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HAZHIR Welcome. This is 15.879, System Dynamics Research Seminar. And this is a seminar series that each semester
RAHMANDAD: we have a variant of it. So we have about four different versions of this course that we iterate through over a two-year period.

So this version is one focused on building classical modeling skills, covering the gap between what you get in 15.873 or any variant of a full semester course on system dynamics and what you need to be able to do serious modeling in an actual consulting project, in research projects. This is a gap that typically students don't have much opportunities, in terms of resources, to do self-study on.

We also don't have that many courses around-- across the world to cover the skill sets here. So I hope we have a fun seminar series throughout the semester together. But also, I hope that we can create some material that is useful, more broadly, for anybody who wants to learn system dynamics beyond the basics. So that's why we are actually recording these sessions. And we will share that through the OpenCourseWare Project of MIT. So that's the plan.

But I guess, to get us started, it's a good idea to go around the room, get ourselves introduced, so that everybody knows everybody else. This is, for a research seminar, not very small, but still a fairly small class. Welcome, join us. So yeah, we can get us started.

So I'm Hazhir Rahmandad. I'm on the faculty in the system dynamics group here. I've been around at MIT as a faculty member since 2015. I was at Virginia Tech in the industrial engineering department for a few years before that. And I did my PhD here at MIT.

I do different types of research, some of it more on organizational dynamics and strategy, some of it on public policy, public health, and some also related to methods. So that's me. Maybe go around the room and also catch up with folks online.

OK. As you can see, we have a very diverse group from everywhere in the world. So this is going to be fun. So today is our first session. I think, most of you, we have been in touch. I tried to share material on the class and both the syllabus, but also a little bit of a reading and some topics that we will discuss today.

So today, I think maybe half of the class is more on the theory administrative stuff and half of it on discussing the problems that we have for this week. And then the coming weeks, it will be mostly hands-on. So basically, this is a very hands on class.

So OK, on the administrative side, the class is three hours. We will take a break in the middle of the session in this room and also on the Zoom. You have the Zoom links on the syllabus. And this is a small class. So we will largely use emails. And so I've created an email list. And anybody who is not on the email list, please just send me an email. I'll add you to that.

We also have a shared Dropbox for sharing the material. Again, this simplifies not worrying about Canvas access for people who are not at MIT. So if you don't have access to Canvas-- to Dropbox, again, just drop me a note. I'll add you. Grades, I don't think anybody here cares about grades for this specific course.

In general, this is a learning opportunity. If you care about grades, let me know. So I can tell you more. But to the extent that there are grades for some of you who get grades out of this course, it's based on your weekly modeling work, assignments, and also active participation in the class.

So as I mentioned, this class is being recorded. We actually have a full camera set here. And Tom is taking care of that. Thank you, Tom. So that's going to be later edited, put into a package that goes into MIT OpenCourseWare, along with the rest of the material from this class.

So actually, we do have a media release form. I think many of you have already signed that. If you haven't, I have hard copies here. So feel free to pass it along. If anybody hasn't signed, you can share that with me, the signed version. And if you have any questions, let me know. We can talk about it.

Then we have-- let's see. So the structure of the class is going to be pretty standard. So basically, before the class, you will have a modeling task each week to work on that I would provide it to you a couple of weeks ahead of time. For the next week modeling task, I think I provided it a little bit in the middle of this week.

So the idea is that you work on modeling the thing that is upcoming in the coming week, but also think about the week after problem so that we have a conversation about that problem in the class in preparation for the next week. So today, we will talk about the problem that you will be working on in the coming week, in terms of the detailed modeling. And we will be working on some actual-- not modeling tasks today, today is mostly on architectural decisions in modeling projects.

So the class will be basically broken down into two parts. The first part, the larger chunk, is focused on the modeling. And the way we do it is you folks will be submitting whatever you have created, in terms of models. And there is details of how to submit that in the syllabus and also inside each of those assignments.

You put it on the Dropbox. We randomly pick a few of them. We go through the models together, we critique them, we think about places where things could be improved. And that process will hopefully help everybody learn some of those skills. So we will do that with as many of those models that we can in our limited time.

And then we spend this smaller part of the end of the class discussing the next week's problem and thinking through the high level architectural choices, the definition of the problem, and so on together so that we are on the same page and we have converged on some of the harder architectural choices before you are left alone to try to tackle these modeling challenges.

Now, this structure, I hope, is very helpful for you to learn from each other's challenges and also gain the confidence to tackle a full modeling project on your own because this is what you're going to do every week. Now, it will be challenging, depending on-- there is some variance in your background in modeling and prior experience. So some of you may find it easier. Some of you may find it really challenging. Stay with it. Hopefully, by the end of the semester, everybody here will be in good shape, in terms of building solid, relatively simple, but models that can be used in practice for research or consulting work.

I'm also designing this partly with an eye towards future learners who want to do self-study in system dynamics. And the way I'm envisioning the material to be useful for them is that they go through these weekly material, they start by doing the assignment for each week, perhaps after watching the discussion on the architectural choices in the week before, then they review the models that you have submitted, especially focusing on the ones that we discuss in the class so that they have their own critique of those models.

Then they watch how we critiqued it in the class. So that way, you calibrate your own way of critiquing a model with how the class does that. So that would be one kind of a feedback opportunity, even though we don't have live feedback for hopefully many, many learners who may use this material later. Then they will come back to their own models, based on what they have learned from that critique, and try to improve and get their models to as good a place as they can get.

So this is a protocol for people who will use this in future, not really relevant to you. But I'm highlighting it because, as we go through the class, you can see how it may benefit others in the future as well. So that's a little bit of administrative background. Let's see if there are any questions on that. And then we can move into more content for our work.

AUDIENCE: I'm taking the class as a listener. Is there any differentiation between those taking it for credit?

HAZHIR Yeah, so basically, no, in the sense that I'm not going to tell you, oh, why didn't you submit something or please
RAHMANDAD: do this or that? You should decide. You guys are here with different goals. Some of you are trying to do everything that we are going through the class. Some of you are more in the listener phase. I'm OK with that.

In terms of participation in the class, be actively participating to add value. If you're here, you want to contribute. But for those who are taking this course for credit, then try to do as many of the assignments as you can. I think, if you can't do some week, just send me a note beforehand so that I don't call on you that week, you don't feel embarrassed about it. But other than that, that's all good. And if you're not taking it for credit, but you are here to learn, then do the assignments. It's going to be helpful for you. And we have more material to discuss in the class.

AUDIENCE: So there's no difference when you're selecting which models to critique?

HAZHIR I am thinking that I would give a little bit more priority-- so in the probability distribution of being randomly
RAHMANDAD: selected, I'll give a little bit higher priority to those who are taking this for credit so that they have a higher chance of being picked and, therefore, getting a little bit more feedback on their work.

But everybody who submits something will have a non-zero probability. And I haven't yet set up that spreadsheet. But I'll do that for next week. So that's the plan. Other questions? OK. Anybody online, anything that you want to share or ask any questions? OK.

So when we talk about system dynamics modeling, we're actually talking about a big category of possible model types. And that is very important. What is the purpose of the model we are building would have a big impact on how detailed your model needs to be, how empirically grounded it needs to be, what kind of a process for model building you may use.

So it is important to be mindful of those use cases. And we are not going to cover all of those use cases in this class, partly because some of those use cases require a lot of detailed work that is beyond the scope of this class. Some of them require a lot of working with stakeholders, group model building type of activities that is not well designed for what we can do in this class.

But I want you to be aware of these different use cases because the process you learn here is optimized for a subset of these modeling practices. It is useful for all the other ones as well. But you need to know that there are additional components in your skill set that would be beneficial if, for example, you are doing modeling to bring a group together or you are doing modeling to do predictions in a very detailed, future-oriented task.

So here are a few examples or key categories of uses of system dynamics models. So what I call process consultation, I'm thinking of it as a broad category, that models become useful artifacts for helping a group, a set of stakeholders, to come together, have a more productive conversation about a complex problem.

So in this case, group model building would be one of those approaches to bring a group together to build a qualitative model, usually at the beginning, and then typically adding more quantitative models, though there are different schools of doing group model building, where you may start with actually a simple quantitative model from scratch.

So that's a whole set of different goals from a modeling project. Building common mental models, surfacing different perspectives that are in a group of stakeholders, those are very important goals of a process consultation type of modeling project that might be distinct from a prediction-oriented modeling project.

Then we have models that are trying to build generic high level insights about interesting dynamics. These could be very much theoretical. So much of what goes into academic journals, especially in the management space that use models, fall into this category. These are usually fairly simple models, but with a clear, neat insight that you need a model to appreciate that or mental models alone cannot handle that level of complexity.

Usually, the idea is to get insights that are applicable across a variety of application areas. But you are not going to make any strong claims about that insight being the key to explaining a specific empirical case. You are not doing a close match with any empirical data in the quantitative sense.

