[APPLAUSE]

EDGERTON: Thanks a lot. I thought we were going to have a movie first.

AUDIENCE: Yell at the right guys--

EDGERTON: Hey! [WHISTLE] Movie! Go!

[LAUGHTER]

EDGERTON: Where's the movie?

[LAUGHTER]

EDGERTON: Well let's-- there we go. Well, I'm going to sit down and listen to this thing.

AUDIENCE: If we get the sound.

EDGERTON: Yeah, how about a little sound up there. Up in heaven or wherever you are. Whoo-up!

[LAUGHTER]

EDGERTON: Sound yet?

AUDIENCE: A little bit.

EDGERTON: [WHISTLE] Louder!

AUDIENCE: I want to see.

[LAUGHTER]

AUDIENCE: Doc, you may not believe it, but you may be annotating this film.

EDGERTON: OK. Anyway, this is a movie named what? Did anybody read the title?

[LAUGHTER]

Hey!

[APPLAUSE]

You have to turn on a knob up there somewhere.

[VIDEO PLAYBACK]

-Thus became the the vital elements of man's visual quest for knowledge.

One form of natural phenomena, lighting, both fascinated and terrified him. His curiosity about this strange phenomenon was to provide him with a key to a whole new way of seeing his world.

[MUSIC PLAYING]

EDGERTON: There's the title.

-In 19th century England, William Henry Fox Tablot, an early photographic scientist, is reported to have observed an unusual phenomenon during an electrical storm. He noticed that water running from the eaves of his home was not in a continuous stream as ordinarily seen, but was broken up into droplets when observed in the light of a lighting flash. Fox Tablot realized that the short duration lighting flash had enabled him to see this phenomenon as it really occurred. Later, he utilized a man-made spark to demonstrate this discovery photographically in the laboratory and lecture hall.

Years later, [? Borach, ?] a German scientist, employed a spark as a scientific tool to observe fast moving events by the shadowgraph technique. Although the light of [? Borach's ?] spark was weak by today's standards, he successfully produced a shadow that could be recorded permanently on a [INAUDIBLE] beak.

At the University of Prague, Professor Mach successfully produced shadowgraphs of bullets in flight. Later, in Vienna, further studies from shadowgraphs were the basis for his theory of shockwaves.

Shadowgraph photography, using spark illumination, was a forerunner of photo instrumentation technology, as we know it today. Early researchers modified the shadowgraph into a system for recording front surface detail of the phenomena under study. And by adding reflectors to the light source, the luminous efficiency was increased.

Sophisticated light sources have been developed for [INAUDIBLE] movements of light. This [INAUDIBLE] is capable of generating 6 million beam CandlePower of light at durations ranging from 20 to 600 microseconds.

The xenon flash tube produced a brighter source suitable for a wide range of applications in science and industry, and in ordinary photography. By pulsing this flash tube several times as the object passes in front of the camera, a series of pictures may be recorded on a single plate, or a sheet of film.

This multi-flash technique is known as stroboscopic, or strobe photography, and provides a method for recording a series of time related pictures.

Multi-flash strobe also finds wide use in today's medical applications.

In many instances, the multiple flash strobe can be used to study phenomena by direct observation without the use of photographic materials. By adjusting the flashing rate to match the frequency of the event, the motion appears frozen, and the velocity can be determined when the flashing rate is known.

[WATER DRIPPING]

[LAUGHTER]

Another valuable technique, known as streak, or smear, photography, utilizes film moving continuously through the camera. To understand the principles of streak recording, we'll look at this guitar string as the camera sees it.

Normally, it appears like this. However, if we shrink the camera's vertical opening narrower and narrower, the vibrating string is seen as a dot traveling back and forth. This dot writes a continuous record of its motion onto the passing film. By knowing how fast the film is traveling, one can accurately determine the frequency of the vibrations. One of the advantages of streak recording is the ease with which motions [INAUDIBLE] phenomena can be continuously photographed and studied.

Some high speed cameras operate by simply increasing the speed of a conventional movie camera. This high speed camera, for example, can photograph events at speeds up to 500 pictures per second, or about 20 times faster than conventional movie cameras. They're known as intermittent high speed cameras, because they hold each frame of the advancing film motionless during exposure. They're especially well suited for studying human motions and slower mechanical actions.

[CHEERING]

[LAUGHTER]

[MUSIC PLAYING]

Higher speeds can be accomplished by placing a rotating prism in the camera between the lens and the film. The key to the operation of this is the rotating prism's ability to move the image onto the film as it passes through the camera, thereby eliminating the necessity of stopping the film for each exposure.

The result is that the image is exposed onto the film as though the film were not moving at all. The rotating prism also functions as a shutter. As each facet of the rotating prism passes, a new picture is recorded on the film.

