So last time, we talked about image quality assessment. Today, we start modality part. So we talk about X-rays first. And I would like first to mention your study habit or some tips. So when you do complicated subject, like medical imaging, it's a good habit to do preview, review, and important thing. I repeat multiple times. And you show the poster I made on the foundation part. Also, you show the poster I did for my graduate class. And they like the poster very much, by the way. And this morning, I show some map for mathematics. This is too big a topic. All things, modern mathematics, classic branches, and the new things covered. The physics, you have relativity and quantum mechanics. I think, in a way, this is a mixture of science, engineering, and art. And it's a good habit if you like. When you review X-ray modality, then you may just as a hobby, a habit, you make some review card somehow like this. And when you do MRI, you can do similar thing. And at the end of the day, you can do a poster for modality. And you cannot reproduce my poster for graduate class because that one has a lot of mathematical and physical governing equations, deeper stuff. But here, we try to give you a general introductory exposure. So you can do undergraduate counterpart. That would be fine, if you like. This is my suggestion. I think always nice you learn things. You have an outline. This is like what I'm going to say today. Today, you see outline. I think for X-ray modality, I'm trying to use this outline format. And you see the key point. And actually, imaging, I give you some basic knowledge. Some of them I already mentioned to you in the introductory first lecture. And I reproduced some images. We need a review. I myself also need a review. And after multiple times, you get a deeper and deeper understanding. So that's very cool. And today, we talk about three most important things. So source attenuation detector. This is logically very reasonable. So you need to generate X-ray. So without X-ray, without rice, you cannot cook. So you need a source that actually interact with the human body. You need the interaction. So you need a certain good degree interaction. Even no interaction actually passes through, see you as air. There's no information. If you observe all the X-rays, X-ray cannot penetrate, and all X-ray photons are observed in your body, then you carry no information out. That's not good. So contrast mechanism means you just partially observe X-ray. So some organ take more, and the other organ or components take less. Then you see difference. The contrast give you information. The information carried by X-ray photons escape the human body. You need to record the information. That's naturally you have detector. So source interaction detector, that will make a simple imaging chain. So you need that. So first, let me give you some basic knowledge. You show this before. So Ritigan discovered X-ray by accident. So he played around with some cathode tube and actually generated X-ray. At that time, they didn't know. And they just found some strange things. So you put the tube in a box, and some phosphorous screen got exposed. And you see some picture. And this cross is metallic. And the X-ray project a saddle here. So all these things cannot be explained unless you assume some physical rays. And we don't know. They didn't know at that time. So they call it X-rays. So Ritigan rays was discovered when the first Nobel Prize. And nowadays, we know much better about X-rays. We know X-ray radiation is a portion, a special kind of electromagnetic waves. And the wave lines, it occupies a specific portion of the EM spectrum. So visible light, we are most familiar. So we can see. And you cannot see things that do not mean the things do not exist. This is like an iPhone. And you cannot see electromagnetic wave. But I receive email all the time. You take a picture. Now and then. And then you send the picture to your friends, maybe in California, maybe in China, Japan. You never know. So the electromagnetic wave governed by Maxwell equation is a really cool thing. So you just have the sinusoidal wave travel through the space. And there are the magnetic field and the electrical field. The two field components are orthogonal. So you have all nice physical stuff here. But for our purpose, we just know that we have this wide spectrum of radiation waves available. And we can make use of it for different purposes. For medical imaging, we can use different portion of EM waves for medical imaging. And for this reason, we have x-ray imaging. And this part is for nuclear imaging. And you have optical imaging and the microwave, radio wave. We use that for magnetic resonance imaging. So the relationship is very clear on this big picture. And all radiation waves are characterized by wave lines. And the energy is inversely proportional to the wave lines, lambda. And the direction is proportional to frequency. And this h is a fundamental constant, the Planck coefficient. And the c is speed of light. And some unit that you may remember. And we used to deal with daily object. But here, we talk about very small wave lines. And we work in the domain of nanometers. Nanometer and m is 10 to the power minus 9. It's an order of magnitude larger than atomic scale and the measurement called the angstrom. So you have a small o on top of a. So that's just easy to remember, 10 to the power minus 10. So this is about x-ray energy. The position of x-ray energy in wide EM spectrum. So this is clear as a general knowledge. And if we narrow down, we see x-ray range. So you see the wave lines between 100 nanometer to 10 nanometer. So very small wave lines. So in this range, we call the radiation waves x-rays. And they are not all the same. And when you have a little higher frequency, and I mentioned that the higher frequency, you have a higher energy. So we call x-ray harder because more energy. And if a lower frequency, longer wave lines, the x-rays are weaker. We call it soft x-rays. And the different kind of x-rays can be used for different applications. So for medical application, for mammography, you use a little bit of soft x-ray. But when you try to penetrate a big piece in the body with bony structures, those dense objects, you use a harder x-ray. So the x-ray energy will be raised to about over 100 keV. So keV is just an energy level. So those physical things, even higher energy. And you use it for airport security screening. Some luggage can be really heavy. So you need even higher x-ray energy to penetrate the object. Otherwise, all x-rays will be stopped by the object. You'll have no information at all. You showed this before in the first lecture. So this is just one view, x-ray film, a digital x-ray film. And then you just see 2D image. Everything superimposed together. Your heart, your lung, your ribs, and all superimposed together. This overlapped view is not the best, but it indeed gave us insight into human body. If you break your bone, you have bullet inside, you can see immediately. So in emergency room, this can be very helpful. So from this projective view to cross-sectional view is a big jump in the field. We call it x-ray computed tomography. So you can see cross-section clearly, and have resolution as fine as 300 microns resolution. So you can see small details. And how you can make a cross-sectional image we will explain in next lecture. Just a review with you. So you'll see x-ray imaging can be so useful. Then you'll feel motivated to know how we can have x-ray shots, and we have detector, and how we can play around to tease out the information as much as possible. In the future, we can make x-ray shots very portable, powerful, and you could even imagine, I think you can do nothing stop you just thinking out of box. The iPhone can make an x-ray picture, who knows? But I think there are