The theory testing variety of these kind of insight models tries to push it one level further-- that is, not only tell a story, but also test the strength of that story for explaining specific cases. So you may have data from a single case or multiple cases in a panel data set of sorts. And you will build a simple model, estimate that model with that data. And then the strengths of those parameters will inform how strong are the mechanisms. And you can go into a more quantitative space with models in this space.

I would say that is in the minority, in terms of work that is already out there in the literature. There are domains, in pharmacokinetics for example, that you see these types of models and they are bread and butter of mathematical modeling. You estimate those models.

And they are been informative for a bunch of actual practical questions. In management, there are fewer of these theory testing using dynamic models work, even though theory testing is the vast majority of literature in this space. So there is actually opportunities to build that, I think, in management research as well.

And then you have use cases that are more applied, whether it is for predicting things, and you build a dynamic model to try to project what will happen in the future. We did examples of those around COVID with a bunch of collaborators. That's a pretty viable space. You need models that have a decent level of detail complexity to be able to basically capture the variables that are observable in the real world, but also to be feedback rich, very well grounded in the empirical data. Usually, you have to go through estimation of these models to be able to do some meaningful predictive work.

The types of models we build for prediction purposes are most useful for longer term predictions. If you are doing short-term predictions, there are lots of other tools from machine learning and statistics that are better candidates because, in the short run, you don't need the long-term feedback mechanisms that we capture in our models to think about problems.

Then you have a variety of models that are more focused on policy design, decision support tools. And there could be variants that are focused on a single decision, whether we go ahead with this investment or with this merger or with this project or not.

For those types of decisions, you want a well calibrated model, fairly detailed. These are usually very big investments in terms of time and effort that goes into these models. So the decision needs to be actually pretty substantive. That is, if you're spending a couple hundred thousand dollars in building a model, the impact of that decision, or a delta in the quality of that decision, should be in millions of dollars to justify that.

So for simple decisions, it may not be worth the effort. And that creates a whole area in consulting. For example, in dispute resolution, in legal cases, for big projects, that is where these detailed system dynamics models have historically been very successful.

Then you have decision support, which is a little bit different, in the sense that it is more focused on a regular decision, that each decision, per se, may not be valued in millions of dollars, but it is taken repeatedly. And having an underlying dynamic model, whether it is for supply chain management or for production management and so on, can be beneficial.

And a lot of operations management work uses these types of models. Many of them have components of optimization combined with components of dynamic modeling. So that's another related area. Again, well grounded in empirical data, usually has more detail than the generic insight type of models, more engagement and time spent in building and maintaining those models. Especially, the maintenance is important. And they need to be updated as things go.

You can think about models that go into training modules, as management flight simulators or for working with the stakeholders to help them appreciate some of the interesting dynamics. Those models need to be very robust. They are usually a little bit more detailed than the generic insight models because you need the policy levers that the stakeholders care about to be well integrated into those models. But they are not usually calibrated to any single case, even though they need to be in the right empirical space for it to be useful.

So as you can see-- and you can come up with other subsets. But I think these are covering some of the more common ones. They have different flavors. And in terms of the size and complexity of the model, you can think about small exploratory models that are more focused on understanding dynamics. And you create, explore some simple policies or you go one level further. You try to not only build theory, but also test theory when you calibrate some of these models. And then you go down into more calibrated, detailed models that are for the strategic decision support for single decisions or continuous types of decisions.

So our focus, by and large, is in the smaller sized models in this class that could be used for helping explore different policies, building good intuitions about serious organizational challenge. They are actually very useful for even high level strategic consultation and thinking about problems. You get a lot of benefits of the more detailed, calibrated models in the earliest stages when you're building these higher level, but feedback rich models. They are also tools for process consultation, for engaging stakeholders, and so on.

We have a version of this seminar that is focused only on calibration of models. So when you're interested in more detailed estimation work, there is a whole machinery. And it takes quite a bit of time to set that up and learn all the basics there. But this is where we are focused on for this class.

Also, to give you a little bit more feel for time distribution and how much effort goes into different types of modeling efforts, you can think about, if you have a big enchilada of a model that has all the bells and whistles and is well calibrated and is detailed and so on, the biggest chunk of that work is actually going into the calibration work estimation, connecting it with the data, which requires you to go collect the data, estimate the model, do analysis. So that's actually the biggest chunk of the time that goes into those big strategic models, big consulting models.

And also, these are things that you can break down into chunks. And some parts of the team could be focused on collecting the data and cleaning it up. And some part could be on the technical estimation side and some on the analysis side. So you usually tackle these problems in larger teams rather than a one man or woman show modeler situation.

And then on the insight building, which is the smaller part of the modeling tasks, there is both the modeling and the analysis. And for this class, we think of modeling and analysis as very tightly connected. And if you went through the memo that I shared with you, you probably noticed that iterative modeling process, where you add a chunk, you understand that chunk, and then you go about adding the next chunk of the model and so on.

Now, for this class, we are going to go through a modeling process that has some of the major components of any typical modeling initiative. But we focus on a subset of those activities. So basically, if you break down the modeling process into problem definition, building a qualitative model, building a simulation model, doing the calibration and estimation, and doing the analysis and insights, we are not spending too much time on problem definition because I usually try to come up with a decently well-defined problem definition for you.

And then we will have a conversation in the pre-modeling session, where we discuss the problem definition. Sometimes, we may have reference modes, sometimes even not have very specific reference modes. Sometimes, we may discuss momentum policies when they make sense. Sometimes, we wouldn't.

We usually wouldn't even go through a list of variables. So those are steps that are useful in defining the problem. We don't necessarily go through all of those in this class. By the way, anybody knows what are momentum policies? This is probably a new term for many of you.

So momentum policies are, if you're working with a stakeholder, they usually come with a problem that is more pragmatic. They need to solve something. And usually, they have their existing priors on what would be a decent solution if they didn't do any modeling work with you.

You want to elicit that so that you know what is their starting position, they know what is their starting position. And what are the benefits of doing that? First of all, it informs you what kind of policies you actually need to be able to reflect in your modeling work and analyze in your modeling work. So it tells you something about the structures that are needed to capture those policies.

So that's number 1. Number 2 is that, in a few sessions or a few months, depending on how long an engagement you have, you probably have changed, in the process of modeling and working with your client, how they think about the problem and how they prioritize different policies.

So you want to have put a stick in the ground that allows them to see how far they have come along, how much their thinking about the problem has changed, how they would now differently prioritize different policy levers so that they can appreciate what the modeling process has added to their thinking.

This is important because the way we usually engage with stakeholders in a modeling project is very continuous. At every stage, you want them to be involved. Now in this class, you are not going through the process consultation type of modeling work. But you want engagement in any actual project because that's how people actually change their minds. They are not going to trust some black box model that you throw at them.

But that means they gradually change their thinking. And three months later, everything seems obvious. So they may not appreciate how much the modeling process has helped them change their perspective. So having these momentum policies at the beginning helps them see the impact of the modeling project appreciate that much more clearly. Anyway, we are not doing momentum policies in any serious way in this class. We don't have clients. And this is not as much focused on that. But it is an important component in thinking about problem definition when you're working with clients.

So typically, I give you some version of a qualitative model, sometimes with explicit causal loop diagrams, as we had for this week, even though we are not building models along those causal loop diagrams we had for this week, sometimes with just a verbal description of the mechanisms that are relevant.

Either way, you have the outlines of the qualitative model. Your focus will be on building the simulation model that captures those dynamics and doing the analysis, building insights. And that analysis process is a very iterative process, in the sense that you yourself, in your week long journey, you may start with the simplest chunk that you think you can model.

You model that, you understand that, and you need to be very specific about, OK, I'm leaving out a lot of things that are in the problem definition because I don't feel comfortable I can incorporate all of those in my first iteration of the model. That's the right way to do it. Don't try to incorporate everything, if you don't feel comfortable with that. And we'll talk about how you would feel comfortable or not as we go through this.

It's completely legitimate, fine to come to the class and say, half of the things that you asked for in the problem definition are not part of my model because I didn't get a chance to get to that iteration to incorporate those. That's fine. Take this iterative approach seriously. And the iteration means there is another step. And that is the analysis step.

And the analysis step is critical. We'll talk about it. It is by far the most underappreciated and underutilized part of the modeling process. I see it in lots of senior people submitting papers with models they have not understood. And if they have not fully understood your own model and why it is behaving the way it is, you can't really generate insights for others. This is so common that, if you just fix this issue in your modeling work, you will be ahead of 70%-80% of the pack in terms of what you can actually generate insight.

OK, so that's a little bit of a big picture overview on model types, modeling process overview. Now, for the remainder of the theoretical part of the class today-- and as I said today, we have half of the class more on theory. In the future, we wouldn't have this much theory. So I would not be talking this much. For the remainder. I want to go through basically what you had in the memo, understanding that some people didn't have a chance to go through it in depth. But also, you may have questions. And we want to have a conversation around those.

