DUANE BONING: So I want to welcome everybody here in Singapore-- or there in Singapore, and here in Cambridge. My name is Duane Boning. I'll be one of the two lecturers for our class. We'll get into some of those logistics and details in a minute, but we've got some preliminary things. Since we've started videotaping you already, one thing you need to know is there is a video recording policy.

Pretty much everybody here will be videotaped. If you don't want to be videotaped, there are a couple of seats here on the right. If you do want to be videotaped, you can come and be accessible and viewable. Right at the front, you can see there's these little red tabs on the desk. That's in the blind spot of the video. I think some of these were being handed out as you were coming in, but if you didn't get them, here's another copy of that videotaping policy.

So what we do is most of these lectures are, of course, live, video linked with Singapore. There are occasions in the calendar where it's a holiday in one place or the other. When it's a holiday here, we don't meet. When it's a whole holiday in Singapore, but not a holiday here, we will still meet here in Cambridge, but the video version of the local lecture will be available on the website so that folks in Singapore can catch up on that.

And in fact, we understand the first one of those is this coming Thursday. Is everybody ready for your holiday? It's been a long, hard term already, right? Is that right, Singapore? OK. Yeah, that's the Chinese New Year, so there will be no class meeting in Singapore on Thursday evening.

Let's see. OK. Has everybody found their way to the Stellar website already? Anybody who has not seen the Stellar website for this class? I'm asking in part because, if you are not actually registered-- let me go to the Stellar site here-- oh, this may not be viewable in Singapore.

This is accessible only to those registered in the class, I believe. So if you're having trouble getting to the website, please email me right away, and we will add you to the roster, even before you get registered. It will be important, because all of the materials for the class are deployed through the website. In fact, it'll be very rare when we have any kind of handouts to give in class. Lecture notes, reading material, reading back-up, assignments, weekly problem sets-- all of that material is through the website.

Now, what I will typically do-- let me see if I can get back here-- usually I will try to have the PowerPoint slides loaded a day before the lecture. One thing that I noticed in a few past years is sometimes little groups of students would work together and delegate somebody to print out the lecture slides and bring a set of copies for their little group.

So for example, the LFM students would often have one person printing out that morning or the night before, if they were available. So you guys can self-organize. If you actually like having any kind of print-out to take notes on a copy of the PowerPoint slides, feel free to print those out or self-organize to share that duty. Again, we're not going to be making copies available directly in the class.

So what I want to do, first off, is talk a little bit about the class and the assumed prerequisites for the class, and then we'll come back and I want to get us to know each other. I know many of you have had some classes together. Others of you are perhaps new to each other, so want to share a little bit of experiences so we know what the basin of experience is-- because this class is meant to be fairly interactive.

It is a manufacturing process control class, and one of the best things about it is many of the students in the class have an awful lot of experience. For example, the students and the leaders for manufacturing program, LFM, are typically coming from several years of industrial experience.

Similarly, students have had a lot of experience, whether it be doing experimental work with processes in-- as part of their program, or what have you. So it is meant to be interactive. We depend on you sharing your experiences, your insights, your doubts. In many cases, those can be often the most interesting part of the subject-- say, I tried that-- didn't work. Here's why-- because a lot of the classes about tools and experiences for dealing with manufacturing processes.

And then we'll get into a little bit more of the details, some of the course schedule, and some of the other logistics. Jumping ahead a little bit here, there's kind of a long chain listed formally on the course catalog for prerequisites-- says things like 2.008, or 2.810, or 6152J, and then also a couple of other subjects like 6041 or 15064J.

What we intend to convey with these prerequisites is, number one, they're not specific hard prerequisites for those subjects. What we mean to convey is you should have hopefully some substantial experience with some manufacturing process. So that's things like 2810, 6152J. So 2810 is essentially the manufacturing physics subject-- manufacturing processes subject in course two.

I recognize some of you for that. I think I gave a guest lecturer in that subject on semiconductor manufacturing. So that would be one example. 6152J is a course six, electrical engineering computer science subject on microfabrication-- not only semiconductor, but also MEMS microfabrication. And so that would be another example through coursework, where you might have gotten that kind of experience. And then similarly, you might have actual true industrial experience.

So the goal here is actually to just go deep enough or build on a deep enough knowledge of some process technology. This semester of the subject, I will actually be using semiconductor process technology a little bit more than we have some semesters in the past to illustrate, and demonstrate, and to get some practice with some of the concepts that we're dealing with here.

But many of the problems will also deal with macroscopic processes, from metal bending to forming and other sorts of processes. A little later, we expect Dave Hardt, who is the collector. He'll be here. And his background especially emphasizes the panoply of mechanical and broad based process technologies, whereas my experience is a little bit more solidly in microfabrication-- both in semiconductor, and more recently, in micro-electromechanical systems, or MEMS fabrication.