[MUSIC PLAYING]

[SIDE CONVERSATION]

[LAUGHTER]

[LAUGHTER]

[LAUGHTER]

If photoability has enhanced the usefulness of rotating prism cameras, so has the development of more sensitive and higher resolution instrumentation semi-films. Modern day films enable the researcher to record many phenomena--

EDGERTON: It's about time to cut this film off. Let's turn off--

AUDIENCE: More people ask them to stop the film, please.

-[INAUDIBLE] higher recording speed, a certain film can be attached to the inner side of [INAUDIBLE].

[END PLAYBACK]

EDGERTON: [WHISTLE] Turn off the commercial. Now we can get on down to business. This was supposed to be a preliminary to get us into the high speed action.

It seems only about yesterday that I saw my first strobe light in action. I was a freshman at the University of Nebraska, and they had an open house, and one of the upperclassman hooked up a strobe, and it consisted of a neon lamp, a Ford spark coil-- they're square things-- nobody is using them anymore, and a commutator, and a battery. And in a dark room, it was all right. You could see things. Almost. And I must admit that the light was too weak, it was the wrong color, the flash was too long, the control was inadequate.

But those things were brought into a focus, so that when the time came, something popped in I could see that would improve it. I was ready. It made a tremendous impression on me, and I hope that the strobe demonstrations make a big impression on you, and sometime something in your career will pop out, and it will be useful to you.

The human eye is a marvelous thing, but it lacks the ability to see anything that moves. Anything that moves at all is a blur, and is lost, as we'll see with these drops and things.

Incidentally, strobe alley is always open. How many have been to strobe alley? How many haven't been in strobe alley. Well, you better get over there, or it'll be [WHISTLE] for you.

[LAUGHTER]

It's open 24 hours a day. It's the only museum in the world I know of that's open on all days, all times of night. It never closes. It's in the hallway, and we have some of these hydraulic dripping machines that go on forever. And be sure to run those. They're push buttons. You know how to do that? You push a button, and they work.

So I want to show you a strobe or two. Is that all right? Now this is a xenon one, one of the latest in the line. So this is the motor. You can see the motor's running.

AUDIENCE: Yeah.

EDGERTON: He says he can. Now see if the strobe will push a button here. Look at that. And I reads-- Can you read this? What does it say?

AUDIENCE: 2,249.

EDGERTON: Well, apparently that isn't going at that speed, is it? Now I put a mark on there, and when I stop that mark-- that's a piece of chalk-- by turning this knob. Now what's the speed of the motor?

AUDIENCE: 1,980.

EDGERTON: Wrong. Well, you just read the dial. You didn't read the speed of the motor. That motor's going a different speed.

[LAUGHTER]

Now let's multiply that by-- if its one flash every two revolutions, what would the speed of this be? You got your computer with you? He hasn't got a computer. It will be about 4,000. So I'll bring it up. Bring it up, bring it up, bring it up. 4,000. Nope, it ain't there. Went off scale. I'll push it on the next scale.

[LAUGHTER]

Well, this is a wonderful demonstration, isn't it? Nothing is perfect. Who's working on the cord? On, it says. Push, external, internal. Hey.

AUDIENCE: Got it.

EDGERTON: Hey, look at that. Thanks a lot. Who did that, you? Congratulations. Now I'm going to bring it up and see where it stops again. There was only one mark on there, now there's two, three, one. What speed is the motor going now? I don't know.

[LAUGHTER]

Well, anyway, it's one flash per so many revolutions. The thing you get in trouble with is this motor may go around ten times, and you flash it every 10th time, when you read this dial, it has nothing to do with the speed, except it's a multiple of the reading. Now how can you tell what the speed is. Well, you keep going up, until you see that it's double. So that's 2,714. What's twice that?

AUDIENCE: 5,428. Of course you get some in between that you get in trouble with. Now there's one in between where you get two. I used to know how to run one of these. There's 10,000. There's three there now. Two. 10,000. Hey, there's one there. That's 5,411. So 10,000, I should get two, shouldn't I? Hey, is that pretty close to two? OK, so what's the speed of the motor?

[STATIC]

You get a prize.

[LAUGHTER]

You get a prize for giving me the right answer on here.

[LAUGHTER]

The reason I was showing you that, when you're doing any measurement work, you always have to have doubt. Never believe what you get. Check it. Check it, and check it, and double check it. Now this disk was made to help confuse you.

[LAUGHTER]

It's a geometric design. Each one of these rows has one less black dot in it. When you get up to speed, it looks like nothing. Because your eyes are no good, you can't see anything. I'll set the speed back here, and be sure I get it right this time. Gee, this is interesting back here. My goodness, look at that. Oh. Hey, look at that. Wow.

[LAUGHTER]

You about ready? Now you noticed I was going 5,000 times per minute, but with this it's going a lot less. Can you see around the corner here? There's the disk running. Now watch it. Now watch it carefully. Watch it very carefully.

AUDIENCE: Whoa!

EDGERTON: Let's see if I can keep out of these wires here. Lucky I'm an electrical engineer. This is all explained in a little black book. Where's that little black book? Thanks, Gus. A little black book, entitled *Electronic Flash Strobe.* I've forgotten what page it's on. Whenever you have an equal number of spokes and the frequency and the speed, there is an integral relationship where those stand still. If you can figure out what it is, it helps you. It's useful.