So I created this memo with the realization that there is a lot of art to modeling that is just hard to pin down. And it creates a very steep learning curve and also a very variable learning curve, depending on the individual and the opportunities they get to engage with modeling tasks.

So you would see folks who may spent a couple of years in their learning journey and still not feel comfortable tackling the types of problems we are trying to tackle in this class. And part of that steep learning curve is that not every idea for how to do modeling well is well documented and even well specified.

Experienced modelers don't necessarily have a very clear theory of how they do it. So some of it is like biking. You can't explain exactly how it happens. So I tried my best to verbalize and theorize around what some of those skills and artsy parts of the skills are and how you can actually implement those.

And the way I found it most useful was to draw on the common mistakes and common challenges and pitfalls that I see early modelers deal with and try to say, OK, in response to this common challenge, what would be some of the solutions that may be helpful?

So as such, it is actually a little bit subjective. It is coming from my experience of working with lots of students and folks who are doing modeling work and my own challenges learning these. But for whatever it is worth, I hope it is useful as you go through the process.

Now, I'm hoping that I will be editing this memo over the semester based on our experiences as well, so that it becomes a more useful guide for others in the future. So if something is resonating, highlight that. But also, if something is not working for you-- you tried something and you didn't know what even it means the way I have expressed it-- bring it up. This is going to be helpful to make something more useful for the broader community.

So big picture-- I, so far in the memo, have highlighted seven different failure modes of sorts, though you could aggregate some of them together and break down some of them separately. And for each, I'll go through some of the key ideas for solving those.

So starting with unclear problem definition, perhaps one of the most common issues with modeling projects, and a couple of ideas for tackling it-- that is, starting with a clear problem definition. That's obvious. But how do you get to a clear problem definition is the question. Partly, you could do that by specifying important architectural choices. And we'll talk about some of those.

So having a problem focus is key because it determines everything that you do in the modeling project, every choice you make-- what variable goes in and what variable doesn't go in, what is the boundary of the model, how detailed you need to get, whether you need to bring in quantitative data or qualitative data is enough.

All these things are only answerable if you have a clear problem definition. When you don't and your problem definition is kind of wishy-washy, the risk is that you're trying to model a system, you think of the system, you have a view of the system, and then everything could be argued that needs to be included in the model.

And then it creates-- usually, that approach, even if you are a very talented, capable modeler in terms of technicality of equations, you will end up adding so much detail complexity into your model that the model crumbles under its own weight. And also, it cannot communicate with anybody because it becomes such a big, unwieldy beast that nobody can understand what is happening under it. So the problem definition is your measure for deciding what is in and what is out and all of the architectural choices that go with it.

Now, the way we define a problem, there are different approaches for defining a problem. And three of them, I think, are more common. Perhaps the first one, which is reference mode driven, is the most common in the system dynamics community. But it's by no means the only way to define a problem.

But the basic idea there is that you have a historical behavioral mode, a reference mode. So things have been changing over time. Our profitability was growing. But now, it has stagnated over the last couple of years. You're trying to understand what drove those dynamics over time.

So having a clear reference mode is a very good starting point because then it grounds you to whatever is needed to explain that mode of behavior or at least create plausible hypotheses for explaining that mode of behavior. And anything that is not relevant for that explanation would, for now, be out of the problem definition and model boundaries.

So that's one way to tackle a problem definition-- pretty common, relatively easy in the sense that, once you have a reference mode, the next steps fall in place. Then you come up with qualitative stories of, OK, what might be the mechanisms. In collaboration with the stakeholders, you may generate a set of causal loop diagrams that help you come up with mechanisms you think may explain, for example, the exponential growth mode at the earliest phase and the slowdown separately in the later stages and so on.

So that's method 1. The second method starts with mechanisms. That is, it says, oh, there are some interesting structural features in this problem space. So maybe there are two actors who are competing with each other. And that competition, I want to understand what are the implications. So it already puts you in a space you need to think about interaction between two actors.

Now, whether you formalize it as a game theoretic case or something more heuristic, that's an architectural choice. But that limits the space of things you want to explore. You may have, for example, dynamics of word of mouth. And you're interested in its implications. So this gets you something similar to a Bass diffusion model in the simplest case.

And then you may say, OK, what if we have another other components added to this-- for example, the expansion of potential adopters in a Bass diffusion model as the product becomes more viable, better in terms of its quality, its prices, and so on. So there is endogenous dynamics of improvement in the product, which then opens the door for a larger group of population to be interested in it.

So once you have specified these mechanisms, now you have your marching orders. I want to build a generic model that captures those mechanisms and explore the implications in terms of some policy question or some theoretical question. This approach is actually very common. In econ modeling, this is typically how people build models. In much of the theoretical organization theory, this is how models are typically built.

And in fact, you have canonical core models in this space, whether it might be the NK model or the multi-armed bandit model or the prisoner's dilemma model, that are basic building blocks. And then people add components to them. And that is how you make new contributions. That is, OK, that canonical model, take it, add this additional piece. Let's explore what will happen, how it changes our policy conclusions, how it changes our theoretical intuitions.

So that's the second one. Sometimes, you can get from a reference mode to a core canonical model by capturing some of the mechanisms. That is common. So the two are not excluding each other, but different approaches to get to similar things, ultimately.

Then you have a different approach that is more focused on the policy questions that your client is asking. So you have a stakeholder, a client, yourself. You have a few actual policy questions. Should I do x? Or should I do y? And then the question is, what model can help you address that question thoroughly and with decent confidence? And the ability to answer those questions becomes the driving force, the light that shows the way in terms of problem definition.

It's attractive because the clients connect with this type of problem definition very well. It is challenging because it is hard to know what needs to be captured and at what level of detail to address those policy questions. So there will be lots of uncertainty about those architectural choices when you take the policy driven approach. And that is, in some way, the reason I don't necessarily recommend that for early modelers. But as you build your capabilities, you become more comfortable taking this approach to problem definition.

So this is one way. Basically, try to define the problem early on, using any of these approaches. That way, you have a clear problem definition. Usually, you want to write it down in verbally. If you have reference modes, highlight that as well. And come back to it, potentially edit it, but also come back to it to decide, when you get into a decision, do I include this feature or not.

Go back to your problem definition. Does it require you to include this feature? Only add things to your model when they're really necessary with your problem definition. And most often, you don't know whether something is really necessary. So that is why we have this iterative approach.

You add components that, at the beginning, sound the most important. And you go to the next levels of importance. And at some point, you may add something and you see it makes no impact. In those cases, it is safe to take it out and keep your model simple. Sometimes, you may leave it in because your clients think it is important. So you need to show them that it doesn't make a difference. That's also legitimate.

OK, so that's one approach to addressing this challenge. The second approach is to tackle your key architectural choices more explicitly, to think about them. And that helps you bring out the problem definition more explicitly. So thinking about what is the boundary of the model, so what is in and what is out, in and out in terms of mechanisms, in terms of components. What works your model?

As you think about this very important architectural choice, you will see that you have to be more clear what is your problem definition. That is how you can make this choice. So as you argue for yourself, do I include demographic change or not, do I include competition or not, do I include endogenous growth in my investment pool or not, or whatever is relevant to your problem, those types of questions will force you to think more clearly what is my problem that I'm trying to solve based on which I am inclined to go in this direction or that direction.

And if you track that internal thinking and you put it down on the paper, you'll see whether you are converging around a single problem definition or for each decision you are drawing on different ideas and different problem definitions. If you see the latter-- that is, your drawing for each question on different potential problems-- that is a problem. That is, you need to actually leave out a bunch of those problem definitions and focus on a core one, a unifying one, or something that is a subset of those.

So boundary of the model is very helpful, very important architectural choice. In our course, actually, the boundary of the model, we don't play with it too much because, again, we are going to define problems a little bit more clearly. So as such, this is an architectural choice we will discuss in the pre-sessions a little bit. But you wouldn't be too much worried about it in this class.

Time horizon-- very simple, but also still very important. That is, over what time horizon we care about the dynamics and the outcomes. And that determines a lot of questions about what is a legitimate stock variable or source of inertia, what is the right level of aggregation. The time horizon typically sharpens what are the policy questions you care about, how long is the horizon over which the outcomes matter for you. And so you want to think about it clearly early on.

Then the next very important architectural choice is the aggregation level. This is how detailed you want to make your model or how high level it would be. The heuristic that system dynamicists typically use is the more aggregate you can stay, the better for you.

Now, that heuristic has good logics behind it. It helps you with building simple models quickly, get feedback, work with the stakeholders without overwhelming them with detailed complexity. Usually, it gives much more clear structural insights. The insights are not lost in detailed complexity.

