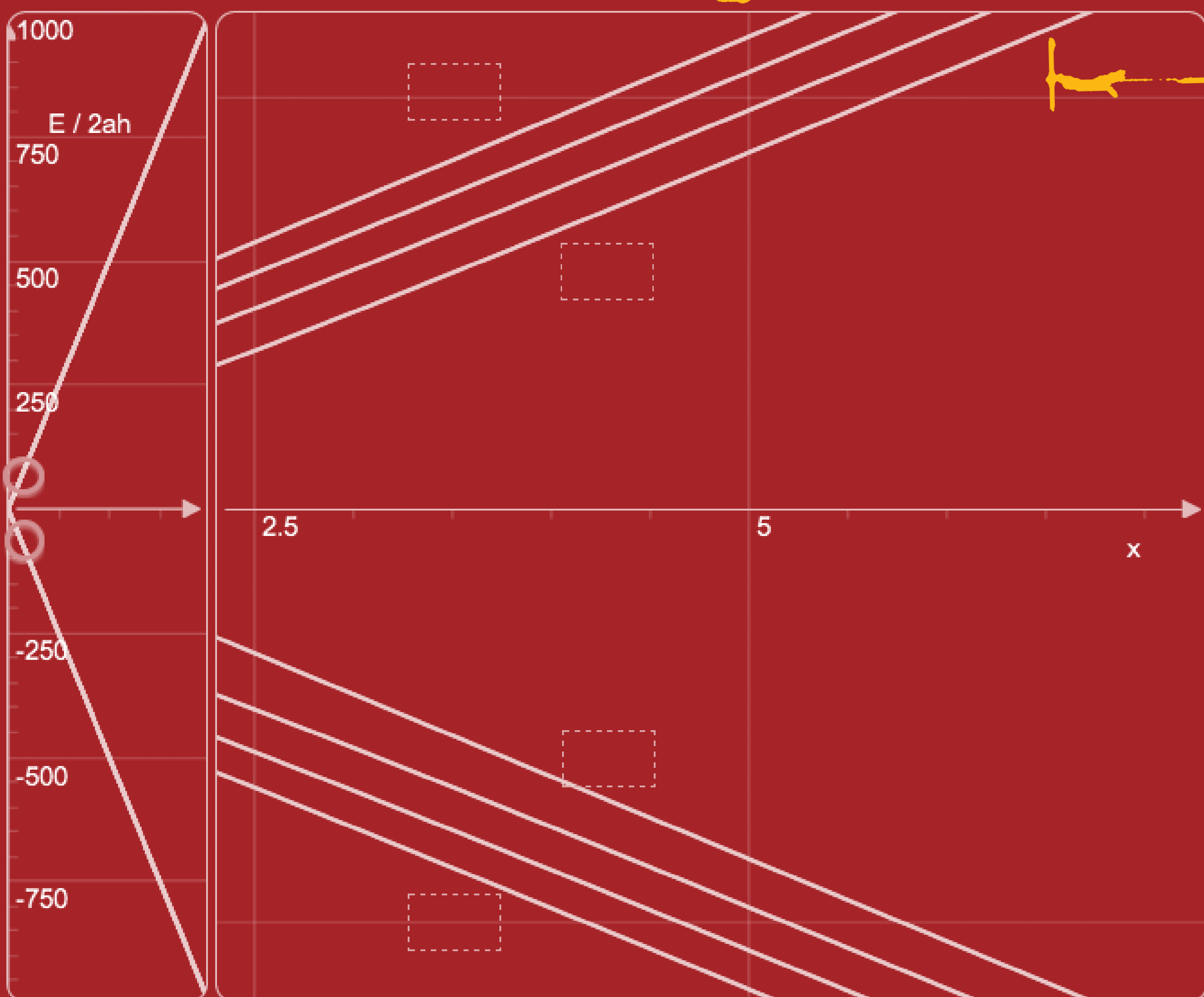
Energy levels at intermediate magnetic field

(1 point possible)

The energy eigenstates at intermetiate values of the magnetic field can be approximated by quantum numbers (m_J, m_I). This regime is shown in the diagram below, which is a magnified view of the areas show in the red ellipses.