possibilities. One open question, how can you make cheapest x-ray shots? You know the scotch tape? And some papers say you just take a piece of tape out of the scotch tape holder. The x-ray will be generated. So this is something, if you're interested, you can Google the concept. So a lot of new ideas, potentially very important. And you showed this before, and I mentioned this number of view got increased. And it's just a very cool thing. You can review it again and see if you have a better understanding after this lecture. OK. Medical x-rays is very important. Medical x-ray imaging techniques, like the playing film, like CT images, are so popular. And some of my friends, my former mentor, mentioned the modern radiology, the cornerstone, working house, number one is x-ray imaging. With x-ray imaging, modern hospital can do good work. Take it away, it will fail. You take any other modality away, it can still work as long as x-ray, medical x-rays, are in operation. So x-ray imaging is relatively cheaper and widely available. It gives you high resolution, fast speed. The third line, I want to emphasize, it also gives you high geometric accuracy. What do you mean by geometric accuracy? Like MRI imaging, you see the picture, but the picture may be deformed. Based on the MRI picture, without the correction, the deformed picture may give you illusion. You see some tumor here, but actually the tumor looks right, but it's displaced somewhere, just like you stick a pencil into a cup of water. So the pencil got bent, and you cannot trust it. So you just see the face is there, you just try to cut directly, but you will miss the target. CT gave you very high geometric accuracy. Based on that, you can shoot a reason beam, you can guide surgery. That is very important. And in many cases, an x-ray imaging can be sensitive and specific. So now you know what do you mean by sensitivity and specificity. Sensitivity is to say you have the disease, then you report you have the disease. So yes is yes, and the specificity on the other hand is really something I mean no is no. So this is very important. And even in cases, actually CT or imaging cannot solve your problem, but at least it will help you select additional imaging techniques. So you can just guide the next step. The downside I put in purple, x-ray radiation is harmful potentially. And if you control the radiation dose, that should be OK. Make sure each CT scan will give you radiation dose level somehow comparable to natural background. And you do a CT scan, roughly it's equivalent to take an international trip. You fly from America to China. And you fly very high, you receive a decent radiation. And that dose is more or less comparable to a highway CT scan. So if you do not worry about doing international trip, you actually enjoy it. Then the CT scan is not that bad. So do not feel too worried about it. But on the other hand, we are working very hard to reduce the radiation dose. And therefore, past several years, greater progress has been made. So right now, the radiation dose has been greatly reduced. Still, you have a comparable diagnostic quality. And then the image quality problem with x-ray imaging is a poor, soft tissue contrast. And the benign and malignant tumor will show clearly in MRI images. But in CT images, it shows, but not so clearly. And sometimes you need to inject a contrast material reveal medicine in minutes. OK. And the global x-ray, medical x-ray market is huge. So you have multiple billion business. Few years ago, and this trend keep going up. And never stop. It seems a lot of new possibilities. And again, I will mention some new technology in minutes. I mean, in this lecture. So medical x-ray imaging comes mainly in two general forms. And the left-hand side is relatively cost-effective. Just one view. Then you see overlapped picture. And the right-hand side, you still have one view at a given time instant. But you really want to reconstruct a cross-sectional image. So x-ray sauce detector will keep rotating around the patient. And also, patient table can be translated. You have a whole body measured from different orientations. Then you have enough data to reconstruct image volumetrically. This is x-ray imaging. Additionally, you show heavy equipment like this when you go to airport. So x-ray imaging also widely used to detect some explosive things or some weapons. And this becomes routine. So so much for general introduction. So you have idea what's x-ray and what kind of x-ray radiation do you have and their practical utilities. So next part are more important. So we talk about sauce interactions and detector. And with sauce and detector, you can make an imaging system. And just hold them together, then you can start doing medical imaging, medical x-ray imaging. So this is a typical x-ray tube, x-ray sauce, x-ray tube. And these two terms are used frequently. And the idea has been clearly explained in your book chapter. So you read the first book chapter. There are some descriptions. And I will review with you. Just briefly, I didn't reproduce the picture in your book. And this is just more colorful. So I like this one. But the idea is something like this. This is not hard, very interesting. You have filament. Filament just use tungsten. You coil up a thin wire. And then you pass the current through the coil. Then you have a very high temperature in the coil because it is just a strong current, a high voltage. So high power deposited into the material. So the tungsten coil or filament got very hot. So some electrons becomes very active, so easily moving around. Why you make a coil? Because you make a coil, you increase surface area. You have more free electrons available. Then we subject these free electrons into an electromagnetic potential, or called voltage potential, across this filament and this target. This target has a name called anode. And this is a name called a chisel. So just like the battery, you have plus and minus, you form a circuit. So here you have the filament. Here you have the tungsten. So you really want to apply across these two ports and make a field. And the field potential is strong. So that these electrons are attracted, accelerated towards the metallic target tungsten anode. So because I mentioned it's very hot, electron becomes very excited. They are bouncing around. And once you have the potential, electrons are dragged, pulled, accelerated towards the target. So electrons hit the target. And the electron and the material interaction will generate x-ray. I will mention in the next slide. So this is the overall process. And this process will generate a lot of heat. And if you have too high temperature, you could even melt the tungsten target. So to deal with the thermal problem, you need to do certain kind of cooling. Can you put water or some cooling things inside the tube? No, you make it a vacuum. Otherwise, you put water in. The water will stop electrons. So that will not be very efficient. So inside is a kind of very high degree of vacuum. So the heat will only got decimated while the radiation, the thermal radiation, not very efficient. So we have another way, just rotate the tungsten anode. So you got a very hot, then this is a rotated way. So the electron beam hit another place, a little bit cooler. So you keep doing this. And we got the x-ray tube working in the sealed glass container. And originally, it's a glass container. Nowadays, they use some ceramic things to make for different technical reasons. And there's a high rotation speed, high precision. And I heard from my friend at GE Global Research Center. And this high voltage actually tube technology. And it's very high tech. And you need a lot of precise engineering and a careful insulation and so on. It's not easy. So this is a key element. And you can read the book chapter for more details. And