So today we start with the last chapter on ultrasound imaging. We first cover ultrasound principle, and then we talk about imaging mode and so on. This is the schedule. After two ultrasound lectures, we are done with the green book. Optical imaging and machine learning are not in the textbook, but we will cover them anyway. Machine learning is very hard. Optical imaging is also important. You just need to read the ultrasound chapter. I think about 20 pages is a nice read. You can treat it as a good story. So today let me just walk you through the chapter, the first part. So we focus on physical principle, so talk about what is the ultrasound wave, how you generate, how ultrasound wave interacts with biological tissue. These are physical foundations. Then we talk about some engineering stuff. Transducer, how you generate ultrasound. So you talk about single crystal based transducer. Whenever you see transduction transducer, that means energy is changed from one form to another. In this case, the mechanical vibration into electrical signal, or electrical signal into mechanical vibration. Transducer, ultrasound transducer by name. So we use the device to generate a mechanical wave, and the wave is echoed back, introducing vibration on the crystal. That will be naturally converted to electrical signal, so you go two ways, round trip. We talk a little bit about resolution aspects, specific to ultrasound imaging. Resolution, spatial resolution pretty much. Literal resolution and axial resolution. And about imaging contrast, I mentioned natural contrast, also we can introduce so-called micro bubbles, that's a very cool idea, improve the ultrasound imaging contrast. Micro bubbles are not very much mentioned in the chapter, but I will explain some new stuff there. So this is kind of outline, and each imaging modality you focus on outline, so you know what I'm going to cover, what you should understand. So these are key concept, focus again on the key point principles, you try to understand what's going on. Okay, and then we talk about medical imaging, and mainly five modalities. We already covered x-ray imaging, nuclear imaging, MRI, these three big things, the next one is ultrasound, the last one is optical imaging, and you will learn optical imaging, also very unique and useful. Ultrasound imaging has certain advantages, say it does not involve any ionizing radiation, it's a mechanical wave, so this energy is sent through mechanical waves, so no x-ray or gamma ray involved, so this is good, so you do not worry about DNA damaging, potential cancer risk, and so on, you don't need to worry about that. Ultrasound imaging, the speed is quite high, and the transducer, this is an image of this ultrasound probe, or ultrasound transducer, you just move it over your abdomen, or just check your cardiac function, or just see how small baby is doing inside the mother, so this is the phantom here, so it's a very, very good thing, low cost, high speed, however, as any other imaging modality, ultrasound imaging suffers from its own weaknesses, and say the penetration depth is a question, and we know x-ray is good at imaging between tissue and bone, so bone-tissue interfaces, and the tissue-air interfaces, so talking about tissue-air interfaces, we are indicating, x-ray imaging is very good for lung imaging, so lung CT is widely used, and also bone structure imaging, bone-tissue interface, can be well resolved with x-ray imaging, all these interfaces, different kinds of material putting together, that means the material properties are quite different, so in ultrasound terminology, we say acoustic impedance are quite different, whenever you have two pieces of material, they are mismatched in acoustic impedance, we will explain more later, ultrasound couldn't penetrate very well, it will echo back, so you send x-ray, try to go through lung, or penetrate bone, you cannot do a good job, so you need to find a good window, like soft tissue, if you want to see hard, you need to find a good place, you see through ribs, so you can capture cardiac function, so ultrasound imaging so-called effective, so shown here, generated sound, something, features, boundaries, scatters, just send signal back, in the mechanism called reflection, or scattering back, you can also do transmission, not very typical, transmitted ultrasound imaging, and also we can do image-guided surgery, with ultrasound guidance, ultrasound images can be registered back, to prior CTOMS guide, so guide surgical procedure, and the neural applications, and you can use ultrasound, focus the ultrasound, to stimulate neurological structures, so just try to treat depression, and so on, so this is rather, I mean, this point, is rather new application, neurological stimulation, I know DAPA founded hugely, in this new frontier, and ultrasound is not electromagnetic wave, we know MRI imaging, you involve RF signal, so that's just alternating magnetic field, X-ray imaging and nuclear imaging, you have X-ray or gamma ray photons, and these photons can also be treated as waves, they are just a part of wide electromagnetic spectra, so shown here, so we know X-ray imaging CT, nuclear imaging MRI, or talking about these EM waves, somehow related to Maxwell equation, if you talk about wave, or you talk about Boltzmann equation, if you treat them as particles, but ultrasound imaging is different, and the last one, optical imaging, we go back, still electromagnetic wave, ultrasound imaging is totally new mechanics, just mechanical wave, and it comes in different frequencies, and what we can hear, like my lecture, or some birds singing, in the acoustic range, so this is just lower frequency, somewhere here, the ultrasound is really something we couldn't hear, frequency too high, used for medical imaging, industrial non-destructive evaluation, you could use high-power focused ultrasounds, for other purposes, it can be powerful enough, you can use ultrasound knife to cut tissue, you can heat tissue, and you can do other things, but our purpose is really ultrasound imaging, so this is just general description. Let's look at this link, so basically just look at this picture, so you have a ringing alarm clock here, clearly you can hear ringing, and you contain the clock inside a container, so you have a wall, you can put air in and out, and you have another device here, you can just extract air out of the container, so you have the ringing clock, you keep take air out, and water you will hear weaker and weaker sound, until you couldn't hear any sound, then you open this wall, let air rush in, you hear the sound again, so this is to say, the sound wave travels through air, and all the mechanical waves need medium, without medium the sound wave cannot go through, so this is just some very important observation. The medium, like air, so have a bunch of molecules, and with the transducer or some vibrator, you push molecular particles towards one direction, you drag them back, you just go back and forth, so you will generate rarefraction and compression, in alternating fashion, so these together look like wave wave will travel along the direction you are pushing, in this case z direction, so this looks better, you have sound sounds, you just keep vibrating, so you think you push air, this way just get back, that way just generate the sound wave, looking at this picture, so you have higher density and lower density, you have higher pressure and lower pressure, all related to equilibrium status, and also you look at small molecule, it will be moved towards that direction and come back, then goes the other direction, keep vibrating, the wave travels down the road, but the particles still there, just vibrate around, so wave is something in a way, separate from particle motion, particle just vibrating, they never move too far away, so the sound