MITOCW | Lec 3 | MIT 2.830J Control of Manufacturing Processes, S08

DAVID HARDT: My name is David Hardt for those of you who I haven't met yet. And I'm filling in for Duane Boning today or sitting in or guest lecturing, whatever you want to call it--

AUDIENCE: You're not guest lecturing. You're co-lecturing.

DAVID HARDT: Oh, yeah, I'm a co-lecturer. Yeah. Yeah, that's right. No, I'm guest lecturing because-- you know the story.

So I think my role today is to in some ways repeat what Duane Boning has talked about in the first two lectures from a little bit more of a mechanical engineering perspective. But I'm going to also throw in some things, you might just say a personal perspective on the problem. And I've got too much to try and do in one lecture, but that's sort of typical of me anyway. But the notes are on the web if you want for the things I have to skip over.

Now, the first part of the lecture is to notice this scene. And someone was pointing out to me the other day, said, it must be tough for you this summer, because you go between these extreme environments. So I found this picture of what I call a tree tunnel. Does anybody know where this picture was taken? In January.

AUDIENCE: [INAUDIBLE]

DAVID HARDT: It wasn't at MIT? It's a little washed out. So you can't see what these things are in the distance. If you saw those you'd probably know in an instant if you know--

AUDIENCE: Barges?

DAVID HARDT: Anybody in Singapore know what that picture might be taken? Oh, come on. All right, where do you think this picture was taken?

AUDIENCE: Outside.

DAVID HARDT: All right, OK, so here's a tree tunnel in Acton, Massachusetts, in January. And here's a tree tunnel on Sentosa island in Singapore in January, just about the same time, same kind of view. The difference is that those are probably the second largest collection of container ships in the world, something like that, which is the main landscape feature off of that coast of Singapore. OK, just to let everybody know what the other side is enjoying on their weekends.

So here's what I want to try to do today. I want to go back and talk a little bit more about process definitions from the point of view of geometric change of an object. And I think Duane has already talked about this a fair amount. But I want to relate it to that model or that view of processes to a couple key mechanical processes as examples.

And then something that we always do is talk about this taxonomy for control. It's a framework. It's all these rather abstract terms that say, here's a way for you to think about every process that's ever been invented and try to understand how it relates to some other process, with respect to things that affect how we control the process. So that's our taxonomy for control.

And then we'll go through a couple mechanical examples. I'll use the process of simple machining, a turning process, a blending process, and a molding process. We used to have a lab in the course that we did-- in fact, the guys in Singapore did it this summer as part of their summer orientation. They actually did this lab where they went through and made parts using these three processes. And we studied the process control aspect to that.

And they're ubiquitous processes, but they also can be reduced to some simple enough concepts that you can try to understand this idea of the origins of variation, why did things vary, instead of it being a purely random event, instead of sort of throwing up your hands and saying, I have no idea why anything happened, let's just model it as a random process, we say, no, let's try to see if we can separate those things that have a clear cause, which we may or may not be able to control, and those things that we just don't know about.

And then scrambling at the end, I'll try to get to this concept of states and properties. And again, this is more of a framework issue. But it is an issue of looking at any process, looking at all the different factors that enter into the outcome of the process and just parsing it really into four areas in this idea of what we'll end up calling thermodynamics states, those things that are kind of transient, come and go, and properties, those things that are inherent in the process.

And then we'll separate the process into the equipment that executes the process, which kind stays there day after day and year after year, and the material that you're changing as part of the process. And, of course, that changes in every cycle of the process. And that distinction between the two is extremely important.

So here's the model you've already seen. And the first part of this is to notice that we've taken the manufacturing process and said, well, again, there are these two elements to it. There's the material, which is again sort of coming and going. And by its very nature, the fact that every time you run the process, there's a new piece of material in there, that's going to have a different characteristic for its variability than the equipment, which, again, is unless you buy disposable equipment, you generally keep around for years.

And then there's an interaction between the two. And that interaction, if you really want to abstract it, could be called a directed energy exchange. It always takes some energy to cause the material to change. And what are you trying to change? You're trying to change its geometry, usually only its geometry. Often properties change as a result of that. Or sometimes you're changing properties, like a hardening process or ion implantation, something like that. You're taking one material and through this process transforming it in some way.

And, again, just to remind you, we have this simple functional relationship that says, well, guess what, the output is a function of all the inputs. And that's really all it's saying. And defining it right now, saying that the outputs are some vector-- or the outputs can be described as a vector, which has all of the relevant geometry and property characteristics of the process. So it would be dimensions, material properties, things like that.

And process parameters, using a really generic word for those input variables, because I'm going to distinguish between inputs and parameters a little bit later, and just saying that there's some functional relationship between the two. And, of course, here's the functional relationship, all that stuff that's in there.

So if we just focus for a moment on processes where geometry change is the most important one-- and I don't know, speaking from my perspective on this class, that's going to be 100% of what I talk about. I think when we get into semiconductors, there's a little bit more on material modification. But I think certainly most of the stuff you've seen has been on a manufacturing process, meaning we change the geometry.

Now, what causes the output to change? Well, there's a directed energy exchange with the equipment. And that energy exchange can take the form of any of the relevant forms of energy. So we could have a mechanical exchange, where you impose a force or a displacement on something. We can have an electrical change, where you run a current through something, or have an electric arc something like that. It could be thermal. And certainly, there are many processes where the transfer of heat is the key way that you change a geometry. And certainly, it could be chemical. Think of an etching process or anything like that. All of these energies directed the correct way can be thought of as geometry change mechanisms.

Now, how do we direct this energy? If I just say, I've got some thermal energy sitting around. How do I make sure it goes to the right place? In effect, that's the goal of the equipment. That's why this one little thing, which my thermodynamics friends would go crazy with, but calling energy a vector quantity.

It matters where you put the energy, right? If I want to take this bar and maybe do something to the center of it thermally, and I've got a thermal energy source out here called a piece of equipment, maybe a torch or something like that, how do I make sure it goes to the right place? Equipment, material. This is one of my easy questions. I make sure I hold it in place, right? Yeah, go ahead. Go ahead.

AUDIENCE: So I guess by way of relative positioning, these two are in the correct positions.

DAVID HARDT: Yeah, I mean if I had like a point source, a laser or an arc, or something like that-- laser is a better example-- and I needed to do something right here, maybe thermally deform this or join it or something like that, then the key would be how both the value of that energy and where I put it. So location would be really important. So that's one way of thinking of the concept of a directed energy source. If I want to bend this piece of sheet metal, which was originally flat, and I have a displacement device, it's probably a good idea for me to put that displacement device in the middle, not over here, and to have that displacement device have a certain shape to get what I want.

Think about this one for a second this one. I don't know if you can see this. Let me try my document camera. Come on, doc cam. There we go.

This is an injection molded part. It's from a precision yo-yo. And what's the energy we're talking about there? This was injection molded. I think most of you here have had some hands on experience with injection molding. If you haven't, I'll explain it in a few minutes. But where's my directed energy source there? Or if you have any trouble getting your head around that, how did I come up with that shape?