Analysis becomes much simpler. When you have higher level of aggregation, you don't need to figure out feedback loops that go through many thousands of variables. You can capture the same core ideas with dozens of variables. It makes analysis in other ways also simpler. If you're running a calibration and you need hundreds of millions of simulations, you can't do it in a model that has millions of variables in the first place. But you can easily do it in a model that has hundreds of variables or dozens of variables.

So aggregation level, there are good arguments to go in the more aggregate level. But there are also good arguments to go into the more detailed level. And that is not what typical system dynamics practitioners would recommend. But in many other fields, people are focused on, actually, let's go one level deeper in understanding the microstructures that generate the dynamics we care about.

Usually, the theoretical knowledge you have is more detailed. If you look at the physics of the problem, you know more about the next level of detail. And that sometimes means you have good data at lower level of aggregation. To utilize that data effectively, you benefit from disaggregation. If you aggregate, you are losing a lot of granularity in your data-- both quantitative data, but also qualitative data about how things actually work.

And sometimes, to enforce internal consistency, you actually need to go one level deeper. For example, if you skip pricing mechanisms in models of markets and try to just use supply and demand to balance each other without an explicit price, things get hard. It's not impossible. But internal consistency of that model is harder to maintain.

Sometimes, you benefit from it for having policy levers at the level of detail that actual decision makers care about. So if you aggregate a lot of things, the policy levers you have at that very aggregated level are different from what actually people on a day to day basis deal with.

So I'm telling all of those to highlight the fact that aggregation level is not an obvious choice. It actually needs to be a very conscious choice. I generally-- yeah, go ahead Sepideh.

AUDIENCE: I was wondering if the availability of data also affected aggregation level.

HAZHIR Absolutely. So that's one of the reasons-- typically, if you have very detailed data, especially if it is consistent--
RAHMANDAD: that is, across different sectors of the model, you can use the same kind of-- if you have individual level data panel, for example, if you build the model at the population level, you lose a lot of statistical power because you don't leverage the heterogeneity across agents in estimating your mechanisms.

It also means you are estimating mechanisms at a higher level of aggregation which are not the same as the lower individual level of aggregation, for example. So the definition of those effects are also qualitatively potentially different. Now, sometimes, they have a close matching with the lower level of aggregation coefficients. Sometimes, they don't.

So absolutely, data is one of the reasons. But there is always a trade-off. You go into more detail, it becomes harder to have the broad model boundary that we talked about as another important architectural choice. So there is no right answer. It is really your problem definition that determines the level of aggregation.

And as I mentioned, the big difference between very detailed operational models for operational decision making or even big one-time decisions is partly this issue, that you do need the additional detail, both to build confidence with your clients, but also to know that you have captured the key mechanisms at the right level.

Once you have a feel for your boundary of the model, another important architectural choice is the sources of inertia. That is, what are the factors that create inertia in your model, given the time horizon and the boundary of the model? So if I have a population sector, there are obvious choices for thinking about candidate stock variables that create the sources of inertia and so on. But thinking about that, again, helps you with clarifying your problem definition and why you want to include some stock or not.

OK. So that's a little bit of two approaches to tackling the big challenge of problem definitions that are unclear-- one starting with clarifying your problem definition. The other is thinking through your architectural choices. Alexander?

AUDIENCE: Just kind of stepping back, could you discuss when it's most appropriate to do dynamic modeling as opposed to econometrics or optimization?

HAZHIR So typically, when you're trying to understand how things changed over time or would change over time, that's
RAHMANDAD: where the feedback mechanisms become critical. And therefore, you can benefit from the tools that we deal with.

Now, the examples you gave, like econometrics modeling, is more the question of empirical grounding of the model that you're building. So there are questions about the assumptions that go into your model. So you could have models that, for example, are making the equilibrium assumption-- a stochastic equilibrium assumption, but they are still based on the equilibrium assumption. So they are interested in the long-term regularities or the forces that create those long-term regularities inside the system.

And typical dynamic models care about capturing the transitions between those long-term equilibrium levels as well. So they would have the equilibriums built into them. Otherwise, the model wouldn't work. But also, you care about the dynamics, the transients, the challenges of moving from the current position to another position. So that's the key difference.

Now, there is another difference. That is, your assumption about actors in the system also makes some variants of modeling approaches. So in system dynamics, we typically think about actors that are behaviorally realistic-- now, that is a very vague term. What exactly does that mean? You need to define it-- versus actors that are always rational in optimizing something very clearly.

Now, it doesn't mean we should exclude rational actors from our modeling. In some cases, it is a good assumption. I'm right now building a model of cities. And I'm assuming firms are rational in how they decide to hire people and get capital because that's a much better approximation for my use case than an ad hoc behavioral heuristic.

But I'm comfortable with letting some other parts of the model not be following that rationality assumption. So that's how you think of actors in your model also impacts these choices and whether this is the right tool and right fit for you. We could talk more about it. But I think, in practice, the theory is harder to say without having concrete examples. So I think, when we go into examples, things become more clear.

OK. So the second big failure mode or challenge-- this one is not a failure mode. It's just you start and you don't know where to start. You just feel overwhelmed. You're staring at a blank screen and don't know how to add, what to add, how to go forward. And the major solution to it is this idea of iterating and adding structures in small chunks.

So typically, for a novice modeler, I would say, add a single stock variable. That is, after considering the sources of inertia and your architectural choices and problem definition, pretty important. Add that stock variable and think about its inflows and outflows or even if it needs both inflows and outflows. Maybe it just needs some adjustment towards some underlying level, underlying goal.

Put equations for that, analyze that component of the model, make sure you're understanding what is happening, whether it is a single stock or maybe just a couple of stocks that are coupled together. To analyze, you benefit from a few steps. For most model chunks, putting it in equilibrium is a good idea.

Now, there are some exceptions to this general comment. But putting that piece of model in equilibrium allows you to understand its behavior much faster, much more cleanly because you can give it a shock, step function, ramp function, pulse function and see how it behaves, whereas, if it is not in equilibrium, it is already having its own dynamics. And now, whatever you add to it is confounded with those transient dynamics. It is much harder mentally to separate those from each other.

And also, putting chunks of models in equilibrium will help you put your full model in equilibrium later on and do the same type of analysis, so you always have a model that can start from equilibrium. Not all models can be put in equilibrium analytically. When you have nonlinear relationships, sometimes you can solve that analytically. There are numerical methods for that. We can talk about it when we get into more challenging equilibrium questions, how to do that.

Then you want to analyze what is happening in your model. And analysis here has really three important steps. So you pick the behavior you're trying to explain. So I added a chunk. Maybe it's a stock management chunk. I put it in equilibrium. Now, I give it a shock. I add a step function into it. Or I add a ramp function into it, into the demand that is coming into the system, for example.

And I see that the model behaves in some way. Maybe it oscillates, maybe it grows, whatever is happening. You pick that behavior and come up with a hypothesis. Why do you think it is happening? Now, coming up with a hypothesis is not trivial. If you just look at your model and try to say, oh, I think it is because x, y, z, 99% you're wrong. So don't even go down that road. Start with causal tracing.

Now, there are other ways to come up with hypotheses. But I think the good old causal tracing is pretty good. It works well. So what is causal tracing? You're looking at this variable. You double click on it. You look at the things that are driving that variable. In Vensim, in other software, there is a graph option that shows all of the drivers of that variable.

So you go backwards and say, OK, among these three variables that are driving my core variable, which one is more clearly showing that same mode of behavior or driving that mode of behavior? Usually, one of them is a good candidate. And you can make that judgment call very easily mentally by just looking at it.

Then pick that variable and go backwards and pick that variable and go backwards. You do this. Usually, there are two outcomes out of this tracing process. Sometimes, you land on a feedback loop. That is, at some point, you go back to one of the variables that you already have traced. So then that creates a feedback loop that is a good candidate for explaining that mode of behavior.

Sometimes, it doesn't lead to a feedback loop. It just leads to an exogenous input coming into your model. It basically is telling you that the main driver of that mode of behavior is some exogenous thing. It might be the shock that you gave into exogenous demand that is primarily driving the behavior. So it is not boring, but not that groundbreaking as well.

So that becomes a hypothesis. So this is the critical step. People go up to this step. And then they say, oh OK, I figured it out. And then they go to the next step. And they already have lost the game. So at this step, you need to test that hypothesis. What is testing of the hypothesis?

So if I have come up with a feedback loop that I think explains that behavior, it means I need to go and disrupt that feedback loop without disrupting anything else in the system, without disrupting other important feedback loops, and see whether the behavior that I started with changes. That is at the heart of testing any hypothesis in the scientific method. You remove the causal factor and see whether the behavior changes.

If it does, it is good evidence in support of your hypothesis. Again, you can't be 100% sure. But it is good enough evidence that, at this point, for a pragmatic modeler, you can say, OK, let's assume this is a good explanation. If not, then you need another hypothesis. You need to go back to your causal tracing, see where the logic didn't work, come up-- there is perhaps another pathway that you missed and go through that.