wave is important, and similarly you have electromagnetic wave, so I want to explain to you how do we form a wave, how come you have the wave, so if you have totally rigid body, you think you have a rigid state, you vibrate the state, you push in from one end, the other end will move the same way, because by definition this is a rigid state, but why you have wave, we say the wave is formed in a simple or relatively simple kind of twist involved, so you involve conservation of mass, so the total mass cannot be changed, and now you have a relationship between pressure and the volume of a material element like gas, then you certainly need the fundamental law, Newton's second law, let me explain to you how mechanical wave is formed, and how electromagnetic wave is derived that involves the Maxwell equation, usually in a graduate level class, which I will teach next semester, I will explain, so I myself really understand what's going on, so the understanding is more important than detail, and also then we need to focus on regular steps, I also want to know the detail, those details are mostly what I'm interested in, involving the fundamental governing equation, once you know the governing equation and the basic principle, the rest are details, you can always figure out, or if you need it, you Google, you find the detail, but if you do not have a fundamental understanding, you just don't know what's going on, you basically repeat what others told you, or you just use the device or some tool as a black box, I do not enjoy that part, I really want to know what's going on, I want to have insight, I want to generate new ideas, so now how we form an ultrasound wave, so how to form ultrasound wave, so this is the idea, you think the sound propagates through air, you hear me because the ultrasound wave, the sound wave goes from myself to your ears, and then you get a piece of material, so here all the water molecules, so if you like, you can also think this is not a piece of air, it's just an elemental material, biological soft tissue, so you think the ultrasound wave is introduced from my body surface into the abdomen, this is the same idea, but anyway, just think the air here, so you have an element of air, so you treat a big object as a collection, many small voxels, this is a typical voxel, just stay here, just with volume, pressure, displacement, all just in equilibrium status, so nothing wrong, then you push one side towards the right-hand side here, so you introduce displacement towards the right-hand side, so you introduce this displacement, so this displacement denoted in lowercase w, so in your green textbook, it also says lowercase w is displacement, displacement is increased, defined positive direction, right-hand side wise, so you increase that, what will happen? You increase this distance, so this small volume element will be reduced in terms of volume, so volume, what happened here? Volume will be reduced, so I try to explain the understanding of how you form waves, the volume will be increased, then I mentioned earlier, there is a relationship between volume and pressure, whenever the volume is reduced, the pressure is increased, because the total amount of mass inside this small container or small voxel is fixed, so the pressure is increased, this pressure is increased, then this overall force on this element is produced, and the net force has a result to push this material element right-hand wise, so it just tries to change the blue thing, will try to induce in turn the green thing, that means the net force on this material element according to Newton's second law, it will generate acceleration, because you push the material element this way, so there will be a net force that way, the same direction, the force generates acceleration, lower case a is acceleration, acceleration increases, because of the positive acceleration, the velocity will be increased, because of velocity, new displacement, green displacement, this w is increased, it's going to move that way, you follow this logic, these three things, not too complicated, but it's not straightforward, it's not that straightforward, it's a second order thing, so you see the red element, blue element, green element, they play together, and they play together, this is not like the case I mentioned earlier, this rigid stick will not have wave, you put one hand, the other hand simultaneously will move the same way, because the rigid stick will not change, it's an elastic thing, you can just change, we say some comment, when you move this side, you move this side, you have a velocity, you think you have velocity u here, on this side, and this placement is linear relationship, instantaneously, velocity times delta t, just put t here, so you have this linear change, and on the green side, so you have velocity u, u comes from acceleration, this placement results in pressure increment, so pressure increment is still linear relationship, the increment is linear with respect to delta t, small t instant, but on the other hand, this side, this placement is a second order thing, so this half a is constant, and this t squared, so when you have a small delta component, t squared, that means it's a higher order small quantity, so that means roughly, you push this back, the other side doesn't have enough time, to move as quick as the other side, so this is the original element, this is just one pixel, you push this way, this side will move, but slow, so you got a whole thing comprised, that's why you have the pressure increment, so this does not come simultaneously, not in synchrony, so you have a delay, so as a result, you have a wave from this side, so keep driving one element at a boundary, the wave will be delayed, and the wave will come in phase, as a function of depth, so at a different location, you still see the same wave form, but the phase is not, the phases at different locations, will not be all the same, so because the phase is different, so overall you see the wave will really move down, it's not happening like a rocket, like a rocket disk, so you can just do the pushing, push in and draw back, and it will move all the way, no wave, but in this case, due to the interplay, or interaction explained, and you have this delayed phase, and phase will, in other words, phase will propagate through the medium, this is the wave, you have the wave, and if you look into mathematical detail, and you just try to focus on one variable, either you focus on w, that's placement, or pressure, you focus on any variable, and utilize the relationship I mentioned, the pressure, acceleration, and you cancel out other variables, you will end up with a second order, partial differential equation, something like this, so this is wave equation, how do you remember wave equation? So wave equation is very cool, in one dimensional case, so you have the displacement, or if you like you can put pressure, whatsoever, so one variable, in one dimensional case, the second partial derivative, with respect to spatial variable, this is g, and the right hand, is still the same variable, second order partial derivative, with respect to time, so the quantity can be displacement, volume, pressure, you name one, let's say w, w is displacement, so this w, the second order thing, second order with respect to space, is the same as second order partial derivative, with respect to time, so space and time are connected, in the form of second order derivative, so forget about this constant, you can arbitrarily select your unit in space and time, to make this constant just one, so basically they say space is equal to time, in terms of second order change, so whenever you see governing equation like this, and you have wave equation, and the solution is sinusoidal wave, it will propagate through the medium, and the speed of the wave is c, and how