Proposal for a KITP workshop on
Quantum Control of Light and Matter

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Quantum control refers the application of controlled coherent interactions to direct the dynamics of quantum systems. It is one of the most exciting frontiers in atomic, molecular and optical physics, spanning physics, chemistry and applied mathematics, with excellent interactions between theory and experiment. Within the context of chemical dynamics, the objective is to design specially tailored laser pulses to selectively break bonds in large molecules. However, the application to many other areas of physics is growing rapidly, including controlling photoionization, photoemission, high harmonic generation, fluorescence quantum yield, laser pulse properties, directional current in semiconductors, controlled deposition and nanolithography, nuclear magnetic resonance, manipulation of ions in traps and neutral atoms in optical lattices, laser cooling, and quantum information, all using optimally shaped pulses.

One of the most intriguing aspects of quantum control is the role of quantum coherence both in the light and in the matter in achieving the desired objective. In contrast with classical control as applied to macroscopic objectives, where the desired objective may be steering a satellite, designing an electrical circuit, or the flow rates of chemical reagents, in quantum control the desired physical objective is normally obtained via constructive and destructive interfering pathways. Thus quantum control often goes by the alternative name of "coherent control". The ability to exploit and optimize the wavelike properties of matter for physical and even technological objectives has captured the imagination of scientists from a wide range of disciplines.

The mathematical tools of quantum control are in principle the same as those in classical control, and include the calculus of variations and its close relative, Optimal Control Theory. However, in the same way the quantum computation raised an entirely new set of issues in computer science, with algorithms based on quantum interference, quantum control raises an entirely new set of issues in control theory and entails mechanisms that are entirely different from their classical counterparts. The new set of control issues arise from several key differences from the classical case: a) the governing equation, the Time-dependent Schrodinger equation is a wave equation; b) the wavefunction is a complex quantity; c) classical control deals largely with systems that are linear while in the quantum case the control variables enter the system dynamics multiplicatively, resulting in what is called bilinear control. c) the time scales involved are normally femtoseconds, but can range from nanoseconds to attoseconds; d) for many applications no real time feedback is possible, although adaptive feedback and learning algorithms may be useful; d) the complex pulse shapes that emerge from calculations can be synthesized in the frequency domain using liquid crystal phase masks, and transformed back to the time domain to obtain shaped ultrashort pulses, with a repetition rate of thousands of times per second.

Despite the great excitement of the field, and significant experimental successes, many of the fundamental problems are still unsolved. Here are some examples of problems that will be central to our workshop:

a) One of the most intriguing aspect of quantum mechanics is the role of measurement. Since most of classical control theory is based on assumption that the state of a dynamical system can be measured without disturbing the system dynamics, feedback control in quantum systems is conceptually very different. The theory of real time measurement and feedback control is a subject of fundamental and practical importance. Many applications of these ideas including measurement induced quantum state preparation, magnetometry using cold atom, etc. are beginning to emerge. Significant developments can be foreseen in the future.

b) Unlike classical systems, it is quite common in the setting of quantum control to have a large ensemble of atoms, molecules or spins that are simultaneously controlled by the same electromagnetic field. The members of the ensemble may show slight variations in their Hamiltonian. Finding optimally shaped electromagnetic fields that can compensate for this dispersion is a rich subject that has been explored in magnetic resonance applications. However a complete theory of controllability of a inhomogeneous ensemble of quantum systems is still missing.

c) In many applications of quantum control like control of chemical reactions, the natural Hamiltonian of the system is not known. Finding methods to learn about the natural Hamiltonian of the system and then control it is a subject of system identification. Numerous conceptual and application oriented breakthroughs are expected in this area.

d) In real chemical systems, the factors that truly limit the experimental yield are not well understood. When optimal pulses are discovered, either in simulations or in experiment, their interpretation is generally difficult, and each new case requires new analysis. The mathematical nature of the optimal pulses is not well understood: are their multiple optimal pulses? Do they satisfy any special mathematical properties, for example orthogonality properties?   What general statements can be made about controllability of quantum systems in the continuum, which is the generic case for chemical control? What general statements can be made about quantum controllability in the presence of dissipation and dephasing?

