed to make itself. Ulam persuaded von Neumann to consider cellular automata as a possible mechanism since they are self-replicating by nature. Quantum cellular automata don't exactly self-replicate but they mimic each other in a sense. The idea was first developed at Notre Dame in the early 1990s and has taken off from there.

The ubiquitous Professor Lidar discussed quantum error correction a bit later in the session (see the conference announcement on page 6) and adiabatic quantum computing made its return immediately following in an interesting talk by William Kaminsky (MIT) in which was presented a general approach to determining the asymptotic scaling of resources in random instances of NP-complete graph theory problems in adiabatic quantum computational resources. An important conclusion was that adiabatic quantum computers based on quantum Ising models are much less likely to be efficient than those based on Heisenberg or quantum rotor models.

The midday session was the second dedicated to **Quantum Cryptography and Quantum Communication (II)** and was particularly notable in that it contained one of our student award-winning papers, a summary of which is presented by the paper's author, Gleb Axelrod (UIUC) after this general conference summary. Other interesting papers in this session included Jan-Åke Larsson's discussion of security aspects of the authentication process in QKD in which he pinpoints a security weakness in the authentication process. A bit later, Som Bandyopadhyay (Montréal) presented work that showed the qualitative link between local distinguishability and entanglement lies at the level of stochastic rather than deterministic processes (an example presented included someone's prized goat and a Ferrari). If I recall, this is what led to a multi-party hallway discussion in which Rob Spekkens asserted his conviction that entanglement was in some way related to the exclusion principle (clearly so since the latter is tied up in distinguishability). I have yet to convince anyone that the uncertainty principle and the second law of thermodynamics are also related (see my summary of my own talk above).

In all honesty, after Som's talk I went to lunch and returned for the afternoon session on **Quantum Entanglement** for just long enough to listen to Barry Sanders (IQIS/Calgary) to discuss entangled Gaussian states. In particular, the major revelation in their work was that all tripartite entangled Gaussian states achieved through three-mode squeezed light are actually su(1,1) of the type first developed by Sebaweh Abdalla. This suggests potential ways to generalize both theories and applications of multipartite Gaussian states.

After Barry's talk, I realized that my brain had curdled, perhaps a result of the combination of four days of physics and a night of food poisoning, all at over 5000 feet in altitude (thinking back on it, I'm surprised I didn't start hallucinating). As such, I called it quits that day and, since I had a morning flight out on Friday, I also missed the final two GQI-sponsored sessions: **Quantum Information at the AMO/Condensed Matter Interface**, co-sponsored by DAMOP, and **Decoherence and Quantum Control**. The chances are pretty good I wouldn't have made much sense of them anyway due to the state of my brain, which is too bad because I am sure they were very interesting. Nonetheless, my daughter's birthday party was coming up and I simply could stay no longer regardless.

Finally, we close out this summary of the very successful 2007 March Meeting with summaries from our two student paper award-winners. The award for theory is graciously sponsored by the Perimeter Institute and includes a cash prize of $500 and this year's recipient was Gleb Axelrod of the University of Urbana-Champaign (UIUC). The award for experiment is graciously sponsored by the Institute for Quantum Computing (IQC) in Waterloo and likewise includes a cash prize of $500 given to this year's winner Frank Koppens of the University of Technology in Delft (TU Delft) in the Netherlands. We would like to thank the IQC and Perimeter Institute for sponsoring these awards. Without their generous financial assistance this level of award would not be possible. We would also like to thank all the student presenters, the faculty who nominated them, and those who agreed to serve as judges for the competition. Finally, we extend a big thanks to Chris Fuchs who organized everything surrounding these awards.

The following two articles are summaries of these student paper awards given by the winners whom we also thank for spending the time to write newsletter-length summaries.

2007 GQI STUDENT PAPER AWARD FOR THEORY

Numerical Modeling and Optimization of Type-I Entangled-Photon Sources

One of the most robust ways of generating entangled photons is by the process of spontaneous parametric down-conversion. In this scheme, a high-frequency pump photon is incident on a pair of nonlinear crystals, and can split into two low-frequency photons which are entangled in their polarization. Developing such sources that are bright and high-purity is crucial for quantum key distribution, quantum teleportation, and tests of nonlocality. However, the purity of these sources is reduced because not all of the produced photons pairs are indistinguishable. Due to imperfect phase matching in the crystals and the finite bandwidth of the pump laser, down-converted photons are produced in a range of wavelengths and directions. Also, because the down-conversion crystals are birefringent, each polarization component of the pair acquires a different phase. As a result, each pair of photons becomes distinguishable, which results in effective decoherence and lowers the purity of the source.