Identify the lines in the diagram by dragging the correct (m_J, m_I) label to the boxes next to the lines:



(1/2,3/2) | (1/2,1/2) | (1/2,-3/2) | (1/2,-1/2) | (-1/2,3/2) | (-1/2,1/2

A Transformative Teaching Experience in Atomic Physics at MIT

by Isaac Chuang and Wolfgang Ketterle

This article describes the experience of the authors in teaching the atomic physics graduate course, what motivated them to develop an online version of it, and how they combined the online course material with interactive classroom sessions for teaching MIT graduate and undergraduate students. It also tells the story how one MIT professor, Wolfgang Ketterle (WK), who emphasizes tradition in his teaching and research, and who used only chalk and blackboard in his early teaching, was inspired by another MIT professor, Isaac Chuang (IC) to introduce new technology into the classroom and eventually became a poster child for MIT's digital learning. And yet, he remains convinced that educating students is much more than conveying knowledge; the best teaching lets students experience the personality and passion of a teacher in an interactive environment.

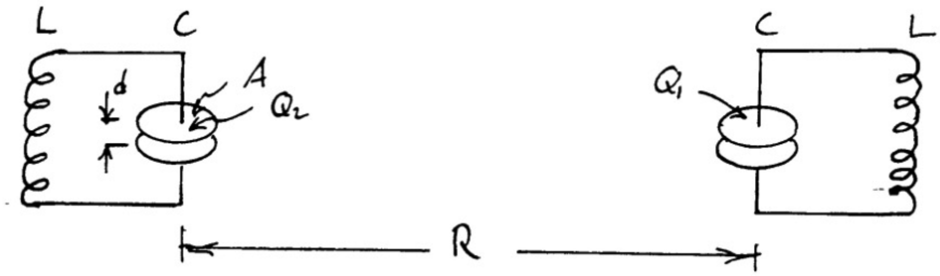


FIGURE 1

Sketch in the old course notes by Dan Kleppner *to explain the van der Waals attraction between neutral atoms by the interaction of two semiclassical LC circuits.*

The Atomic Physics course at MIT: technological evolution in teaching

The graduate course in Atomic and Optical physics, first taught by Dan Kleppner in 1968 and further developed by David Pritchard, reflects the soul of the Atomic Physics group at MIT. When one of us (WK) was a postdoc in 1990, he took his first advanced atomic physics class from Dan and Dave, and enjoyed the many special and sometimes unusual perspectives offered by this course, leading to a deep conceptual understanding of the underlying physics. The course went through major developments: it was expanded to a two-semester course in the 1990s by one of us (WK), including laser cooling and trapped atoms. When WK taught the course with Vladan Vuletic, chapters on single photon physics and light-atom interaction were updated. When the two of us taught the course together, aspects of quantum computation and entanglement were featured. The course notes were originally written by hand (or with troff, a relic from the mainframe computer epoch), but were finally modernized to LaTeX and eventually shaped into a student-editable wiki, in the early 2000s. Throughout all these developments, we preserved the spirit and the tradition of the course. For instance, the course emphasizes the correspondence between classical pictures and the quantum mechanical description *(Figure 1)*. The students see the equations for Rabi oscillations for the first time in a purely classical treatment of a magnetic moment precessing in an external magnetic field. Such magnetic resonance methods were explored by I.I. Rabi and N. Ramsey, two pioneers (and Nobel laureates) who shaped modern atomic physics between 1930 and 1970. Their spirit can still be found in MIT's Atomic Physics course, since Dan Kleppner's PhD advisor was Norman Ramsey, who was a graduate student of I.I. Rabi. And WK was Dave Pritchard's postdoc, who himself was Dan's graduate student; atomic physics at MIT is a family affair!