So that's one of the prerequisites. Now, the other prerequisite that we kind of assume-- and if you don't have, you might be doing a little bit of quick background reading-- is indicated by things like 6041 or 15064, and that is some basic probability and statistics. We'll actually be developing quite a bit of the statistical machinery, so if you don't-- haven't had a full subject in that, not to worry-- I recognize many of you also from-- is it 2.853, 2.854?

Get that subject right-- that's Stan Gershwin's manufacturing process? What is it? Manufacturing systems-- manufacturing systems, where we had a two or three-lecture sequence on basic statistics and statistical modeling. We'll actually revisit some of that, so you'll see some of that again, but then be applying that to problems of manufacturing.

I'll go over this detail, and then we'll come back to get some introductions from you guys. This semester we actually have two required textbooks. The great thing is a new book has come out. It came out nominally 2006, but it was only available starting last year. And that's a book by Gary May and Costas Spanos. Gary May is at Georgia Tech. Costas Spanos at UC Berkeley, and they had developed a course on semiconductor process control that was very close to a subject in the dim, dark past that I used to teach dedicated entirely to semiconductor process control.

So finally, we have a book for that. It's a nice condensed book, and you all should try to get that, because we're going to have readings from this book starting pretty quickly. So you might have to go to Amazon, do two-day shipping or something like that. If somebody has Amazon Prime, you can use that and get free shipping. I don't know if any of you do that.

The other book is *Introduction to Statistical Quality Control.* This is more broad based. May and Spanos illustrate everything the semiconductor process technology. Montgomery is basically a statistical process control, a little bit of design of experiment. It really emphasizes the statistical machinery that we're going to be using. So you are expected to either go and get both of those-- both of these books have been put on reserve in the MIT library, so if you don't want to spend the money, you can, I guess, do the painful thing of trying to go to the library and read there.

At least the Montgomery book is a great book to have on your bookshelf long term. It'll be a great reference book throughout your career. The semiconductor process control-- certainly, if you're going in the semiconductor area, that's also very useful.

OK, so the grading in the class-- the way this works is we will have-- I think it's something like eight weekly problem sets, primarily in the first 2/3 of the class. And then, in the last third of the class, we stop the problem sets and you'll go into a team project. The problem sets will comprise about 40% of the grade in the class.

We'll have two quizzes-- one about a little bit more than a third of the way through, another one a little bit more than 2/3 of the way through. Those are about 40% of the grade in the class. The good thing about having those quizzes during the term is we do not have a final exam. Anybody heartbroken about that?

[APPLAUSE]

OK. However, the reason we don't is that, in that last third quarter of the class, we switched gears a little bit and ask you to start applying some of the techniques and tools that will have been talked about through most of the semester in a team project. I'll talk more about what that team project is a little bit later. So that's meant to be a fairly substantial effort. The team project is going to be a team project. It's going to be typically three-student teams. And of course, that should be very collaborative in nature.

In contrast to that, the other assignments are meant to be individual efforts. Now, working on the problem set, I think it's great to interact, talk with each other to understand the problems, even to bounce off possible lines of attack or solution approaches, but where we mean-- especially on the assignments-- the weekly assignments, the problems sets-- is everybody should do their own independent write-up.

I find that writing and explaining not just writing down the answer number, by the way. We will expect actual articulation of your thought process. That should be an individual effort. Now, we'll come back to that the assignments a little bit. We'll try to emphasize this, perhaps, as well a little bit more on the assignments themselves.

The perspective I'd kind of like you to take on these weekly problem sets is not that you're trying to come up with the answer number like you might on an exam or something like that, where you just needed the number, but instead, a little bit of what I think of as a practicing manufacturing perspective-- I couldn't call it an industrial perspective or an academic perspective, but the key thing that you have to do, and will have to do throughout your career is convince.

So you have to convince us that the answer that you're putting down makes sense, why it's reasonable. So you need to articulate the thought process, not just come up with answers. And that's part of the reason why we really want that to be an individual effort, an individual write-up. And of course, everybody's already gotten to the course URL.

So going backwards a step here, let me introduce-- I hoped that Dave would be here by now-- must be having a very difficult decision point and in the voting booth there-- who to vote for. Again, I'm Duane Boning. I'm a professor of electrical engineering and computer science.

Dave Hardt. Will be here a little bit later. Let me introduce for you the teaching assistant, Hayden Taylor. We do have microphones here. Why don't you say a couple of words?

HAYDEN TAYLOR: [INAUDIBLE]

DUANE BONING: Yeah-- good. There's the camera.

HAYDEN TAYLOR: Hello, Singapore. I'm Hayden. I'm in electrical engineering. I work with Duane on manufacturing approaches for microfluidic devices. We work a lot with polymers. And I'm excited to work with you all this time. Feel free to email me at any time. I'll be organizing office hours, and I'll announce that on the website when the time has come.

For those of you in Singapore, I suppose we'll have to have virtual office hours. I'm very happy to talk over Skype or something like that, if you want, so feel free to drop me an email. Thanks.

DUANE BONING: And Hayden just got back a little over a week ago-- is that right-- from Singapore.

HAYDEN TAYLOR: That's right.