[LAUGHTER]

Now I'm going to turn the motor off put and let the thing stop. Whenever one of those rows stand still, this integral relationship holds between the frequency and the number of dots in the frequency.

And this disk is used in music for tuning instruments. You swing into a microphone, change the frequency of the light, you look at a disk that's run by a constant speed motor, and you can tell whether the girl is sing a flat or a sharp, or whatever it is. Some people can tell without this strobe.

[LAUGHTER]

Now it's very important if you're working with buzz-saws to be careful, you know. Don't get too close to them. Be sure the buzz-saw is stopped. And there have been people hurt with machinery, because it looks like it's stopped, and it's not stopped, and this causes some trouble. Like one guy who come in, went to the foremen and said, "Look, my finger's missing."

He said, What did you do?"

"Well, I just went over to that saw, and I stuck my finger into it like that."

Now he had two fingers missing.

[LAUGHTER]

Now this is a scientific experiment to show motion, and what we're going to do is show this dot rotating in there. We put special ink on this dot so that it will slide around.

[LAUGHTER]

Let's see if I can make that ink slide. I'm going to shake these balls around a little bit. Whoo, there they go.

[LAUGHTER]

Now if I go a little more, you can stop it. Whoo, here we are. That's one flash per revolution. If I go down to 11/12, the ball goes one way. If I go to 13/12, it goes the other way. And in between you get some other patterns that come for free. The thing was designed to show the ball going around, and these other effects are just thrown in extra.

Now there's another disk I have here, but this is for juveniles, so I'll not show it to this crowd here.

[LAUGHTER]

These are in strobe alley. Everybody's seen these disks. We never get tired of looking at some of them.

And of course, one thing I like to demonstrate is the exposure time of a flash unit. Now be careful, don't get too close to this. It goes quite a bit faster due to the fact that it's a smaller thing. I'll try to stop it.

What speed have I got there now? You're getting cautious. He's getting cautious.

AUDIENCE: 4,182.

EDGERTON: Wrong. I don't know whether it's wrong or not, but if we go to 8,000, well-- There's one little mark on that thing there. Let's see if can go to 8,000. Hey, look at all the blades in there. The trouble with these digitized things is they go so fast. 13, 12, 11. There we are, but there's two there. So, it's right. It was 4. So 4,000 is how fast that thing is going.

Now if it was real dark in here, and we had a camera on this, we could take a picture of the end and see how blurred it is. That's the important thing of a strobe.

How fast is a flash in this lamp? Well, there's a lot of other ways to do it than look at a rotating thing. With a photo cell, we look at an oscilloscope, and we can say, how many microseconds does that last.

When you're working with people, you can use 1,000 microseconds. Doesn't make any difference whatsoever. But most strobes that are used for taking pictures are 1,000 microseconds. If you want to work with birds, ordinary birds, like sparrows and things, you'd go down to 100 microseconds. If you want to go hummingbirds, you have to go down to, oh about, 50. If you want to go to bullets, you have to go down to about a microsecond. It's all a matter of arithmetic. What is it, distance equals velocity times time? Is that the equation?

When you know how fast the bullet's going, and you want how far it goes in that time, do that equation on your computer. You got a computer at home, haven't you? You push it, and some numbers come up. And it will tell you how many microseconds you have to have in order to have a thing stopped. And a microsecond is a very short interval time, and it's very useful. Very useful interval of time.

Now I have this dripper here we show to everybody. Let's see if it works. Yeah. Sure, it works. And the interesting thing about this experiment is first, you look at this water, and it shows you that your eyes are no good. Because the pump is sending water in here at 60 times a second. And it actually consists of drops, but you can't tell it, because you haven't got the ability to see drops. But if you turn the strobe on, there it is. And if you want the thing to go up, you whistle. [WHISTLE] You want it to go down, you go, [WHISTLE].

[LAUGHTER]

Actually, the whistle had nothing to do with it whatsoever. It's this knob up here. It's this knob up here that turns the thing and changes the frequency of the light. At 60 cycles, it stopped, because the motor here is running at 60 times per second, so the drops are coming out at 60 times per second.

If any of you want to build one of these for Christmas for some kid, the instructions are in that black book on page 161. The pumps are made out in Ohio somewhere, and the strobes, everybody's got strobes these days. So it was no problem in making a-- this is a double pitter hydraulic habiting machine. The single ones, you take one thing and make it go.

Let's see what's next. Let's turn on this first experiment, first slide, first slide-- amazing, look at that. The first slide shows that all strobes, the whole world of strobes, is divided into three parts.

First is a flash lamp, which takes the electricity and converts it into light in a short time. You can't do this in a tungsten filament, because the filament takes too long to get hot and get cold. But with gas, you can put that electricity through in a millionth of a second, and away goes the light, way up to a very high value, and comes down.