AUDIENCE: Heat and pressure.

DAVID HARDT: If I had heat and pressure to put the liquid plastic in there, that kind of filled the mold. But what determined the shape?

AUDIENCE: The mold.

DAVID HARDT: Yeah, the mold. And what's the directed energy in this case? If I'm saying the direct energy leads to the shape of the part, the geometry change--

AUDIENCE: The forces.

DAVID HARDT: Pardon me.

AUDIENCE: The mill cutting courses from whatever bit used to cut the metal.

DAVID HARDT: We're talking about plastic molding right now.

AUDIENCE: Right. But to make the mold.

DAVID HARDT: Oh, to make the mold. Yeah, I see where you're going with that. But I'm thinking about just the molding process. The tooling somehow was magically there.

AUDIENCE: I think the directed energy in front of the surface. So everywhere where we have surface, we direct energy.

DAVID HARDT: Exactly. So now, the one big distinction between these two is that here it was pretty clear that I had a pretty localized source of energy. And, of course, the case of heating this would be the same. Or as you'll see later, turning with a pointed tool. Here, everything's happening everywhere at once. And the direction, if you will, the spatial aspect of it is imbued not by how I position something, but by the shape of the tool.

So you start to see that they're kind of two extremes here. There's the case where this geometry is determined primarily by a spatial distribution of energy exchange, which is stretching it a little bit here, but a shaped tool. And as Simon said, everything happens everywhere at the same time.

Whereas in this case, things are changing over time and quite different things happening at different places. And an more extreme case again, which I'll get to later, is if I'm coming in here with some sort of a point source-- let's say heating it or applying a force here-- there's nothing happening out here. It's all happening right here. And the net shape that I get has a lot more to do with how I move that interaction port, otherwise known as a tool, than it does with the tool shape. Tool shape is important, but it's of secondary importance. OK?

They're supposed to go away now. There we go. OK. Well, they didn't go away. It's good to see you guys.

So now, we talk about it and we say, it's about geometry change. And I've kind of thrown out some different ones here. How do you change the shape of anything? Well, we already talked about one. It's pretty obvious. Take out a knife and a piece of wood and you can change its shape by removing wood chips. Whittling, that's your basic shaping technique. Well, that's essentially one of the most common ways of making anything.

We etch away silicon. We machine away material. We can oxidize and burn things off. We can do it in a number of different ways. So removal of material is obviously one way of doing things. Pretty obvious one. How else can I change the shape of something?

AUDIENCE: You can add material.

DAVID HARDT: I can add material to it. Yeah. Or join or something like that. So I can reform things. OK, how else?

AUDIENCE: You can deform the material.

DAVID HARDT: I can deform the material like this. This started out, it's a fixed piece of material. I didn't add or subtract anything to it. But I changed the shape by bending it. How else? Let me see what I've got here. Plastic deformation of the material. So a constant volume, constant mass process. The first case, you're throwing material away. Adding material, which I think is what people were already talking about.

So one of my famous professors here at MIT called this machining and negative machining. So it's kind of another way of thinking of it, but adding material, subtracting material. The ultimate manufacturing tool would be one that took from here and gave to there and that sort of thing.

What else? There's one other? Where does this fit in? It doesn't fit any of those.

AUDIENCE: Formation.

DAVID HARDT: Yeah, you guys took 2810, right? So you probably already covered this. But, yes, formation of material, so where you go from a liquid or vapor state, it solidifies against some energy exchange medium or form tool. And you come up with that shape. OK.

What else? That's only four? This is every manufacturing process in the world in the universe.

AUDIENCE: Well, it's kind of under addition. But you're actually growing material, using chemical, biological process, like a silicon crystal.

DAVID HARDT: OK, good. We'll call that addition. It ruins my punch line if we don't. Any others? Well, I mean the point is that again it is a matter of definitions, and you could cut this more finely.

But this pretty nicely characterizes every manufacturing process with respect to geometry change. We could have a parallel set for property changes, thermodynamic changes and implantation changes, atomic changes, so forth and so on. But for this it seems to cover pretty much everything. So if you look at a manufacturing process or you look at something going on in a factory and say, is this a manufacturing process? One of these things should be going on, if it's a geometry change process.

So what controls the geometry change? Was, who said, the location and intensity of the energy exchange. So we already talked about this for turning. And here's just a schematic of a simple turning. This is actually the experiment we used to do where you just-- or you guys actually did it again, where you just come in so-called orthogonal turning, and you come in and reduce the diameter of this stock.

And more formally, we would say this is the location of the maximum shear stress. You bring in a tool. And the material is spinning in this case. And there's essentially no stresses on it. Then you come in with a tool and start applying a significant force over a very limited area, in such a way as to create a critical shear stress, and the material decides to leave. And so in an abstract sense, I can think of machining as locating a very concentrated maximal shear stress point at different places in such a way as to at that location make the material disassociate with it.

Yeah, so we already talked about this one, heat transfer at the mold surface and injection molding.

So another extreme of interaction to give you an idea that there's more than one way to remove material, and certainly anybody with a mechanical engineering education, any sort of shop or manufacturing experience says, oh, yeah, machining, that's it. And that's how you remove material. But, of course, we remove material in a lot of different ways. And, of course, anybody from a EE or semiconductor background says, oh, yeah, removal, that's chemical etching or something like that. And that's true also.

But then you have many things, these beam type processes, which are very important for a lot of different processes. But think the extreme case of a process where things are very localized and you're just doing something in a very small region and then you move that region around the part. It might be something like laser processing, laser beams, using laser beam to cut and moving it. This is meant to be a picture of a robot moving it around.

So the robot is very important in this case because it's providing the motion and moving the laser tool. And, of course, this has been taken to extreme with these femtosecond lasers, which can affect at any given instant, will only ablate material and, I don't know what, sub-micron areas. So you can really localize it if you want to.

And then you've got you've got other things like this, like a CVD process where what you're actually doing is locating a chemical reaction across the entire surface of something. And again, that location is determined primarily by whatever substrate it is you're trying to coat. In this case, we're trying to coat.

But just to throw this out, if I have a nice clean uniform substrate, even with-- well, let's just take a flat one, a flat disk, and I need to coat it with a chemical vapor deposition process. So I've got this vapor, and it's going to deposit and solidify on the surface. What's going to determine the final geometry of that surface, of that coating of the surface?

AUDIENCE: [INAUDIBLE]

DAVID HARDT: Yeah, well let's assume this is just sort of this chamber filled with the vapor and then you introduce this in there. OK?

AUDIENCE: Time.

DAVID HARDT: Time certainly is a big part of it, yeah.

AUDIENCE: Topology.

DAVID HARDT: The topology of the substrate. And I'll just throw in the other is that-- because I want to make the point that with any of these processes that occur with a distribution sort of simultaneously, the ones that Simon was talking about earlier, there's always this concern that you don't have uniform spatial distribution. So what I was getting at is there was no intention of having directed vapor density or anything like that.

