PROFESSOR: So this first lecture is a spirited but lighthearted introduction into the course. I usually never talk about technicalities first. I want to talk about the excitement of the field first. So I will talk about technicalities a little bit later.

So when you take a course in AMO physics, the obvious question is, what is AMO physics? What defines our field? Actually, by far the best definition of what AMO physics is-- it is what AMO physicists do, which is defined by a community of AMO researchers.

And this is really characteristic for our field. I will tell you in the next 10 minutes or so about these enormous dynamics of the field, how AMO physics has changed in a fraction of my lifetime. And what happened is, I felt, whatever I was doing-- and it turned out to be very different of what I did 10 and 15 and 20 years ago-- has stayed in the center of AMO physics. So myself and the whole community, we're moving, and took the field along. So therefore AMO physics is what gets AMO researchers excited. It's not a joke. It's the way it sort of happened.

Well, a little bit more mechanically, we can define AMO physics. AMO physics is what is made out of the building blocks we have in AMO physics. So defined by the building blocks. And in AMO physics, we build systems out of atoms, or molecules, and then photons, or light, and in general, electromagnetic fields-- electric, magnetic fields, microwaves and all this. So in other words, everything which is interesting and we can put together with those building blocks, this is AMO physics now. And this may redefine AMO physics in the future.

Now, historically this meant that those building blocks, atoms and molecules, were available in the gas phase. So you had gases of atoms, gases of molecules, and

you studied them. And almost all of AMO physics was actually about individual particles, individual atoms, individual molecules, because in the gas phase at high temperature, pretty much, you learned that in statistical mechanics each particle is by itself. And the partition function of the whole system is just factorized into partition functions of the individual particles. Well, maybe with some exception-- occasionally, particles collide. And the field of collisions-- collisions between atoms and atoms, atoms and ions, atoms and molecules, molecules and photons-- this was widely started in AMO physics.

Well, now the field has really moved away from just individual particles and collisions between two particles. What is in the center of attention is few body physics. And that of course takes us to entanglement. For instance, people study entanglement of eight ions in ion traps. And of course this is deeply related to quantum information science.

Or if you want to go from few body to many body, this is now starting to overlap with condensed matter physics. And this is now widely studied in the field of [INAUDIBLE] atoms and quantum gases.

Now, when we talk about many body physics, we get, of course, into overlap with condensed matter physics. In condensed, I would actually say now a larger fraction of AMO physics and condensed matter physics overlap strongly, that we speak the same language, we study the same Hamiltonian, a lot of theorists apply the same methods to topics coming from either field. However, often in technology, how the systems are studied, there's a different culture, different tradition, and still two different communities.

And the overlap comes about because there are systems in nature which you can say-- they are natural two or few level systems. Of course, we've helped nature a little bit by engineering. Those systems are, for instance, quantum dots or NV centers in diamond.

Or another overlap with condensed matter physics is that AMO physics is now-- one frontier of AMO physics is the optical control of mechanical oscillators. Micro

cantilevers, membranes, tiny mirrors in cavities, they have mechanical motion. And the mechanical motion is strongly coupled to the photon field. Of course, for fundamental AMO physicists, a mechanical oscillator is nothing else than an harmonic oscillator.

So one can say-- and this is sort of my third attempt in defining for you what AMO physics is-- AMO physics is almost defining itself by low energy quantum physics. So all of the quantum mechanics which doesn't take place at giga and tera electron volt, which takes place at low energy, this is AMO physics. Of course, maybe not all of it. Usually when it is in [INAUDIBLE] solution, it's biophysics, and it's distinctly different from AMO physics. Or if the solid state is involved, then it's more condensed matter physics. But I would say there is one part of solid state physics which is already becoming interdisciplinary with AMO physics. And this is when the control of the system is not done by wires and carbon probes but it is done by lasers.

So if you have a solid state system and you use all of the methods you apply to atoms, you use electromagnetically-induced transparency, coherence, all those concepts, then AMO physicists feel at home and they don't care if the two level system or the harmonic oscillator is an ion oscillating in an ion trap or whether it's a small cantilever, the methods and concepts are the same.

So therefore, one could say AMO physics is sort of the playground where we can work on extensions of simple systems which we understand and cherish. And of course, our exactly solvable problems are the hydrogen atom-- my colleague, Dan Kepner, would have said, maybe the hydrogen atom, if you understand the hydrogen atom, you understand all of atomic physics. I'm not so sure. I would actually say, in addition to the hydrogen atom, you have to know the two-level system. And of course, you have to understand the harmonic oscillator.