DUANE BONING: [? We ?] spent a couple of weeks there for some of the SMA program things. The core secretary will be my assistant over near my office in EECS headquarters in building 38. And that's [? Charlene Blake. ?] So if you have some administrative questions, your best bet is probably emailing Hayden and me directly.

I'll be the lead lecturer this term. Normally, Dave Hardt is the lead lecturer. He's actually nominally on sabbatical this term, but-- so I'll be taking care of more of the administrative things, and he'll get to give fun lectures. So if you have administrative things, please-- probably best to contact either me or Hayden directly. If you have questions or need to drop off, for example, late problem sets, that can be done with [? Charlene. ?]

And we'll have to have to let [? Charlene ?] know that she really outdid herself on the breakfast here. So at any time, as soon as you're done with one, we have lots more to eat, so feel free to wander over and grab a little bit more.

OK, we'll dive back into a little bit more about the course, but I thought it would be a little bit fun to just quickly go around and hear a sentence or two about-- and I'm particularly interested in what kind of process background, or manufacturing background, or technology background you have-- or if you don't have much background, what kind of areas you're especially interested in, or potentially interested in.

So we'll do that quickly here on the Cambridge end first. I know many of you, again, have been taking classes together, so you know each other better than I you. I recognize some faces here a little bit. But this is part of my way to get to you as well as for you guys to get to know each other.

OK, let me go through a few of the other logistics, and then we'll start getting into a little bit of introductory material. I think we've already done some of that. Let me come back to the team projects, because I think it'll be important for you folks to be starting to think very early about possible projects and possible team formation, because that will help-- as you're learning some of the tools and techniques in these different kinds of topical areas, you can pay more attention, because you'll know, OK, I really want to think about process diagnosis for this particular project, or what have you.

So the typical kinds of topics-- generically, the topics in these team projects involve things like process diagnosis; process improvement, often with a little bit of statistical process control, detection, and debug kinds of things; process optimization and robustness-- things like use of design of experiments to characterize the process, and then seek to optimize some outputs, as well as minimize some variations and get to a robust process; and then a number of more advanced applications, perhaps dealing with things like yield modeling or defect modeling-- these sorts of projects.

And the basic expectation in these team projects is you'll need to learn a little bit more background on the basic process and what the problem is. A really interesting aspect of these projects is it's best-- it really works nicely if we can tap into a nice rich set of existing data, or in some cases, even generation of new data arising out of either your past experience or your current research.

So for example, one of the, say, typical three-team members might have access to-- hopefully only public, shareable-- nothing secret-- public data from their work experience. Some of you may have generated a big set of data for your master's thesis, or this or that, and we're only able to look at this aspect of the problem, because that was the key question, but it was sort of nagging at you.

There's all this other rich data that you would have thought it interesting to look at from other perspectives-- things like building very simple response surface models for. But you didn't really have the chance to go down that path. So keep your mind open, thinking ahead to the project as we go out-- go throughout the term, and say, oh, that's an interesting topic. That's an interesting technique. That reminds me of a very interesting data set that I came across back a year ago or whatever-- because that might form the basis for a very interesting team project.

The output of this are two parts. There will be a world presentation. So the team will present-- in fact, the last two class periods, the very last week of class, will be dedicated to these team presentations. And then there will also be a project report. Unlike the problem sets, where everybody writes their own separate problem set, the team writes the project report. So that's one document that comes together from the team.

Good-- so let me pop back. We're not going to ask you who you voted for, but we figured it was a tough decision, because it was taking a little while. We've already done all the introductions, so now you, fortunately, know most everybody.

DAVID HARDT: I hope everybody knows that I got dressed for the occasion. What am I [INAUDIBLE]?

DUANE BONING: You have to wear a tie to vote in the US. You may not know that.

DAVID HARDT: For those of you who don't already know me, I'm David Hardt. And I'm actually on sabbatical this semester, which means I don't teach any classes and I don't sit on any committees.

DUANE BONING: Why do you wear a tie if you're on sabbatical?

DAVID HARDT: So I'm here today to sit on a committee and do some teaching. Yeah. But I welcome you all to probably the best class at MIT-- and hello to all of our students there in Singapore as well. I hope you're enjoying the weather. It's beautiful here. And the only reason I'm late is that I had to drive the other way to get to the polling station, and I got trapped by a huge traffic jam. So I'm a dedicated voter.

DUANE BONING: Thank you, Dave. OK, so let's get a little bit into the-- an overview of what we're going to be dealing with throughout the semester, and then dive in a little bit on some concepts and basic background and terminology. So some of the key ideas that we're after in this subject is really dealing with basically the problems in manufacturing.

And the biggest problem of all is really dealing with quality and manufacturing variation. Other aspects of manufacturing are often very particular to the specific process technology that's arising, but there's a lot of very generic issues with variation, and the control, and elimination, and modeling of the process, and the variation, and ways to reduce it.