The idea is I've got this uniform cloud of vapor. And it's reacting with the surface. So why might it vary spatially? It's certainly going to vary over time, because it takes time for this stuff to solidify. But it's also going to vary spatially, because who said it's uniform?

And one of the things you want to think about when we're talking about manufacturing is always sort of question any statement of uniformity or constancy or things like that, because inevitably there will be variations because the topography of the substrate might change. Who knows? And in fact, it does happen, especially as you go to larger and larger wafers. You'll get important variations in the chamber, temperature variations. You could get concentration variations. All these kinds of things can cause problems.

One other that I'll mention because I showed this piece of sheet metal and talked about it as a concentrated energy exchange. Here's another example of a non-concentrated energy exchange. This is a large piece of sheet metal. This dimension here is about 6 feet, aerospace manufacturing. And it's being pulled across this tool and deformed in here. I actually have a sort of video of this which I couldn't find.

But you can see it being pulled down to the tool. And because of the reflections of the light, you can see that there's not a single portion of this large piece of metal that isn't being changed at any instant in time. So clearly, this is everything happening everywhere all at once. And in effect we're pulling it across a shaped tool. So in the end, we're imposing this displacement field on it.

So this gets us to this concept of the taxonomy. You can see that-- I've been kind of ranging widely over a number of different processes, either directly or by implication. And we want to kind of draw some conclusions from this. So the first is that there are two extremes to these interactions, the so-called serial interaction. And schematically here it's best described as my femtosecond laser, infinitesimally small area of interaction over the large area. So that at any instant I'm only affecting a small part of the material.

But then I move it. I have a time history of this. And that's what determines the geometry. Now, of course, in a real process, even with the femtosecond laser, if you get to small enough, there are spatially distributed effects. And as I go to larger and larger tools, this gets worse and worse.

But if we make a definition that the area of the interaction of the energy interaction is small compared to the tota area that I want to change, then it's clearly what we'll call a serial process. If the opposite is true, if the area of that interaction is on the order of the total area that I'm trying to change-- and again, the icon for that would be stamping out a car hood or something like that-- the area of interaction is the same as the area that I'm trying to change. Same with this part, the area of interaction is the entire area.

Then we have a parallel process. We run into a couple of interesting variants on that. If we take a very common process, rolling, to create sheet or just plate reductions-- I'm coming in with material that looks like this. I'm coming out with a material that's much thinner.

Where does this fit in this taxonomy here, this part of the taxonomy? Is it a serial process or a parallel process?

AUDIENCE: Serial.

DAVID HARDT: Serial. OK. OK, so we have 50% of the electorate going for serial in this mostly democratic primary. Parallel? 50% saying parallel. I guess it goes to the super-delegates. OK, you guys in Singapore and to you, you guys, you want to break the tie here? What is it? Is it serial or parallel?

AUDIENCE: I think it's parallel.

DAVID HARDT: OK, so 51% for parallel. Anybody there say serial? Yeah, we got some serials here.

AUDIENCE: It depends on the light.

DAVID HARDT: Yeah. Yeah, now, we're getting to it. OK, it depends. If I had drawn this in 2D like this and maybe sort of drawn it in extreme and didn't even show this necking, just kind of showed it doing this, then you'd be pretty tempted to say, oh, that's a serial process, because all the action is right here. Look at this huge area that I'm affecting and all the action is right there.

If I had drawn it in a front end view and here's the material, you look at that, and say, oh, that's parallel. Everything's happening everywhere at the same time. So just a cautionary tale, it's not either or, it's neither nor. It's sort of preponderance of, if you will.

So this is a good example of why they're actually important, even though it's mixed on here. And I'm going to jump ahead to the sort of who cares, which may not have a satisfactory answer today. But the who cares is if I'm running, in this case, the Alcoa Tennessee-- that's a real town-- the Alcoa, Tennessee, cold rolling mill that makes all their beer cans stock, and I'm really concerned about extremely good thickness control, because when it goes into the high speed canning machines that thickness has to be right on. Otherwise, the walls will tear or it won't form properly.

What do I control? Just intuitively, what would I control to affect the geometry parameter called the thickness?

AUDIENCE: Distance.

DAVID HARDT: Distance between the rolls, yeah. So I control the thickness by controlling, let's say, this distance right here. Which thickness does that control? Does it control this thickness right here, or this one here, or that one there, or maybe that one there, or that one there? Yeah, all you're doing-- there's one spacing area. And if you say, oh, yeah, it's exactly right here. And then I make little disks and make my cans with the material over here, who's to say it's going to be right?

So even in this case, I've actually got a mixed problem here and a mixed control problem. So, yeah, here's a case where displacement-- this trajectory we're talking about, just like this deal, you want to think of it that way-- I'm directing the energy source by displacing it. That's part of it.

But then how do I change the thickness distribution, the parallel part of the process? Well, I'd actually probably have to change the shape of the rolls. You do a little bit. They actually do both sides. And that does help.

But let's say I do both sides. So this is exactly right. This is exactly right. And the middle looks like this, which is not uncommon. It becomes fatter in the middle. What do you do?

AUDIENCE: Change the rolls.

DAVID HARDT: Yeah, but I don't want to do that. Yes, you would change the rolls. And, in fact, what they do is they build roles with a little bit of camber in them. Because you know the center is going to deflect up a little bit. So you put some camber into it. Believe it or not at Alcoa, that's still not good enough. This stuff is very precise.

I shouldn't quote the tolerances. But it's on the order of in my newly converted SI brain, I think it could be 15 microns. It could be in the 10,000th, several 10,000th of inch in terms of thickness tolerance. It's not very thick stuff to begin with.

AUDIENCE: It would be like locally heated through--

DAVID HARDT: Yeah, in fact, that's what is done. To get small displacements, to be able to actually arbitrarily-- not arbitrarily-- but to put some different profiles on that, you'll locally heat it or cool it in response to the feedback to actually slowly move the tool locally a little bit fatter here and a little bit less there. You can imagine if you only need 10 microns, something like that, it doesn't take a lot of heat. And, yes, indeed you're going to say, oh, how localized can that be? And that's the trade secret they won't tell anybody about but.

Yeah, so in this particular case, notice these two different modes of modes of interaction lead to two different ways of controlling it. In one case, it's very simple. I'm going to buy a Servo system. It's going to be really good. It's going to be very stiff. And I'm going to say, make that 2/1,000 inch gap and you get 2/1,000 inch gap. In the other case, it's like, oh, my gosh, you know, I've got to change this spatial distribution somehow. The extreme case is to shut the thing down, put in a new set of roles. And the other is to come up with some clever way of deforming it.