So these are three paradigmatic Hamiltonians, and a lot of understanding of much more complicated systems really comes from taking the best features of those three systems and combining them. If you have questions or comments, this is an

interactive class. Feel free to speak out or interrupt me.

OK so, now we know, or we don't know, what AMO physics is. Let me now address-- how has AMO physics developed? And I mentioned to you that AMO physics has done breathtaking evolution in my lifetime, or even in the shorter part of my life, which is my research career.

Well, traditionally, almost all fields in science started with observing nature. The pursuit of science was born out of human curiosity to understand the world around us. And atomic physicists, well, they started to observe atoms and molecules, usually in the gas phase, and what they were doing.

And already there was some evolution, because original observations at low resolution were taken to a completely new level when high-resolution methods were developed, when lasers came along, when people had light sources which had fantastic resolution and eventually finer and finer details of the structure of atoms and interactions between atoms were resolved.

But AMO physics is a field which has taken the pursuit of science much further. So there is not just observation of nature-- and I want to write that with capital letters-- there is CONTROL OF NATURE. And you maybe take it for granted, but you should really appreciate it, that controlling nature, having control over what you study, modify it, advance it, take it to the next level, is really something wonderful.

It is completely absent in certain fields, like astrophysics. In astrophysics, all you can do is, you can observe. In atomic physics, we create the objects we can observe.

So the control of nature, the control of our atomic physics system, developed in stages. The first kind of control was exerted about internal states. If you have an atom at thermal energies, it would only come in hyperfine states which are thermally populated, or molecules come in rotation states, and well your limited control was simply to raise and lower the temperature.

But with the advent of optical pumping-- this actually happened already with classical light sources before the invention of the laser-- so with optical pumping,

you can pump the internal population of molecules into, let's say, a single rotational state. So this is control over the internal Hilbert space. And this was actually rewarded with a Nobel Prize to Alfred Kastler in 1966.

Of course, the next step after controlling the internal degrees of freedom is have control over the external degrees of freedom, and this means control motion. This was of course pursued by understanding the mechanical aspect of light. How do photons mechanically interact with atoms? This eventually led to laser cooling and Bose-Einstein condensation. And those developments were recognized with major prizes.

Well there is more to it than controlling internal and external degrees of freedom. You can then also say, well, how much can we control the number of building blocks? And eventually AMO physics advanced to exert control onto single quantum systems-- single photons, single atoms. A single atom in a cavity exchanging a photon with a cavity thousands of times. So this control of single quantum systems was actually just recognized with a Nobel Prize a few months ago.

Well, at this point I sometimes make the joke, we have gone from big ensembles in many, many quantum states to single photons, single atoms, in a single quantum state-- a single quantum state for many particles is Bose-Einstein condensation. So we have really gone down to single atoms, single photons, single quantum states. Well, what comes next? To have no atoms and no light in vacuum.

Well, the vacuum has some very interesting properties. And if you talk to Frank Wilczek, the nature of the vacuum and dark energy is one of the big mysteries in physics and in science in general. But the study of that is definitely outside the scope of AMO physics.

So what happens is, when we have gone down and have now control over the building blocks, now we can sort of go up again in a controlled way, create complexity by assembling a few photons, a few atoms into new entangled states, so we can now take our system into very different regions of Hilbert space.

So what is defining now the control is, we want to use this pristine control over the building blocks to now put in something which hasn't existed naturally before, or when it existed it was completely obscured, completely hidden by thermal motion or by you can say homogenous broadening our lack of control. And the best buzzwords are here now entanglement and many-body physics.

It's hard to capture that as in a diagram, but let me try that. I don't know actually what I'm drawing, but I think you get the message that this is sort of Hilbert space. And I have 2 x's. One is sort of entropy, high temperature, and the other one is complexity.

And for quite awhile, people studied hot gases. So these are gases, there's a lot of entropy in it. The complexity is actually not particularly high. And everything is described by a statistical operator-- the density matrix.

The pursuit of cooling, and actually, control-- gaining information about a system is also a way of cooling. If you know in which state the atom is, the entropy of the system is zero even if you haven't changed the state of the atom. So control and cooling, control measurement and cooling, has now taken us to the point where we have systems which have no entropy anymore. They are very, very well defined.

And our goal now is to take these systems to much more complexity where wave functions become entangled and we have strong correlations in many-body systems. But this is now, maybe here, this is now described by wave functions. But here is the wave function of a single particle, and here we have highly correlated, highly entangled many-body wave functions.