since x-ray was discovered, the x-ray tube technology pretty much remained the same. The working principle remained the same, but it got refined step by step for higher x-ray flux. Anyway, so this is the overall principle. And the y electrons hit a constant target. And you will have x-ray. Why you can generate x-ray? So this is your first red diamond. The x-ray was generated mainly in two mechanisms called Brice-Durand effect. And we have a general x-ray radiation through this mechanism. And the second is called characteristic or photoelectric effect. And then I found two icons from Google to explain the idea. So you have a primary electron beam hitting the constant target. So the target, you have a lot of things like this. It's a nuclei. And the electrons go through the material. And some of them, maybe lucky enough, just go through. But a majority of them will interact with the material. So one way, you see, you have one electron moving nearby a nuclei. A nuclei is positively charged. Electrons are negatively charged. So you have a traction force between them. So as a result, the trajectory is no longer straight. It will get bent a little bit. When you get bent a little bit, the x-ray radiation will be generated. It depends on how strongly you bend the x-ray primary path. And then you have different values, different energy of x-ray radiation. This is a continuous x-ray radiation. This is one mechanism. The other mechanism, the primary electron beam just kick an inner cell electron away. So this inner cell electron got kicked off. So you have a hole left there. Then the upper cell and the outer cell of electrons will jump down to fill in the gap. And as a result of the difference in the energy level between different electron cells and the characteristic x-ray emission will be generated. So you have specific x-ray energy or specific x-ray wave frequency. And it will be seen this way. So these are two mechanisms. So you need to know these two mechanisms. Then you know the x-ray spectrum. So the bryastronome radiation is continuous. And the higher energy and the lower intensity. So very low energy electrons will generate a lot of x-ray radiation at a lower energy. But low energy will not be seen, because low energy will get attenuated by the tungsten material. This interaction happens in the material, sub-surface level. So the x-ray generated there to let the x-ray go out. So the tungsten material itself will filter the low energy out. So you would not see those very low energy. It got absorbed by the tungsten target. And also, at a high enough energy, over 70 keV, and then you start seeing characteristic x-rays. And the tungsten material, the bonding energy, the innermost shell has a certain energy. You can only kick those electrons in the inner shell out when you have enough incoming electron energy. So you wouldn't see those characteristic x-rays in lower energy range. So you have this k alpha, k beta characteristic x-rays seen here. So the highest x-ray energy level determined by the x-ray tube voltage. So the highest voltage, you can have highest electrons. And if that is turned into x-ray radiation, you will have the same energy level. But the chance will be lower than relatively lower energy x-ray photons. This explains the overall shape of the x-ray spectrum. So the x10, pretty much determined by the highest voltage across the tube. And the intensity really depends on the tube current. The higher current, you will have more x-ray photons produced. So in your homework today, one question related to that. And the next one is copied from your textbook. You see the same thing I explained before. So this cathode oftentimes is deformed in a certain way. So you have the cathode electronically charged to have the force helping focusing the electron beam so that you have a relatively small target. You want to make an x-ray source spot small so you can have a crystal clear image. So this focusing effect is helpful. And also, you could use some focusing coil in this middle region. The purpose is just to focus the electron beam into a narrow beam, hit a small focus spot. That spot will be your x-ray focus spot. So you generate an x-ray. You don't want to make an x-ray focus spot too big. So if you have a too big x-ray focus spot, so x-ray photons coming from all orientation. So the structure will become blurry, like motion blurring. And you make an angle. Say this angle, you call it a theta angle. Between vertical direction and this surface, the anode surface, so x-ray will be generated along this dark line. But since you have this slope, the visible or the nominal focus spot size can be computed as this length times sine theta. And this angle really helps you to make a focus spot smaller. So this is a nice trick. And the field of view, the coverage for imaging purpose really depends on the distance from a focus spot to the patient. The patient goes further away. The coverage will be even larger. And this angle is delimited by this theta angle. So the coverage will be equal to 2 tangent theta. This is theta. So if you draw a vertical line here, so this will be theta. So 2 tangent theta times the source to patient distance. So these relationships are straightforward. And the x-ray intensity is proportional to KVP. KVP is a voltage across the x-ray tube. It's KVP squared. And also proportional to tube current. The stronger tube current will give you more free electrons. Then you will generate more x-rays. So all these things copied from your textbook. So you can review yourself, just guide you through. But you really need to read your textbook. And this is a new type of x-ray tube. And they're very expensive. I believe maybe half a million or quarter million something. And we do not test you. Just to let you know, it's a good idea. The idea is to inject some metallic liquid metal. Then you just have a stream of liquid moving down, very thin. Then the e-beam gone. Generate the e-beam in a similar way, as I mentioned. The e-beam interact with liquid metal will generate x-ray. So this is a new mechanism will give you much brighter x-ray radiation. So just some idea to let you know. So show much about x-ray source generation and the working principle of x-ray tube. And these things, in a way, I would say easier than your Fourier analysis. Pretty much just descriptive. If you believe in what the textbook tells you, just the knowledge, you just pick up. So it's easier. So show much about x-ray source. And by the way, I just interviewed. This week, we just interviewed graduate students trying to get a student. And the new students are trying to find a PhD advisor. And just a half hour ago, maybe no, one hour ago, I interviewed a student. She is in nuclear engineering major. And I asked her a question. I say, OK, x-ray generation, he learned this. So this is nuclear. This is positively charged. OK, I'll just put it here. Interesting thing. And I asked her, and the x-ray was generated in two mechanisms. First of all, it's just this de-acceleration thing. So you say, x-ray passing nearby the nuclear, so the electron passing by the nuclear will generate x-ray. So I asked her, this seems somehow confusing. So let me ask you this question. So the electron moving towards the nuclear, moving this way. So this part, because of the extraction, the negative charge, the positive charge, so this part, the electron will get accelerated. So we are gaining energy, not giving up energy. We are gaining energy. When you move out, so move out this way, the right-hand side, and this negative charge, and this negative charge will get de-accelerated. So when you have an electron shooting this way, so this part gets accelerated and gaining energy. You move out, you're losing energy. This is a symmetric process. How come you have extra x-ray energy to give out to generate x-ray? If the