So in some sense, dealing with variation is one of the key themes in the subject. And what we're going to start with in the first couple of lectures is basically dive in, get a little bit of process physics background. On Thursday, we'll dive in a little bit more on semiconductor fabrication, and then, on Tuesday, we'll see a variety-- Dave will talk about a variety of forging and other process examples that give a wider perspective on manufacturing, and the physics that are at work, and where variation naturally, inherently arises in those processes.

Then, well, once we've got a little bit of a feel for where variation comes from, we want to dive into some of the techniques for understanding that and dealing with it. And that really gets us into statistical models. And we'll talk in great length about the contrast between physical models of the process based on detailed understanding of the specific mechanisms at work versus empirical modeling of the process based on data-- data and observations.

The wonderful thing about data is it's real and it encompasses all of both the ideal behavior and the non-ideal behavior. And a lot of what we've dealing with, again, is the problems, really trying to understand where variation is coming from, what its characteristics are. If we can start to get a model for some of that variation, now we've got a handle that we can use to try to eliminate it-- either eliminate it up front or control it and compensate for it.

Some of the techniques that we deal with for dealing with, again, that data is building effects models, designed experiments. You may have run across DOE, design of experiments. It's a form of statistical technique, and we will be learning the details of that and applying some of those approaches with basic input-output data sets and data models, both in specifying the right set of experiments to perform to very efficiently sample sample our process, and then the ways to model that.

And perhaps one of the most important ways of using those empirical models that we get of the process is to improve the process, do process optimization, really looking for improved operating points that have reduced sensitivity to variation, that really improve the robustness, as well as meet multiple objectives. So we'll do a little bit of optimization-- multi-objective optimization coverage as well.

So let's talk a little bit about, what are the-- oops-- what are the goals of manufacturing process control and manufacturing processes? What are some of the key characteristics you would have of a good process? What are the things you would like to either minimize or optimize?

So I already gave you an advanced look at one. I'll throw out one. Of course, we're very often interested in minimizing the cost, and cost rises in a lot of different ways. What are some of the ways that cost arise? There's the inherent materials coming in. What are some of the other costs associated with a process? Anybody-- Singapore as well--

AUDIENCE: Labor.

DUANE BONING: Labor, yeah.

AUDIENCE: [INAUDIBLE] overhead, support.

DUANE BONING: Overhead, support.

AUDIENCE: Time.

DUANE BONING: Time. Yeah, in fact time process-- time is certainly a characteristic that we might want to optimize for. That would be a typical characteristic. Cost has many of these flavors. Yes?

AUDIENCE: Setup costs--

DUANE BONING: Setup costs-- so setup costs are an interesting one. In various times, we'll touch on some of these operational issues. Many of you have had [? 2853. ?] We said-- which was really about manufacturing systems and things like scheduling, throughput-- those kinds of issues. And so time is a little bit of that as well-- not just the inherent manufacturing, physical action on the product time, but also transport time-- all of these kinds of other issues.

This subject will not be dealing so much with logistics. It'll really be much closer to the things that impact directly the product itself. But certainly, setup time can have an interaction-- processes setup in general can have a strong impact on processed quality. Very often, for example, in semiconductor processing-- maybe this will resonate with your experiences in other processes-- if we change substantially the process setup in a particular piece of equipment, the first few wafers will behave very differently before the equipment gets to a stable state.

Sometimes we even run dummy wafers in order to equilibrate that setup. So setup is a good one. Some more-- what are other things? I'm sorry--

AUDIENCE: [INAUDIBLE]

DUANE BONING: [INAUDIBLE]. Certainly.

AUDIENCE: Equipment.

DUANE BONING: Equipment, yep. We want to use the equipment as efficiently as possible, and maintain it.

AUDIENCE: [INAUDIBLE] a good machine or a bad machine--

DUANE BONING: Good machines and bad machines-- absolutely. And in fact, probably the first third of the class, the classic statistical process control, will be all about detecting whether the equipment is behaving as it should. Is it in a good state or in a bad state?

AUDIENCE: [INAUDIBLE]

DUANE BONING: So here we had quality control--

AUDIENCE: And rework.

DUANE BONING: --and rework, yeah.

AUDIENCE: Energy.

DUANE BONING: Energy, yeah. Yes, that's a good point. Actually, I think, dealing with energy, as well as the consumption of materials and the output of materials, is becoming a more and more interesting aspect of manufacturing processes. Let's see. When was it? Sunday night-- just to share another anecdote-- I was serving on a panel at a big semiconductor conference.

Actually, it's the semiconductor-- biggest circuit design conference in the semiconductor industry. And I was on a panel all about environmental or green manufacturing. And so the reduction of energy usage is becoming a very big deal, as well as the output of things-- in semiconductor side, output of global warming gases and so on-- the reduction of those. So that's a good point.

By the way, I was on a panel at 7:30 on Sunday evening. People here-- what happened on Sunday? That was Super Bowl here. I was not very happy to have to attend the panelist dinner the second half of the Super Bowl, but as it turned out, I'm very glad I missed it.