So at least for me-- but all predictions are notoriously incorrect when you look at them in a few years from now-- but for me, this is where the future of our field is moving, to get into interesting regions of Hilbert space where no person has been before.

As an experimentalist, and with a lot of experimental graduate students in this room, I want to emphasize that a lot of those rapid developments of the field are driven by

technology. So it's driven by technology advances.

In the '50s and early '60s, people thought AMO physics is pretty much dead. Only a few people with gray hair continue what they have done and the field will eventually die. But then technological developments made it possible to do major conceptual advances.

I've mentioned the conceptual advances-- let me now say a few words about the technology which has driven it. There was one phase of developing lasers which I experienced when I was a student. But those lasers were fantastic. They were very narrow already, very stable, but they were very expensive and very complicated. So if you had one laser, this defined your laboratory and then you studied a lot of things with the single laser you could afford.

Well, you're probably not used to one big dye laser pumped with a big argon ion laser. It was a $250,000 investment for the lab. And of course, you couldn't afford a second laser. It required 50 kilowatts pf electrical power. And all this power had to be cooled away by gushing water through thick pipes. So it was an expensive undertaking but you could really do wonderful science with it.

So what I've seen in the last 20 years is the proliferation of solid state lasers, starting with diode lasers and continuing until the present year. So now, in a lot of our laboratories here at MIT, we have 10 lasers. And we've stopped counting them, because adding a laser to the system is almost like adding an amplifier to a circuit or adding another circuit to a data acquisition system.

But it's not just the simplicity of the lasers which we have now, the robustness-- to have 10 lasers in the lab, it's fine. Previously, if you had three lasers in the lab, you spent 90% of your time just keeping the lasers running.

Those lasers, not so much continuous-wave lasers, but pulse lasers have also very, very different properties. Laser pulses got very, very short-- femtosecond or even attosecond. Shorter pulses means that the energy is now focused to a much shorter temporal window. Therefore, laser pulses of very, very high intensity-- if you focus a

short pulse laser on an atomic system, you can easily reach an electric field of the laser which is stronger than the electric field of the atom.

So in other words, if you have protons and electrons-- well, maybe the outer electrons, not get down to the single protons. But maybe an ionic core, and you've electrons. Now, you should first look at the motion of free electrons in the strong field of the laser and add the atomic structure as a perturbation. It really takes the hierarchy of effects upside down. So the appearance of high intensity lasers has given rise to a whole new field of atomic physics.

Lasers got more precise. The invention of the frequency combs, recognized by the Nobel Prize in 2005, meant now that we can control laser frequencies at a level of 10 to the minus 17. And this has completely redefined precision metrology and has advanced the control over atoms and molecules I've mentioned before.

Finally, another technical development which plays a major role in research being pursued here at MIT and elsewhere are the development of high finesse cavities. High finesse cavities in the microwave range-- then they're superconducting-- or high finesse optical cavities by having super mirrors. It is actually those super cavities which have enabled the study of single photon physics. Because after all, photons move away with the speed of light. And if you want to observe a photon in your laboratory, it has to bounce around zillions of times in order to have enough time for the photon to do something interesting.

So sometimes a field at the frontier of science is defined by paradigms. If you want to explain to somebody why your field of interest is cool and exciting, you usually do it by picking a few really exciting examples. And I want to show you how, over the years, it has advanced.

Definitely in the '50s and '60s, you would have mentioned that we understand now atomic structure of multi-electron atoms. Optical pumping just started. So these were flagship developments of AMO science.

The cool thing to do in the '60s and '80s was, use the new tool, the laser, applied to

atoms and do laser spectroscopy. Sub-doppler spectroscopy, sub-natural spectroscopy, resolving hyperfine structure-- wow. I mean, this was really exciting in those days. And well, the older people I have met, my teachers, my thesis adviser, these were people who started their research career before the laser was invented but then, as a young researcher, embraced this new tool and helped to redefine the field.

Definitely in the '80s and '90s, the cool pictures were those of magneto-optical traps, atoms standing still and hovering around. So the new aspect where mechanical forces of light which led to laser cooling and trapped atoms.

In the late '90s, of course, the excitement was about Bose-Einstein condensation. And it was really Bose-Einstein condensation which drove AMO physics from single atoms, maybe two atoms colliding, to many-body physics.