electron moving nearby the nuclear, this way. So again, the right-hand side, and then you have a traction force, and then you have a component. This way towards this direction is acceleration process. If you move out in a symmetric position, so the positive and negative, they attract each other. So you have the same component. This has a de-acceleration effect. So when you imagine the electron flying through nearby the nuclear, so these two processes are symmetric. And you're gaining energy, you give out energy. How you have extra energy to give out? Because this is really the net sum is 0. And see data sum analysis, and I discuss the viscous. The trick is that, indeed, in this case, you imagine idealized case. The electron moves into the nuclear, moves away, or very near nuclear. And the acceleration, de-acceleration, they are symmetric, no energy to give out. But the trick is that when the electron goes in this way, you've got a band-aid. The band-aid thing is some keyword. When you get a band-aid, so de-acceleration process will have a longer time to play. So that's the way to produce the additional energy. So this is a really deeper question to get more understanding about x-ray generation. And this phenomenon also happens with this single-channel radiation facility. So the electron beam get band-aid, means the direction is changed. Then you have x-ray radiation. So you need to think about this. Nothing really mystery. Between these particles, you have the fundamental force governed by the inverse distance square law. Then you are governed by energy conservation. That's a fundamental law. So with these fundamental things, you could understand deeply. It's not just this equation. You get band, you got x-ray, give out. What's happening? There are some fundamental physical reasons. So these things are just green basic thing, not required. But just say the physical things, mathematical things, and then you should have a deeper understanding. You know what's going on. And this will position you well in the research and certainly in job interview. Anyway, the next part, talking about x-ray attenuation. Once x-ray is generated by a tube or singletron radiation, we use x-ray to probe samples, present object. We want to get information out. So how x-ray get attenuated? And I mentioned to you, even no interaction, then the object will be totally transparent to x-ray. And that will not be good for imaging purposes. Total absorption will give you no signal. So partial absorption will be good. And the partial absorption through two effect. And the scattering and the photoelectric effect, I need to add a photoelectric effect as well. And we will get to that in the next slide. So the x-ray attenuation is due to interaction between x-ray photons and the object molecules. And the interactions happen at atomic level. And you look into the detail. So you'll see the human body really decompose into molecules, atoms. And then we see you have x-ray tube. You generate the primary x-ray beam. Some of them get through. Some of them got totally absorbed. And the others scattered away. So this is an overall picture. So the types of interaction between x-ray photons and matter can be grouped into four categories. The first one, you got lucky. You always got lucky sometimes. So no interaction. So x-ray photon goes away. And on the other hand, you have totally unlucky. And you got the x-ray photon captured by the matter. So we call it photoelectric effect. So the x-ray photons are absorbed totally. And then the second two cases, the x-ray photons got scattered away. Scattered away, and we'll have two forms. One form, the scattering angle is so small. And the energy is essentially the same. This is called really scattering or coherent scattering. Because the energy is the same, the x-ray frequency is still the same. So it's coherent. The frequency is the same, and the phase is the same. So that's fine, called really scattering. On the other hand, you have a larger angle scattering. That is called incoherent scattering or competent scattering. So you have energy partially lost. And this is somehow similar to what I explained to you for x-ray tube working principle. When you have this larger angle, this larger angle really goes back to the picture I explained here. It binds the x-ray path away. And when you do this binding, the de-acceleration effect takes a longer time. So you really take energy away this way. And the difference between the energy loss, difference from original energy and the extra energy you took away becomes x-ray radiation. So this way, you have competent scattering. You have a larger angle. Then this x-ray photon energy will become less. And the additional energy in this case becomes heat, most of the cases. So you have this really micro- or nano-level interactions and make x-ray energy rearranged. So these four types of interactions should be remembered. And the low interaction and total absorption and scattering, incoherent and coherent. Coherent scattering is small angle range, just zero degree or very small angle. And competent scattering, or other angle. So competent scattering takes a major share. For medical imaging, the interaction, most importantly, competent scattering and the photoelectric effect means total absorption. OK. And then we have this summary slides. So for medical x-rays, you mainly have photoelectric effect. And then you have competent effect. The scattering has competent and really, but really, this is so small portion. And we can say, when you use x-ray tube to generate x-ray cells, usually medical x-rays up to 140 kVP. And for x-ray energy is less than 80 kVP, photoelectric effect is more important. And all of that, so the competent scattering is more important. It's really scattering just a tiny bit portion. And not so important traditionally. And nowadays, research results indicate really scattering contains critical information, small angle scattering. And therefore, benign malignant tumor and other x-ray signals wouldn't give you a good indication. But a small angle scattering can tell you if the tumor is good or bad. But how you can detect really scattering is another topic we wouldn't mention in this class. And the interactions between x-ray photons and the tissue are not limited to photoelectric effect and the competent scattering. And there are other interactions. And then say pair production and the photo disintegration. And these two effects will become more important when you use a much higher x-ray energy. And that will not be for diagnostic purpose. Rather, that will be for therapeutic application, like radiation therapy. When you direct high energy x-ray or general releasing beams, like charge the particle protons towards tumor, like a barbecue, you kill the tumor. You cook the tumor. That's not for diagnostic purpose. So you have this big picture about interaction between x-rays and the biological tissue. Competent scattering has a major implication for radiation protection. When you shoot x-rays to a patient, and then you put, in this case, you put a detector beneath the patient. So x-ray goes through. But you need to protect radiologists and technicians from x-ray radiation. So these x-ray radiation, mainly from competent scattering, as shown here. So you need to put light glass. And you need to wear a certain coat. Otherwise, day by day, you will accumulate a lot of radiation dose. Patient did that only once, maybe once per year. But you work in the room all the time. So this is a critical issue. So we say the primary x-ray photons will get attenuated by biological tissue. And this is a cumulative process. A number of x-ray photons will get reduced rapidly. And then you can imagine you have a tissue layer. The certain tissue layer will absorb a certain fraction of x-ray photons. You can change the thickness of the