By now, there are several regular meetings on the subject of quantum control, all of which last just one week:

1) The Gordon Conference on Quantum Control of Light and Matter (August, 1999, 2001, 2003, 2005, 2007 and alternate years).
2) Ringberg Castle, Germany (December, 1999, 2001, 2003, 2005, and it has a tradition for meeting in alternate years, although it is not clear if this tradition will continue).

3) Quantum Control form a more Engineering Perspective (PRACQSYS 2004 (Caltech), QCSS 2005 (Caltech), PRACQSYS 2006 (Harvard)).

These meetings highlight the fact that there are at least two, and possibly three or four subcommunities within quantum control that work on different physical systems and use different languages: chemical reaction dynamics communities, the NMR community, the quantum optics community, the quantum information community, and the mathematically oriented quantum control theorists. There has been preliminary interaction between these communities. However, the existing meetings of one week duration are too short for the communities to really learn the methods and modes of thought of the other communities, and hence to transfer techniques and strategies from one area to another. One of the main goals of having a KITP workshop is to allow sufficient time for the subcommunities to be together to learn each other's language and to allow for transfer of methods from one subcommunity to another.

In addition, we intend to invite key representatives from the attosecond community to exchange ideas about how the methods of quantum control can be useful for the problems of interest to that community. Attosecond science is a new frontier in optics, for two main reasons: it allows for the interrogation of processes on previously inaccessible time scales (particularly electronic dynamics), and because it is closely related to the quest for generation of high harmonic generation, which could lead to table-top coherent XUV and soft x-ray sources. There is a growing awareness within the attosecond community that high harmonic generation can be enhanced significantly by precisely controlling the coherent electronic wavepacket in the recollision process that leads to the harmonic generation. When asked about their interest in participating in a KITP workshop on quantum control, the response of the attosecond community was enthusiastic, with three leading theorists saying they would be interested in coming at least one month and potentially for the whole time.

We propose that the meeting be of three month duration in the Spring-Summer of 2009 (preferably mid-April until mid-July). We intend to dedicate the first week to be a tutorial week, both for students, postdocs and advanced researchers, with several key speakers giving a pedagogic overview of their fields and methods, and a desciption of the key unsolved problems in their subfields. Such a tutorial week would set the stage for the entire 3-month program, and it is anticipated that many participants may come for this first week and then come back for a 3-week or month-long visit during the remainder of the workshop. We anticipate that during the rest of the program there will be approximately one lecture per day, with some multi-day tutorial series to help the subcommunities learn from each other. We do not intend to have a conference in the middle or end of the program, since there are already quite a few conferences in this area. We would, however, like to have one or more focus weeks into which we try to cluster the visits of experimentalists, which normally do not exceed one week. We will make every effort to include minorities. The list of potential participants below is 15% female (marked with *).

The following people have agreed to be coordinators

David |Tannor (Weizmann, theoretical) [chemical, optical, control theory]
Navin Khaneja (Harvard, theoretical) [spin systems, control theory]
Gustav Gerber (Wuerzburg, experimental) [chemical, optical, learning algorithms]
Steffen Glaser (Munich, experimental) [spin systems]
Hideo Mabuchi (Cal Tech, experimental) [quantum optics, feedback control]

Tannor and Khaneja are both interested in being present for the entire duration of the program. Gerber is the experimental counterpart of Tannor and Glaser is the experimental counterpart of Khaneja; both are interested in being coordinators and coming for one month. Mabuchi is also enthusiastic about being a coordinator and is interested in coming for most of the program. Although he is an experimentalist, his position is at Caltech and he will be able to travel back and forth easily. Most likely, he will find a theoretical counterpart (Doherty, Wiseman…) to help coordinate.