In 2005, we introduced the use of tablet computers in teaching the Atomic Physics course; this offered a number of advantages. The write-up can be posted after the lecture, eliminating the need for students to copy from the blackboard. It is possible to show the prior class write-ups at the beginning of the following class. The lecturer is facing the class when writing on the tablet, whereas at the blackboard he turns his back to the audience. It is possible to paste diagrams and figures from original publications into the presentation, and tedious and not very educational parts of a derivation can be prewritten so that they take less class time. On the other hand, a smaller area is displayed (compared to large blackboards), and the lecturer is more static, being seated while writing. Over several semesters, we asked the class for their preference, and always a clear majority of the students voted for the tablet over the blackboard.

Motivated by Dave Pritchard and his quest for reaching individual students, another technology introduced into the Atomic Physics classroom was clickers, a personal response system with which students respond to multiple choice questions, and the results are immediately displayed as a histogram. This addresses the challenge of reaching silent students, who don't respond or raise their hands when the lecturer asks a question. Clicker questions introduce a change of pace in the classroom and get the students' attention. If the histogram for a seemingly simple, but subtle concept question shows a similar number of yes and no responses, the class realizes that they collectively don't have a clue, and it creates an enormous suspense, offering an opportunity to deliver an explanation in a memorable way. Originally, we expected that clicker questions would be a way to introduce short exercises and control questions into the classroom. However, once we realized the potential of the method, we became more and more creative in finding questions which addressed possible misunderstandings and invalid analogies. Eventually, we took some pride in finding questions where the answers would form a flat histogram! With some of these questions we were able to entertain (and challenge) our colleagues at faculty luncheons. Those questions (and the questions and discussions triggered by them) take classroom time away from other material, but overwhelmingly, when asked, the students wanted rather more than fewer clicker questions.

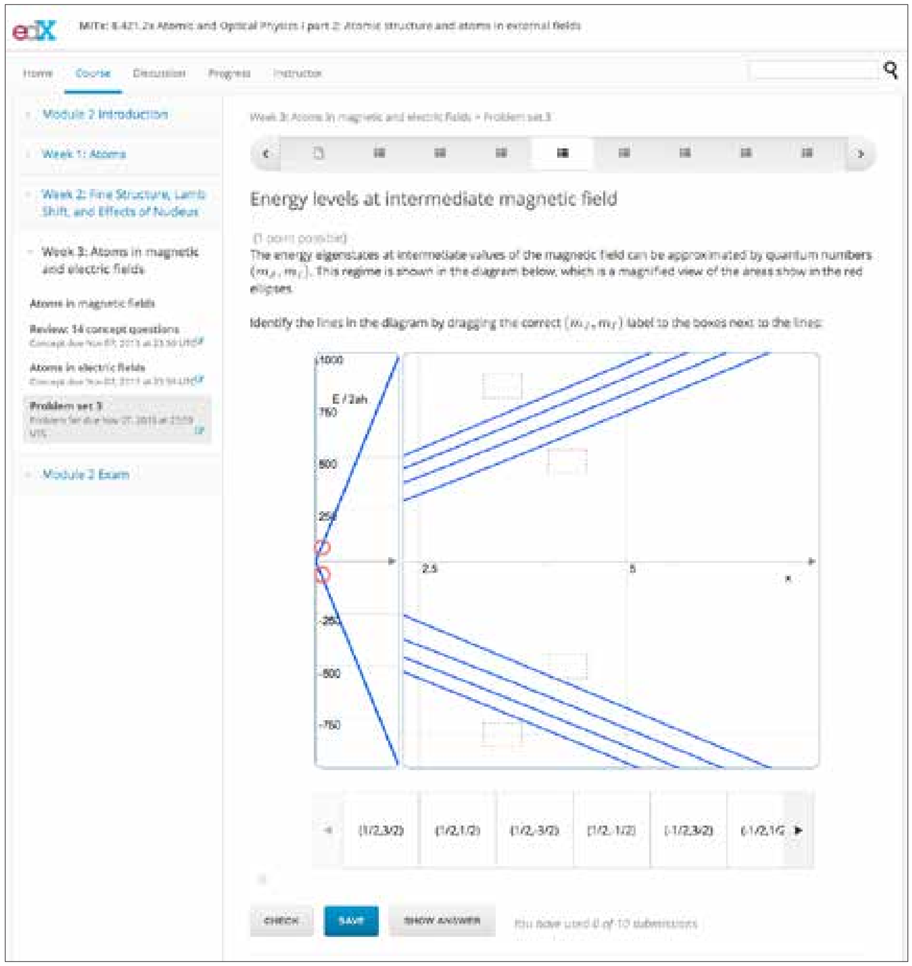
The atomic physics lecture sequence was videotaped in 2013 and 2014 and published on MIT's OpenCourseWare (OCW) site. The main motivations were to document the MIT Atomic Physics course; to allow MIT students to watch lecture videos when unable to attend a lecture; and to allow students and professors worldwide to see how atomic physics is taught at MIT (see *http://ocw.mit.edu/courses/physics/8-421-atomic-and-optical-physics-i-spring-2014/*).