So why do we worry about the two modes of interaction? It leads directly to how we would ever find the knobs on the machine to change what we're doing. Now, that will become most important in the last part of the class when we talk about process optimization. And you're saying, what can I do? What can actually change on a process? What can I change real time, millisecond? What can I change, maybe-- in this case, this is an unusual example-- what can I change on a frequent basis? But in most cases, the major change you do with tooling and things like this is on hourly shift, yearly basis. So your ability to affect the output once you've kind of literally cast it in stone is greatly changed by whether it's a parallel or serial process.

OK, so just to summarize this again, so for this lumped or serial case, the time trajectory of that interaction port is one of the most important things. So robotic manufacturing, which was all the rage for many a year, until we found out it wasn't really such a thing to be rageful about, it works for a limited class of processes pretty well. And your classic CNC machine, the CNC machine of the '60s, which sort of got generalized in the '70s and put everywhere, essentially means if you want to put in the terminology of what we're talking about today usually means the ability to control trajectories in a very repeatable way. So it's not just a machine that can follow a trajectory, it's also the ability to generate the trajectory and things like that.

And then in this distributed-- I've used two different terms here-- but distributed or parallel case, more than anything, it's the shape of the energy distributor, you know, patterns, molds, masks, heat distributions, things like that. I think we've seen enough examples. We're sick of these now.

Oh, yeah, well, you'll see this in a moment, but a lot of the so-called rapid prototyping methods that popped up in the '90s, or solid free form fabrication as the government likes to call it, stereolithography, sort of the first big one on that 3D printing and developed here, are serial processes. And they figured out how to put down-- they turn out to be usually serial addition type processes-- figured out how to put a dot of material down at a time to build up a structure. And that dot itself was cohesive enough that if you put it down, it stayed there and you didn't need anything to hold it. And I'll talk more about that in just a moment. But I think we've kind of talked about-- these are all interesting examples.

So if we talk about a taxonomy to kind of bring together the energy source, if you will, for the geometry change, the way we apply it, and a couple other things that will come up in just a second, then we can-- and I think I've said why for the mode, the change mode-- oh, actually I haven't. I'm sorry about that.

Why does it matter-- let me go back to this. I think I won't bother with the slides. What I called mode before was really my energy source. Why does it matter whether I'm using mechanical, electrical, thermal, or chemical as my change agent? What difference does that make? It's just energy, right?

And again, back to lecture 1, what do we care about in the process? Quality, number one in this class. But also we worry about rate. And we worry about cost. And we worry about flexibility.

So with respect to which energy mode is involved, what difference does it make in this consideration? Simon.

AUDIENCE: Well, in the way we can control the process, we need to know what [? eventually ?] is involved, so we can change the [? size ?] of the energy.

DAVID HARDT: Yeah, sure, absolutely, so I would control these in different ways. But let's assume I could do that. I know how to control mechanical energy. I can change forces and displacements and velocities, electrical currents and voltages. Thermal, that's a little bit different. I can certainly control temperatures. I can also try to control their distributions. I can sometimes control-- heat flux is a little bit harder to do. And chemical, I can control concentrations and temperatures and maybe reaction rates as a result of that. Yeah.

AUDIENCE: [INAUDIBLE] if you're affecting a large area or smaller wafer versus a big stack of [INAUDIBLE]

DAVID HARDT: Yeah, I thought you were going someplace else with that. But, yes, there is a size scaling. But the example you gave actually, though, a wafer, in terms of the relative size of the features that I care about is actually huge when you think about a wafer compared to a tiny little sub-micron line, and then I think about a car hood with a little feature in the middle, the wafer is actually bigger.

AUDIENCE: I was thinking of the [INAUDIBLE] with the changes in-- I mean--

DAVID HARDT: Yeah, yeah, yeah. OK, I think you're getting to what I wanted to do. Let me see if I can get any more here and then we'll see. Yeah, [? Kimmy. ?]

AUDIENCE: The rates are definitely change of [INAUDIBLE] mechanical is usually faster than [INAUDIBLE]

DAVID HARDT: Yeah, yeah, believe it or not, when you think about this, you always think of electrical, oh, that's the gigahertz range, and all that kind of stuff. And that's true if all you need to do is move electrons. But we have to move material around here. So this tends to be very fast. If I apply a mechanical load to something, I can modulate that load pretty fast these days if I want to.

And when I bring a tool into a piece of sheet metal like this, how long does it take for this to react? Well, essentially, at the kinds of time scales we're talking about it, it happens instantaneously. Compare that to how long it takes to etch something or do certain deposition processes. We're doing these nickel plated micron scale tools. I just saw a presentation last night, three days to make a tool with 50 micron features on it. That's not what you'd call smoking. So pretty low stuff.

So rate-- we can argue different things. You can have fast chemical stuff and so forth and so on. But in general, there's a speed issue here. What else? That's rate. What about quality?

AUDIENCE: There are also side effects of the process.

DAVID HARDT: Yeah, side effects. I like that. Say a little bit more about side effects.

AUDIENCE: Well, you got the theoretical. Maybe I want to cut a perfect square. But the tool is not going cut perfectly square edges. So depending on what process I use, it may have undercutting or rounded edges.

DAVID HARDT: Absolutely. Absolutely. So there's something here inherently related to quality, at least two things that I can think of. One of them is related to what I'll call diffusivity in the general sense, not just purely in the thermal sense.

If I apply a load to something, as you're saying, if I apply a load to something, even with a point tool, there's a stress field that develops in it and that sort of thing. And this will be a little bit facile, but I can make an argument that says, OK, if I apply that load to here, it diffuses. And so I wanted to put the load in a tiny point, but it actually spread out and so I didn't get exactly what I want.

How about if I put a thermal source in there? And the worst part is not only does it dissipate, it just keeps dissipating. Probably never reaches equilibrium. So it's really going.

How about a chemical reaction? One of the problems we have with that, of course, is if you do thick etching, you have undercutting, because it-- don't go there. But it's going there. It wants to go everywhere and other things like that.

So, again, you have different diffusion characteristics here, depending on what's going on. So your ability to control the shape, to get a minimum feature size, to get a level of precision, will vary depending on what you have here.

And what else do you think is important to quality? Obviously, my ability to sort of direct things exactly where I want them to be is important. What else do you think is important to quality?

AUDIENCE: How about repeatability?

DAVID HARDT: Yeah, sort of the how well I can repeatedly apply this energy and have the same thing happen. And that will vary again, depending on the nature of the interfaces here. For example, if thermal conductivity is a big part of it and you're continually bringing new material into contact with an old tool, it could be a different heat transfer coefficient every time. In mechanical cases, if I'm always coming back with the same tool, except for long term where, maybe it's a little bit more repeatable.

There's one other aspect to it now. Now, think a little bit more about where we're going with the class with things like statistical process control, which says, let's find out things that are not quite right with the process and fix them and that will improve our quality. And then in the more active process optimization stuff, where we say let's adjust things until they're really right. And then actually at the end, we'll talk a little bit about active control, where you're continually adjusting.

But think of it this way, because you will be thinking about this, here's the process. I just measured its result. It's not good enough. I need to improve its quality. And I can't go buy a new machine. So I have to have the ability to adjust something. I have to have the ability to change something.