The next question is, how do you get the electricity, high energy electricity? To do it, that's the thing in the middle. That's called the capacitor, and it's an energy storage device.

Have I got this aimed the right way? No. There we are, I had it aimed right at me. There's the energy storage device. It's a capacitor, and it has the remarkable ability to store electrical energy and discharge it very quickly.

Now when you want to take a picture in a millionth of a second of a bullet, you have to have a million times more energy or light than you would in taking a picture in one second. And that calls for a capacitor. And glory be, we've got the capacitors. I don't know what we'd do without them.

And the third thing is electrical power. And that's easy, we have a battery, or electrical thing, or a converter, or something. Any electricity works all right, as long as it's the right value. We have to fuss with that, but there we are.

Now the fourth item is, how do you get the flash to occur at the right moment? And sometimes this is a chore. Now that thing is turned by an oscillator to make it go. If I was taking a picture of a bullet in here-- I should have done that.

[LAUGHTER]

We got a bullet flying right through here. When it gets right here, the problem is to turn the light on for millionth of a second, then off. So the bullet moves an [INAUDIBLE] distance. But this is a very poor place for a shooting range. So that's out.

But timing is sometimes the most important thing. Now the other things you need to know about a flash unit is how much energy is in there, and that's generally done in terms of watt seconds. But who cares about watt seconds. Now this unit was in pretty good shape until I had it on in Mauritania, it got run over by camel out there in the desert somewhere.

[LAUGHTER]

But with a little tape and a little epoxy, I got it back together. So there's my lamp. That's number one. Capacitor, number two. And a battery, number three. That's a five-year-old battery. Would you like to test it? Yeah, you want to stay away from that. This is supposed to be a shock-proof connector. Look at that. And then there's a little blinking light in here that makes it go.

Now the things you need to know about a flash unit are first, how powerful it is. And the criteria I like to have is how many CandlePower-Seconds is that lamp? CandlePower-seconds. It's so many CandlePower multiplied by seconds is CandlePower-Seconds. Energy, right?

And the second thing you need to know about it is the duration of the flash. Well this is about a thousandth of a second. So I can take a picture in the thousandth of a second of people sitting here. You aren't moving, are you, Gus? Don't move.

And the other thing you need to know is how to calculate the guide factor, and that's all in that black book, how you do that. Guide factor is the aperture times the something. What?

AUDIENCE: [INAUDIBLE]

EDGERTON: Now we're cooking. Yeah, this audience knows more than I do. This particular unit, this equation aperture is equal to the square root of something beam CandlePower-Seconds. That's the thing I just gave you. How many beam CandlePower-Seconds is this? This is 1,600. 1,600. I dare you to dig up 1,600 candles out here and burn them all at once. For one second, that's the amount of light that comes out of this thing. And then they multiply that by the film speed and divide it by a constant. The constant goes from 15 to 25.

Now I have daylight film in here, which is ASA 25. So I use a constant of 25, so they cancel. Then I have to take the square root of 1,600-- I used to know how to do that-- you push a couple of buttons, and out comes 40. And 40 means aperture times distance.

So I'm going to take a picture of Gus and his kid here. At 10 feet, what aperture do I use? 10 feet, therefore I'll wind the camera, be sure there's film in it. Now don't move.

Did anything happen? Now that's a lousy way to take a picture. You should have picked the lamp off the camera, right? Too bad my arm isn't a little bit longer. Sit up straight, I want to get your two heads a little closer together. And act like you're interested.

[LAUGHTER]

This is supposed to be an interesting lecture. Now I hope you learn a few practical things. This kind of photography is marvelous. If you want to photograph bugs or birds or anything, you do have some problems to--

AUDIENCE: Excuse me, Doc, can we turn this off? You're sabotaging your whole video.

EDGERTON: Sure. [WHISTLE] See how it works?

[LAUGHTER]

Now, let's see, we got the first slide out of the way. What's the next slide? Everybody with me?

I was going to tell you something about my first technical work. My father, in a small town in Nebraska, thought, I ought to get a job. And he went down to the electric light plant, and asked the guy down there if he needed somebody to help. And he said, Yeah. So I went down, and he handed me a broom.

[LAUGHTER]

And at 7 o'clock every morning, I had to sweep out all of the dirt that these farmers did when they came into this little town in Nebraska. And then, after school, I read meters and and shoveled coal.

In those days, every town had its own electric plant. You'd shovel coal into a boiler, and it would make steam. Steam goes in and runs a big Corliss engine. Corliss engine drives a great big generator. That's where I found out about synchronous generators. I was really impressed by that generator. This great big Corliss engine, this big belt running this thing. And then I'd go out and shovel some coal, and bring it into the guy. That was my job.

And I noticed the coal pile was getting smaller and smaller and smaller. And I calculated that in about two weeks, we're going to run out of coal.