do you derive c? You can derive c, and in this case the c is determined by material property, rho is material density, and this kappa, kappa is equal to inverse of the bulk modules of the tissue, so this is again the material property measure, density you know, this is just bulk modulus, may not be that familiar to everyone, but basically the more rigid the tissue, the smaller is the value of kappa, so just see how stiff the material is, usually biological tissue are very soft, and when you have tumor, if tumor is benign, it's soft, if tumor is malignant, it turns out to be hard, so you don't want to have very hard soft tissue, so this is wave equation, and relevant concept, I want to mention so-called p-wave and s-wave, or longitudinal wave or transverse wave, and you recall what I explained, you keep pushing the air volume towards one direction, then you move away from that direction, you kind of just push in, pull back, you keep doing this, so what you generated is longitudinal wave, you can do so for air, for soft tissue, or if you like you think a very long stream, and you just do this oscillation, and it will introduce relatively sparse, relatively dense region, so this dense and sparse region will form a nice pattern propagated down the road, so from one end to the other end, so this is called longitudinal wave, certainly you can vibrate in another way, you can do so this way, so this way the vibration direction is orthogonal to the wave direction, this is called transverse wave, electromagnetic fields are transverse waves, the mid-transverse waves, so transverse and longitudinal are just different forms, and just as your general knowledge, again this is longitudinal ultrasound wave from sound source, so all the days I don't know if it's still possible, all the days when I see doctors, they use this kind of fork, just generate sound, just move in a different direction, try to test if I can hear, and this is sound source, you have longitudinal wave, this is wave propagation direction, whether we are talking about longitudinal or transverse waves, and you always have so-called wavelengths that is distance between adjacent peaks, or the densest regions, and likewise equivalent to the distance between the valleys, means the sparsest regions from here to here, this is called wavelengths, and this is amplitude, so you have a peak, and you have a trough, it's just a valley, so you have a sinusoidal form like this, the sinusoidal comes naturally, whenever you solve wave equation, regardless of mechanical wave equation or EIM wave equation, so this concept you showed before when we reviewed the phasor, and the Fourier analysis, and why the sinusoidal is important, because it is a solution to wave equation, wave equation is important in many ways, and the sinusoidal also building blocks for Fourier transformation, so anyway these are just general knowledge, you say sound speed, remember wave equation has coefficient of 1 over c squared, so you solve equation, you see c is the speed of sound, and the speed of sound depends on material property, so if you generate sound wave in air, in steel, in biological tissue, the sound wave is not the same, so if you check the equation, you know the dancer, the staffer, the material, the faster the speed of the sound would be, so these are typical values, what's the speed of sound in air, in lung, so it's just in different things, usually just the dancer, the material, the larger the speed, also in the same material, or in the same medium, and the speed is the same, but you can vibrate, like I put air or I use transducer, to examine my abdomen, so the material is the same, but you can vibrate at a different frequency, the speed is fixed, that's just determined by the material or medium, the higher frequency the sound wavelengths, because you have to make one larger than the other sound, so that speed can be the same, so this is just some general knowledge, nice thing for you to know, then we look deeper into sound wave propagation, so the sound wave propagated into the field, the energy would be carried into the medium, so we talk about wave equation in terms of displacement, the first derivative of displacement is velocity, so the velocity is shown here, so typical velocity you have the number, and also the sound wave will introduce the pressure, in the field the pressure is computed here, at a given point it's computed here, it's just proportional to rho, c, u, z, so you have these two things, and since the wave equation can be solved, as I explained, the p pressure is in a wave form, and this velocity is in wave form, so you can put both pressure and velocity, in this sinusoidal oscillation form, so these two things together, and you can define this intensity i, so this average intensity over period capital T, so see this multiplication, u and the velocity, so the p pressure is unit force, it's force per unit area, so the p pretty much is force, so if you have force, you move certain thing over distance w, that's the work you did, so this is the work you did, because this is not distance, not displacement, it is rather first derivative, so then you think this rate change, put together force times displacement, and you talk about the work per unit time, so this is the power going through the area you are thinking about, so the ultrasound wave really travels through the medium, carrying the energy, so this intensity is what we are measuring here, so just think about p, u, and right now you just think u is displacement, then p is force, then p force times displacement, that's work, but this is not displacement, that's just displacement over time, so work over time is power, so i is intensity, this is power intensity, basically give you idea, how do you link velocity, pressure, and intensity, and these things can be solved from the wave equation, but we just present the definitions, so you understand intensity can be measured this way, and ultrasound wave propagates through medium, and the wave will be attenuated, so the amplitude changes a lot, and later on you will see ultrasound intensity, or amplitude of ultrasound wave, decay as a function of penetration depth, so it's exponential decay, pretty much like Beer's law, so we use relative intensity and relative power to describe the change, so we introduce log scale, so this is not totally new signal noise result, often times you talk about relative change, relative result, because relative result has too huge range, and you want to comprise the range, so you use log scale, just for convenience, log scale happens in two ways, if you just talk about intensity or power, then you just do log, you multiply by 10, if you talk about this relative intensity, talk about amplitude, you time by 10, but if you talk about power, you really have 20 log result, this 20 is too really means the amplitude should be squared to have power measure, like in circuit analysis, so what's the power? The power through a resistor is R times I squared, so the amplitude should be squared to have energy, optical imaging same thing, you have optical wave change with amplitude A, then what's the power? Power is proportional to A squared, so this is just difference between amplitude and power, that's why you have 10, here you have 20, 20 you can put 10, then this 20 will be this 2, you need to square the amplitude result, so this 2 can be put here to make it 20, so you can review the definition under the slides of the class, and here are some numerical examples, so you can just review, see how you can get the amplitude reduced by half, how deep you should go through the medium, this is something like in X-ray or gamma-ray imaging, the concept half value layer, something like that, so you can review this, just this kind of example review questions, just be familiar with fundamental