Online course in the fall term 2015

With MIT's launch of edX, and a transition from OCW to more dynamic, massive and open online courses, the Atomic Physics course was well positioned to transform and evolve to a higher level of sophistication, and also to contribute a unique offering to the world.

FIGURE 2

***Screenshot of the 8.421x MITx on edX** course on Atomic and Optical Physics, showing a graphical homework problem in one of the problem sets.*



For the worldwide MITx on edX course on Atomic and Optical Physics, the material was segmented into five modules and all the homework assignments were turned into online problem sets—meeting the challenge of creating input modules for responding to questions on advanced topics *(Figure 2)*, the video lectures *(Figure 3)* were modularized and captioned, and in the Fall of 2015, the course went online, with MIT graduate TAs moderating the forum and answering questions. Overall, the course attracted over 6,800 unique participants (who registered and also clicked at least once into the course material), and 217 unique individuals who earned 430 completion certificates, spending over 12,000 hours on the course. The most participants came from the U.S., India, Germany, and the U.K., respectively. Relative to country population, the top four countries were Greece, Canada, the Netherlands, and the U.S. On average, 4.8% of the participants earned certificates. Eighteen individuals earned certificates in all five modules. Only 13% of participants self-reported as being female, though this fraction was much higher (above 20%) in Columbia, Poland, the U.K., and Greece. The course content comprised 16 chapters with 331 videos and 228 problems; 58 of these problems were concept questions, presented interleaved with videos. The videos totaled over 26 hours, and on average were each a bit under five minutes in length. Assessments included short pre- and post-tests, to be analyzed by Dave Pritchard's educational research group for evaluating the learning experience; elucidating patterns in effective use of online materials; and studying item difficulty and discrimination.