So the manager very seldom came out. He sat at a desk in there with a bunch of papers and an adding machine. They used to call those computers in those days. And he was in there looking at these papers, and I was very hesitative and knocked on the door. And I said, "Sir, it looks like you've only got enough coal for two weeks."

"Two weeks?" He pulled out a lot of papers about his curves and stuff, you know, like to get-- And he said, "According to my records, we've got enough for three months."

Well, that stopped me, see. I can't say, "You're a so and so."

[LAUGHTER]

So I said, "You better get up from that chair-- you've been sitting in there for a month that I know of-- and come out and look at the pile. Look at the coal pile."

[LAUGHTER]

And that's the advice I give all these guys who sit and look at computers. They look at these curves, I say, "Get up and go out and look at the coal pile."

[LAUGHTER]

[APPLAUSE]

We had a lot of fun about that.

And then, while I was there, the transmission lines came in. High voltage, 33,000 volts. From the east, they came all the way from York, Nebraska to Aurora.

[LAUGHTER]

And the electricity was cheaper. And the engines were stopped, the generators were stopped, the coal pile disintegrated. They tore down the chimney. And when you go out to Nebraska, all those beautiful things that I was working with, they're all gone, like pyramids have disappeared and things. So things are changing.

I did learn, while working with those people, about persistence, though. I really enjoyed working with them, because every time any cyclone would go through and blow down everything, everybody worked day and night until they got the electricity on. Everybody was very persistent, and that's a good characteristic to have.

Well, when I got through high school, finally, I went down to the University of Nebraska and learned a lot more about generators down there. I learned why there was four wires coming out of them. When I was in high school, I couldn't figure out why they had four wires coming out of generator. In a generator, I have two wires coming out. One going in, one going out. And I have four, and one of them didn't carry any current. Well, what a ridiculous situation. I frowned all about those mysteries. I've forgotten them now, but that's all right.

[LAUGHTER]

When I was about to graduate down there in Lincoln, my father said I ought to go back to Boston Tech. He didn't know that they changed the name in 1880 to MIT. So I had some communications, but I got an opportunity to go to General Electric Company in Schenectady for a year to test on their test course.

In those days, they used to hire brand new, fresh college graduates from all over the country, and put them in this test course. And they'd take these big motors, and say, "Hey, you. Hook that motor up and put it under full power, and see how much energy you can get out of it."

And it was wonderful. I went there with my eyes open, learning all about these big machines, and it was a marvelous-- did I push the wrong button? Push the button again. Some of these machines were tremendous things. Can you see the size of that motor?

If you look closely, there are two little boys out there in front of it. That's me and my companion, Francis Boucher, from Nebraska. We spent four years in Nebraska arguing about what we were going to do with the rest of our careers. Now he said he wanted to be a teacher. He wanted to influence the younger generation. He wanted to put in all his effort in getting the next generation going. And I said, phooey, I'm going to be a big industrialist and run electric light plants all over Nebraska, and hook them all together.

[LAUGHTER]

Well, guess what happened? He became a big executive in General Electric Company, and look what I did.

[LAUGHTER]

[APPLAUSE]

Well, soon I was a grad student at MIT. They finally let me in here. I should tell you that, before I left G.E., I was going to work one night, and the boss came in and said, "Look, we need somebody to run the night shift. It's a very responsible job, it runs only 12 1/2 hours a night. You go to work at 7:00, and you get off at 7:30 in the morning. You have to run about ten students. Tell them what to do. Keep them busy all night long. You get a raise from $0.60 to $0.65 an hour, and you get a little overtime." And I thought, "Glory, hallelujah." So I took it.

I found out the next day they'd offered it to everybody in the whole place. They all said no. I was the last in line, but boy did I learn a lot. That was a wonderful experience.

[LAUGHTER]

I paid my tuition from that overtime money. In those days, it was $300 a term. Can you imagine that? Cold cash. Working that overtime, I walked in and plunked it down on the--

Well, I was really glad to come here, and-- I pushed the wrong button again. And let's push it again.

And that's the staff at MIT in those days. My goodness. They don't show up too good in it. But there is D.C. Jackson. D.C. Jackson was a czar. He ran the place. He did a wonderful job of it.

And over here is Hudson. His middle name was God.

That's Bill Timbey and R. R. Lawrence. He taught electrical machinery. That's what I wanted to learn. I was going to learn everything about synchronous motors, because there are all kinds of interesting things that happen in motors. You know, electromagnetic fields running around, chasing each other. And they had a man here teaching machinery named Lyon. So I got acquainted with him, and we started working on a thesis project.

And this man here is Carlton Tucker, who ran the machinery laboratory. They used to have a whole lot of motors, and everybody who came here had to run all these motors. And he had him a wonderful set up for measuring those motors, and he was so proud of it.

Well, I came in, and I started to set up some laboratory things. This is the way the lab looked. All these machines have all been destroyed, and thrown away, and given away. But that motor in the middle there was 150 horsepower synchronous motor, and I decided we were going to get the electrical characteristics of that, and try to put some sudden loads on it, and see what would happen. And what happens when you put loads on it, if you put more and more load on, finally, you put a certain critical load on it, and bang. All the circuit breakers go out, and everything else. It's wonderful.