So think about what it takes to change these, just as I was saying before with the rolling case in the-- yeah, go ahead.

AUDIENCE: I think for some mechanical processes, it's easier to stop. But for the chemical, thermal, even if you know the problem, it can be hard to stop the process. It's hard to stop.

DAVID HARDT: Yeah. I mean, I'm not trying to come up with winners and losers here, because they all have advantages and disadvantages. But you're absolutely right. There are big differences. If, for example, there's a time aspect to it, mechanically I can pull that force off, and it goes away. There's a wave that goes through the material. But it goes at sonic rates. The thermal could take a long time to change anything there and certainly the chemical depending on scale could be like that too.

So it is important to know what these different energy sources are, if only to say, OK, these types of things are more important when you're really faced with the decision of what's the best I could ever expect this process to do. I've worked. I've done SBC. I've done process optimization. There's a fundamental limitation because it uses mechanical energy. I'll never be able to do the following or so on.

So you have these types of things interacting with how we apply them. And, of course, you could say it's impossible to use all these in all their different ways. But actually that's not entirely true. So kind of said all that. So let's go on.

Now, this eye chart is an attempt to take this entire taxonomy and then just populate it, this chart, with some examples. And some of these are no-brainers. And some of them could be a little bit controversial.

So what this says is cross here, this is the removal mode of transformation. And here is addition, and here's formation, and here's deformation. And in each case then, it's divided in half with serial and parallel and then four different energy sources. So you look at each one and say, OK, where where's my favorite process?

So serial, removal. Mechanical, cutting, grinding, broaching, polishing, water jet. Water jet is mechanical. It happens to be fluid mechanical. But it's mechanical. Electrical, serial, wire EDM, take a single skinny little wire, drill a hole, something like that. Put a whole bunch of them together. Do it all at once, say with a formed electrode. Now, it's parallel EDM.

Photolithography with a wet etch if you want to think of it that way is basically a parallel process. It's etching everywhere at once. But you just happen to put a mask in a few places. That's your tool. So that it can't resist.

I think Duane has already talked about chemical mechanical polishing, which I'm told by the experts in the field is really mechanical polishing. So if we take the C off of there, then CMP is a mechanical parallel process. If it's chemical mechanical process, then I guess it has to show up in both of them. Which is it? Is it both?

AUDIENCE: The chemistry softens the surface, and not the mechanical abrasion. So you have both.

DAVID HARDT: OK. But the chemical by itself would not remove any material.

AUDIENCE: That's correct.

DAVID HARDT: Chemically assisted mechanical processing.

AUDIENCE: Strangely enough, the abrasion by itself would no remove any material.

DAVID HARDT: Any at all? That's interesting. OK. Well, that's actually an example here of where the chemical part is actually affecting properties, not unusual. So this is still true if I'm only talking about the geometry change part of it.

There's a bunch of other ones here. One of the interesting things is if you come over here to something like hot isostatic pressing, a powder metallurgy or powder ceramic process, where you take uniform powders and compress them in a mold. So that's obviously an addition process. And then I sinter them and then I do other stuff to it. And I do it all at once in a form tool, a can, and I'm all set. That's clearly a parallel process. And the result depends primarily on the shape of the can.

Then Ely Sachs at MIT kind of invented this process called 3D printing. And if you look at 3D printing, it's not exactly this. But it's essentially the same as saying, OK, I'm going to put down each piece of that powder one piece at a time. He does it by joining the powder one drop at a time. He puts a binder on it. Instead of binding it all at once, he puts a drop down at a time. It's an ink jet type process.

Now, it becomes a serial process. And think about the difference between these two processes. If I've got this big press that has to push this powder into a green compact, big piece of equipment, going to have an expensive tool, whereas this 3D printing, it's a desktop-- thing are desktop versions of it-- desktop thing, all I have to do is type in a CAD file. It does a section file of it. It creates this thing. And I've got essentially equivalent parts, not exactly equivalent, essentially equivalent parts.

So clearly this serial process is much more flexible, really great. And I probably can control the quality better because of it's not quite right, I just change the program a little bit. If it was a little bit too wide the last one I made, I said, well, let's reprogram the geometry and bring it in a little bit. And it just does it.

Whereas if I'm doing the hot isostatic pressing, I've got this big expensive tool, and it's not quite right and I can't heat it and cool it like I did with the rolls on the aluminum, I'm kind of stuck with it. So why would anybody do HIP, when you've got 3D printing?

AUDIENCE: Rate and cost.

DAVID HARDT: Rate and cost, absolutely. You do the hot isostatic pressing in minutes, seconds, that sort of thing. The 3D printing, the fast ones, are going to take you minutes to hours. And it's volume dependent. Whereas with the HIP, it's much, much less so.

In general, why does anybody do parallel processing? Because it's really fast. And the example I always like to give is imagine if someone took a block of steel or better yet aluminum and said, OK, I'm going to make all the body panels for your car, the thin little body panels, with my machine tool over here. Just imagine what it would take to build that, as opposed to going to a modern high speed stamping shop.

Has anybody seen automobile body stamping going on? Yeah. How long does it take to make a side panel for a car with like integral door frames and all that other stuff? Each given operation probably takes about 2 seconds. There's multiple stages. So maybe we'll give it 10 seconds by the time it's done. But blank metal in one end, and these huge complex structures coming out the other end at incredible rates. You're not going to do that with a serial process.

Although I will say they've done some things with laser cutting and laser welding where the thing really whips along. But it's still got a ways to go. And it's much more costly.

So all these things do matter. And they come in different ways. Oh, just because I always like to do this-- stereolithography, how does that work? It was the original-- I think-- the original rapid prototyping process. Anybody know what stereo-- what's the trade name for that now? That's the most commercial of them. There's a machine right down the far end of this hallway in the architecture department that's an STL machine. Stereolithography? I guess it's become passe now. Yeah, Adam.

AUDIENCE: It's just-- I don't know what liquid is, but you select part of that liquid material with the laser. And then it runs that.

DAVID HARDT: Yeah, that's right. There are these photo curable polymers that will be in a liquid state at room temperature and with just regular light on them. But if you hit them with the right wavelength light, they will polymerize. They're UV curable polymers that are used for a lot of things, like contact lenses and things like that.

But this particular case, what they said is, well, instead of putting it in a mold and flashing it with UV light everywhere, what if we put a little tiny spot of UV light on it? Will it form a little ball of polymer? And the answer was sort of yeah.

So you have this bath. I haven't walked by there this month. But there used to be one of these glass walled classrooms down here at the far end of the fourth floor in the architecture department this white box with a clear window in it. And it's kind of lit up. And there's usually something going on in there.

And what you'll see is a bath of nearly colorless liquid with a platen on it. And the platen starts at the top with the very thin layer of fluid on it. And this laser, usually not visible, but this laser will be dancing across the surface, tracing an outline. And that outline will become solid. And once it's polymerized, it'll move it down and do it again.