OK, so we've hit some of these other ideas here. Here's one that nobody mentioned. Flexibility is also very key in manufacturing processes as well. We're increasingly finding that the same manufacturing line needs to be adaptable rapidly to be able to deal with a bigger product mix than ever before.

So some of the focus in this subject, again, is going to really be on the processes, and variation, and quality in the processes. A little bit bigger emphasis is going to be on unit processes. The entire aggregation of the overall sequence of product to make the overall-- or sequence of processes, aggregation of the unit processes to make the entire process line, and process flow, and the final product is important.

We'll touch on some of these kinds of things of stack up of quality across multiple processes, but we'll be-- end up emphasizing developing techniques like statistical process control, design of experiments and optimization, with a little bit more of an emphasis on the unit operations. Part of the reason is more and more for really high-quality manufacturing-- the recognition is you can't simply inspect or hope to control at the end of the overall process. You have to have every unit process along the way running as effectively and at the highest quality possible.

So again, the number one emphasis here is going to be dealing with maximizing quality, conformance to specifications, and so on. And some of these other things that we've already talked about here-- things like improving throughput, improving flexibility, reducing cost-- those are going to be secondary. There will be interactions with some of these topics that you have run into or might run into another in other subjects.

And actually, a very interesting area of research-- in fact, an active area of research of Stan Gershwin, who some of you had in 2853-- is this interaction between quality and quantity-- that is, typical operations and how you manage the sequencing of parts through the line-- the interaction between throughput and quality-- for example, dealing with issues of setup, dealing with issues of slight degradations in quality and how that might impact things like scheduled maintenance or unscheduled maintenance.

So it's a very interesting topic. We'll occasionally, again, overlap slightly with that, but our number one emphasis here is dealing with the process, understanding and modeling the process, and dealing with quality and variation. So here's a few typical process control problems. I'll share a couple of these. And just to wake up Dave, on the next slide, we'll let him say a few words about some of the other examples.

So here's a typical example. Probably, in fact, the number one problem-- or number one challenge in semiconductor manufacturing is the minimum feature size is very, very small-- becoming smaller with each technology generation. The minimum feature size is typically the channel length of an individual MOS transistor. That's often the most critical parameter, and it varies.

With current technology, we're down in heavy-duty manufacturing at 90 nanometers. Some of the leading edge manufacturers have gate or channel patterned lengths of 65 nanometer. Occasionally, you'll hear those terms thrown out. What that means is the minimum feature size being patterned is about 65 nanometers wide. That's small. That's tiny. And as we continue to scale, that variability in the width of that is becoming tougher and tougher to achieve. So very often, there will be challenges on the manufacturing line to detect-- monitor, detect, and then compensate for those kinds of variability.

An emerging technology-- here's an interesting one that connects up with, for example, some of the Singapore MIT Alliance research efforts. A DNA diagnostic chip might have uneven flow channels. So for example, here, these are often microfluidic devices manufactured through embossing processes, where one might be using a polymer and trying to create channels that might be 10 microns wide, 10 microns deep-- and maybe, in some places, very, very narrow, for example, or very, very shallow-- maybe 20 to 40 nanometers deep.

I mention those because those are actually real numbers for some of the researchships that are being developed here at MIT in electrical engineering, mechanical engineering, and elsewhere-- very interesting properties, when one gets down to that small dimension. And some of those properties depend critically on those dimensions, as you can imagine.

So in fact, the manufacturing process problem is, how do you get processes that work in a controllable fashion? How do you inspect and detect feature sizes, geometric parameters, roughness of the geometry, as well as some other material properties in order to achieve the optimal functionality that one might need-- for example, controlling the flow of individual DNA from one place to another through these incredibly tiny, tiny channels?

What's another example? Somebody mentioned assembly. Assembly is a manufacturing process, and the worst example of this is that toys that come disassembled-- they never fit, at least when I try to assemble them at home. Geometric fit and how those imperfections can build up, even if-- an interesting aspect-- even if a few parts are close to nominal when you try to put them together, sometimes the aggregate doesn't work out so well.

And then there may be other example-- for example, very high-density electrical connectors. And I think, Dave, you had some example-- this comes out of an LFM thesis, or?

DAVID HARDT: No, this was actually research we did [INAUDIBLE] a number of years ago. And it's actually just like-- it's actually a trend with all these that [INAUDIBLE] for years. Of course, [INAUDIBLE].

DUANE BONING: Can you guys in Singapore hear Dave? No?

AUDIENCE: No, we cannot hear.

AUDIENCE: [INAUDIBLE]

DAVID HARDT: [INAUDIBLE] mic's not working. Just because this is sort of a theme-- you can imagine electrical connectors-- big heavy ones, like used in cars or in old electronics back in the tube days, where you could grab hold of some of these connectors with your hand-- just the metal part itself. Now, as electronics has become more and more dense, as things have become smaller and smaller, the requirement for higher and higher density of connectors-- if not just to handle these high-density chips, but just look at the back of your computer-- some of those connectors there-- particularly the interconnect type of connectors.