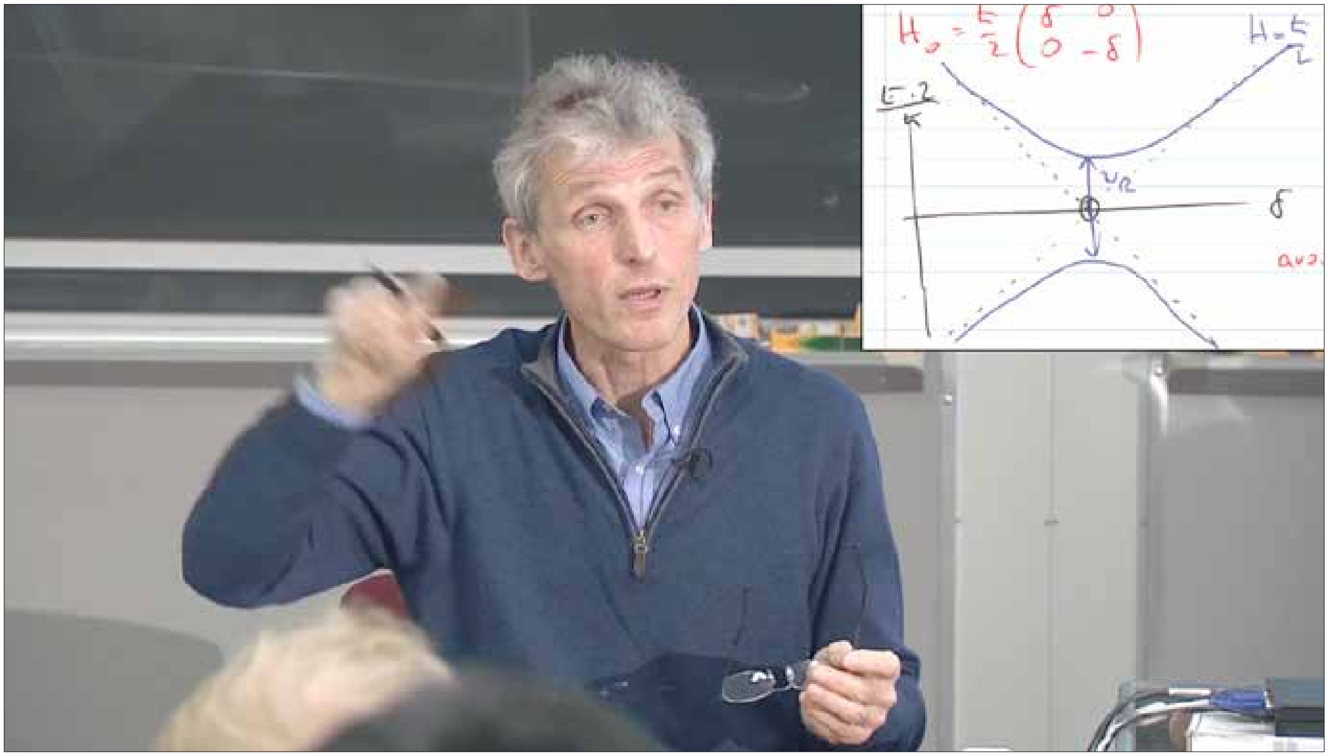


FIGURE 3

***Video shot of Wolfgang Ketterle** in the classroom, with annotated tablet slide content, as typically used in the online course.*