definition, rather than measuring relative change as generic result, here you just want to use log result, and certainly with appropriate scaling factor, just for convenience, nothing physical I would say, just convenience, okay, now we talk about acoustic impedance, this acoustic impedance is not dramatically different from electrical impedance, remember when we learned circuit analysis, we have resistance defined as result between voltage and current, and later we defined impedance, capacitance, inductance, also as voltage over current, but in the general case, you have phase change, so you have complex number, but you still have complex value voltage, or complex value current, or just phase expression for voltage, or phase expression for current, here the voltage is driving force, it's a potential difference, and in ultrasound field, the driving force is pressure, the mechanical wave, you push, the P is pressure, as you push, place the same role as electrical voltage, then the current is electron flow through the conductor, but here the flow is not electron flow, so you have IR molecule, or soft tissue molecule, just moving towards one direction, at a certain moment, at instantaneous velocity, u at location, u, z, so just given location, you have the velocity, instantaneous velocity, P and u keep changing, but if you solve wave equation, you can show, it's beyond the scope of this lecture, P, instantaneous P, and instantaneous u, u, z, at location u, z, this result is constant, so it's just always the amplitude for pressure, or amplitude for velocity, both are changing, but the result is constant, because it is constant, we call this characteristic measurement of the material property, we call it acoustic impedance, that's meaningful, if the result keeps changing, it's not constant, you cannot define as an intrinsic property, so this is definition of acoustic impedance, acoustic impedance is important, when you do ultrasound imaging, you need to make sure, the acoustic impedance of your ultrasound transducer, and the acoustic impedance of biological tissue, like my abdomen, you need to put some middle layer, to make sure acoustic impedance values are in match, otherwise you cannot deliver energy into the body effectively, you cannot collect the signal effectively, efficiently, so this is physically relevant quantity, so you define this in a heuristic way, the pulse over flow, so this acoustic impedance, pretty much like an electrical pulse voltage, over electron flow current, the same thing, so this is a heuristic definition, and we can show, again we can show, we can show mathematically, but I wouldn't show, this value z, I say we show this is a constant, by solving wave equation, mechanical wave equation, when you solve the wave equation, not only you show this is constant, also you show this is determined by intrinsic material property, rho and c, rho is material density, at that location c is speed of sound, in the type of material, and furthermore, you know the c, earlier we mentioned c is 1 over square root rho kappa, so you just replace c with definition, with the formula for c, and you just arrange a little bit, you got equation 3.8, and the ratio acoustic property, and the first table in the chapter listed here, it just got a feeling, you see in air, each second the sound wave will go over 300 meter, but in kidney it moves much faster, because biological ratio much denser, where is highest speed found inside human body, and we know the bone is densest structure in our body, so you see ultrasound will travel much faster in bone, than in other components, other types of biological tissue, so this is 3500 meter per second, so this is just some typical tissue acoustic properties, so next, we talk about ultrasound-tissue interaction, and earlier we mentioned the interaction, certain EM waves, with biological tissue, like X-ray CT, we talk about attenuation, and complex scattering, gamma ray, pretty much the same thing, biological tissue relaxation, T1, T2 parameters are for MRI imaging, for ultrasound imaging, it's still energy propagation, interaction with biological tissues, so the idea is somehow similar, reflection, so the sound wave or the light wave hits the boundary, can be reflected back, this happens when you have acoustic impedance mismatch, and at boundary, like tissue boundary, more specifically we say air-tissue boundary, bone-tissue boundary, you have strong reflection, and reflection is not so much deal with X-ray and gamma ray imaging, because X-ray and gamma ray photons are so powerful, you basically go straight away, and with phase contrast imaging, I think I mentioned that, I went to Japan to talk about phase contrast imaging, and it will be banded very lightly, so you need greetings to measure the banding, but for ultrasound imaging, the reflection, the wave direction is changed substantially, so this is due to the wave lines, and the X-ray and gamma ray wave lines is so soft, but for ultrasound, the wave lines are much larger than in the X-ray and gamma ray cases, so the reflection, just remember, change in direction, I try to make it simple, so you remember, reflection at boundary, reflection at boundary, reflection changes in direction, then scattering, so energy, so you send energy, beam of energy, going one direction, and due to reflection, and different kinds of scatterings, so energy propagation will change direction, so energy will get, energy beam will get diffused, eventually becomes bouncing around, so this is something like competence scattering, so you have energy diffusion here, and absorption, in X-ray case, the counterpart would be photoelectric effect, X-ray photon is turned into heat, the energy is totally observed, so ultrasound imaging, the ultrasound wave remains in intensity, it sends the wave into the field, the wave moves water, the biological molecules moving around, they have internal friction, so the friction generates heat, so energy will get reduced, so energy into heat is called absorption, and also in the wave we keep oscillation, you think something oscillates this way, then you happen to push this way, so you just move in opposite direction, this is also a way to attenuate the energy, so you have friction or this match, so you just get energy absorbed, so as a result, just like X-ray going through human body, the beam intensity gets weaker and weaker, so ultrasound beam into human body will become weaker and weaker, and the pressure amplitude will become weaker and weaker, the displacement becomes less and less, so all due to energy absorption, more accurately due to attenuation, energy can be absorbed, and all energy be redirected, so from one direction, the intensity will decay according to how much beam energy is absorbed or scattered away, so this is just several mechanisms I would like to mention, looking at your figure 3, 3.3, so simple case, you inject ultrasound beam perpendicularly, and you meet a surface boundary between two kinds of material with acoustic impedance, G1 and G2, so part of beam will be reflected back, and the rest will be injected into the medium along the same direction, so this is a special case, more general case, you have incident beam making an angle theta i, means incident, and some beam reflected back, so theta r couldn't see, means change of glass, so then you have some transmitted wave, so making angle theta t, so the transmitted wave, so this angle, the incident angle, is equal to reflection angle, and it's not necessarily same as transmission angle, and the relationship shown here, so how much energy is reflected, how much energy is transmitted, and these two processes are complementary, so energy must go into the medium, one way or another, either reflected or transmitted, so the total energy should be the same, I'm saying the incident energy should equal