Well, the industry that made that made it the same way for years, and it worked fine. And it's a great example of how variability is actually a relative term. And so the variability was relatively small. It was small relative to the characteristic dimension that you needed.

But as that shrunk down, these major manufacturers found out that they really couldn't use their old technology to meet this. Of course, they went through a lot of the procedures we're going to go through and they improved things, but they couldn't meet those dimensions, and had to make a technology change as well.

DUANE BONING: This is my sneaky way to get an extra [INAUDIBLE].

DAVID HARDT: Also, on this minimum feature size-- and I'd ask Duane to comment on this-- I was once with a gentleman from IBM Research who told me they were just now-- this was maybe five, six years ago-- just now getting into some of the advanced techniques that we're going to talk about near the end of the term here.

And I was a little bit surprised, but then he pointed out, back when the feature size on the chips was large-- I don't know what large was-- micron scale or several microns-- the inherent variability of the processes was fine-- fine to manufacture these things. But when you get down to the nanometer range, all of a sudden, you have to look at some other techniques.

So there are these timeless things, like toys that don't fit together and other things related to larger dimensions, but then this idea of the ever-shrinking mechanical dimensions of things leads to an ever-increasing importance of process control. So our future is guaranteed.

DUANE BONING: I'll skip ahead, because maybe [? not ?] going through all of these, but if there's another one or two of these from your experience that you wanted [INAUDIBLE].

DAVID HARDT: Well, these are three large-scale issues. This is usually where I ask if anybody here works for Boeing or any other airframe manufacturer.

DUANE BONING: We have some automotive. We have some [INAUDIBLE].

DAVID HARDT: Yeah. The automotive actually does a lot better on variation control, because they have-- as you'll see, it helps to have some volume and to be able to learn and to get your processes in steady state. Things like airframes are still sort of one-off. And because of the large dimension there, it's really not an unpleasant-- it's not a pleasant thing to watch two halves of an airplane being put together-- although they've gotten a lot better than they used to be.

What was it they used to say-- that the number of thousands of pounds [INAUDIBLE] flying in a 747? [INAUDIBLE] we're also going to talk later-- actually, I'm not sure we will this term, but there's an interesting LFM thesis done on these plastic throttle bodies for fuel injection. This is a little bit different issue. This was an entirely different way of making a classical part. It had been made for years out of aluminum-- machined aluminum-- well-defined process, well-understood process control.

Then, for good and sufficient reasons-- mainly weight and production economy-- they went to injection molded parts, and variation became a big problem. And how to get rid of it was a-- was and still is an interesting issue. So a number of things come up, often because of change-- not always just because of things being in stasis.

DUANE BONING: Thank you. So again, some of these points that Dave made about, for example, the question or example you posed on semiconductor manufacturing we'll talk a little bit more about on Thursday, because it was a very interesting transformation from defect-oriented problems as the real yield and quality limiter to dimensional control. And essentially, parametric variation is the killer now.

OK, so one of the things-- this connects up again also to a point that Dave just made-- is that there is an evolution of manufacturing process control many industries had gone through. And you will often see a trajectory where an industry may actually start with a process that is not all that stable, and they essentially have to inspect every single part that comes out-- 100% inspection may have relatively high scrap rates-- even a few percent, for example-- with low throughput, and correspondingly high cost.

So this might be thought to be a characteristic of immature processes, but it's also a characteristic of incredibly complex processes. So you would really like to avoid that. Quick question for-- well, some of the guys from semiconductor know this. Do we have 100% inspection of semiconductor chips today?

What do you think? Do you think every single chip that comes off the line gets inspected, measured, verified that it produces? Do we have high costs or-- somebody who knows the answer-- well, I think perhaps it depends on what the chip is. You think every single microprocessor chip gets inspected before it gets packaged and put in a PC? You bet. You bet. On the other hand--

AUDIENCE: [INAUDIBLE]

DUANE BONING: Oh, absolutely. A microprocessor chip might sell for a couple hundred dollars, so it's worth it. Now, if you're talking about a semiconductor chip that is a discrete diode worth probably a fraction of a penny in terms of the manufacturing cost, yeah, you-- it's a much more simple and less complex thing, and you probably don't need 100% inspection there. But most integrated circuits, at the end of the day, still need inspection at the end. Yeah, Hayden?

HAYDEN TAYLOR: I thought it might be worth remarking that I think--

DUANE BONING: Speak loudly.

AUDIENCE: Can everyone hear me in Singapore? No.

DUANE BONING: Just shout.

HAYDEN TAYLOR: OK. I think Intel, when they test their chips, they determine what the maximum operating frequency of any given chip is, and they sort them so the chips that happen to operate at the faster end are put in more expensive machines, and those that are slower go in the cheaper machines. So they actually get some extra benefit from the testing process.

DUANE BONING: Right. So based on the quality or the performance, they can bin the chips and get differential pricing. Of course, they would be most beneficial if all of the chips operated at the high end. And so in some sense, that's both a limitation and an advantage. You can get a premium for the highest performing. But it's a great example of the range of variation and the effective, ultimately, on the end performance.