tissue layer so that this layer just absorbs half of incoming x-ray photons. So this is really a probability. So the half-layer concept is important. So if you have this half-layer shown as yellow, so 1,000 x-ray photons will become 500 on average through the first layer. That's through the second layer, the same layer, same probability that 500 x-ray photons will become 550. Keep going. A few layers later, you'll get very few x-ray photons. So this is not a very efficient process. Like x-ray generation, you have a lot of electron energy. And through the thermal effect and the tungsten filtering and the x-ray source filtering process, only about 1% of it becomes usable x-ray photons. And through this kind of exponential attenuation, the total number of x-ray photons really arrive at a detector, a very small percentage. So we need to make an algorithm very smart. We need to make x-ray detectors very sensitive. So this is my general concept about x-ray attenuation. And I will let you relax a few minutes. Then we will get a little bit more quantitative. We will list the so-called Beer's Law, the relationship of a mathematical model to describe x-ray data you collect. OK? Next question, sir, we're using all of those in the whole We use all of them. We use all of them. And this all goes through the patient. So in that sense, we use all of them. OK. OK. OK. Very good. OK, let's continue. So now you have a pretty good general physical picture. Let's get a little bit more mathematical. How do you quantitatively describe the relationship between incoming intensity of x-ray beam and output intensity? It means that x-ray flux goes through the patient. So let's take a simple case. If you just have a square pixel, it's a homogeneous material element. The incoming flux is pretty much the same thing. We think about the same energy level. So how many x-ray photons really enter this pixel, picture element? How many of them will really go through along the same direction? So you have input Ni and output No. You call it output. OK. And this certainly depends on what's the material. So that's characterized by linear tannuation coefficient called mu. And also, how thick is the material? And you can specify as delta x, just as a step. And this is described by this exponential relationship. And there are some mathematics behind how you derive this exponential tannuation relationship. And certainly, you can. I don't want to get too much mathematics here. If you consider a very thin layer, then a small percentage of incoming x-ray photon will be absorbed by this infinity thin layer. Then the probability for the x-ray photon to get absorbed will be directly proportional for the thickness. We're talking about very thin layer. So then you can build a differential relationship. You solve that first order differential equation. The solution is naturally this exponential decay. This exponential relationship appears in many, many places, like a chemical reaction, like nuclear radioactivity decay, and the same thing. If you are interested, you just check textbook or Google. This is the simplest first order differential equation. So I will not list these details, but we do use the results. That's exponential decay. So the key variables linked in this formula. So input, output, and then we have exponential form. That's a result of a solution of first order differential equation for the differential relationship I didn't show here. But anyway, so you have this minus mu, mu called the linear time coefficient, and you have delta x. This is for one material element. And in reality, you will have many material elements, say, three. What's the relationship between input and output? And we want to express the relationship in terms of material property along the x-ray beam path. Then you can just keep repeating this relationship. So this input, this output, so for first element, mu 1, the output for mu 1 is the input for mu 2. And the output for mu 2 is the input for mu 3. So you just cascade this relationship, and then you will see these things keep multiplied together. So the first time you have mu delta x1. Then this whole thing, this output becomes input. Then you need to find the second stage output. Times e to the power minus mu delta x2, then delta X-rays. So you just got this second line. This is just straightforward, but it's so important for x-ray imaging. And if you can, let me drink some water.

We can keep doing this. So for n element, you will get this relationship. So all the terms added together, you got this relationship. And then we gave a name for this summation. We call it resum. Resum is not a good name, but it is a name widely used. So it means you just do summation along a ray. And what unknowns you are adding up together, so all mu k delta x. This product, partial product, is unknown. You add all these unknowns together. Really, you know delta x, because delta x is what you specified. You really don't know mu k. So this is called resum. So you have a bunch of unknowns added together. This is a linear combination. So it's a linear system. So on the right-hand side, you have ni divided by no. Then you have a natural log. Natural log is just to undo the exponential part. So you see the unknown is on the left-hand side. And on the right-hand side, you know log. You know ni, you know no. Because ni is what you generated with YouTube. You calibrated YouTube, so you know that. And the no is just transmitted actually flags. And then later, we will mention to you, and then we can measure actually flags. So you can measure no. So this is relationship. And certainly, this is just a discretized case. And then you imagine you make the pixel very, very small. In a limiting case, the summation becomes integral. So this is called the line integral. Mu x is a distribution of linear tenuous coefficient. That is a picture you want to make. And you do not have a magic camera. You take a picture, then the mu x will be shown. You really can only use x-ray to perform indirect measurement. You really want to know what is each mu x. You cannot measure mu x individually, directly. But you can measure resum. So this is called indirect measurement. Or you can measure line integral. So this is what you can measure with x-rays. And you do not have a direct image, cross-sectional image. But you can have overlapped signals. And that are in the form of resums or line integrals. You can perform many measurements like that. So this is a linear equation. And it gives you the relationship between unknown and what you can measure. So x-ray images is formed based on x-ray linear tenuation mechanism. So you have a tenuation contrast. So this is an example just to show you the contrast mechanism. Suppose you have a piece of tissue. And here you have some bump. So this is a nodule, we say. Then let's actually go through the normal tissue background. And also, x-ray probe into the tumor. So the x-ray attenuation is shown here. Because this total length is not delta x. Here we call it x. So you still have this relationship. And in the normal case, you have incoming flux attenuated by e to the power minus mu x. And in the nodule case, you have this delta z added on. So this is a decimal structure is your nodule. So what is the contrast? Contrast means normal signal. And then minus disease of the signal. So that's the difference. Normalized by normal signal. You do the calculation. You see the contrast is expressed as this term. It's always less than 1. And therefore, z equal to 1 centimeter. So you have a 1 centimeter tumor. And therefore, mu equal to 1. Just the reciprocal of a centimeter. You can compute the contrast is 63%. And the soft tissue more or less the water. So water mu is this much, 0.2 something. So if you plug in that number, the contrast becomes even lower. So this just to give you an example. You see