to reflected energy plus transmitted energy, but what is the relative ratio, the relative ratio, you can measure in terms of pressure amplitude, the pressure amplitude, if you make it squared, that means the intensity, the power, power ratio, so just talk about pressure ratio, it depends on these angles, and also acoustic impedance, g1 and g2, so the energy transmission is determined by these formulas, and that's why you need g1 and g2, why acoustic impedance is important, because you need these values to calculate how much energy gets reflected, how much transmitted, so this is just the fundamental questions you need to answer for ultrasound imaging, so these formulas, you need to know the pressure ratio, and if you square the pressure ratio, you got energy ratio, that means reflected energy transmitted, sorry, it's transmitted energy over incident energy, it's something less than 100%, and this is reflected over incident, so incident always serves as the denominator, so you can compute the ratio for reflected energy and transmitted energy, how energy is divided between the two materials, so this is just some general description, and you need to become familiar with this special case, so this case is important, so you see these two formulas, and later on I will use homework questions to help you review transmitted and reflected energy, and this is very much relevant to ultrasound imaging, you want to send ultrasound energy into your body and collect the signal, so if the surface and the transducer will match, all the energy, ultrasound energy will be reflected back, no energy will be delivered into human body, so you cannot do imaging, so this is just a rough idea, so we have a few minutes rest, so from 1 o'clock we continue to finish this lecture, so this is talking about energy intensity reflected over total incident intensity, so if you have G1 and G2 the same, G1 and G2 the same means, really this is not two pieces of material, it's just one piece of acoustically uniform thing, G1 equal to G2, according to this formula, G1 equal to G2 is uniform, and then this total result will be zero, that means no reflected energy at all, so the energy as we mentioned, some of it will keep moving through the medium, like air or tissue, so no reflection at all, just keep moving forward, there's a wave propagation, so this is one extreme, on the other hand, if G1 and G2 are dramatically different, one is very large, the other is very small, just say one G1 is zero, then the reflected result will be one, that means just what I said, the beam hit the boundary, and get back, no energy will be injected into the tissue, so you cannot see what's going on inside the patient, so this is not good, you have to do something, and later we will see, you need to do acoustic impedance matching, but anyway, so remember these two formulas, and the mechanisms, and in which ultrasound wave could interact with biological tissue, then as I already mentioned, the intensity of the acoustic wave pressure will be reduced, as you go deeper and deeper into the medium, and why the intensity of pressure amplitude becomes smaller and smaller, because of attenuation, so why you have attenuation, because you have absorption and scattering, so energy is either absorbed, or just redirected into other directions, so along the primary beam direction, the intensity of the pressure amplitude will become less and less, this is not very strange to us, and we see exponential decay, and in nuclear imaging, in X-ray imaging, so we see the exponential decay all the time, when we have the exponential decay, and we know how strongly the targets, or the features are interacting with the probing beams, and based on the attenuation, we can say how strong or how light the features are, so this is the imaging mechanism, you have contrast, and again the same comment can be applied, you don't want something absorbing energy quickly, so just like you do X-ray imaging, you don't want all X-rays to be absorbed by a patient, in that case, the detector will see nothing, or everything, every photon eaten by human body, so no information carried out, on the other hand, you don't want X-ray or ultra beam go through the body without any attenuation, so that way all beam goes through, and you still have no information about human body, ideal case, you have half energy absorbed, and half the energy transmitted, so about half, depends on which way, absorbed more or absorbed less, based on this, you have most amount of information, so you can derive a tomographic picture, again I mentioned to you before, I believe when I give you examination, I try to write majority, just roughly, so just the class average, 50%, so in that case I have best opportunity to see what would trick you, and what you can solve, so I have best spread, and I can judge your relative performance, and based on this, in the final, in your formal transcript, I will assign you A, B or C, again, don't worry if you feel the average is not high, I purposely don't want you have high average, so I can see relative performance, the final grade distribution will be consistent to what we have before, and what we have before are very similar to other class average, so you wouldn't be unfavorably graded after all, so this is just talking about contrast mechanism, and for ultrasound imaging, so attenuation coefficient here, mu in terms of intensity, and alpha in terms of pressure, just the two equivalent ways, so this alpha is proportional to a constant alpha 0, and then the variable is proportional to frequency, with scaling factor alpha 0, so this B factor, this B factor for diagnostic ultrasound, this B is about 1, so the relationship is pretty much like this, in other words, the higher frequency, you will get stronger attenuation, so the coefficient is linearly proportional to the frequency, this is not something surprising, because higher frequency means you vibrate more seriously, and you vibrate a molecule more frequently, you will introduce greater friction, so you will spend more energy, so this will make the ultrasound wave decay, in terms of intensity or amplitude, so higher frequency means you do more work, you just try to introduce conflict frequently, so for different materials, you have different alpha 0 values, and again, these numbers are just for you to exercise, and we mentioned the implication of reflection coefficient, so this is pretty much what I already mentioned, so you cannot penetrate ribs or some air bubbles easily, because acoustic impedances are not in good match, and also if you do brain imaging, the brain green matter and white matter, they are pretty much acoustically uniform, so uniform thing, the uniform medium, the ultrasound wave goes through, like what I mentioned, totally transparent, everyone got 100, I couldn't tell who are better, so the other extreme, so the tissue and the bone and rib interface, the tissue and the bone mismatch, so mismatch the ultrasound wave couldn't penetrate the rib, everything reflected back, so I couldn't tell, just like everyone got 0, I couldn't tell who is better either, so you really need to find a good window, look into human body, and get a good balance, so this is something I already mentioned, you can read it yourself, and here the ultrasound will introduce a thermal and a non-thermal effect, I mentioned the thermal effect already, the non-thermal effect is quite interesting, and it could be used to increase cell membrane permeability, and so on, so there are several interesting things, like to increase blood flow, so you have some novel utility, like I mentioned, you focus the ultrasound to stimulate neurological structure, to treat certain diseases, so all these are just some ultrasound effect, and you can review, so just a few slides I copied from another instructor, so now we move to