So once you have done this for a couple of reference modes in the model, in the dynamics of the model, you should be able to feel comfortable that, OK, now, I understand my model. That's great. That's what you want to be, somebody who understands their model. But you, again, need to test that.

So testing that step is just change the model parameters, all model parameters. In Vensim, you have a single button. You click. It changes all of the model parameters by 10%. And it reports to you the behavior of various outcomes that you care about. You can define what is the outcome you care about.

Make predictions what will happen to those outcomes before doing this test, and then see whether your predictions are correct. That is, if I increase parameter x, whether my profits go up or come down. If your predictions are all correct, that means you have already built the intuition you want. If they are not largely correct, then it means you haven't done your homework completely yet.

So that's the process of analysis. It may sound a lot. It is not trivial. That's why, in the diagram I was showing you, about half of the time should go into analysis. The modeling part of putting equations is important. But if you don't do the analysis, your modeling will become slower and slower in every iteration because now you are seeing all kinds of weird behaviors you don't understand. And then you end up with other failure modes we'll talk about.

Any questions on this analysis process? This is very important. We will practice it. You will practice it every week. But this is a little bit of a high level description. We could go into details of it for specific applications. And folks online, please unmute yourself if you have any questions. If you want to join in and say anything, don't hesitate.

OK, so let me now bring the next three pieces together and just talk about those challenges and some of the ideas for tackling them all together because they are closely related. So aggregation choices, we talked about them. Bad aggregation choices mess up your modeling project quite significantly. And they are hard to reverse.

Once you have decided that I'm building a very aggregated model, going to a detailed individual level model, for example, will be basically building a new model. It's a new project. And so people have sunk cost fallacies. They wouldn't make that choice of changing architecture easily. So you may spend months on bad architecture. And then you just don't get what you want out of it.

A very common problem I see, at the level of formulation and the level of putting variables on the diagram, is unclear constructs, folks coming up with variables that they are not quite clear what exactly the definition is for themselves. So that's another common challenge. And then bad stock selection is also very common, very challenging. If you don't have the best stock variables, everything else falls apart in your modeling work.

So how can you tackle these challenges? So on the aggregation one, unfortunately, there are not many general rules. It is really problem specific. As I said, because of all the pros and cons of both aggregating and disaggregating, I'm not able to give you any general rules other than really think about it carefully.

So one of the very common failure modes that I have seen is system dynamicists, classical ones, would just pick a very aggregate level of analysis and don't consider alternatives and close the doors to a lot of benefits they may get from disaggregation for specific applications. And then that forms their whole modeling journeys.

And then you hear folks that are, for example, used to agent based modeling. And they see everything as, OK, I need to go model at the level of single individuals. So they miss opportunities to simplify their models significantly and benefit from aggregation. So the general failure mode you can avoid is to just think about this choice very explicitly. It's OK to be wrong. It's OK to be challenged with how to do it. But think about it at the very beginning of your modeling project.

Then stay consistent with your level of aggregation across different components of the models. As we go through these iterations, you add chunks to your models. If some chunks are at a very detailed level of aggregation and some chunks are very aggregate, things are probably going to be problematic for you. It's just coupling between these different levels of aggregation becomes hard.

You also don't benefit from the details. If you have part of a model that is very aggregate and, therefore, you think your level of confidence is whatever simulated plus and minus 50%, what's the point of optimizing another part of your model at the level of 1% variance if it interacts with a part that has so much uncertainty? It's just wasted modeling effort. So keeping things at the same level of aggregation avoids those types of wasted extra details.

And this is also a very common problem. So I do a lot of epidemiological modeling and read through these. So you see models that are so detailed they model every individual in the country and how they move around and so on and so forth. So that's very detailed level of aggregation.

And then they are missing huge feedback mechanisms about, for example, risk perceptions' impact on people's behavior. These are things that change behavior at the level of an order of magnitude. So if you're modeling the walking of people in the city, but missing a factor that is order of magnitude changing the dynamics, this is an unbalanced model. You're going to waste a lot of energy.

You may even get it published in *Science and Nature* because people get impressed by a detailed model-- many, many people, not everybody. But the actual insights that come out of that model are probably useless because you have spent so much time on things that ultimately are, on the margin, making no difference and have lost track of things that make a huge difference. So this is a very common type of a problem, largely because people haven't done that careful trade-off analysis-- what is in, what is out, what level of detail I need to have.

Usually, another thing that helps is to stay close to an actual case. That will help you with selecting the right variables. So this is more about the challenge of unclear and overlapping constructs. So if you have a case in mind, it will sharpen your thinking. It will allow you to say, OK, what I mean is, for example, how many other people you go and interact with in the community in my model of COVID-19 on a daily basis.

So by thinking about COVID-19, you can define your contact rate more clearly. You can say, OK, what do I mean by interact? I don't mean sending email. I mean physical contacts that are a few feet apart or less and so on. So you make the constructs much more clear when you think about a generic-- a specific case. Even if your model is going to be generic, having a specific case in mind really helps.

Another thing is not only define your variables clearly-- that is, have clear definitions-- but avoid conceptual overlaps. So if you have something about morale and something about job satisfaction and another variable related to motivation, you start to see these constructs that are overlapping conceptually. And they will mess up your model because you will start tracking the same underlying idea through different variables. You create these loops that are not exactly the same, but largely the same. And nobody can really figure out what is the clear way of modeling and bringing them together. So avoiding overlapping concepts is very important.

Then on the issues related to sources of inertia, stock selection, start with sources of inertia. And there are different ways to do that. We have talked about, in the basic course, about the snapshot test or freeze test. You just freeze the system or take a snapshot. What is observable? What is visible? Those are candidate stocks. But they are not always the right stock variables for your problem.

Another source of insight into sources of inertia is perception processes, where people are learning about some information. It takes time to adjust their perceptions, adjust their assessments, adjust their measurements. That's another source of stocks.

Any physical accumulation is typically a candidate, not necessarily the best one, but a candidate. Other settings give you common options. If you're modeling firms, you typically have people as employees or as customers. You have resources, whether it is in terms of machinery or money. And they give you stock and flow chains for how those resources are going through or products, how they are flowing through their system or tasks and projects. So you have good candidates to start with from your general knowledge of the space. So those are, again, good candidates.

You generate a bunch of candidate stock variables or sources of inertia, and then prioritize them. And then once you have a source of inertia, you prioritize it to be high level. For example, I have people in my model of the world. Then you need to define what are the good stock variables. And at that level, some of it is about the aggregation level. So you may disaggregate or not disaggregate. You need to make some conscious choices there.

But basically, pick the stock variables that are at the heart of those sources of inertia to the extent that you can. And then there is the MECE principle, mutually exclusive, collectively exhaustive principle, which can inform stock selection as well. So you want to stock variables that are mutually exclusive.

Two stocks should not be able to hold the same person or the same widget or the same dollar at the same time. They should be mutually exclusive. But also, collectively exhaustive-- that is, they should cover the space that you're trying to capture. If it is people in your company, whether they are rookies versus experienced, that's one way to cut them.

Whether they are based on their tenure, that's another way. Or based on their gender is another way. So what is relevant to your problem? But have that MECE principal. And in fact, the MECE principal, not as strictly, but qualitatively, is useful for thinking about other concepts as well. That is, when you have-- it avoids the overlap. So the MECE part-- the ME part is important for that.

AUDIENCE: I have a question on the level of aggregation. I think this came up almost a year ago in the same room in one of the lunch seminars. And the idea was, if we have a model, trying to build a model in one level of aggregation-- for example, in population-- and we're having issues with the formulation or with the decision of going with the flow or stratification between two different levels, for example, is it ever reasonable to build a toy model on an individual level aggregation, for example, just to resolve that issue without formulation, and then come back to that?

HAZHIR Yeah, absolutely. So that's quite a good idea, in some cases, when you don't know whether your aggregate approximation is a good approximation for the more detailed level of aggregation. So building a chunk toy model, making that comparison, and making sure you have a good approximation will allow you to stay at your higher level of aggregation, but being also cognizant of what the lower level dynamics entail.

There are also related ways that you can build more aggregate models by thinking about the individual level dynamics very explicitly. So we have a paper with Saeideh Fallah-Fini and colleagues, 2013, that formalizes that process. For example, if you want to look at weight dynamics in a population, you can use a model of individual weight dynamics, but then use that to derive the equations for the aggregate population level model explicitly. And so there are ways to make these even more formal, the connections between the level of aggregations, but not for every problem. Any other questions?

OK, last-- not last, but one before last is basically the problem with bad formulations. It's a very generic term. And therefore, there is no single answer. But there are some ideas that help you with building good formulations. Probably the most important one is do not innovate. There is a whole host of formulations out there. Use them.

Now, you may say, I don't know those good formulations. There are resources to actually pick them up, if you haven't already. I would say those folks in this class that you have already taken a course in system dynamics, you are familiar probably with 50% maybe more of standard formulations you could use in typical modeling challenges in this course and beyond.