[LAUGHTER]

Professor Tucker, he wanted a nice, orderly life. And there were a lot of students starting to work. We needed to work. Well, the lab closed at 5 o'clock. Clunk. There was a guy that came around, pulled all the switches out, and locked it up.

Well, I went to Professor Tucker, and I said "We've got to be able to work nights and weekends on these very important research projects."

He says, "Impossible. It's never been done before."

I said, "That's no reason." And then I said, "Can't you figure out some way we can do it?"

"No," he says, "I can't. You'll have to go up and see the president." So I said, "Okay." So I got up from the chair and walked over to the door. "I'll be right back." And he said, "Hey! Wait, wait, wait, wait, wait, wait, wait, wait, wait, wait."

[LAUGHTER]

He didn't want to see the president anymore than I did.

So he said, "Okay, we'll let you go ahead, and we'll give you keys. But we want you to watch the safety rules, because electricity is dangerous. And if there's two of you working, it's all right." So we finally got in.

Then I started rigging up these poles. You notice those poles there? Can you see that pole, and those wires? Those were all connecting this oscillograph to that motor. I was measuring every conceivable thing in that motor I could think of, except the power angle. That's the angle between the salient pole and the rotating magnetic field. If you put load on, that goes. And you can't get that on the oscillograph. But everything else is on there.

And I could tell by various things that were happening that Professor Tucker wasn't too happy with all my transmission lines in this laboratory. And one day-- his office was right up here in the upper corner, up in here somewhere, and there's a stairway over here, and there was a crane in here, it's all gone now-- he came down this stairway, and I could see him out of the corner of my eye, and I said, "Well, here it is. I'm going to catch it now." And when he got about 10 feet away, I turned around and said, "Oh, good morning, Professor Tucker. By the way," I said, "step real high. There's 2,000 volts on all those wires."

[LAUGHTER]

And he turned white. He was an expert with telephones. He never worked with anything higher than six volts.

[LAUGHTER]

There's more than one way to get what you want in this world.

[LAUGHTER]

Now Professor Lyon got me interested in the mathematics of these machines. And it goes, the equations of the motion, there's a second degree, non-linear, differential equation. It's exactly the same equation as a pendulum, when it swings over large amplitudes.

Now the physicists solved the pendulum equation, as all of you know, when you worked on your physics, by sine theta equals theta. Then, you've got a linear equation, and outcomes all the equations. You pick them right out of the book, and out comes frequency and the damping, all that stuff. You know what I'm talking about?

Well, with the sine term in there, and with damping, there's no way to do it with formal mathematics. You have to have a computer. And the first computer at MIT is-- look in front of you. It's built out of a watt hour meter and a Kelvin disk. It's an analog computer. And boy was it a job to make that thing run. Wow.

There's Bush running. He wasn't in that other picture. Vannevar Bush, he's written some excellent books.

There's the equation up on the board there for synchronous motors.

[LAUGHTER]

Would you like to see them a little closer? Okay. Here they are. Look at that. Aren't they beautiful? With a small load, you get a nice sinusoidal thing that's like an oscillating curve. As you put more and more load on, pretty soon whammo! All the breakers go out! And that's the critical thing.

For this particular motor, it was about 7/10 or 8/10 of full load suddenly applied would take that motor out of synchronization. So the problem was how to measure that.

Well, fortunately, I went back to General Electric that summer for a summer job, and Doctor A. W. Hull, a physicist from-- I think he was from Princeton-- was working on hydrogen thyratrons. Mercury thyratrons. And they're a thing of the past now, but there's one.

And here's a picture of it, so you can see it better. And they're a marvelous thing. Down here at the bottom is the little pool with a spot of light dancing around, a cathode spot. And you have to have a circuit with 110 volts on it, and five amperes going through there to keep that little spot dancing. And that means there's five times-- there's 20 volts dropped. Five times 20 is how much? Watts is taking the vaporizing mercury, and it goes up and condenses in that big bulb, then runs down in little drops.

And then, over here is your anode, and your grid around it, so you control it. So I thought, "Hey, just the thing. When I get back at MIT, we'll put a capacitor across there for a load, and we'll put a peak voltage here in phase with the voltage, and we'll let this light shine on the rotor, and take a picture, and we'll measure that angle." So wham! That was all there was to it.

There's the motor. There's the rotor standing still. This is rotating high speed, so it goes from there to there in 120th of a second. Here's the mercury tube hid behind this thing, so it won't blind you. And by taking motion pictures of this-- there's the whole set up.

All the parts were taken from various places. That's a two by four here. It came out of the stockpile. Here's a power transformer, capacitors for power correction, and there's the youthful experimenter trying to make this thing go.

And it was great. We got some beautiful movies showing these things happening. And there was a slight correlation between it and the mathematical thing. Enough so that we could say, oh yeah, yeah, yeah, we know why. We know why those aberrations are there.