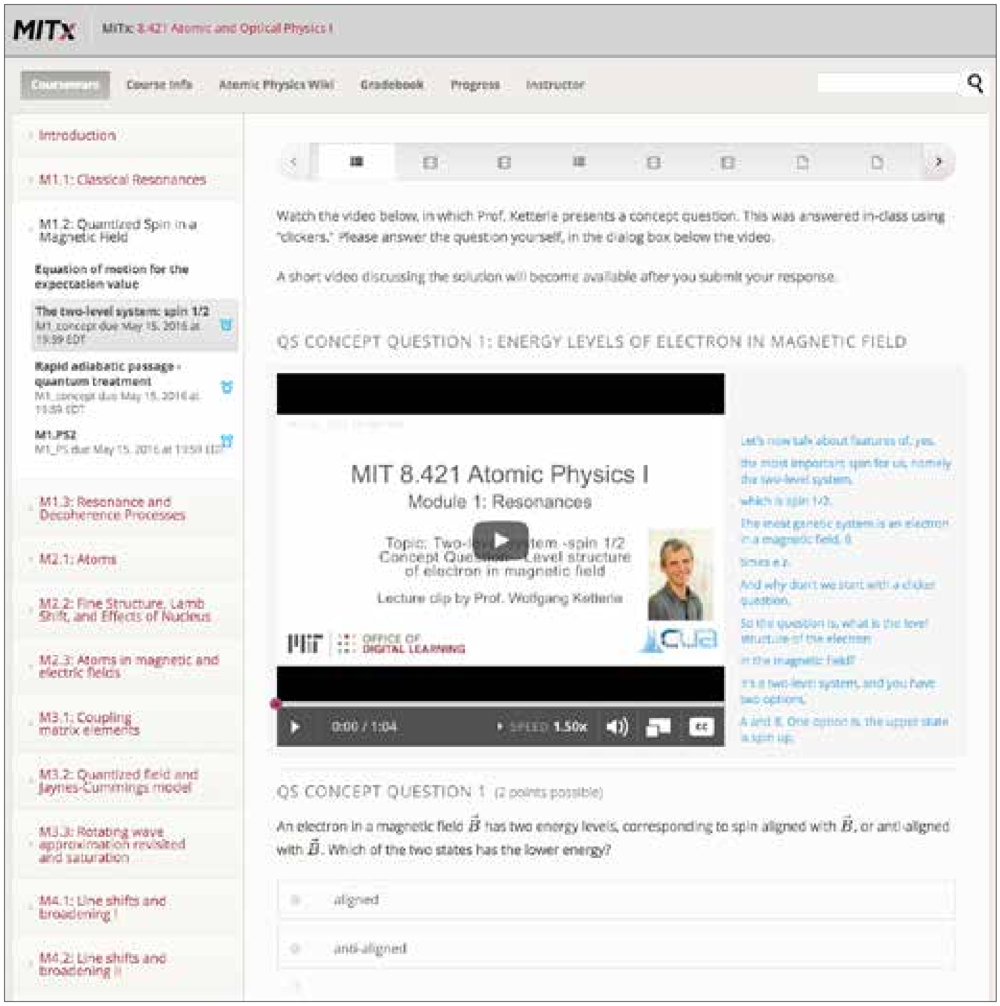
As faculty at MIT, since our primary mission is to provide the best education to MIT students, we wanted to immediately try out how the new online material could be used in a residential setting, with MIT students. The physics department gave permission to have MIT students take the online MITx on edX course for full MIT credit, when combined with weekly classroom discussions, a weekly recitation session, and a term paper. Just the right amount of students (six) signed up, enough to explore new formats in a small class setting, but not draining students from the regular residential class (which we teach in the Spring term). The weekly discussion sessions were a new experience. We realized how one could create deeper insight by engaging the students in discussions about the topics of the video lectures. The discussions also revealed that the students may have understood the material superficially, but got confused when asked to show expert abilities, e.g., to summarize limiting cases or describe the interplay of different concepts. And the students asked many questions, often challenging even for us. They asked for more discussion time, and we extended the weekly meetings from 1½ to 2 hours since we couldn't find a convenient schedule for additional meetings.

The anonymous feedback questionnaire at the end of the semester did reveal some weaknesses, e.g., many typos in the wiki lecture notes, or incomplete solutions to online homework problems. Also, most students said they would prefer a mix of online homework and traditional homework over online only.

However, 100% of the respondents preferred the new format. *All* students preferred video lectures with discussion sessions over traditional classroom lectures. This was a striking and unexpected outcome. We are, as MIT professors, live performers—but now the students prefer videotaped lectures! One student wrote: "I cannot stress enough how helpful the video lectures are for this course. I'm the type that prefers to take many notes during lecture, and I was able to get all of that out of the way before ever coming to class. I could pause the videos as often as I

FIGURE 4

Screenshot of the online course website *for the Spring, 2016 residential "flipped classroom" version of the Atomic Physics course.*



liked to make sure I'd written it all down. Then in the discussions, I could refer to my earlier notes and add comments as they came up."

Eighty percent of the students found the discussion sessions "extremely helpful," 20% "very helpful." One student commented: "Discussion session is very useful. I just hope I can get the material or note by professor so that I can review afterwards. These materials are so good that I even want to read them again in the future."

Spring term 2016 — flipping the classroom

Based on this strong positive feedback from the experimental small section, we felt we couldn't merely stay with the usual format anymore, thus we overhauled tradition and deployed a new "flipped classroom" version of Atomic Physics during the Spring term of 2016, with an enrollment of 40 students, and WK as the lecturer. This new format had video lectures and online problems *(Figure 4)* and two or three classroom meetings each week (a total of 10 overview lectures and 10 discussion sessions held by the lecturer, and 10 recitation sessions held by teaching assistants), plus a midterm exam and term paper. The online homework was complemented by three traditional problem sets that required written submissions, which were graded by the TAs. In the following, WK writes about the experience from a first-hand and personal viewpoint.