For going to 70%-80%, you can use the molecules that have been built by the community. Mostly, Jim Hines has invested in creating a coherent taxonomy of these formulations. You can see a screenshot of it here. But it's available through Vensim. It's available through the sdmolecules.org website.

So basically, there are simple formulations. And it also has a hierarchy, logical hierarchy. It starts with a simple stock variable. And then a stock is the ancestor of a lot of different formulations. And you can see that ancestry. So proportional split, closing the gap, [? Bastof ?] is the stock. Those are the parents. And then you can see more and more complex items as you go down the-- let's look, for example.

Here, we have the Hines experience coflow. So you would go through that. That might be new for most of the folks here. If you look at that formulation, you wouldn't recognize it. But it comes from Hines coflow, which may still be new for you, which comes from first-order smooth that you most likely already know about.

So you may see that half of these things or more you already know. And then the new ones you can go through learning. And the way you would learn these molecules-- one way at least-- is, first, look at the causal diagram and write down the equations. Make sure you can write down the equations.

Try to guess-- if there are ones that you already know, you should be able to. That's the definition of knowing the molecule. If you don't know, if it's a new one, try to guess what would be the formulations. And then identify what are the key inputs and outputs. So think of each as a chunk of a model that can be plugged into any new modeling task.

So think, what are the pieces that are inputs-- that is, it should come from other chunks of your model-- and outputs-- that is, useful for other chunks of the models? And then there is a lot of things that don't usually interact with the rest of the model that's inherent to that piece, including a bunch of parameters. So know about those. Identify what's the meaning of those parameters.

Then think about where you can use this chunk, in what kind of applications you can use those. And finally, predict the behavior of this chunk for a few standard inputs-- pulse, step, ramp, maybe oscillatory inputs. So if you change the inputs into one of these, what would be the expected-- what is your expected outputs? See whether you get that expected output. You can easily just copy and paste any of these and build a simple model of that chunk, test it, make sure you internalize an intuition for those behaviors.

Because when you go into applying these molecules, you need to know what kind of behavior you expect to come out of each chunk of a molecule. If you don't have those intuitions, you don't really know what can be plugged into your model. And then you may end up thinking that, oh, maybe I should innovate and build a new structure. And that's a recipe for bad formulations.

I think, for this class, by the end of the semester, maybe one formulation you are allowed to innovate. The rest you should be able to get from existing structures. I mean, that's about right, I think. Honestly, really new formulations, they are things to celebrate. They are not easy to come by. If they are really solving a meaningful problem, they should be added to the molecules. They should have their own publication. And this is how things also happen. That is, good, new formulations are rare.

OK. So that's number 1 on the formulations, use existing ones. Replicating other classical models is another way to learn these formulations. And that's another good way of doing it. A few other tips is, when you want to build any chunk of a formulation, we are going through these iterations. So you have iteration 1. I have this stock. I'm trying to formulate its flow. I have identified some possible molecules that can be helpful for formulating it.

Think through what is the objective of that chunk, what are its inputs and outputs and how those inputs and outputs should be connected with each other. That's the objective of that chunk, is creating some outputs with respect to some typical inputs. What are the acceptable ranges for those inputs and outputs? Make sure you impose those acceptable ranges within your equations for the output. For the input, it should be imposed in whatever chunk is providing the input to this part of your model.

Then think about the regularities between inputs and outputs, whether they are the ones you want, whether it may do something weird, whether it is robust under extreme conditions. And then think about key mechanisms that this chunk is trying to capture. And do you have parameters that allow you to change the strength of those key mechanisms?

So this is one of the places where I usually try not to use table functions because they limit my flexibility for changing the strength of mechanisms. So if there are simple analytical functions, I usually go with those rather than table functions that are very flexible, but are not easy to change because, in your analysis, in your calibration, you will need to be able to change the strength of different mechanisms. So those are some ideas for, when you get into building a chunk, think through these pieces explicitly.

Then the other intuition is limit inputs to your formulations. Any single formulation equation, try to limit the number of inputs to three or fewer. What's the benefit of that? It helps you break down the logic in your model into smaller chunks that you can intuit and understand. It doesn't create surprises for you. It is easier to explain to others. You can look at those intermediate outcomes and diagnose when there is a problem. So they're all good reasons to limit the formulations to three or fewer.

Discrete formulations-- for our typical continuous time continuous state space, system dynamics models are usually not very helpful because they create discontinuities that are hard to trace in terms of the impact on the behavior of the system. They usually reflect discrete thinking as well. People use if/then/elses very freely to capture their first order thinking about the problem without really going through those items on the top of the list.

So to the extent possible-- now, sometimes, we do need min, max, and if. But generally, don't go with them as your first choice. And then ensuring unit consistency is probably the biggest, easiest thing you can do when you're building formulations. That's very simple, but very powerful.

And one last item that was on our list is the big challenge of chasing a desired behavior. So this is how we get our PhD students in their general exams into trouble. Basically, you want the model to behave in some way because that's the reference mode, typically. That's the motivating thing.

And then you are trying to get that behavior out of the model. But you don't know why the model is behaving the way it is behaving. So you end up changing the model parameters with the hope that it will work, it will give you the desired result. You do that for a while, usually to no avail.

Then you get frustrated. And you say, OK, it is missing some structure. So you add some additional structure to fix that problem. And now, you have even burdened yourself with an even more complex problem that you don't understand. And this is the most frustrating and the biggest hog of your time. Never go down this road.

If you want your model to behave in some way, you need to be able to basically set the parameters and it should behave the way you want it to because you have understood how the model behaves. You have gone through your analysis pieces. You know why it is behaving currently the way it does.

And then you can say, OK, this behavior is what I want or, oh, I want it to behave this way. It just means I go to parameter x and increase it or decrease it. And it will behave the way it should because I understand my model. So always go through understanding rather than any kind of a blind search in the parameter space. Never do that. It's very common. It never works.

OK, so that's that, I think, for our theoretical space. So let's see if there are questions. And then we can take a break and come back with the more practical looking at problems today together. Questions, thoughts?

Let's come back together. And folks online, please join us as well. OK. So for the remainder of the class-- I think we have an hour and 10 minutes or so-- we will be basically talking about architectural choices, but in the context of a couple of examples that hopefully you had a chance to look at those. We will bring them up on the screen as well.

So when I talk about architectural choices, basically, there is a set of interconnected questions. What's the problem definition and the audience for that problem definition? Who cares? Who are you trying to communicate with? Who are you trying to help or help them see the world a little bit differently?

Then what's a good time horizon for the problem? What are the mechanisms that should be included in the model? What's the boundary of the model? And what should be left out? Leaving things out is always important. Then the level of aggregation question. And finally, key sources of inertia and the stock variables.

So we have already gone through these. Now, let's go and practice them. You want to actually ask all of these questions for every modeling problem before you get started with putting structures on the Vensim or Stella or whatever your software package is.

So we are doing this for two problems today. And then hopefully, we'll have also a little bit of time talking about the next week's problem and maybe some of the architectural choices there. Although, most of them are already baked into the problem definition.

So the first one is the thoroughbred horse market. So most of these are coming from John Sterman's *Business Dynamics* textbook. I provided what you needed to learn about it in the problem definition PDF. But this is the story of thoroughbred horse market, the number of thoroughbreds born in the US. There are other reference modes in the problem definition that you have.

Basically, it went through a boom and bust of a sort. This market became very common for people, for very wealthy people, to try to have these racehorses. And then at some point, it crashed. And basically, John uses this as an example to put flesh on the idea of bubbles.

So there's a generic structure for bubbles, where people's demand for whatever they are looking at goes up because it is becoming more expensive and because they think there is room for growth. So you can think about Bitcoin's bubbles and crash, goes up and crashes. And every five years, we have had one of these big. Right now, we are at the top of the current one. But at some point, probably this will also go through the same mode of behavior.

Either way, the thoroughbred horse market, then John goes through giving an answer to that challenge. So the challenge asks you to build a causal loop diagram. He builds a causal loop diagram in the reference manual for the class-- for the book. So this is the big picture of that. I think you have the PDFs. If this is not big enough, I think it's a little bit harder to read from the end of the room.

But the basic story here is you have-- let's see, yeah. So you can think of the thoroughbred prices, thoroughbred racehorses, prices as a central variable here. And then you can think about what is driving that. Well, it is largely the demand versus supply. So you need to then figure out where the demand and supply are coming from.

Supply is coming from breeders deciding whether they should invest into breeding and bringing in more horses. And there are delays, biological delays in horses coming to-- basically being born and being raised to the age that they can be in the market.

There is also the expectation formation for what the price in future would be. So that expectation formation depends on the price itself. So there is a process for modeling or thinking about how the expectations are formed about future prices. There is an extrapolation process. And that future price expectations also impacts what people expect in terms of capital gains from having these horses that are appreciating in price, so you can actually sell them later and make money, not only from what you earn when they win races-- and some of them win races. And there is an active winning market for it. And that increases earnings. But also, there is the expected gains.