It's always easier to analyze those things by looking backward, so if I'm now getting closer to the past, I have to be a little bit vague. But in the 2000s, I think hot topics were ultracold fermions and the study of entanglement and correlations.

And what is the paradigm now or in the near future? Well, I think you have to help to define it. If you make an interesting discovery, this is what people will be pointing to and would say, this is what now defines AMO physics.

Some candidates are, of course, if there is a major breakthrough in quantum computation-- let me put question marks here. In the field called atom science, we may actually do some progress towards topological states which have different symmetries and different properties.

And another emerging frontier is micro-mechanical oscillators. The last couple of years, we just had the breakthrough for the first time. Mechanical objects were cooled to the absolute ground state. So at least for that community it was, but for many of us, Bose-Einstein condensation was 15 years ago. Any questions?

Well, eventually we have to talk about this course. So I've told you about, at least, a snapshot of where AMO physics is, how it has developed, and on what trajectory it

is. In this course I want to present you the concepts behind many of the major advances in the field.

So over the years, quite often a topic was added to the course, because I felt, hey, that's getting really exciting, that's what people want to do in research, that's what graduate students want to do here. And then the subject was added and other subjects were dropped. I know in the '90s, I was teaching aspects of laser cooling, sub recoil laser cooling, which was the latest excitement. This year, I may mention it for 30 seconds.

So the course has evolved. It wants to stay connected to what is exciting, what is hot, and what prepares you for research at the frontier. 8.422, the second part of the two-course cycle in the graduate course in AMO physics, is somewhat different, not radically different, but is somewhat different from part one, from 8.421.

First of all, 8.421, 8.422 can be taken out of sequence. We alternate between AMO 1 and AMO 2. And whenever you enter MIT, you're probably in your second semester, take whatever we offer. So I expect-- let me ask you, who of you has taken AMO 1? Yes, statistically, it should be about half of the class.

It can be taken out of sequence because that's the way how we've structured it. But to give you one example is, in 8.421 you really have to learn about hyperfine structure. You have to learn about atoms, you have to learn about Lamb shift and all that. So you have to learn what all these atomic levels are.

And here in that course, in 8.422, I will say, here's a two-level system and then I run with that. And we do all sort of entanglement, manipulation of two-level systems. So it helps you if you know where those two levels come from, but you don't really need the detailed knowledge of atomic structure, for instance, to understand that.

So this is why the different parts of the course are connected, but in terms of learning the material, somewhat decoupled. I've spoken to many students who said there was no problem in starting with 8.422. The only sort of critical comment I've heard is that taking 8.422 first and then 8.421 is anti-climactic. You see all this

excitement in the modern physics, and then, eventually, you have to work on the foundation.

Prerequisites for this course-- the course announcement said 8.05. It is actually 8.05 and 8.06. The main part of 8.06 which we really need here is perturbation theory-- time independent, time dependent perturbation theory, and this is usually covered in 8.06. However, I've had students who took the course without 8.06. If you're really determined and want to acquire certain things by self-study, you can follow this course.

So the topics we will cover include QED. I really want to talk about light-atom interactions from first principles. Sure, 95% of what we're doing is just done by saying we have a matrix element, which maybe the dipole matrix element. But you really have to know what are the approximations, what are the conditions, which lead to the dipole approximation. And I want to do that from first principles, and we do that starting on Monday.

So a discussion of light-atom interaction has two parts. One is the simple part-- excitation and stimulated emission. Because this can be simply described by a unitary time evolution, and you can do a lot, if not everything, by using Schroedinger's equation. Things get much more complicated and richer if you include spontaneous emission or, more generally, if you include dissipation.

Then we talk about open systems. And for fundamental reasons, we need a formulation using the density matrix, a statistical operator, and a master equation.

One major part of the course is discussion and [INAUDIBLE] derivation of the mechanical forces of light. This will include a discussion of important experimental techniques using those mechanical forces. So various simple and sophisticated methods of trapping and cooling.

We will spend some time in not talking about atoms at all. We're just going to talk about photons, about single photons. We want to understand where the photon nature of light makes light very, very different from a classical electromagnetic

wave.

Also, it's not the focus, we will come across basic building blocks of quantum information science. Pretty much when atoms and photons interact, this is a fundamental quantum gate.

And we'll talk about the many-body physics off quantum gases.

So maybe it becomes clearer what we are covering by saying what we are not covering. And this tells you that there is at least some selection of topics. It's not that we talk about everything.