the next part, the next part is more engineering stuff, and the first part pretty much the physics, and the physical principles, and the governing equations, imaging principles, the contrast mechanism, now we talk about ultrasound scanner, or probe, or transducer, they're more or less the same thing, so first talk about single unit, then we talk about multiple units put together to form a linear array, or to make a two-dimensional acoustic imaging array, so just hardware, like CT scanner architecture, so you have this acoustic unit, or acoustic imaging array, and then I mentioned image resolution, image resolution, the contrast, a little bit of micro-bubble, we are done, so how we generate ultrasound wave, I already mentioned that you keep, say, pushing in, pull back, you vibrate, this is just what I mentioned, or you just vibrate a rope, you pull a spring, so these are heuristic ways to tell you how you generate wave, and ultrasound wave must have frequency, you cannot do with your hand, you need some device, so piezoelectric effect is fundamental for ultrasound imaging, it's enabling technology, I think piezoelectric effect, once got a Nobel Prize, something very cool, so you can use it in two ways, in direct effect, you have sound vibration, sound vibration will introduce pressure waves, so pressure waves will act upon a piezoelectric crystal, like this one, the pressure keeps changing, so you have pressure, positive, zero, negative, keep having pressure, so the crystal piezoelectric material kind of squeeze, let it go, relax, keep doing this, so once you have relative deformation in one dimension, in this dimension, and the magic thing, and the electrical potential will be generated across the two surfaces, shown here, so the top surface, this is the top surface, bottom surface, and you just press, let it go, then the electrical potential or current will be generated this way, so this means transduction can be done, from mechanical energy in the ultrasound vibration, into electrical energy, into sinusoidal current or voltage, so this is one way, the other way, so if you introduce sinusoidal voltage across the piezoelectric ceramics, then you have the voltage applied across the two surfaces, and the relative deformation will be introduced, depends on the voltage, voltage is high, go this way, voltage is negative, it goes this way, so you keep changing, so the crystal will be vibrating this way, so you think you put this oscillator on my body, the ultrasound wave, if the frequency is in the ultrasound ring, the ultrasound wave will be generated, so ultrasound wave, in this case, will go towards the right-hand side, so this is a two-way mechanism, so that means we can use such an element to generate ultrasound wave, the wave goes and hits some surface or scatter, then the energy, the ultrasound signal will be generated, they are tracing back towards the transducer, and the reflected signal, the ultrasound echoes, will cause relative motion of the surface, then you get electrical signal, so you can think about imaging this way, you first use sinusoidal oscillation, generate the ultrasound, you're done, so the signal generated moving into human body, then the signal, due to the mechanism I mentioned, will be generated send back towards the transducer, and this signal will cause relative vibration, mechanical vibration, mechanical vibration will generate electrical signal, so you get electrical signal, so you have a two-way vehicle, so this is very cool, called piezoelectric effect, and you may wonder, this is how you generate ultrasound wave, how you receive or detect ultrasound signal, you may wonder why, and you have piezoelectric effect, so this is, I really like things, it's a cartoon or infographic illustration, and it's a good idea, so this is a very good idea, so just show you how you have this magic piezoelectric effect, so suppose you have some crystal structure like this, the structure is balanced in terms of static force, and also in terms of static electric field, so you see you have positive charge, negative charge, so arranged symmetrically, so this is an overall electrically neutral, so no problem, so if you have half a tangent T, you just pull the two parts horizontally away, so shown here, so this crystal structure is stable, but elastic, deformable, so it will move this way, so that says, originally, you have an electrically neutral situation at this point, but because of this deformation, so the positive charge is moved relatively upward, so the top surface will become, will be changed from neutral status to positively charged, because see, here the negative charge is pushed down, the positive charge is brought up, so this becomes a relatively positive surface, and likewise here, the negative charge is put down, the positive charge is pushed in, so you feel more, if you put a positive charge here, you will feel this surface is relatively electrically negative, so you got this situation. On the other hand, if you use the opposite tension or compression, you do this way, so this negative charge is just pushed further up, and this positive charge is pushed further down, so the top part will be relatively negative, likewise the bottom part is relatively positive, so you see the mechanical deformation will be labeled as an electrically polarized top and bottom surface, so this is just a simple visualization of piezoelectric effect, so with this understanding, you will feel more comfortable with your transducer diagram in your book chapter, so you have the crystal, this is piezoelectric material, and here you have a matching layer, the matching layer I mentioned before, and you need to put all things together, you need to have a damping material inside, and I will mention damping effect later, so you have acoustic insulator, make sure acoustic wave will travel along this direction, and the conducting wire is a conductor, so you can apply electrical voltage across your piezoelectric crystal, so this is just an overall idea for a single crystal transducer, you can put it into a device, essential thing is like this, but you have a cable for electrical power, you have a handle, just put the surface on top of human body, either chest, breast, abdomen or arm or anything, just try for different purposes, so these are some commercial acoustic ultrasound probes or transducers, and I think the future iPhone is a different idea, every day I have some idea, most of them may not be very good, some of them are really good, I think the iPhone in the future, you can make this surface kind of acoustic crystal, so you can have the piezo converted into electrical signal, I think right now it's kind of like that, so you can have your piezo, you get a signal, but eventually I think the iPhone could make a two-dimensional ray of acoustic transducers, then everybody, if you like, before you go to sleep you just put the iPhone, just so you can scan your whole body, every day if you like, and also the smart software can tell you, you have examined your abdomen, everything fine, you examined your breast, no tumor, but you only examined the left side, you didn't examine the right side, so you can see the picture, the software can guide you to do professional work, so you can do ultrasound imaging yourself anytime if you want with your iPhone, so this piezoelectric machine learning and digital signal processing, all things together can do amazing things in the future I think, so imagine the damping effect, why we need that, think about ultrasound pulse, oftentimes we send ultrasound waves as a sequence of pulse, it's not as a continuous wave, you can do both ways, but if we use ultrasound in pulsing mode, you send the pulse, it goes through the body, the weight comes back, and this is one very useful mode to find the depth, and to find the velocity, so if