If you're doing experimenting, you never get the experiment to come out exactly the same as the theory. Because most theories are limited to what are in equations. But the real world has got a lot of other interesting things in it that don't come out right away. Glory be, huh?

Well, if you look closely at this, you'll see a fellow up there named Stark Draper. And he came over one day, and he says, "Hey, where's that lamp with four flashes in ten microseconds?"

"Well," I said, "it's right there. That mercury tube. See it right there."

And he said, "Why don't you do something useful with it?"

"Well," I said, "we're working day and night on these motors."

"Well, who cares about motors," he says. "The world's full of other things. Like my lab is full of valve springs, diesel jets, and things."

So I said, "Okay, I'll build a portable one."

And so this is a portable strobe. My first portable strobe.

[LAUGHTER]

And you can tell it's portable because it's on a truck.

[LAUGHTER]

Instead of mercury, I had moved to argon, because mercury's got this pool of liquid stuff in there, and it's messy when it's sloshing around. And argon you can do just as well in a big reflector, so I could concentrate the light on this little tiny valve spring up there. The whole object was to light those little tiny valve springs.

And he looks kind of skeptical. But he found out that, as he runs this motor faster and faster and faster, pretty soon he has problems keeping it-- because the cam. The springs are strong enough to keep that valve spring down on there, and with a strobe you can see it. It's so beautiful. And so that solved that problem. Well, they're still using it over in the engine lab for very exciting things.

The whole thing, after 10 years or so, and when Germeshausen got in on the deal, the strobe began to get smaller. And here's this thing here. It weighs 12 pounds. It probably puts 10 times as much light on a subject as that big clunker. And he's showing it to one of my favorite audiences, kids below 12. When they get over 12, it's a waste of time to be talking to them.

[LAUGHTER]

Here's this machine. And it says on page 161, the pump is a critical thing and it's made out in Ohio somewhere. It's all described in this black book on page 161. It's wonderful for kids. Well, any aged kids. Doesn't make any difference what.

One of my jobs in Aurora was to go up here and change the electric light bulbs. There were four 200 watt light bulbs up here, so the people on the prairie could tell where Aurora, Nebraska was located. It's 150 miles west of Omaha.

When I came back, we started working on strobes. I said, "Hey, they should have four strobes out there!" Because these tungsten lamps burn out about once a week, and somebody had to climb up there and unscrew that bulb, and put a new one in. And with strobe lamps, they'll run for years. So right now, there are four strobe tubes out there in Aurora. If you ever go through Nebraska, slow up just a little bit.

[LAUGHTER]

And you'll see these four blinking lights. A lot of people drive in town and go around the square, "Hey, what are those blinking lights doing up there?"

In those days, it was something new. Now you see them on airplanes, and tall radio towers, and everything else. They're a wonderful thing to attract your attention. When you run them at real low frequency, they cause a lot of trouble, and you can spot them right away when you know them.

Now this has been one of the most successful experiments I've ever done, because in the 20 or 30 years those lights have been up there, there hasn't been a single airplane that hit that courthouse.

[LAUGHTER]

Now you'd be surprised at the number of different units that have been made. This picture was taken, I think, 15 or 20 years ago, and these units are all in the junk box, or in the Smithsonian Institution, or some other place. They're all gone. I thought the world was finished then, but we'd hardly even started. And probably the same will apply to things that we're working on today.

Yeah, today the flash units are multiplying like rabbits. Every time you turn around, they got a new one. And also, some small cameras-- you can't buy a camera without electronic flash attached. Already in it. Permanent. So things have gone a long way, since they predicted this would never leave the ground.

Now there have been a few things that didn't take commercially.

[LAUGHTER]

My friend, Eddie Farber, out in Milwaukee, invented the Strobo-Dome.

[LAUGHTER]

What are you laughing about?

The guy that was using it lost interest when he found out there was a 500 volt battery up in that thing.

[LAUGHTER]

Most of them now have a photoelectric cell here, which reads the light, and turns the light off when the exposures right. So you don't have to think. See, we had to calculate on this machine. Remember how we had to do all that calculating for exposure. Don't do that anymore. You just aim it, it opens, and the light goes on, the light goes off. But I couldn't figure out what that white thing was until one of the students pointed it out. He says, "Hey that isn't connected to the strobe. It's connected to the girl."

[LAUGHTER]

I used to laugh. My last few classes were teaching freshman. And I used to teach them everything I knew real fast. You know they learn real fast when they're freshman. And I'd say, "Let's go out and shoot something today. What do you say, boys?" You could see the disappointing look on their face. We're going to go out and catch a golfer, and try to get a picture of a golf ball. "Okay, let's go out and catch a picture of a golf ball." Well, the golfer's there, but he couldn't find the ball. A near-sighted student down there.

[LAUGHTER]

Actually, he's solving the synchronization problem. He's putting two small wires on the far side of the ball, so when the club comes down and hits the ball, and the ball starts to move, it knocks the wires together. Flash. You got the picture.