In order to quantify this decoherence, and develop ways of minimizing it, we have developed a numerical model of our sources. This model takes into account the properties of both uniaxial and biaxial down-conversion crystals, the pump laser bandwidth and spatial modes, and photon collection irises and filters. The result of the calculation is a density matrix that represents the collected two-photon polarization state, which we can use to determine the relative effect of each experimental parameter on the quality of the state. To verify the model, the predicted states were compared with experimentally obtained quantum state tomography data, showing good agreement. Using the model we have also designed spatial and temporal phase compensation crystals to reduce the phase decoherence and improve the brightness and purity of our sources. This code will be freely available to the quantum optics community as a resource for designing and characterizing optimized entangled-photon sources.

-Gleb Axelrod
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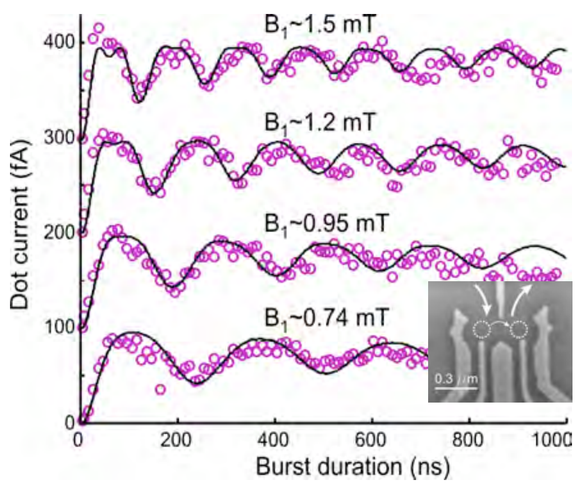
2007 GQI STUDENT PAPER AWARD FOR EXPERIMENT

Coherence and control of a single electron spin

A single electron spin is an exemplary object for studying quantum phenomena like coherence and entanglement in a solid-state environment; a rich field which has become experimentally accessible during the last decade due to the achieved high level of coherent control of a variety of isolated quantum systems.

The progress in the field of manipulating confined spins in quantum dots was substantial since Loss and Divincenzo's [1] proposal on electron spins as quantum bits. Important examples reflecting this progress are the realization of single-shot read-out of a single electron spin [2], and coherent coupling of two electron spins [3]. However, the final step to produce a real quantum bit, namely the possibility to rotate the spin of a single electron in a quantum dot, remained beyond reach for a long time.



Coherent oscillations of a single electron spin. The current flow (vertical axis) reflects the spin direction, and the spin rotation angle is controlled by the duration of the oscillating field burst (with amplitude B1). Curves offset for clarity. Inset: scanning-electron-microscope image of metallic gates on top of a two-dimensional electron gas. Quantum dots (indicated by white dotted circles) are formed by applying negative voltages to the gates.

Recently, this control of the quantum state of a single electron spin has been realized via electron-spin-resonance (ESR) [4]. One of the main difficulties was the presence of unwanted electric fields coming together with the on-chip generated oscillating magnetic field. This made it hard to rotate the electron spin and read it out at the same time. However, it was possible to get around the side effects. By confining a second electron in another quantum dot alongside the first one (see figure inset), it is possible to read out the spin direction of the first electron in a very robust way. Namely, for two electrons confined in a quantum dot, the Pauli principle tells us that the energy is higher if the spins are the same, rather than opposite spins. By looking whether the electron can move to the other electron in the adjacent quantum dot, it is possible to read-out the spin state. Applying bursts of the oscillating magnetic field allowed full control over the rotation angle of the spin and subsequent detection of the spin direction revealed coherent (Rabi) oscillations as shown in the figure.

Once this control over a well-defined quantum object is gained, the important and fundamentally interesting question is how long a superposition state is preserved. This can be measured via a Ramsey-type experiment where the spin is rotated from an eigenstate to a superposition state and after a short free evolution time rotated back to an eigenstate. The probability to find the same eigenstate again reflects to what extent the coherence is preserved. When averaged over many experimental runs, we found that on average the coherence was lost already after 30 ns. Not surprising, however, because the nuclear spins in the semiconductor lattice couple collectively to the electron spin, leading to an uncertainty in an effective magnetic field [5,6] (so-called Overhauser field). Current research is focused on different ways to reduce this uncertainty in the Overhauser field, while the coherence loss due to the nuclear field could already be reversed to a large extent via a spin-echo technique. We found that coherence was preserved for at least 500 ns, which is promisingly long for future experiments.

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