you do that, you send a signal, so make the piezoelectric material vibrate for a while, then you stop, so this vibration, like this sinusoid, a segment of the sinusoidal signal, as your ultrasound pulse goes in and back, you don't want this, you send the signal, you don't want the transducer keep vibrating, you know, this is like the bouncing ball, you drop on the floor, no damping effect, no friction, it will just keep bouncing up and down, likewise, if you don't do anything, it just keeps bouncing up and down, so the pulse will be quite long, so if you have the bouncing ball in some liquid or in air, the ball feels friction, it will just quickly, the amplitude goes down, it's called a damping effect, this is a little bit damping effect, this is a strong damping effect, with the damping effect, the frequency will become, the high frequency vibration will reduce the amplitude quickly, so without undamped, this means undamped bandwidth, so just keep oscillating, so you have a long vibration, in frequency domain, so in spatial domain, you have a long period for high frequency oscillation, in frequency domain, you will have a narrow and high peak, and if you just use a damping effect, so in spatial domain, you vibrate for a while, quickly it goes to zero, so you really have a pulse, in frequency domain, you have a wide distribution, you have a relatively smaller amplitude, but this is needed for pulse, also some pulsing-based imaging, and the quality factor, the Q factor, is defined by this result, 2 pi, this is central frequency, and this is bandwidth, this is bandwidth, half width at, the full width at half maximum bandwidth, just measure the shape of this transducer property, with damping material, Q can be 1 or 2, so things like that, then in this picture, you see that you have the damping material, now next, we talk about matching layer, look at this picture, and I did this before, I mentioned I got kidney stone problem, you just see where the stone move around, so you got this gel, gel is ultrasound, no harm and no pain, but this gel make you feel very messy, this is the example, but why you need this gel material, so this is the reason, and also pay attention, you have homework, I give you idea, but I wouldn't give you all the detail, so you have acoustic impedance, for piezoelectric material called PGT, so this is your transducer, you have acoustic impedance, keep vibrating, then you have Z skin, on top of skin, you couldn't see, but there are many small air bubbles, and those things, so Z skin and Z acoustic transducer, they are quite different, and I explained to you earlier, when you have two materials put together, and they are quite different in terms of their own acoustic impedance values, when these values are not the same, and pretty much energy, you vibrate transducer, this acoustic energy cannot be effectively delivered into human body, so the ultrasound wave pretty much reflected back, just like you visit national park, the mountain area, you say hi, and you hear, say hi, hi, echo keep coming back, this acoustic, the sound wave energy getting back, but for imaging purpose, you want the wave go into the body, and fly back, so in this case, the trick we can use, okay, the trick is to have a matching layer, this is a matching layer, this is a matching layer, so the energy delivery will not be directly from material one, piezoelectric material, into the skin of human body, that's Z skin, you would not do this, you do this, you get echo, but you put a matching layer here, then the process is divided into two steps, the first, the energy is delivered from piezoelectric material, the vibration, into the gel, then the vibration gel, again, in turn is delivered into human body, the transmission is done in two parts, and we show this formula, the energy intensity transmitted, from medium one to medium two, in this case, is a matching layer, is described by this ratio, then this is not done yet, and this should go further, so from matching layer to skin, Z skin, so you do this two-level delivery, so this is total transmission, and you know acoustic impedance for transducer crystal, Z, P, ZT, you know Z skin, so these two things you already know, now only unknown is the matching layer, so what the acoustic impedance of an ideal matching layer should be, so that this energy intensity transmission rate is maximized, so this is a calculus problem, so you see this is a function you want to maximize, the unknown is the matching layer, you perform first order derivative, you set it to zero, then you analyze, the result is that this matching layer should be square root, or geometrical mean of the two acoustic impedance values, so this is your homework, and the transducers, modern ultrasound imaging devices, oftentimes packed in either one-dimensional, or two-dimensional transducer arrays, so here you have, see here, this piezo element, this is array, and you have electrode, electrode is to apply oscillating sinusoidal signal, electrical signals, so that relative vibration can be introduced, then you have matching layers, just to deliver energy, stage by stage, then you go through coupled with the gel, just send the energy into human body, if this is matched well, the ultrasound goes back the same way, so you have one way optimally matched, the other way same argument, so the derivation can be reversed, so you have optimized signal to noise ratio, so resolution versus penetration for ultrasound imaging, if you want to have higher resolution, generally you should increase the frequency, but the higher frequency I mentioned, the attenuation alpha is proportional to frequency, the higher frequency energy will be attenuated much faster, so higher frequency, the smaller the penetration depth, so just this general idea, looking at the beam geometry, this is a figure in your textbook, so you have a single crystal transducer, so vibrate this, so energy will be send downward, and you can have this boundary called near field boundary, so before this boundary, this way called near field, after this boundary we call it far field, in terms of imaging geometry, so before this boundary, the beam dimension, the diameter size of the beam, is more or less like the diameter of the transducer, but after this boundary, the beam gets divergent, gets just diffused, so going this way, so this angle will be determined, related to lambda and A, so all this I just presented as a fact, I didn't derive for you, but certainly if you're curious enough, or if you are in imaging field, this can be derived from wave equation, so you just need to know the fact, have a rough idea, so I wouldn't bother you with derivation, so at any cross section, beam intensity will not be uniform, so along this principal axis, you have strongest signal, and you're moving away, the signal will decay, but oftentimes we see the profile is a Gaussian profile, how you measure this literal beam width, that determines your literal resolution, we use the concept, four widths at half maximum again, because this is Gaussian, Gaussian has a standard deviation, therefore this particular form of profile, the four widths at half maximum can be computed this way, this is again a formula in your textbook, so we hope the resolution, or the four widths at half maximum be small, so that two nearby points can be resolved, if the literal resolution is not good, so these two scatters will give you a signal, they will be overlapped together, you cannot separate them apart, so this is just a literal resolution concept, again the figure, the figure in your textbook, you see the single crystal transducer, can be made into a disk, the disk could have a concave surface, normally like this, with different curvature, stronger curvature like optical lines, so you will focus out better and quicker, so this focusing plane, the focal