So once they got it all set up, we got the golfer wound up, and said, "Okay, smack it." And if you look closely, you can see the ball there. Focus isn't quite sharp enough to see the cracks in here.

So what happens is the club comes down at 150 feet per second, and one side of the ball is going 150 feet per second, the other side the ball is standing still.

[LAUGHTER]

And then there's F is equal to MA applying to every molecule in that darn golf ball, and pretty soon it starts to move. And it pushes the two wires together, and takes the picture.

Now, sometimes people say, "How much force does it take to accelerate a ball that quickly?" Well, let me tell you how to find it out. Next time you get a hold of a ball, squeeze it until it looks like that.

[LAUGHTER]

This fellow kicked the ball and there was some dust on the ball. And the dust stayed there, and the ball went away.

[LAUGHTER]

That's a very useful technique. If you want to know where something was before you hit it, sprinkle dust on it and give it a kick.

[LAUGHTER]

This was timed with a microphone about three feet away. You can take a whole series of pictures with a microphone a foot away, two feet, three, four. And it takes time a thousandth of a second to go a foot, so you can tell exactly where these pictures are taken. But it allows the ball to compress and the strings to get compressed. So that's one good way to do that.

Now, this is a multi-flash picture. The guy wanted me to take a whole lot of movies of golf. And that means a lot of moving film, and a lot of work. And being naturally lazy, I said, "Hey, let's do it all in one film, and give him the film, and say, okay, you figure it out yourself."

[LAUGHTER]

So the light's running a hundred times a second. I got two, big, powerful strobe lights. Now the man, if he had a white suit on, would give me a lot of problems here, because I'd get 50 pictures of him, while one picture of the club. So I got a velvet kimono. And I found out real quick that you have to have his head sticking out.

[LAUGHTER]

Well, here comes the club. See, it's accelerating, and you could plot a curve, the velocity versus time, because a hundredth of a second, that moves about a foot and a 1/4, or something like that. He hits the ball, it slows down, the club slows down, because the energy is taken out of it. Some of it. The ball speeds up. You can measure the velocity of the ball. There goes the ball. It goes that far in the hundredth of a second. And you give the golfer information he isn't the slightest bit interested in, such as the velocity of his tee.

[LAUGHTER]

Now this is Gussie Moran. And you know how fussy girls are about their clothing. Well, she just got this fancy new outfit, and she says, "I'm not going to put on that black velvet curtain." So I say, "Okay, Gussie, hit the ball, but hit it up in the air, so I won't see it against your costume."

Now this picture was a fizzle. I normally throw away all my bad negatives. And I was just about throw this out, and I said, well, I'll make a print of that. And it's down in the Museum of Modern Art in New York.

[LAUGHTER]

[APPLAUSE]

Here's another technical problem. I wanted to get this fellow going up over the thing. Now, for this kind of photography, you turn out all the lights, so that you won't get a blur in between. You follow me?

So I had to arrange down in Boston Garden to have a guy on the switch. And as soon as pole vaulter gets in this position, pull the switch. You can imagine the consternation of that poor guy sailing up through the air, all the lights go out.

[LAUGHTER]

That's the way I would have liked to have had it, but of course, I didn't, because I knew there would be a reaction. There are lots of things in life you have to prevent. Isn't that right? Exactly.

So when we did it I had a shutter that worked in about a hundredth of a second, so I went, (CLICKING NOISES). But I didn't move the film. Film was stationary. And I got rid of the blur because there was no exposure in between. So that's another way to do it.

Well, we're back to the mercury tubes again. Thought we had gotten rid of them. That one's got a nice small bulb on it, because you only run it once in a while. So you don't have a smaller bulb. We built one of these, and we used it for a couple days, and it broke. And we've never built one since. It's a thing of the past.

Because I learned making tubes that, if you put a high voltage on them and tickle them with a high voltage-- I should have brought the high voltage machine over here. I used it for tickling students. If any of them looked a little bit sleepy, I can get their reaction right away. But if you put a high voltage on the outside, and you have just two electrodes on the inside, it'll sit there and do nothing until you hit it with this inspirational trigger voltage, and then it'll go, boing.

And there's a trigger voltage in this one. It's 500 volts, and the trigger voltage is about 10,000. When it hits it, boy, away it goes. Then you've got all these different gasses and all the different pressures, and all the different lengths and diameters. It's a tremendous job. And we have a guy in the audience here that used to work on it. Bruce Newell here used to work on it. Make all kinds of tubes.

And we ended up with xenon eventually for most tubes, because it's most efficient. That means you get more light per watt second put in. It's the best color, which we'll talk about in a moment. And it operates at low voltage. So xenon. And the only thing you're going to learn to spell today is xenon. You don't spell it with a z. How do you spell it? Louder! Louder! X-E-N-O-N. Now remember that the rest of your life. No excuse for not knowing how to spell. You cannot MIT if you can't spell xenon.