We will not talk about the physics above 10 electron volts. We will not talk about collisions-- or maybe I should say, high-energy collisions. We will, of course, talk about nanokelvin collisions, which is the physics of the scattering links and some s-wave collisions which are really relevant to understand quantum gases.

We're not talking about any advanced topic in atomic structure. All we do about atomic structure is done in 8.421. And if you want to graduate in atomic physics at MIT, yes, you have to understand atomic structure at the level of the hydrogen atom. And maybe know a little bit about a new phenomena-- when another electron enters, when electrons interact and that's a helium atom-- but we're not going beyond it.

Let me just mention here that there is, of course, more interesting things in atomic structure. For instance, if you go to highly charged ions, you have QED effects. You can discuss very interesting correlations between two electrons in an atom. And you can have very relativistic effects if you have highly ionized atoms.

If you have bare uranium, then the electron in the lowest orbits becomes relativistic. You can even see, if you scale the fine structure constant-- which has an e squared in it-- with the charge of uranium 92, well, 1 over 137 times 92 gives about 1, so you really get into a new regime of coupling for atomic physics. But we won't have time to talk about it.

And this may be an omission, because there is really interesting work going on. We're not talking about high intensity lasers and short laser pulses. This choice maybe mainly determined by that the experimental program in the physics department is not overlapping with that. But of course, you know we have world class researchers and short pulse lasers in the electrical engineering department. Any question about the syllabus? Questions about what to expect in the next 12, 13 weeks?

Well, then let's talk about some technicalities. I'll keep it short because all this information is available on the website. We run the website of the CUA server. So it is cua.mit.edu/8.422.

When I say all the information is available, I have to say-- not yet. I realized yesterday night that [INAUDIBLE] has re-modified the server. I didn't have access to the server. I just got it an hour ago.

What you will find under this URL is the website from when the class was taught two years ago. And actually, more than 90 percent of the information is the same. I always try to improve the course, but I know it will be more incremental changes and not dramatic changes. So if you look at the website, you'll already get a taste what the course is, but within the next day or two, we'll have updated information.

I know, at least for most of you, I have contact information for MIT registration. But if you are a Harvard student or a listener just sitting in and you haven't registered for the class, I would ask you to send an email to our secretary, Joanna, j_k@mit.edu, because I would like to have an email list for the class for corrections to the homework assignment or last minute announcements. And then we'll add you to the mailing list.

The schedule of the class is, well, we meet at this time on Monday, Wednesday. And let me know disclose, I plan to occasionally teach on Fridays at the same time. Over many years, it has been my experience, if you have a class on Monday, Wednesday at one o'clock, you don't have another class Friday at one o'clock. Is that assumption correct?

So within the next few days, I will tell you on the website which Friday I would like to teach. The reason is rather simple. Like every faculty member who's active in research, I have to go to funding agency workshops and conferences. I try to keep it to a minimum, but on average I will miss two or three classes. And instead of asking a [INAUDIBLE] or a graduate student to teach the class, I would like to teach the class myself. So I will have makeup classes on Fridays.

OK, that's the schedule. Finally, talking about requirements, one requirement is homework. We have 10 wonderful problem sets with a lot of problems which I actually designed from current research. So you will actually recognize that a lot of problems are created based on some research papers which came out of my own group or other groups at MIT in the last few years.

The good news is, there is no mid-term, there is no final, but there will be a term paper. And the term paper is due on the last day of classes.

The teaching team are myself, Joanna Keseberg, our secretary-- that's also where you will be dropping off your homework-- and then we have assembled a wonderful team of five TAs. They are all advanced graduate students.

And actually, I've picked TAs from all of the active groups here at MIT. From Martin Zwierlein's group, I. Chuang's group, Vladan Vuletic's group, and my group. Are any of the TA's around? Nick, Alexei, Jee Woo, Lawrence, and Molu. Each TA will be responsible for two weeks in the course, and the TA will indicate availability and office hours on the weekly homework assignment.

Other details about the term paper, how long the term paper should be, the, kind of, what I regard as an honesty code, that you're not trying to get access to solutions from previous courses, all that is summarized on the website. And once I've updated the website, I'm sure you will read it. Any questions?

OK, well, with that we will actually be ready to jump into the middle of the course and start with some heavy duty equations of QED. But no-- just joking. I think this would maybe spoil the introduction.