A next step typically in some of the evolution of these manufacturing processes involve-- whoops-- involve rework, both at the end of the line, but more often pushing down to unit processes-- where, if you could do a inspection, you still have limited control perhaps over the individual unit process, but you can inspect it, determine something went wrong. And if there is a possibility of fixing it then and there, now you've got a big advantage.

We already talked about also high durability at changeover, and that's an example we already talked about, about how cost rate and flexibility are linked. Of course, all of these-- if you can get quality up, get to higher and higher yield-- that has a dramatic effect, perhaps the strongest effect on overall throughput and the optimal output from your manufacturing plant-- especially in those industries where yields may not be all that high.

For example, in many of the semiconductor processes, if you have 90% yield on a very complex microprocessor, you're doing pretty well. That's not great, is it? Can you imagine 90% output of-- 90% functioning output of syringe needles that we saw, where 10% of them were defective in some way? That wouldn't be very satisfying, I think.

OK, so one of the things that we're going to do a little bit in the next couple of lectures-- and I'm going to talk about a little bit generically to set the stage for that last 10 minutes or so of class-- is characteristics of manufacturing processes-- in fact, something of a taxonomy that Dave will cover on Thursday based on some of the inherent characteristics of the physical action of manufacturing processes.

And we've already chatted a little bit, and we'll see more as we dive into those processes about why they don't always work correctly. So here I'm going to try to get a little bit of the terminology out and give you a little bit of a framework for thinking about the processes, and then some reflection on the different segments of the subject that we mentioned are coming up, and how they relate to a very-high level generic view of the process.

So the key idea in a process, of course, is that we have some part that we want to produce at the end. We do that by working on a work piece. There is some physical material that we are transforming in some important way. We are changing the geometry. We are changing the material properties of that part.

How do we do that? Well, we have to subjected to some process, and we do that through equipment, and in some cases, parts of the equipment-- things like tooling that come in contact with the part. So some examples of broadly, equipment-- and here, equipment we may even rise a little bit as both the physical machinery and the process environment that that machinery generates around the work piece.

So examples might be an an etch bath. So that is a liquid chemical environment that might be done under the control of a piece of equipment. Other equipment that many of you may have come in contact with-- things like injection molders, lathes, drop presses-- and the whole goal of those are to act on some workpiece. So we may have silicon with certain layers already coded on them.

We may have feedstock, things like plastic pellets or [INAUDIBLE], that come in. We may have sheet metal. Sheet metal already may have gone through an awful lot of processing, and we're looking at a unit step that's doing some additional processing on that. And then the output can either be a finished part direct for use or a part that is in some intermediate stage that will, again, go and be used in some larger manufacturing process. So it might be a shaft or a hood or something like that that's going to be further assembled, or an IC chip-- which, from the semiconductor fab, that's the finished product.

But from somebody-- can't remember who said they worked at Dell-- the IC chip-- that's not a finished product. The PC and the assembly-- the packaging and assembly onto boards and the assembly of boards into the [? back plane ?] and so on are an important manufacturing process.

So by definition, we're thinking of a manufacturing process as a change or the sequence of changes in some work piece material. The easiest way to conceptualize this is that it's going to be a change in geometry. We're building up some part. But equally important is a change in some material properties, some constitutive properties of that structure. We'll see lots of examples of that in semiconductor fabrication.

Here I want to give you a kind of a generic conceptual semiconductor process model. And actually, I want to mention a little bit-- this ties into the history of the evolution of this subject. Back-- oh, God-- it's getting to be 18 years ago already-- when we were starting to look at ways to formalize discussion of semiconductor processing, we came up with-- myself and some other co-workers here at MIT came up with some terminology for this conceptual semiconductor process model.

And we talked about it in terms of states and transformations of states, these states being the geometric state and the constitutive properties of the work piece In semiconductor fabrication, that's typically the wafer. And around that, one is generating a process or some environment around the wafer. That may be gases, temperature environment, other kinds of ways of generating and directing energy and material at the surface of the wafer.

The machine itself is a key controlling parameter for how one generates that environment, and the rest of the facility also impacts that environment-- the feed material coming in, the very, very high purity chemicals, for example. Now, what's important about the machine is that the operator only has limited access. The operator, which may be human or may be an automation system, has only limited access to that equipment and the facility through some settings-- some knob settings, if you will, that you can perform on the equipment.

But you also have other directional sensing capability. You have some number of readings that are telling you indirectly things about the machine-- machine states, sensor states, thermocouple states, which are telling you things about the wafer environment-- and then, indirectly-- if you're lucky, directly things about the state of the work piece itself, telling you things like the thickness of the film being grown on the wafer.

And then we had a term, which is really kind generic to semiconductor processing, of a recipe that basically defined the settings, and perhaps even could be generalized to a control algorithm, if you will-- which might be a little bit more of a generic terminology-- for dealing with responses to the readings. So now you can think about things like real-time control-- or run by run control, which we'll talk about later-- that looks at how one determines what the settings should be on the equipment.