the contrast mechanism. So this same thing. I should remove this. It's just adapted a little bit. So now we can say the X-ray data measurement model is summarized on this slide. I use the largest diamond here. So this is important. We see the incoming intensity of flux is I0. And then now we assume all these X-ray energies are the same. So we have a monochromatic X-ray beam. This is an idealized case. A real X-ray tube generates a wide spectrum. But here, let's assume being consistent to what I described to you. So this is a monochromatic beam. The incoming intensity is I0. Then the output is IG. And I think I could call it anything. Here, just call it IG. And it's just a grayscale signal. And in contrast to color CT, later on, we mentioned we have energy-resolved X-ray imaging. We can really get spectral information. The G really here means grayscale. So you've got a tiny-weighted output here. The relationship between input and output is shown here as a Beer's law. We call this Beer's law. We have an exponential attenuation factor here. It's an e to the power minus is a line integral. This is all re-summed together. So this is for monochromatic X-ray data model. So this is just something like this. Input and output linked through the line integral. So if you know input, you know output, you take a log. And what you measure is a line integral. So this is clear. But the real thing, this X-ray tube, you have many X-ray energy levels. So you need additional integral. So you basically say, OK, so for a given energy, X-ray energy, and then you have the output. But you have different energy levels. The real output, you need to put all these things together because nowadays the medical CT detectors is in the energy integrating mode. So all X-ray energies, no matter soft X-ray or hard X-ray, it just accumulates all energy together. Then report to a reading. Then we have this most practical popular model called a polychromatic model. So you have this additional energy integration. And you have DE here. So it's really just the same thing as in the monochromatic case. But you need to integrate with respect to energy. All energy is put together. You have a total energy. Then you report a total energy. Total energy is still a number. So you still have grayscale picture. A very important concept is actually Ki's, the linear attenuation coefficient. And as you show here, it's not a single number. Really, it depends on energy. So higher energy, usually the linear attenuation coefficient will become smaller because higher energy penetrate material more easily. Then you have this Ki's phenomena. So you keep increasing X-ray energy, say over 70 kV. All of a sudden, the attenuation coefficient jumps a little bit. Why is that? Because at that Ki's, the photons got energetic enough. So the photoelectric effect takes place. So the energetic X-ray photons kick out the electrons. And they got totally absorbed. So you have this energy jump. OK? So this Ki's is chemically specific. For different atoms, you have different Ki's. So this is very important. If you can do energy resolved imaging, you can pick up Ki's. You can do material decomposition and the chemical mapping. Otherwise, if you're talking about the total energy measurement, you are measuring all the attenuation effect. So that is equivalent to area under the curve. If you have a detector, you can measure linear attenuation as a function of X-ray energy. Then you really measure the curve itself. So now, the medical imaging in hospitals and clinics, you see grayscale thing. They use energy integrating mode or current integrating mode. You measure the area under the curve. We are working on energy sensitive X-ray imaging. So we are trying to measure the curve itself so that we can resolve the Ki's. We can do chemically specific imaging. And then we can do some contrast agent nanoparticle labeled imaging. You can resolve nanoparticle. You can do molecular X-ray imaging. So that's the future. Then you need an X-ray contrast agent. And you have multiple agents under investigation. Most common things are gold nanoparticle, iodine, gadolinium. So those things have distinguished Ki's. And without energy sensitive imaging, you wouldn't be able to tell this bright signal is due to 100% iodine or due to, say, certain percentage gold, then certain percentage bone, and the other percentage water. You couldn't tell different. Only if you can measure the curve, you have an opportunity to do Ki's imaging. And how can we measure X-ray data, measure X-ray signals? And then we come to the last part. We need to talk about X-ray detector. And in your book chapter, a good portion of text was devoted to film and all the technology. I'm not going to explain those out of data technology to you. But you read it. It's still good to read. And then you have some general knowledge. And I talk about some most important thing, how X-ray signals really detected this digital element in the modern X-ray CT machine and the future X-ray imaging equipment. So energy integrating detector is the most popular and practical and mature technology. Really, this energy integrating detector, you just record the total energy the detector element intercept. Doesn't matter if it's from high energy X-ray photon or low energy X-ray photon. And it works in two modes. And one is indirect mode. The other is direct mode. So indirect mode, again, these are easy thing and nice to know. So indirect mode like this. So X-ray photons comes in after transmission through patient's body. So X-ray photons reach the detector element. The detector element has a primary sensor material that is X-ray phosphor, means the material interact with X-ray in a way that X-ray energy is completely or partially absorbed. Then the energy is converted into visible light. So that's called phosphor. Phosphor, it's just to give you a lot of visible light. So X-ray has a higher energy. Visible light, if you check the EM spectrum, has a longer view line, lower energy. So one X-ray photon will generate multiple visible light. So visible light will interact with the next layer. You have photodiode electrode. So this light-sensitive mechanism will convert visible light into electrical current. Then you have a circuit. You read out the current. So that's why I say current integration. So this detector is sometimes called energy integrating, sometimes called current integrating. You do have these charges summed together. So high energy X-ray photons generate a lot more visible photons. And the low energy X-ray photons generate multiple visible light photons, but not as many as a higher energy X-ray could generate. But all these things eventually becomes charged. And at the second layer, these charges becomes indistinguishable from higher energy or lower energy X-ray photons. Who cares? So they're put into the same basket. Then you report a current reading as a proportional to total energy. That's why we call it energy integrating detector. You report a number. This reflects the total flux after X-ray attenuation in the patient's body. So this way, you got data. You measure X-ray signal this way. The second mode, direct mode. So X-ray interacts with some semiconductor material. X-ray is converted directly to charge the particles. Really, X-ray hates the semiconductor material, like silicon, like some CGT material, will generate an electron-hole pair. Then this material is subjected to high voltage bias. So the charged particle will be separated from a current. Again, the current can be read out by your circuit. That's a signal. And again, in this design, any electron-hole pairs will be treated the same way. So you've got a total reading of current formed by X-ray radiation. So this is just a working principle of X-ray detector, most commonly used nowadays. I want to mention this important concept, anti-scatter