What I actually like to do is, to make the transition from the introduction to the discussion of atom-photon interactions and quantum electrodynamics, I always like to start the course by giving you an appetizer by talking to you in a lighthearted but hopefully profound way about the system, which helps to showcase what are we doing in this course. And until a few years ago, I would have started with the simplest example of laser cooling, simply beam slowing or optical molasses, in the simplest possible picture, just to give you a taste of what we will be doing together during the semester.

But as I said, AMO physics is moving along. And what I now want to use as an example which clearly synthesizes many aspects of this course are atoms in an optical lattice. So let me, in the last, next 20 minutes or so, make some connections to different topics of this course by using as a starting point a concrete, very simple system, but very, very rich and profound, and these are atoms in optical lattice.

So the situation I want to use here is that you have two laser beams which interfere. And those laser beams form an optical standing wave. So next week we will learn how this electromagnetic wave interacts with atoms. So we have to put a few atoms into the system.

And we will derive, from first principles, the QED Hamiltonian, which, after a lot of manipulation and eliminating complicated terms, will be the dipole interaction. But of course, each symbol here is an operator, and there's a long story behind that.

In about two months, we will describe light-atom interaction with a formalism which uses a Bloch vector and the optical Bloch equations. There is a vector with three components which describes what is the state the atom is in. One component will tell us if the atom is in the upper or the lower state, whereas the other components tell us whether the dipole moment of the atom is in phase or out of phase with a driving electromagnetic field.

Well, if there is part of the dipole moment which is in phase with a driving electric field, then the suitable expectation value defines a mechanical potential. And if the

electric field is a standing wave, then we generate, through light-atom interaction, a periodic potential for the atoms.

We will learn everything which we have to know about this potential. In a simple case, it is simply the Rabi frequency divided by the detuning of the electromagnetic wave. But we will find it very interesting to look at it from very different point of view.

And maybe let me use this example to point out that I'm really a big friend of explaining the same physics from very, very different perspectives. And when we talk about optical standing waves, we will use a picture of a classical potential, like a mechanical potential, and the atom is just moving around. We will use a photon picture that every time the atom feels a force, photons are involved. You don't see them in the classical potential, but photons are behind it, and ultimately, the forces of the classic potential come from stimulated absorption emission of photons.

I may go down to the microscopic level. And I may ask you, but in the end, it's an atom, but the atom consists of electrons. And the electrons are simply oscillating because it's driven by the electromagnetic field. It's actually something which most people are not aware of, but you can ask the question now-- is the force in the optical lattice on the atom, it's ultimately a force on the electron?

Well, if you have a charged particle, you can have two kinds of forces-- an electric force or the Lorenz force. And I don't know if you would know the answer, but an atom is in an optical lattice, is the force just the [INAUDIBLE] the potential which the atom experiences, is that fundamentally due to the Coulomb force exerted by the electric field of the light, or is it due to the Lorenz force exerted by the magnetic part of the light?

Who knows the answer? Who doesn't know the answer? OK, great. I was actually surprised when I derived it a few times for the first time. And it's not in the standard textbooks. So anyway, I hope, even for many of you who know already a lot about the subject, I hope I can add other perspectives for you.

OK, so what I've discussed so far is that the standing wave of light creates now a

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periodic potential for the atom. And we will understand it from many, many different perspectives, from the photon type, quantum optics perspective, to the most classical description.

So what immediately comes to my mind is that we now want to look at this periodic potential in two different situations. We can ask, well, whenever you have light, spontaneous emission is a possibility. And we may ask, what happens when spontaneous emission is not negligible? And we discuss that approximately in week nine of the course.

Then what happens is, an atom has an excited and a ground state. And those in the excited and the ground state, do the atoms feel the periodic potential? Well, eventually, we have to generalize the notion of ground and excited state into [INAUDIBLE] states, and I will tell you all about it in a few weeks.

But the situation can now be, when an atom is in the ground state, it has to move up the standing wave potential. Then it's getting excited with a laser. It has to move up again the standing wave potential. And then there may be spontaneous emission.

So what I'm just describing here is a situation where the atom is mechanically moving up the potential. It's excited at the top of the potential. And it emits when it's on top of the potential. So the atom is doing mechanical work, and this is called Sisyphus cooling.

This is the way, this is one method, one mechanism, of laser cooling which leads to the lowest temperatures in the laboratory before evaporative cooling is used. So that's some cool aspect we will come along by discussing motion in a standing wave, but taking into account that photons are emitted and really understanding when and where are the photons emitted.