The flipped classroom experience was transformative for me. Without the pressure of covering lecture material in class (this was done by the video lectures), I could let discussions freely develop, deviate from my prepared material and often make references to (or tell anecdotes about) the development of the field or recent research. I felt that I could bring in all of my experience and personality into the classroom. This format encouraged many students to think through the material more deeply. In my more than twenty years of teaching at MIT, I have never experienced such an interactive and engaging atmosphere. Students asked many questions during class, and usually, after class, I had to stay for an extra 20 or 30 minutes to address questions by students. I did not use the class time freed by the video lectures to introduce additional material, but added extra layers of interpretation and discussion. I often used atomic physics phenomena to discuss general aspects of quantum mechanics (coherence and decoherence, symmetry and selection rules) and how to interpret them in different ways, e.g., classically or perturbatively, or in terms of dressed states. In the middle of the semester, feeling uncertain if I met the needs of the students, I included in the feedback questionnaire whether I should put instead more emphasis on atomic physics material, but 94 % of the students preferred the general quantum physics discussions.

Five graduate students served as TAs for this class, and they also participated in, and reveled in the transformation. In particular, because most homework questions were auto-graded online, the TAs spent less time doing mechanical grading and much more time offering office hours and presenting mini-lectures. As a result, they spent more face-to-face time with students, and creating new material to help improve understanding, e.g., by contributing to the wiki. Moreover, the TAs were excited by the potential for easily re-using all the video lectures, online problems, and wiki in their own future teaching careers.

This overhaul of the Atomic Physics course is one of the largest it has ever seen, and it received enthusisastic feedback from some of the students. One student wrote: “8.421 was my favorite class that I’ve ever taken. The online lectures freed up in-class time for engrossing free-form discussion sections that I miss greatly now that the class has ended. I greatly preferred that style of teaching over the standard in-class lecture format.”

Still, there were issues to pay attention to, as revealed in the end-of-term feedback questionnaire. This showed that two thirds of the students were not involved in research in atomic physics, but took the course out of general interest or to fulfill the breadth requirement. Since in discussion sessions, often the atomic physics graduate students asked questions, it is in hindsight not surprising that 50% of the student checked that “The discussion topics were often too advanced for me to understand, but still gave me a perspective,” or commented that the class should have included more general motivation and more basic discussions. Going forward, it is not clear how to balance the interest of the expert graduate students with the needs of students outside the field. One possibility would be to split the class time into more basic and more advanced topics.

Some students were concerned about the work load: to watch video lectures and attend classroom discussions and recitations two or three times a week. We tried to reassure them by promising not to introduce additional material during the classroom sessions, but rather help them to understand the material. Also, attendance was optional, and they had the option of watching only the lecture videos, which would expose them to the same material presented in previous semesters. However, attendance of classes was very high throughout the whole semester. In the end, several students criticized the high work load ("I think that the format is an excellent idea, but some serious work needs to be put in to make it take no more time than a standard class") and some redundancy between video lectures and classroom discussions. On the other hand, one student observed this repetition positively, writing that "Wolfgang would give a live overview lecture, then I would go online and read the wiki notes, watch the detailed lecture video while taking notes, do the online problem set, and finally attend a second live lecture with Wolfgang. Consequently, the basics of AMO are now as second nature to me as swinging a baseball bat."

Student opinion was divided about online problems. Fifty percent of the class liked the mix of online and paper homework, whereas 40% opted for paper only, and 10% want online only. Reading through the more detailed comments, it becomes clear that for more complex problems and derivations, the paper format was preferred, but that students liked shorter and conceptual questions online with the immediate feedback on whether or not they got the correct answer.

Although the student's comments show potential for improvements, we are convinced that we have taken a big step into the right direction. Seventy percent of the students want us to "essentially keep the new format," and some students were even enthusiastic: "I am thrilled I had the opportunity to take this course—I feel I have grown considerably in my understanding and in my capacity to engage in fruitful research in AMO physics. The biggest success of the course was the enthusiasm, time and energy the teaching staff devoted to the course for the benefit of the students," and one student simply stated that "all classes should be taught like this."