And then as the prices go up, there is a status value associated with owning a racehorse. And that is another source of the demand. And in fact, some of the people, because they have multiple racehorses that are now very expensive, they may actually feel they are in a whole different category. And so that creates another source of pressure on demand.

So those are the core mechanisms here. And so let's say we have the mechanism. So this is the boundary of the model. In a sense, we don't want to go beyond this boundary, add other structures that are relevant. For any real problem definition, we would actually need to consider what else is important and whether all of these things are important. But for now, let's just stick with that and think about audiences.

So who would be an audience for this problem? And there is no single correct answer. But I'm curious. So share your thoughts on who would be a good audience. And then based on that, what would be the right problem definition for them? It's open. I'm not going to talk more. Oriana?

AUDIENCE: Maybe one group could actually be high net worth individuals who would be interested in having horses or a variety of other types of investments like this, whether it's fine art or wines, like you mentioned.

HAZHIR Yeah.

RAHMANDAD:

STUDENT: In which case, sorry, you should probably be tracking prices and time horizon. Well, actually, I guess my concern, my question with time horizon is, what set off the bubble? Because it seems like it was in some level of equilibrium and closed off within very high net worth individuals until the Inflation problem made people who probably shouldn't have been in there to begin with think it was an inflation hedge. So you got an excess of people into the thoroughbred industry. So I guess, I'm a little confused about time horizon because it seems more of a response to some external shock rather than a completely inside model behavior.

HAZHIR Interesting. Yeah, so for bubble models, when they pop is usually a mix of endogenous dynamics that has made things too inflated. And people who are looking at the fundamentals cannot justify it, and then an external trigger, that kind of changes the minds of enough people on the margin that they decide to get out of the market. That puts a downward pressure on the price.

And as soon as the price starts to slow down or come down, things will go awry in the opposite direction, bring down the market. So that, as you say, is not predictable because those external shocks may come at times that are not in your model boundary.

But for the time horizon, you don't need to worry too much about those. You want to have long enough time horizon that captures the underlying pressures inside the system that could ultimately lead to a collapse, even without this external popping of the market. So external shocks can bring it forward or sometimes delay it because they make the space very attractive, even though the underlying fundamentals don't justify it.

So with that, net worth individuals as you client, high net worth individuals, good. What's the problem for them? Should they invest or not? Something along those lines. So you are helping somebody make decisions on investment. That's one audience that is different, for example, from I want to publish a paper in a sociology journal about dynamics of bubbles in luxury goods. The two have overlapping-- in fact, they may both start with this diagram. But they are two different audiences who require different levels of rigor.

So if we had these two different audiences, a sociology journal versus a high net worth individual who is interested in figuring out what to do in this market, whether to get in or get out, how would that impact your architectural choices? Any thoughts? What are the requirements that come with these two different audiences? Alexander has his hand is kind of--

AUDIENCE: I think, for the sociology journal, that's more of a theory building paper. And so I think it's better for the model to be simpler and not necessarily exactly calibrated to data, just as long as it corresponds to it. So it's more easily understandable by an audience that doesn't have a modeling background, typically. And then I think, on the other hand, if you're trying to suggest prices, you probably want to have much better calibration with the data.

You probably want to have a deeper level of aggregation. Maybe there's different types of investors. Maybe there's different types of readers and so on. And so that way, you can maybe not-- maybe it would be difficult to predict. But you could have a much better idea of what the trajectory of these prices and such will be.

HAZHIR
RAHMANDAD: Yep. So those are very important distinctions. So definitely, if you go with a sociology journal, the purpose of the model is actually building intuition and communicating it with high bandwidth clarity. That means very simple model, just qualitative mechanisms at a high level, nothing beyond this level in terms of the qualitative model. And then the quantitative model should not have more complexity conceptually than this. And the level of aggregation should be high and so on.

Whereas, if you are helping a high net worth individual make actual decisions with million dollar investments in this space, then you need good calibration, some additional details. You need a lot of actually external inputs into your model-- that is, things that are not fully endogenous-- because real world doesn't work only with endogenous dynamics we know about and care about in theoretical modeling, but also is driven by a lot of shocks from the general economy.

In this case, it makes a big difference. The stock market makes a big difference. Interest rates make a difference. And you may need to trace down and see what is the stock of breeding horses that are in different parts of the country, how many breeders are active. So you may need to collect additional data. Your level of aggregation probably goes at least one level deeper.

So the audience matters, even if you are just sticking with the same qualitative diagram. The time horizon actually could also vary. That is, for your generic model, would it be longer or shorter?

AUDIENCE: [INAUDIBLE]

HAZHIR Why?

RAHMANDAD:

AUDIENCE: [INAUDIBLE] to witness different types of dynamics that can arise from the structure [INAUDIBLE].

HAZHIR Yeah, absolutely. So the theoretical model actually typically benefits from a longer time horizon. You want to see

RAHMANDAD: all of the implications play out. If you're capturing a feedback mechanism, you need to show them that it has an impact. So that's the reason.

On the other hand, for the investment decision, ultimately, your horizon for decision is the next year or so. Now, you are also thinking about longer term risks. So do I stay or do I leave the market? And so maybe a few more years in the future. But projections beyond that are not relevant for your current investment decision. But you actually need to continuously feed data to calibrate the model, as long as you are in this market or considering this market, to always have a good one year ahead projection of what are the opportunities and risks. And that's a different time horizon, both backward looking and forward looking.

So level of aggregation we talked about a little bit. Now, if we want to go into the question of stocks and sources of inertia, sources of inertia, we could talk about, for both of these potential clients, with similar answers. But when we get into stocks, it really makes a difference which one we want to focus on.

So let's talk about sources of inertia. Actually, for this, maybe it's a good idea that you do it independently for maybe five minutes. What you want to do is to identify sources of inertia that are important, and then prioritize them. That is, if you were going through the iterations of model, analyze, model, analyze that we talked about, which ones would you think are the most important and which ones would be secondary and tertiary?

It doesn't necessarily mean you will always tackle the most important first because it also partly is determined by how comfortable you are modeling those chunks. You usually want to start with the things that are easier for you to model. You know how to model those. So put that aside right now. Just focus on the importance in terms of the underlying dynamics.

If you care about the audience, let's be more inclined towards the theoretical sociological journal audience than the net high worths-- high net worth individual clients that we hypothesized. OK, so five minutes on that. Then we'll get your thoughts and input on that.

Let's start thinking about these together now. So maybe we can reach out to folks online and see if anybody online wants to share their thoughts on important sources of inertia here. You can volunteer yourself, just unmute and say, whoever.

AUDIENCE: I think one of the sources of inertia is between when they decide to breed the horse and when the horse can actually go to the market.

HAZHIR OK. So basically, horse maturity delay, something along those lines. OK, good. What else?

RAHMANDAD:

AUDIENCE: I was thinking about prices, demand and supply. But now, I'm thinking maybe I don't understand the clear difference between sources of inertia and stocks.

HAZHIR OK, good. So sources of inertia are a little bit higher level. That is, you may say, within the space of supply, I see

RAHMANDAD: the biological processes related to horses getting pregnant and having children. I don't know. I'm not using the right terminology.

AUDIENCE: Calves.

HAZHIR Calves, yes, is the right-- is important. So that's kind of-- and then you can go into the specific stocks, if you

RAHMANDAD: wanted to capture that source of inertia. So the source of inertia is a little bit higher level and a little bit more vague. So you may say, in the demand, I think there is some perception processes that are important to be captured or something like that.

I'm just breaking the process into two steps with sources of inertia and the stocks because, depending on the audience, the level of aggregation at which we model any of these sources of inertia could be different. So go ahead with that.

AUDIENCE: That's good to know. Maybe that they're [INAUDIBLE].

HAZHIR Status that is attributed? OK, good. Other sources of inertia? Anybody anywhere?

RAHMANDAD:

AUDIENCE: Probably the dominance of speculative demand over value based demand, so that whole loop thing.

HAZHIR So where is the source of inertia within-- because there is this trade-off.

RAHMANDAD:

AUDIENCE: The recent rates of price change.

HAZHIR OK, something about-- yes, perceptions of price change. Good. So that would be a space with clear inertia.

RAHMANDAD:

AUDIENCE: Maybe a smaller perception inertia-- Perception of gains, net value gains of [INAUDIBLE].

HAZHIR Yes, so winning expected, yep. Alexander?

RAHMANDAD:

AUDIENCE: The perceptions of price change might actually differ between buyers of horses and the breeders. Maybe the breeders are much more risk averse and take longer to adjust their perception.

HAZHIR Interesting. So breeders versus buyers. OK. And this is actually getting us closer to the stocks, which is fine.

RAHMANDAD: There is really a continuum going from sources of inertia to the stocks. What else might be relevant here? Alban?