Well, the second situation is, of course, if spontaneous emission is completely negligible. Then we have a situation where all what matters is the potential, and we can completely forget that it's photons, it's quantum optics which has created this potential. We can simply use a classical potential in our description in our

Hamiltonian.

Now, again, we have two limiting cases. One case is when this potential, or optical lattice, is really deep. Deep means that atoms are sitting deep in the potential and they can oscillate around, but they cannot jump over to the next potential.

So in this situation, you would say, well, that's boring. Nothing happens, the atom just stays put. But what is boring for some of you is exciting for some others, because these atoms are exquisitely controlled. They cannot collide, they cannot interact with other atoms. So these are really the most ideal situation you can imagine for atoms. Of course, if you have less than one atom per site.

And this is the way how you want to prepare atoms for the most accurate interrogations. And you can build atomic clocks, optical atomic clocks, based on atoms insulated in such a lattice, which approach now 10 to the minus 17 accuracy.

Well, if you drive a clock transition, if you take the atom from the ground to the excited state, you may face a situation I mentioned earlier that the periodic potential for the ground and excited state are different. And that would actually interfere with your clock, because the clock frequency depends now on what the lattice is doing to your atoms.

However, and we discuss that in week four, there are what people call magic wavelengths, where you pick a certain wavelength for your optical lattice where the periodic potential is absolutely the same for ground and excited state. So that means you have, then, the perfect decoupling between the ticking of the clock, the internal structure of the atom and the mechanical motion of the atoms in the potential.

And in that situation, you create a situation which has been studied since [INAUDIBLE], namely with trapped ions. If you have a single ion in an ion trap-- and ion trapping is pursued here at MIT in Ike Chuang's group-- you have just a single object completely isolated. And in the form of the aluminum ion, this has just been demonstrated to be the most accurate atomic clock in the world with 10 to the minus

17 accuracy.

So anyway, with optical lattices, avoiding spontaneous emission using magic wavelengths, we can only engineer with neutral atoms what has been available with trapped ions but we can simultaneously have 10,000 copies and look at 10,000 atoms which are all identical copies, identical systems with each other.

So you see already from that example that there will be intellectual overlap and synergy between talking about neutral atoms in optical lattices and talking about trapped ions and how they are cooled and how they are manipulated. And we'll talk about trapped ions at the end of the course, sideband cooling of trapped ions, which is week 12.

OK, so this is the simple but pristine situation that we have a deep lattice. The other limit is now that we have a weak, or shallow lattice. And the new physics which now comes into play is that atoms can move around-- they can tunnel from side to side.

So towards the end of the course, I think the last months, approximately week 10, I will give you a short summary of what some of you may have already learned in the solid state course-- namely, band structure of atoms in optical lattices, Bloch states, effective mass, et cetera. This has now become language of atomic physics, because there is a very clean and straightforward realization of this physics using cold atoms.

What we are mainly interested in, in our research, is when we have atoms which tunnel in this optical lattice. And for bosons, if the interactions get strong enough, the Bose-Einstein condensate is destroyed and what forms is a Mott insulator. This is a phase transition. And for fermions, we have a crossover from a metal to a fermionic Mott insulator.

And with that, we are already overlapping conceptually with condensed matter physics, because the Mott insulator is a paradigm-- one of these paradigmatic examples where you understand some deep physics. It's a paradigm of condensed matter physics where you have only a partially-filled band. Common sense, or

undergraduate textbooks, would say, partially-filled band, this means you've a metal, you've a conductor. But because of the interactions of the atoms, the system is an insulator. So this is where, really, the many-body physics profoundly changes the character of your system. Any questions?

Well then, let me add one last aspect to my introductory example of optical lattices. In a sort of flyover, I described to you what is the physics we encounter when we have an optical lattice switched on and the atoms move around or they don't move around, and both cases are interesting.

But if you think you've explored everything, well, then you think harder and say, hey, there's another angle we can get out of it. And this is, we can take the optical lettuce and simply pulse it on, switch it on and off. Well, what happens is, and then it becomes a time-dependent problem. It becomes something where we can shape and control the wave function of atoms in time-dependent way.

Let me give you one example. If we start with very cold atoms-- can be a Bose-Einstein condensate-- and then, for a short time, we switch on the lattice, afterwards, we observe that we have still some atoms at zero momentum. But now we have atoms which have a momentum transfer of plus minus 2 h bar k.

You can understand that-- and this again exemplifies that we want to look at the physics from different angles-- this can be described that you have an two-photon transition from the ground state with zero momentum to the ground state with two-photon recoil. So you can understand it in the photon picture.