Participants who have expressed strong to enthusiastic interest:
Herschel Rabitz (Princeton, theoretical) [chemical, optical]
Anthony Bloch (Michigan, theoretical) [theory of controllability, non-holonomic control]
Tomasso Callarco (Ulm, theoretical) [ion traps, quantum information]
*Chitra Rangan (Windsor, theoretical) [chemical, quantum information]
Daniel Lidar (USC, theoretical) [quantum information]
Howard Wiseman (Queensland, theoretical) [quantum optics, feedback control]
Misha Ivanov (NRC, Ottawa) [theoretical, strong field physics]
Phil Bucksbaum (Stanford, experimental) [chemical, optical]
Tom Weinacht (Stony Brook, experimental) [chemical, optical]
Chris Monroe (Michigan, experimental) [ion traps, quantum information]
Mikhail Lukin (Harvard, experimental) [quantum optics, quantum information]
Malcolm Levitt (Southampton, experimental) [spins, control theory]
Ken Schafer (Baton Rouge, theoretical) [attosecond]
Andre Bandrauk (Sherbrooke, theoretical) [attosecond]
Anthony Starace (Nebraska, theoretical) [attoscecond]
*Mette Gaarde (Baton Rouge, theoretical) [attosecond]
*Margaret Murnane (JILA, experimental) [attosecond]
Paul Corkum (NRC, experimental) [attosecond]

Other potential participants:
Control of chemical reactions (Theory)
Joern Manz (Berlin)
*Regina de Vivie-Riedle (Munich)
Moshe Shapiro (Weizmann and UBC)
Paul Brumer (Toronto)
Chris Meier (Toulouse)
Volker Engel (Wurzburg)
Ronnie Kosloff (Jerusalem)
*Christiane Koch (Berlin)
*Vlasta Bonacic Koutecky (Berlin)
Stuart Rice (Chicago)

Control of chemical reactions (Experiment)
Tobias Brixner (Wurzburg)
Robert Levis (Temple)
Markus Motzkus (Marburg)
Marcos Dantus (Michigan)
Thomas Baumert (Kassel)
Bertrand Girard (Toulouse)
Steve Leone (Berkeley)
Matthias Wollenhaupt (Kassel)
Ludger Woste (Berlin)
Yaron Silberberg (Weizmann)
Dan Oron (Jerusalem and Weizmann)
Dwayne Miller (Toronto)
Sandy Ruhman (Jerusalem)
Yehiam Prior (Weizmann)
Ron Naaman (Weizmann)
*Roseanne Sension (Michigan)
Ian Walmsley (Oxford)

Attoesconds and Harmonic Generation
*Olga Smirnova (NRC)
*Anne L'Huillier (Lund)
Henry Capteyn (JILA)
David Villeneuve (NRC)
Ferenc Krausz (Vienna)
Peter Knight (Imperial)
Jon Marangos (Imperial)
Manfred Lein (Heidelberg)
Maciej Lewenstein (Essen)
Oren Cohen (JILA)
*Nirit Dudovich (Ottawa and Weizmann)

Spin Systems
Seth Lloyd (MIT)
*Lorenza Viola (Dartmouth)
*Birgitta Whaley (Berkeley)
Niels Nielsen (Aarhus)
Alex Pines (Berkeley)
Warren Warren (Duke)

Control of Quantum Optical Systems and Quantum Information

Gerard Milburn (Queensland)
Michael Nielsen (Queensland)

Klaus Molmer (Aarhus)
Andrew Doherty (Queensland)
Immanuel Bloch (Mainz)
Dieter Jaksch (Oxford)
Peter Zoller (Innsbruck)
Ignacio Cirac (Garching)

Control Theorists

Viswanath Ramakrishna (Dallas)
Roger Brockett (Harvard)
Claudio Altafini (Trieste)
Domenico D'Alessandro (Iowa)
Gabriel Turinici (Paris)
*Sonia Schirmer (Cambridge)
Uwe Helmke (Wurzburg)
Shankar Sastry (Berkeley)