Future atomic physics teaching at MIT and beyond

Driven by this transformative experience, we plan next to develop and deploy online and flipped versions of 8.422, the second semester of Atomic and Optical Physics. This is planned for the Spring of 2017, with versions for both MIT students and for MITx on edX. We will take lessons from our on-campus, flipped classroom experience and "flip" that again, to share with the worldwide audience how MIT has learned to teach this material. This may involve more discussion topics, and deeper connections between MIT and worldwide learners.

Teaching at the highest level and reaching out to the world is an important and integral part of the Center for Ultracold Atoms (CUA), to which both of us belong. The CUA is an NSF-funded Physics Frontier Center [1]. The open, online Atomic Physics course helps connect the CUA with the general public and the scientific community. A graduate level online course in Atomic Physics is important, since atomic physics is a smaller subfield of physics and there are many universities which have no faculty in atomic physics, or too few to reach the critical mass to teach such a course. The CUA is among the world-leading places for atomic physics, and has an exciting research program in exploring the quantum world with atoms and light, and engineering and studying new quantum materials. The Atomic Physics course, and CUA faculty, have educated many students and postdocs who are now in leading positions around the world, and we hope that they are also inspired to use new approaches to teaching.

REFERENCE

[1] Despite CUA successes, support from the National Science Foundation is decreasing, reflecting a general trend in the federal funding of fundamental science. To continue its mission, the CUA is trying to attract additional sponsorship; feel free to contact us for more information.

PROFESSOR ISAAC CHUANG *is a pioneer in the field of quantum information science. His experimental realization of two, three, five, and seven quantum bit quantum computers using nuclear spins in molecules provided the first laboratory demonstrations of many important quantum algorithms, including Shor's quantum factoring algorithm. The error correction, algorithmic cooling, and entanglement manipulation techniques he developed provide new ways to obtain complete quantum control over light and matter, and lay a foundation for possible large-scale quantum information processing systems.*

Chuang came to MIT in 2000 from IBM, where he was a research staff member. He received his doctorate in Electrical Engineering from Stanford University, where he was a Hertz Foundation Fellow. He also holds two bachelors and one masters degrees in physics and electrical engineering from MIT, and was a postdoctoral fellow at Los Alamos National Laboratory and the University of California at Berkeley. Chuang is the co-author, together with Michael Nielsen, of the textbook Quantum Computation and Quantum Information*.*

PROFESSOR WOLFGANG KETTERLE *does experimental research in atomic physics, exploring new forms of matter of ultracold atoms, in particular novel aspects of superfluidity, coherence, and correlations in many-body systems. His observation of Bose-Einstein condensation in a gas in 1995 and the first realization of an atom laser in 1997 were recognized with the Nobel Prize in Physics in 2001 (together with E.A. Cornell and C.E. Wieman). His earlier research was in molecular spectroscopy and combustion diagnostics. Ketterle received a diploma (equivalent to a master's degree) from the Technical University of Munich (1982), and a PhD in Physics from the University of Munich (1986). After postdoctoral work at the Max-Planck Institute for Quantum Optics in Garching, Germany, the University of Heidelberg and at MIT, he joined the physics faculty at MIT (1993), where he is now the John D. MacArthur Professor of Physics, Director, MIT-Harvard Center for Ultracold Atoms, and Associate Director, Research Laboratory of Electronics.*

His awards include a David and Lucile Packard Fellowship (1996), the Rabi Prize of the American Physical Society (1997), the Gustav-Hertz Prize of the German Physical Society (1997), the Discover Magazine Award for Technological Innovation (1998), the Fritz London Prize in Low Temperature Physics (1999), the Dannie-Heineman Prize of the Academy of Sciences, Göttingen, Germany (1999), the Benjamin Franklin Medal in Physics (2000), the Nobel Prize in Physics (2001), the MIT Killian Award (2004), and a Humboldt research award (2009).