But you can also understand it by saying you have some matter waves which are now exposed to a periodic potential. And you simply ask what happens to waves in a periodic potential? Well, that's the same what happens to optical waves when they encounter a grading, and that's the physics of diffraction. So in a nutshell, this happens when we use a pulse on an optical potential.

And let me now finish by telling you that, again, in this situation, we discover the ambiguity or the two-sidedness of a lot of things we do in atomic physics. I've

mentioned to you that the same experiment, the same experimental setup, cold atoms in optical lattice-- you turn up the lattice and you have the world's best atomic clock, atoms just isolated from each other. You turn down the lattice and you have an interesting condensed matter physics system.

Let me just show you that the same two-sidedness of atomic physics-- precision and pristine control and interesting many-body physics-- happens when you pulse on optical lattices. So one application of those optical lettuces is atom optics. You have atoms and when they encounter an optical lattice, some atoms will just continue, will not be diffracted. They have zero momentums. Others are diffracted with a transverse momentum. You can then expose the atoms to a second zone where, eventually, momentum is transferred, and then the atoms come back together.

So what we have here is an atom interferometer where atomic matter waves first go through a beam splitter, are reflected back towards each other, all by photon transfer, and then they're recombined. So this pulsed optical lattice acts as a beam splitter. It is the way how, today, the most precise atom interferometers are built. And this is used for precision measurement, for measurement of inertial forces, gravity, rotation, acceleration, and it is used for navigation and accurate observation of the changes of the gravitational field of the Earth.

Since we just had a talk by Holger Mueller from Berkeley day before yesterday over at Harvard, he talked about the combination of atom interferometer and frequency combs, another development-- let me just mention that. If you derive those laser frequencies from an optical frequency comb, and with an optical frequency comb you can pretty much count the frequencies. So this laser is mode, I don't know-- 100,000 or whatever you are in the comb. By doing that, by combining it, you can actually build an atomic clock where-- let me just say, plus combs-- can give an atomic clock which is called the Compton clock because the frequency is now given by the rest mass of the atom, but divided by a big integer number.

So using completely unrelated developments in AMO science which I've mentioned, the optical frequency comb, combining it with the physics of a pulse standing wave,

you now have an atomic clock which is directly related to the energy of the rest mass.

But finally, if you pulse on an optical standing wave and your object are not individual atoms, non-interacting atoms, your object is the Bose-Einstein condensate or atoms which strongly interact, then you're not transferring recoil to individual atoms, you're transferring momentum to a complicated many-body system. And this means what we are measuring is the dynamic structure factor.

If you have atoms, you want to do spectroscopy, you want to know what energy levels are there, and then you know your atom. If you have a strongly-interacting system, you also want to know what energy levels are there. But each energy level in a homogeneous system or in a periodic potential is associated with momentum and quasi-momentum. So in other words, if you have a more complicated system, you want to figure out what are the possible states in terms of momentum and energy. And the optical standing wave, the pulsed optical standing wave is the way how we impart momentum and energy to a system.

What I actually just told you is a story in my own research career. I was a post-doc with Dave Pritchard. He had trained at MIT in the '90s by a pioneer in laser cooling. And when we had Bose-Einstein condensates in the late '90s, Professor Pritchard and myself, we teamed up. I was the expert on Bose-Einstein condensation and he was the expert on atom interferometry.

So just by sort of exploring things, we took Bose-Einstein condensates and we pulsed on a standing wave. What was on our mind was, hey, let's build an interferometer. But I'm more of a many-body physics person. I suddenly said, yes, but if we now change the momentum and the frequency of this standing wave, what happens? And I suddenly realized that this is a way to measure properties of a Bose-Einstein condensate in a way which hadn't been done before.

So I realized-- and this is maybe the last thing I want to tell you today-- I realized in my own research and my collaboration with Dave Pritchard, that we'd built an experiment, and we just turned one knob at our experiment, and the following day

we were no longer doing atomic interferometry, we were doing many-body physics. So this is, I think, what makes our field exciting. We are using the tools, the precision, and the control of atomic physics, which leads to the most accurate atomic clocks in the world-- atomic clocks, which are the most accurate in the world. And we are using those tools to do entanglement and many-body physics. And I think it's just a compelling combination.

Anyway, that's an appetizer, that's an outlook over the semester. Do you have any questions about the last examples I gave you or the course in itself? OK. No homework assignment today. And we'll meet Monday at the same time here in this lecture hall.