So it's basically causing a chemical reaction, or in this case a polymerization reaction, at a very small area by hitting it with the right amount of activation energy. So that's stereolithography. That would be a serial chemical formation process. You're going from liquid to solid.

We also do-- in fact, I was here last night listening to a PhD thesis from Singapore, where what they did is they took a mold, poured a UV curable polymer on it, flashed it with a UV lamp over the whole thing for about 30 seconds or something, I think, and then pulled it apart. And it was all about the mold, the mold quality, and filling and that sort of thing. And 90% of her thesis was about-- well, not 90%-- a good percentage of her thesis was about making the molds and how well could I extract this thing from the mold?

So physically, the same material, the same process. But in this case, a really good example of going from a directed energy source that was a point to a directed energy source that was really this entire surface. So I guess my point is, and now I guess it's getting a little bit dated, but when these rapid prototyping processes were all the rage, it was interesting to notice that on this taxonomy, they simply, with the fact that some people realized and it's been done for a lot of different things, not just these, but people realized that I can take a parallel process. And if I serialize it, it all of a sudden becomes a rapid free form method. It doesn't need any tooling. And so you've got that example.

You've got what turns out to be-- I guess I'd call it-- it's sort of like a reaction molding parallel reaction process to a serial reaction process. There's also with powdered metals, you can sinter them thermally to get the shape. And when people decided they could sinter it locally with a laser, you could take a powder of metal and zap it with a laser and just get things to sinter to each other locally. So they got they changed the whole equation on how the process is controlled, which has effects on all these different things.

Last thing, because we're not going to talk about it much for the rest of the term, but because it has been an extremely important part of manufacturing, interestingly fading in recent years for good and sufficient reasons, is flexibility. What do you think about if I were to go to different corners of this taxonomy and say, all right, so let's put a flexibility overlay on this? And we'll talk about flexibility here-- I guess, well, two common ways of looking at flexibility are sort of product flexibility. So in our case, it's going to be geometry flexibility, geometry and material flexibility. And the other would be quantity flexibility, ability to vary the capacity or output of something without having big cost variances.

But let's do the first one. We won't get into that second one. For flexibility of this process to work with different materials in different shapes, obviously, the extreme example of flexibility is every part's different. Every part is different, and the setup time is zero. So mass production rates, mass production cost savings, but custom part capability. These are lies somewhere in between there.

But if I look at this broadly, what do you think is the most flexible? Or most flexible or more flexible? If I look at the taxonomy, what area would you look at for high flexibility?

AUDIENCE: Serial processes.

DAVID HARDT: Serial processes. And why?

AUDIENCE: It's like if you're working on a local [INAUDIBLE] So I think it gives you more flexibility [INAUDIBLE] I guess feature by feature and also part by part.

DAVID HARDT: Yeah, exactly. I mean think of, again, the ubiquitous example is a-- I'm trying to think of some consumer-oriented parts of this. But I'm not coming up with them. But, yeah, a machine tool. Take a machine tool with an end mill and it can write your name in a piece of plastic. Once I programmed your name in there and then your name and then your name, there's absolutely no overhead to me switching, because all I have to change is the trajectory of the tool. And nowadays with CNC control, that's a zero cost changeover. There's a minimal cost in creating the programs for simple things like that.

So, yeah, obviously, something that is purely serial makes a big difference. And I'm going to add one other thing, because if I hurry up I'll get at least to mention this. I'll make the case that cutting metal mechanically is maybe the purest form of geometry transformation, pure geometry transformation with no side effects. So that also makes it very flexible in that sense. It's almost as if all I have to do is reprogram the trajectory and nothing else changes and everything's fine. So we'll start from that.

And then we move to other changes here. Let's go to deformation, serial defamation, bending. I'm going to bend this, three-point bending. I'm calling it serial, because most of the action is happening right here. And I'm not using form tools. You can even think of this as using knife-edge tools, and I would get sort of the same shape.

And the main thing that determines the shape, the main thing is how far I push down in the middle. So that's pretty flexible. I mean if I want 45 degrees, I just take it down less. If I go down farther, I take it down more.

But as can be shown-- and it is in the notes, but we probably won't have time to go through it-- as can be shown, it makes a huge difference what this material is and what the underlying machine structure looks like. And it also-- and this really kind of gets us to the next theme here-- it also depends very strongly on the uniformity of this material. So I'll make the statement that the natural variations out of an aluminum mill, maybe not the Alcoa, Tennessee, mill, but the other ones, of aluminum is enough that it can completely confound precise control of a process like this.

The natural variation of a piece of aluminum like this that I'm going to turn just doesn't make any difference. Sure, if I put a different alloy in, or I sneak in steel or titanium instead of aluminum, that's a big mess up. But if I just say, well, you know, here's a piece of aluminum.

We did it in this mill over here, and it came out with the following properties. It's elasticity. It's yield strength. It's strain hardening characteristics. And then I get supposedly the same material from a different mill. And they're 10% different. Not the elasticity, by the way, but all the others. 10% different. Huge difference here, virtually no difference for the machining. So there's an inherent sensitivity of the processes to that.

So if I look just at this purely serial parallel thing, yeah, serial is better than parallel. I think we can show in general that removal tends to be the least sensitive to material properties. It tends to be the least sensitive of all these things. So serial removal kind of wins in most cases in terms of flexibility.

Deformation is generally a killer in terms of flexibility for these reasons that we've talked about. And in many cases-- well, certainly anything that involves a parallel energy exchange sort of starts off behind the eight ball with respect to flexibility. Simon.

AUDIENCE: What about the chemical [INAUDIBLE]? I mean, they throw in all sorts of parts. And they come out with the coating. And I mean there is no dependency--

DAVID HARDT: That's a very good point. That's a really good point. I'm glad you raised that. I hadn't thought about that.

But a process like this, some of these addition processes, any sort of a plating or coating process where you put stuff into a liquid or vapor bath, it doesn't care about the shape, does it? I mean at a microscopic level it might. But, yeah, it doesn't. That's a good point.

So in terms of geometry, which there's the underlying geometry, the substrate, plus whatever thickness you add, to my knowledge, if I have a big piece over here and right next to it a little piece over here, another one over here, they're independent of each other. So they all deposit at the same rate, unless you do something really dumb. It's a good point. Good point.

I don't know how to pull that out. But in that sense-- well, to relate it to what we said before, the energy exchange area is determined by the shape of the substrate, not the shape of the tool. And so in a situation like that, the shape of the substrate, if it's right and I can change it each time I put it in, I get high flexibility with that. Yeah, good point. I have to remember that. OK, enough on the taxonomy.

Now, the last thing I want to talk about is what goes wrong. What we've been talking about so far-- we've made some reference to it-- what we've been talking about so far is how to make major changes. I want to go from this diameter down to half that diameter. Well, I have to push this in. I have to make chips. And I have to push this down so far.

But what I want to talk about is, why doesn't this always come out to the same angle every time? Why is the third part out of the run of 50 different from the 24th part and that sort of thing? And why, when I machine this, is it not the same diameter everywhere? And so it gets into looking at the sources of variation.