grid. X-ray detectors, as I explained, oftentimes do not use on its own. Really, you need a couple X-ray detector array, either linear array or area array. You need a couple detector array with anti-scatter grid. Why you need anti-scatter grid? Really, because you recall the picture I show you. The two-effect photoelectric scatter effect, a lot of scatters for medical X-ray. So a lot of signal will go from different orientation, trying to reach the same detector element. But what we really want to measure is a line integral, means I want the information along the primary X-ray path. So I want to have all the information along this ray. I don't want to have all information, all the X-ray photons scattered and transmitted, all added together. So I want to reject the scattered X-ray photons. So I use a grid. So grid, really, just like a pinhole, many, many pinholes. The pinhole only look into one direction. Only X-ray photons travel along that direction. Defined by this pinhole will reach this detector. And from other direction, like shown here, will be attenuated by the heavy metal wall of the grid. So this way, you make sure you are measuring line integral, not all the X-ray photons superimposed together. This will make a big difference. There are some further discussion here. So you have a higher, you have a larger value for the height. You have a better rejection rate. But again, some primary beam will be blocked. And there are just the many mechanical fabrication issues. The second is the aspect result, the material, and the many engineering details for optimal image quality. So you can read your book and get a little more understanding. And with or without anti-scattering grid will make a big difference. So with the grid, so you see the structure are better defined. You see very sharp boundary. But without the grid, you will see some foggy appearance. And the scattered X-ray photons will be superimposed on top of the fine structure. And this can be very annoying when you try to detect low contrast of the tumor. And when you take out a plane, when you are in very, very good weather, so you see through things clearly. But if you're in cloudy weather, you cannot see through the cloud. So the scattering photon really a layer of clouds over the picture. So we want to minimize that. And also, I found some interesting research. And if you're interested, you can search for virtual grid. And in this case, you do not use a real grid. You use some smart computer algorithm to remove the low frequency scattering signal. Again, I should have put a green button here. I will do so after the class, then I upload again. So so much for energy integration, energy integrating detector. And the next sub-point will be dual energy imaging. So this is very important knowledge. Now, all the CT manufacturers, like GE, General Electric, like Siemens, you know, Filippo, and the four top guys, and these three plus Toshiba. And these three companies try to do energy sensitive imaging. Not all the way sensitive. They try to do dual energy imaging. So they collect the data with two different X-ray spectrum. For Siemens, they use a dual source. So you have two X-ray sources operated at a different tube voltage. So different tube voltage gives you a different X-ray spectrum. So you have more information, spectral information. And the global research uses KVP switching, only one tube. But the tube will keep changing operating voltage. At one view, you use a certain voltage, say 140 KVP. Then the second view, you change to 80 KVP. Then the third view, you change it back to 140 KVP. So this kind of arrangement really gives you two X-ray spectrum. So this way, you have data embedded with spectral information. And I will get to more detail later on. And Philippe used another idea. And really, they modified the X-ray detector. Make the detector not a single layer, as what I just showed you. They used so-called dual layer detector. The first layer observed a lot of low energy X-ray. The second layer, after the X-ray beam passing through first layer, and the higher energy portion got enhanced. Then the second layer detected higher energy X-ray photons. So this way, you got low X-ray and high energy X-ray separated. So this is a core technology. And Toshiba did something simpler. They used so-called dual scan. They scanned twice. The first time scan, it was a high KVP X-ray tube. And then you scan same portion, the same patient again, with a lower energy X-ray. So somehow, like this KVP switching, or like yourself, you still have two X-ray spectra. But you need a double scan time. This is not very good. And also, first scan, second scan, patient may move. You inject some contrast material into patient's body. And then you do two scans separately. That will introduce mass mass, mass registration error. So these three technologies are a little bit better, I would say. The dual energy imaging. Why we talk about dual energy imaging? This is a very important technology, and practically widely used. And let me explain some ideas about dual energy imaging. This is related to the classic paper by some Stanford professor. And this is the title. I didn't put the other name here. But anyway, to understand the key idea, let's just review a little bit about chemistry, chemical concept, atomic number, and atomic weight, or mass number. So you read this a little bit. Let me drink some water. I need to keep drinking water. You read a little bit, and I will explain the key concept. So dual energy imaging has a very strong physical foundation. And for linear tinnitus and coefficient, we know you have a photoelectric effect. You have a competent effect. These two effects are dominating. And these two effects can be physically modeled in different ways. So you have two terms. So first term shown here is for photoelectric effect. Second term, clean, nice enough function, is used to describe competent scattering. So you have two effects. Both effects are energy dependent. The energy dependent part can be modeled this way. So the first one is inversely proportional to x-ray energy to the power 3. And then the second one depends on a more complicated function. It's a function of x-ray energy. So you have two effects. You imagine if you use a two x-ray spectrum, get data, then you solve equation for the two unknowns. Then you can predict what will be the x-ray response at any x-ray energy level. So you have two material bases. And another way to view it, really you think the human body combined with the water and the bone and the mixture of water, bone, sediment, iron. So these two bases and material is equivalent to two physical mechanisms. So physically speaking, you have photoelectric effect, scattering effect. You have two effects. Material-wise, you have water, you have bone. And anything else can be presented as a mixture of these two things. You just do linear combination of the two bases and material. You will be able to accurately simulate or emulate other material type, like a tissue will be certain portion water, certain portion bone put together. So you have the coefficient alpha 1, alpha 2. And they're approximated by the relationship in terms of G and A. So we define G and A as a mass number and atomic number here. So you have capital K1, K2. That's really just the coefficient, say the material density and those things you can solve for. But these things are not energy-dependent. To solve the energy-dependent, solve the equation for energy-dependent information, and you have the energy-dependent term characterized here. So the dual energy measurement can be done for two X-ray spectra, so S1 and S2. The relationship shown here, you have two independent terms. The physical reason is clearly shown here. And if you want to solve for the unknowns, the constant values and the coefficient, and you need to do