distance will be smaller, but if you do this strong focusing, you get a high resolution here, then quickly you get resolution, the profile broadening quickly, if you do more gentle work, so you weakly focus the ultrasound beam, so with a little bit smaller curvature, for this single crystal transducer, you can kind of get a uniform resolution downstream, but the resolution wouldn't be as good as you do strong focusing, here you get a very good resolution, here you get a moderate resolution, but you have a better uniformity downstream along the imaging path, and the F number is used, this F number is used the same way as optical lines, you also have an F number, so it's defined as R is radius of curvature, so this curvature, for any curvature, curvature defined as 1 over R, so this curvature divided by 2A, A is radius of the lines, so they basically say the bigger lines and the smaller R will give you a smaller F number, you focus strongly, so now we're pretty much talking about literal, this literal resolution, and literal resolution as a function of imaging depth, but still literal resolution, so next concept, let me talk about axial resolution, this longitudinal resolution, resolution along the beam propagation direction, so this figure, the first time you view it, it's a little tricky, but let me walk through with you, and you want to get axial resolution, so oftentimes you send a pulse, we need a pulse, we mentioned damping, we need to send a pulse, so we send a pulse, then we know the pulse goes out, I know the speed of the sound, so a while later the echo gets back, so based on this time interval, from the instant I send the pulse, to the instant I receive the pulse, I know this round trip distance, so if I send another one, then right after the first one, I can get the pulse back the same way, so the axial resolution is really talking about we send the pulse one by one, so that we can resolve the boundaries, what's the distance, the minimum distance we can resolve, if the boundaries are too close together, all the echoes will overlap together, just like this case, so all signals overlap together, you cannot tell which one is which, so there comes the idea how you compute axial resolution, it's half of pulse duration times the speed of the sound, here just assume for the first order approximation, we assume speed of the sound is uniform, just say we estimate, see the major players, how weight factors determine axial resolution, basically pulse duration, the smaller pulse you get better resolution, and the speed of the sound, smaller speed you get better resolution, so you think you send the pulse, the pulse, you send the pulse this long, this pulse will move into the biological tissue, so this is total length of the pulse, this leading edge, this end, so this pulse will move into the human body, will hit a surface, hit surface here, hit the surface, this surface is B, hit surface B, also hit surface A, so this A, this B, so we send a pulse one after another, we want the two pulses can be separated, then we say that is the axial resolution, so remember this is surface A, surface B, this is surface A, this is surface B, so you have pulse, just move, first hit surface A, so this is time, hit surface A, this is overall setup, then we let time go, so the time just make sure this is length of pulse, this pulse moves halfway through this surface A, so this is halfway through the surface A, part of the energy will be reflected back, so this is the surface, so if it's not a boundary, it will move halfway, but because it's a boundary, half energy will be reflected back, you see, this is reflected back, this way, you let the same amount of time go, the whole thing will be reflected back, right, so this is the leading edge, this is end, so it's just this leading edge, hit this, reflect back, just turn around, so this is the whole pulse already turned around, on the way back, so this is the situation, you let it go, then just keep coming back, this is the reflected signal, and also this surface is not perfect, and part of the signal is transmitted, so this part say, here, half wave reflected, and also the components, the half wave really transmitted, now hit this surface B, and this surface B will also reflect the signal, so when this whole thing reflected back, during the same amount of time, so this transmitted pulse will be just flipped back, so you got this part back, so then let time continue, so you see, this is reflected signal, this is transmitted, then reflected signal, so these two pulses, this is end, the tail, this is leading surface, they get together, so if this AB get anything smaller than what I show here, these two components will be merged together, so here we define the resolution as distance between boundaries of surfaces A and B, so this distance, if you follow this logic, this logic is just half pulse duration, and half pulse duration is the time, time times velocity is the distance, that's the distance the pulse travel from, the half pulse travel from A to B, so this is so-called axial resolution, so just review a little bit, yourself to get better understanding, so we talk about spatial resolution, lateral and axial, now we talk about image contrast, so two words, hyper, record, and hyper-hypo, so that means the scattered echoes, have a higher scattering amplitude than average, you see the field of view, you can compute the average signal, so if you have stronger than average signal, we call it hyper, if you have lower than average situation, you call it hyper, so per-pole, a little different, so different kind of signal, relative strength corresponding to different structures, so you can read, so you have natural ultrasound contrast, but in some situations, the contrast are not that clear, so these are situations, you have very good contrast, but if you don't have very good ultrasound signal contrast, so I copied a slice from internet, you can use micro bubbles, so you introduce air bubbles with diameters from 2 to 5 microns, then these bubbles encapsulated with aluminum or lipid shell, so they are relatively stable, it could be even enhanced with higher molecular weight gas, so you can make these micro bubbles outside human body, then you introduce micro bubbles in certain liquid into blood stream, so the blood stream then will contain all these micro bubbles, when you send ultrasound signal, these bubbles will oscillate with the ultrasound wave, and also the air-liquid interface is not so transparent, so a lot of signal will be reflected back, so the blood stream, micro vasculature can be seen better, and also you have this polymer or some specially made shells, and you could functionalize the surface of the micro bubble, so the surface could have antibodies, it depends on what kind of antibodies, so these micro bubbles could selectively attach to certain biological features, like cancer cells, so whenever you see micro bubbles as very bright signals in ultrasound image, you can say, okay, there must be some cancer cells, so this way you can make ultrasound imaging a molecular cellular imaging modality, so this is a very good idea, and furthermore you can acoustically enable drug delivery, so you put drugs through blood stream, micro vasculature, move into your whole body, but you know here is tumor, then you just use ultrasound, just stimulate tumor region, the ultrasound will be made in right amplitude and frequency, that will break the bubble, then the drug will leak in the tumor region, so this is a very cool idea, and a lot of new possibilities with ultrasound imaging, so your homework question, this is matching layer, I want you to derive, not very complicated, and the first one also straightforward, so just read the green textbook, and the next lecture, Tuesday, I will finish ultrasound, okay, thank you. Thank you.