And by our definition of a process parameter, we're going to say, well, it-- oops. Don't do that. I'll say yes, but what did I do? By our definition of this, it's all wrapped up somehow-- well, in the end, it's all wrapped up in this functional relationship, but primarily through these process parameters. So we're going to use those to try and understand it.

So let's break down these process parameters in a little bit more of a logical fashion. And I'm going to do it in the following way with the following definitions. First of all, we're going to have alphas associated with the equipment. And then we're going to have alphas associated-- let me go back here actually. I need my picture.

So we're going to have these parameters associated just with the equipment. And I think I've already explained why we want to distinguish between the two. So now, we're talking about properties, variables, things I can adjust, things that happen that are staying with that piece of iron that's bolted down to the factory floor. And then a similar set, but for the stuff that goes in and out of the machine or that flows through the machine. It doesn't go in and out. So that's why we distinguish between them.

So let's just focus-- I don't know, let's focus on the machine, on the equipment. If I think of two broad classifications of a machine-- well, let's see, try this exercise. I think everybody's familiar with a machine tool. Simple lathe, it's sitting here in front of us. And it's not doing a thing. It's not moving. It's not even plugged in.

What alphas, what characteristics can you tell me about it just by looking at it? It's not moving. If you were to describe it from an engineering point of view, what are the kinds of things you'd worry about on it?

AUDIENCE: Stiffness.

DAVID HARDT: Stiffness. How stiff is it? Does it deform? Yeah. That's almost it. That's a good one right there. Stiffness, straightness, some details of mechanical characteristics of it.

AUDIENCE: Thermal expansion coefficient.

DAVID HARDT: Yeah, thermal expansion coefficient, very important stuff. All those things that basically go into is the structure and where I'm going to direct that energy source where I think it's going to be?

Now, I turn it on. It starts moving. And I start machining. Forget about the chips and all that other stuff, but just the machine itself. What other characteristics of the machine are you now going to worry about?

AUDIENCE: The turning speed.

DAVID HARDT: Yeah, the turning speed, exactly. The speed. What else?

AUDIENCE: Accuracy of the rotation.

DAVID HARDT: The accuracy of the rotation, yeah, OK, yeah. But now we've got the turning speed, now what's the difference from the machine's point of view if I've got the tool and I'm coming along-- I think you guys can see this-- if I'm coming along like this? Right now I'm characterizing the machine. And now I'm characterizing the machine. I've hit the material, and I'm starting the machine. What's the difference between when I'm here and when I'm here?

AUDIENCE: Negative vibrations.

DAVID HARDT: Yeah, you've skipped something. Go ahead, I think--

AUDIENCE: [INAUDIBLE]

DAVID HARDT: Yeah, you talked about the speed. So I have a speed here, and I have a rotation speed. But if there's no force, like there's no power, there's no nothing. No nothing much happening. That's good grammar. But if I come along here, all of a sudden the force changes.

So as a minimum, you've got these two sets of variables. You've got how stiff is the machine? How does it react to things like forces? How straight is the machine if I move this way relative to the axis of rotation-- that's your accuracy thing-- is it that way? And those are properties that they're not independent of whether it's moving or not. But you kind of look at it and you say it's the basic characteristic of the machine.

And then you've got these transient ones that are only related to the energy exchange. So you'd agree that if there's no force, there's no energy exchange. But as soon as I have a force and a velocity, I'm putting mechanical power into that thing. And something's going to happen.

So from that we can actually say, OK, there are two types of variables. Think of these sort of ones that are intrinsic variables that characterize the basic properties of the machine. And if we were doing applied mechanics, we'd say, those are the constitutive properties of the material, or they're constitutive properties of our machine.

And then there are the energy states, how things change over time as the energy waxes and wanes and interchanges and things like that. And those are useful divisions, because, for example, how easily can I change the stiffness of a machine? It can be done. I could buy a new one. I could go in and put in some more supports and that kind of stuff. Or I can take some away and make it less stiff. Kind of hard. Yeah.

AUDIENCE: It depends a lot on where I have my [INAUDIBLE] if I have a mill, I can take the table out very far and use it [INAUDIBLE]

DAVID HARDT: Oh, yeah, yeah, stiffness is not a single quantity. You're right. I can find stiffer regions and less stiff regions. But I guess what I'm saying is if you need to elevate the stiffness of-- there's no acceptable spot in it, what do you do? You have to change the iron. You have to go in and make a change. It's not something that we would call really, at this case, a control variable.

On the other hand, if I need to change the speed at which I'm cutting, change the speed at which I'm cutting and it changes. So again, there's an important distinction between those two. And our ability to know them as well as to control them is vastly different.

Now, the same thing holds true for this, this piece of sheet metal in its undeformed state. This is really hard stuff. It's like butter. If I just put this piece of sheet metal down here, how would you characterize it? Yeah, please.

AUDIENCE: Yield strength.

DAVID HARDT: Yield strength, extremely important. Anything else?

AUDIENCE: Elastic.

DAVID HARDT: Go ahead, Adam.

AUDIENCE: Elasticity.

DAVID HARDT: Yeah, elasticity.

AUDIENCE: Thickness.

DAVID HARDT: Thickness.

AUDIENCE: Temperature.

DAVID HARDT: Temperature. Actually, I'm going to disagree with you on that. No. Why does temperature matter?

AUDIENCE: Because it changes the dimension.

DAVID HARDT: OK. So there's a thermal expansion characteristic on this. That's very important point. When I say characterizing this, you don't characterize it by its temperature. You characterize it by its reaction to temperature. I don't characterize it by its stress or strain. I characterize it by its reaction to stress or strain. So those are all-- again, very clearly for piece of metal, it is constitutive properties.

And we could also worry about its chemical reactivity and all this other stuff. But its inherent characteristic of it, which describes how it reacts to impinging energy. So the mechanical energy I put in here combined with its elasticity, its yield stress, and other things, determines how far it bends and how it bends. So we distinguish between the two.

Again, so when this baby is sitting here waiting to be bent, it's got its constitutive properties. As it's being bent, it's now bearing external loads and displacements. It's stressing and straining. And that's a transient state. It's an energy transfer. And those are two different things.

They're both important to determining what comes out here, because if I said, OK, go back to your computers or your textbooks and give me an analysis of what it takes to get this shape, you're going to need to know the characteristics of the material, stiffness, yield stress, that sort of thing. You're also going to need to know what forces and displacements I put into it, which will tell you what happened internally to this thing. What stresses and strains did it have?

Same thing with this, I needed to know what the characteristic of the polymer was. How did it react to temperature? What was its viscosity with temperature? What's its heat transfer characteristics? And then I needed to know what temperature it was, what pressure it saw, and what the heat transfer characteristics of the mold were.