a little bit of mathematics, and you know that X-ray measurement is a line integral. So you do a line integral energy-independent part. You can integrate it together as this line integral, the first portion, the first contributor to the total line integration, denoted as capital A1. The second portion is alpha 2. You do line integral, you've got A2. So if you can solve for A1 and A2, and then you can really recover this linear tenuous coefficient in terms of any energy, because you know this relationship. Based on this physical model, so we know you do two energy-independent energy measurement. You've got enough data to solve these two nonlinear equations. It simultaneously holds, but you have two unknowns, A1 and A2. So think a little bit about this, and you will know. And the dual energy technology, either dual KVP, or dual source, or dual layer detector, give you two independent data sets. Then you can use the two independent data sets to solve this system of nonlinear equation, which contains two unknowns in terms of A1 and A2. A1 is a line integral for this part. A2 is a line integral for the second part. So this is the idea. And then the last topic is photon counting detector. You say the current integrating detector measures the area under the curl. Only give you one number. So that's just black and white, one number, just the intensity. But now, if we can do the energy-sensitive measurement, we measure the curl itself, we measure the linear tenuous coefficient in many energy beams, then you will be able to tell what's the linear tenuous coefficient for soft x-ray. What would be linear tenuous coefficient for harder x-ray? You will have soft, medium, high x-ray-related tenuous coefficient. Then you can make multiple pictures. You can assign color to these energy channels. You'll have a colorful picture. That's the idea. The photon counting detector works in a way pretty much like direct detection mode. So you see x-ray interact with semiconductor CGT, typically, material. It will form electron whole pair. And under bias, the potential. So this electron whole pair generated by x-ray will form a current in the circuit. This is a circuit. So through the voltage and the semiconductor material. So each x-ray photon comes, it will generate an electron impulse. This electron impulse will be detected here. The circuit is so sensitive, it's so quick. When you get one x-ray photon, you have a tiny current impulse. The current impulse will be compared with the pre-set threshold. If the impulse is higher than the threshold, you'll see a bunch of operational operator here, non-linear components I mentioned a little bit earlier. And then you can set the number of threshold. And then you can make a judgment if this x-ray photon generate an amplitude of electrical current impulse. That's just between, for example, the fifth and the sixth threshold. Then we know the energy of that x-ray photon must be between the energy range defined by fifth and sixth threshold. So this is the general idea. And this is only for single pixel. And you can have many, many pixels. This pixel can be made very small. And the state-of-the-art photon counting detector we are getting from New Zealand has a detector pace of 55 microns. And this circuitry called ASIC contains the hundreds, thousands electrical components, like a transistor, those IC components. So this is high-tech stuff and giving you high spectral energy resolution. So KI's imaging model will need a photon counting detector. If you only deal with a human body, one argument is that you do not need a photon counting detector. Dual energy detector ought to be enough, because you only have two material bases. With two measurements, you solve equation. You can predict the material response to x-ray radiation at any energy level. If you only have two material bases, indeed, you don't need multiple energy. But when you introduce a contrast agent, like iodine, gold nanoparticle, then you need energy-sensitive imaging. So that you can have spectral information. You do material decomposition. You can chemically specifically map nanoparticles. And the different nanoparticles, you can tag functional nanoparticle, tag to different cellular molecular features. So you will get a biological resolution, biological information from x-ray imaging. This is the major benefit, potential benefit, of photon counting, energy-sensitive x-ray imaging. And we feel excited about that. And there are some other benefits. Like you have energy information. You can correct for beam hardening, quantum efficiency. You can reduce reducing those. Those benefits are real, but not a major one in my mind. The major one is k-ray imaging. You do nanoparticle contrast-based x-ray imaging. You have more cellular and functional imaging. And we have an NIH grant proposal founded by federal government. And in collaboration with Stanford University and the GE Global Research Center, they are trying to make photon counting x-ray CT. So this will be future technology. And not a remote future, I would say. And last year, a radiology paper was published by some MDs in collaboration with Siemens. And the first set of color x-ray CT spectra or photon counting CT images were reported, giving the dose efficiency and the diagnostic performance pretty much comparable to the current best energy integrating technology. So the field is working to get even better results to have full potential of photon counting detector and the photon counting CT. So this is just nice to know. And another idea we are working on is to use photon counting detector and the energy integrating detector together. And this is pretty much like retina. In your retina, you have both the rod cell and the core cell. Rod cell is sensitive to intensity sensing, so just like a current integrating detector.

So all energy is sensed. And on the other hand, core cell, you can see RGB, so like a photon counting detector. Why human retina system works in this hybrid mode? Because the rod cell and the core cell, they collect and extract different kinds of information efficiently. The energy sensitive detector, photon counting detector, cannot count very high flux. So it's relatively slow. But those detectors do give you energy information. On the other hand, the current integrating detector does not work well in low flux situation. But for high flux, it will give you a very good signal. So our idea is to mix these detectors together. For example, we have grayscale energy integrating detector. And also, we have photon counting detector that gives you spectral information. So you have this mixture. And we wrote some nice papers. And my former PhD student, James Bennett, did a nice work. He published a journal paper in IEEE Transactions on Biomedical Engineering. And his main work is to combine these detectors cost effectively. Those photon counting detectors are rather expensive. And he showed that you can get spectral information from hybrid X-ray detector in a cost effective fashion. So just to show you good PhD research, the dissertation research, I think. OK, we have a few more slides to show you. And I think we organized an IEEE Transaction Special Issue on spectral CT. And this special issue got highlighted by IEEE Transaction on Medical Imaging. And I made this part to see again. So this part, you first see grayscale, then dual energy, two color. So this is grayscale. Then you have a red, blue. This is dual energy. Then you have a rainbow color. This shows the photon counting imaging. So this is a picture from New Zealand. And you can read it yourself. So homework for today. And from now on, we follow the green textbook roughly. So we will select good problems from your textbook. And I selected three of them, and not very hard, so much for today. And several typos I will fix, and I will upload the PowerPoint file.