Now, we came up with a slightly simplified version of the semiconductor process model just focused on the wafer, the process, and the settings. And I want to give you a real quick example of this. Actually, I'll probably skip this and come back to this next time. This is looking at examples for one particular process dealing with oxidation.

Now, what was interesting is we came up with this generic process model. This was early '90s. When I came back to MIT, I started teaching a subject on semiconductor process control dealing with statistical process modeling, yield, design of experiments, and so on. And then I got involved in some research that overlapped with Dave Hardt and some others.

And he had a course, and-- on manufacturing process control, and he had a process model for control circa 1995. Maybe you had come up with it even earlier. And one of the readings that you need to grab off of the website is an overview of manufacturing processes that is circa 1995, '96, where the terminology is almost exactly the same.

And in fact, the overlap was astonishing. The tools and techniques that I was teaching in my separate subject and Dave was teaching in his subject was about 80% the same, and then just the process details kind of changed. So in fact, we merged the subject, and that's how this subject came about.

And again, the key ideas here are there are controls. There is the operator, and some settings, and the equipment, material-- that we're all about changing the geometry and property through the action of the process environment, or these energy states. Now, in this class, we're really going to be focused a lot on the overall process outputs [INAUDIBLE] processes, and in some cases, the aggregation of those.

And just to get a little bit of terminology as a prelude for both Thursday and next Tuesday, one can think about a vector y of characteristics of the product that are important-- shape parameters, particular thicknesses, perhaps material properties-- like index of refraction of thin films-- the conductivity of particular layers, as well as transistor characteristics, for example.

And that is a function of the process parameters, both controls that one can change and other parameters that may be fixed and set for the process. So a key question is, what are these alphas? What are these process parameters? And how do we go about controlling those?

So we'll touch on this picture a little bit more next time, but what I want to skip to here is a-- we'll hear about these different characterizations or taxonomy of the process next time. I want to give you one last description building on this very simplified mathematical terminology at least for the process, which is we can go in and-- here we go.

Here we go. We can split out some of those process parameters as those things that we have control over as inputs to the process. And now, if we do just a very, very simple first-order Taylor expansion, we get some nice insight into where variation comes in a typical process.

So this is the very simple variation equation that, in some sense, helps structure what we're going to be doing through the rest of the term. One can think about deviations in the output deltas in those characteristics, and we can expand that in terms of some of the alpha parameters and some of the controllable parameters.

So this dy d alpha-- that's sensitivity to delta a alphas. What's delta alphas? Those are disturbances that you would prefer were not there. They're not things that you intentionally are changing. Those are inherent disturbances in the process. So there's one component that deals with disturbances.

And then there's also intentional changes we might have, when we want to or intentionally make a change to the control inputs. And so what's interesting is the strategies that we might use for minimizing this delta y. And in some sense-- let's see. Let me get to a nice summary here. Here we go.

In some sense, the goal of the first third of the class-- the techniques we'll be talking about our statistical process control, which is all about detecting these inherent deviations, these disturbances, and seeking to minimize them. Then we can talk about process optimization, things like design of experiments, where we're basically trying to build a model for y-- the output-- as a function of process parameters, and seek to minimize the sensitivity to those disturbances, to have as robust a process as possible.

And then finally, we can also think about active modes of process control, where you actually manipulate some of the control parameters, perhaps in response to observed deviations, to ultimately minimize or counteract, through feedback control, the effects of those disturbances. So that in the nutshell is the map for what we're going to be doing through the rest of the term.

We're going to be dealing, first off, with statistical process control and the statistical background for that. We're then going to be modeling the process, building up design of experiments, response surface modeling technologies for modeling and optimizing the process, and then thirdly, we'll talk about some basic strategies for feedback control to compensate for some of these processes.

So with that, we'll leave you. Folks in Singapore, we'll see you again next week. Again, do catch the videotape of Thursday's lecture. Please go to the website. This lecture is on there, but also there are two-- well, there's one reading that you should grab right away, which is about a-- was is it-- six or seven pages process overview which defines some of this terminology in written form that we've talked about here.

And I will also post what the reading assignment is that you can get started on. I don't think it's posted up there yet, but go out and try to get these books, because there will be-- the reading assignment is basically start on the first two chapters, which are very talkative overview of manufacturing processes. So we'll get you started on those. One quick question, Dave-- is there any information on-- is there a pro seminar when that starts up, that you want to mention?

DAVID HARDT: Yeah. 2.888 is already-- there's a Stellar site on it. I think I've sent most of the preregistered students notes on this, but it starts a week [INAUDIBLE].

DUANE BONING: OK. So we'll have more information on that. Many of you, like those enrolled in the mechanical engineering, MEng program, will know about this already, but this series of seminars from folks from industry and so on will quite likely be of interest to other people in the class. So we'll start alerting you about those evening seminars here as well. So welcome to the class, and we'll see you on Thursday.