So what does this all lead to? These four babies-- to two major things, states and properties-- states and properties. Energy states, transient things, things that don't hang around, things that are just there to accomplish what we wanted to accomplish and then they go away. And properties, which, if you will, we can change them. But they kind of are there when we begin, and they're still there when we're done, and are more inherent to either the equipment itself, essentially the material or the equipment or inherent to the material itself.

So when we talk about energy states, this one can be made much more precise than we have time to do here. And those of us who are students of system dynamics, in the mechanical, not in the Sturman sense, but in the Painter and Richardson sense of system dynamics, understand that you can really do a good job of describing the world by simply talking about energy or power and constitutive relationships. And you can model anything as how it reacts to these things.

So that's really what we've done here. We said the equipment either provides or absorbs some form of energy-- force, velocity, pressure, flow, force displacement, that sort of thing, voltage current, heat transfer, heat flow. And those are the things that determine specifically what happens in the interaction between these two.

And then the properties, which is sort of what's going to happen when that energy is transferred, are all these things we've talked about-- margins of elasticity, plastic flow properties, viscosity, sort of almost the same thing, resistance, inductance, capacitance, chemical reactivity, heat transfer coefficient, thermal diffusivities, intensive constituent properties. Plus, because someone mentioned this before, someone mentioned thickness, so this is extremely important. So are the other two dimensions. These dimensions are important. And these dimensions are important.

And so it turns out the object of all our affection is actually the geometry in the end. So it's sort of an extensive property of the material. But we also have to worry about the geometry before and after. And we worry about the geometry of-- obviously, the geometry of the machine is important. Is it straight? Is it square that's sort of thing.

So let me finish up by just saying that we can have this model and then talk about-- and why did I bother doing this? I mean it's kind of fun. It's intellectually stimulating a little bit. But I think there's one real benefit to it, which is to understand why things vary.

So if I just say, all right, I'm going to subdivide all-- by the way, all four of these things our subdivisions of this vector alpha that we said is what makes everything happen. So I've got alpha. And then I'm going to divide that into what I'll call equipment states, equipment properties, material states, and material properties.

And why do I bother to do that? Well, in the end-- I'll give you the punch line because we're just about out of time-- is some of these are really easy to control, to keep fixed, and to basically know deterministically. Most of them, certain categories, are really hard to do that with.

As an example, material properties, yeah, material property of this, how well do I know the properties of this bar of aluminum or this hunk of plastic? Well, I can do some tests and do this kind of stuff. But, again, it can be shown that these can be highly variable, particularly as I go from this bar to that bar to that bar.

So we're going to be able to argue that unless you spend a lot of time upstream eliminating variations, like unless you do really good process control on the casting and rolling and other processes that go into, this will have variable properties. So this tends to be-- material properties tends to be variable. And as a result, depending on the process mechanics, has a huge effect on what your result can be. Unless-- there are some wonderful processes out there, again, like I said, like machining, that say, I don't really care. I'm very insensitive to that.

Equipment properties-- equipment property, so the stiffness of the machine, the temperature in a reaction chamber, other things like that-- I'm sorry, not temperature. Sorry, the thermal insulation in an oven, something like that. Within limits, of course, there's some uncertainty there. It's not just variable. I should say variable or uncertain. Either one is a source of uncertainty or variation for us.

Equipment properties, well, again, if I pay a lot, I'm careful with the machine, if it doesn't degrade a lot over time, then I'm in good shape. Machines degrade over time. So tool wear is a degradation in an equipment property. It's an expected dimension that's actually changing over time. So this can be variable over, many cases, long times. And that's a maintenance issue, as much as anything else.

But again, that's within a question of how good the machine is. If you build a machine with very sloppy bearings, a sloppy bearing is basically a noise generator. You just don't know where things are. If you build a machine that is supposed to distribute a vapor and it's got some sort of a vapor handling system that's supposed to distribute it evenly, but it clogs easily or something like that, or it just wasn't designed properly, then you've got bad properties. It could cause variability.

Equipment states-- forces, pressures, temperatures, flows, velocities, what do you think about those in terms of our ability to control those and eliminate uncertainty? Good, bad, or indifferent.

AUDIENCE: Good.

DAVID HARDT: Good. We have a vote for good. I would opine that any machine built in the past 20 years, at least, it's really good. And that, if you will, is the victory of CNC type controls, of computer controls. One of the biggest things is that this is now very minimal, minimal variation or uncertainty. I know exactly-- if I have a good Servo and I say, go to this velocity, it goes to that velocity. If I have a good temperature regulator and I say go to this temperature, it'll hold that easily within a degree, and in some extreme cases, a lot less than that. So particularly with the use of active control, we've made that really good.

So the last one-- and I would say end controllable, in other words, not only is it not variable, I can actually tell you what I want it to be. So I'm going to skip discussion of the material states, except to say that they're often-- well, let's say they are variable and hard to know. And I'll give you my one favorite example of that.

Let's say that I have a polymer that needs to be at a certain temperature to do what it's supposed to do. Typical way of doing that would be put it in an oven and let it sit in that oven. So the oven has certain properties that makes it keep uniform temperature. And it has a really good temperature control on it. So if I say heat this to 100 C, it's right there at 100 C.

So I've got this heated air, and it's at 100 C. I take a piece of polymer, and I put it in there. And I wait sufficiently long that it's at equilibrium and the polymer is now at 100 C. And then I pull it out and put it in a warming machine or something like that. What's the temperature of the polymer when I formed it? That's a state of the polymer, right? It's a thermodynamic state of the polymer. I don't know. Unless I measure it, I don't know. I'm not controlling it anymore.

Now, there are also cases, and this is true I think in the semiconductor world now more than anything else is that if I want to control a temperature, for example, I don't measure the temperature of the oven or the chamber. I measure the temperature of the thing that I'm going to make. And an example of that is-- in fact, the machine that this was made on if you guys have used this, the ENGEL down in Building 35, you control the temperature usually on this process by controlling the nozzle temperature and the barrel temperature. And you say, oh, that's the temperature of the polymer.

But what really matters is the temperature of the polymer in the mold, which you never measure. Right? But there's actually a little temperature sensor in the mold that you can measure that. And there's also a pressure sensor in the mold. So you could, if you wanted to, actually measure the pressure on this. But it's hard to do.

So this tends to be-- it's knowable, but sort of expensive to do. So here's the moral of the story. Biggest source of variation tends to be material uncertainties, just inherent in the material and, if you will, the coupling between this energy source and how well it actually gets into the material through sort of an uncertain interface. So all of these things here, these three, are your sources of variation typically in differing measures.

This is the one saving grace. You're going to actually control-- way back at the beginning of the process, you're going to control equipment stakes. So when it's all said and done, what we manipulate here are typically, not always, but typically equipment states. And our ability to do that and how well I can change an equipment state to get a change, the sensitivity of the process, has a lot to do with what I can do with its control.

And the rest of the lecture, which is in the notes, is going through these three processes I've talked about and kind of addressing those issues. So if you have a chance, take a look at the rest of those. OK?

OK, thank you. Thank you all. And I won't see you next time. He will.