AUDIENCE: There can have decision-making processes that also add inertia.

HAZHIR So the delays in decision making processes. Now, you could, again, do the decisions. Which decision we have in

RAHMANDAD: mind may have some differences. It's breeding decision, investment, leaving the market. So they are different. What else? I'm surprised. There is at least one very big source of inertia that we don't have on the screen at least. What is this market about?

AUDIENCE: [INAUDIBLE]

HAZHIR Yeah, so we need something about horses. We have the maturity. That's good. So that's the calves growing up.

RAHMANDAD: But the horses that are active in the market, the current horses are a pretty big part of the dynamics, if you don't have that.

AUDIENCE: [INAUDIBLE] from the previous explanation of the difference between sources of inertia and [INAUDIBLE] because all of these are almost very simple [INAUDIBLE] a broader idea.

HAZHIR Good. So it is OK to-- so right now, I have horses in the market. So that's a source of inertia. You can think of it as

RAHMANDAD: a single stock. But you could actually break it down based on age or based on the capability of the horse or based on-- so those decisions determine the exact stocks you would have. And that's where the difference becomes more clear.

AUDIENCE: Is it because you could break down thoroughbred supply?

HAZHIR For example.

RAHMANDAD:

AUDIENCE: Then it's allowed to be a source of inertia and not just a stock.

HAZHIR Yes. So thoroughbreds supply-- the word supply is a little bit ambiguous. Do you mean the horses that are now

RAHMANDAD: on the market for sales? Or is it actually all of the horses in the stock of all of the horses or a specific age group? So as such, I'm OK with thoroughbred supply-- somebody comes and tells me thoroughbreds supply is the source of inertia. I wouldn't say it is wrong. But I would say I like a little bit more clarity on what you have in mind. If you bring that as a stock, I would say, no, it's not going to work as a stock. It's going to be too confusing. The definition is not clear. We need a more clear definition to get it in place. Anything else?

AUDIENCE: Can I ask a quick question?

HAZHIR Sure, please.

RAHMANDAD:

AUDIENCE: Yep. So right now, we have a causal loop diagram. And that's what we're using to think about sources of inertia. But at what stage in the modeling process are you supposed to do this? Is it at the problem definition stage? Or would you have already thought about variables and causal loop diagrams? It seems to me that we should have thought about this before.

HAZHIR So in the stage that you are building causal loop diagrams, sometimes it is helpful to think about sources of

RAHMANDAD: inertia and stocks, especially when the problems are very physics based. So if I'm building a model of supply chains, I actually prefer to start with clear stocks that I'm thinking about. In my causal loop diagram, I may put stocks and flows in the causal loop diagram in the first place.

For this problem, I don't see the stocks as indispensable for the early stage conceptualization. So in building the causal loop diagram, I'm very comfortable not worrying too much about the stocks yet and bringing them on when I get into the quantitative modeling or thinking about conceptualizing the quantitative model in the state.

Here, we skipped all of the causal loop diagram, qualitative modeling. We didn't talk about boundary. We didn't talk about these mechanisms where did they come from. We took them for granted and started from that point. In an actual modeling exercise, you actually have to go through the whole process of building these. And it is not an easy process. But it is an easier process compared to building the quantitative model, in most cases.

OK, any other sources of inertia? And we could actually start now shifting into discussing the stocks. So with these sources of inertia in mind-- and as we break them down, we could actually-- now, we go into stock variables, if you want. Now, for this, we need a clear audience. We can't continue discussing this without having an audience in mind.

Let's focus, for now, on the theoretical model for a sociology journal, just in the interest of time and level of detail that we can manage right now. So with that, come up with the stocks. And we can add those stocks in the same diagram, in the same list. Basically, under each of these, we could come up with stocks that we think are helpful. So for horse maturity delay, what would be the right stock or stocks?

AUDIENCE: [INAUDIBLE]

HAZHIR Can you speak up? Yeah, Maria?

RAHMANDAD:

AUDIENCE: A population model for the horses

HAZHIR OK.

RAHMANDAD:

AUDIENCE: Maybe we want to separate the females [INAUDIBLE] and then also by age.

HAZHIR Very good. So probably, you could actually use a stock and flow chain for horses that is separated by age-- that's
RAHMANDAD: pretty useful to have-- and by male versus female. So that's probably also relevant, especially on the breeding side of the story. I'm not sure if it matters as much about racing. I'm not an expert in the horse racing.

So now, let's think about that stock and flow chain. I think that's useful because we are talking about horses. We need a stock and flow of horses. So what's a good level of breaking this down for the audience that we talked about? That is, a sociology journal. How would you break it down? Jason, what are you thinking?

AUDIENCE: I don't know about horses, but one useful separation might be horses for racing, and then horses for breeding if they age into that or the other way around. I wouldn't go much more disaggregate than that for a general insights model. Even separating by gender might be too much, and then having to capture the pairing process, unless it's important for the dynamics of speculation we're trying to capture. So assuming gender isn't important for that, I would say just a one or two-stock aging chain might be enough.

HAZHIR Jake, you wanted to add something?

RAHMANDAD:

AUDIENCE: I was just going to explicitly say [INAUDIBLE] juvenile stage [INAUDIBLE] retirement stage.

HAZHIR Very good. So basically, you are speculating three stocks-- juvenile, racing age, and retirement age of sorts. In

RAHMANDAD: fact, it's not obvious right now how much that retirement age stock is critical for the dynamics because it probably doesn't play a big role in the price speculation parts.

It may play a role in the breeding part of the story. That's an interesting question. Where you put the thresholds, I don't know what's the right choice there. But I like the more aggregate version for a model for a theoretical sociology journal. You can't afford to have too many stocks.

So if you can bring down the stocks of horses to two-- that is, horses that are juvenile versus horses that are in the racing age, adult or whatever you call it-- that's probably all you need. Male versus female, important for a more detailed model, not that important here.

There is an issue. When you have some horse in the breeding stock, they are not racing. So there is an impact on that market. But that impact is in the months range, in terms of its time constant. So you could use a fraction of the total horses in their prime age that is allocated to breeding. That fraction, by definition, cannot be more than 50%.

But then that allows you to capture what is the number of horses that are in the racing market and what are the number of horses that are used for breeding, which you do need for calculating breeding rates and the inflow into this stock and flow chain.

So for that audience, you can see really a couple of stocks might be all you need. Maybe even somebody would go with a single stock. Because of the delays involved and the importance of those delays in the supply side, I would not go into a single stock. I'll keep a separate one.

AUDIENCE: Just a question that popped up when you were talking about including a parameter to exclude some fractions for breeding-- what kind of thought process would go into deciding whether that's going to be a parameter or something you choose endogenously?

HAZHIR Very good question. So this is an architectural choice I'm now imposing here on my thinking. And that's not an

RAHMANDAD: obvious architectural choice. The choice is we could have a separate stock for horses that are in the breeding stock versus horses that are not. And then horses can go there. And once you're in the breeding stock-- this is for mares-- it would be a few months that you wouldn't be racing. And at the end of that, you can come back into the racing stock or remain and go back to the breeding stock again.

The choice there for me is how fast those dynamics are. So if the time horizon we are looking at is about 20 years for this market to unfold completely, a few months' delays here is not as big of a deal. So I feel comfortable regulating that with an auxiliary variable that can go up and down relatively fast because that auxiliary variable-- that is, the breeding fraction-- is determined by a lot of other things about perceptions of whether, in future, it will be a good market to invest in and so on.

So with that in mind, I am OK with making it determined by an auxiliary variable, keeping in mind that I have other delays in the perception and decision making process that can carry some of that inertia for me. So I don't need to explicitly capture that. So this is how you think about it.

That is, OK, in this case, this auxiliary variable, yeah time constant of months is not irrelevant. It is potentially relevant. But it can already be captured in some other delays to some extent about how breeders update their perception. So their decision has its own inertia. I don't need a separate stock for it. That's how I'm thinking about it. Good. So that's for a stock and flow of horses. Other stocks?

AUDIENCE: Expected price, yeah, over some expected future price.

HAZHIR Yeah. So basically, you need stocks for capturing price expectation formation. Now, if you are familiar with trend
RAHMANDAD: function or variants of that, you would even know exactly what chunks, what molecule will fit here in your modeling. And using that, you can actually say, OK, this is a trend function. It just tracks What's the rate of growth in the underlying concept-- in this case, the underlying concept being the price. And the rate of change in price, in this case, would be determined by-- I mean, that rate of change requires usually two stock variables to get it well.

You could go with one stock variable as well. But then it is not the best, cleanest formulation. So that's a couple of stocks. But because it is a very standard formulation, you don't need to worry about explaining it to the audiences. So I'm not too worried about adding two stocks here for a trend function because you just say, I'm looking at the trend of this underlying thing and everybody follows what's happening. Good. Other things that might be relevant?

AUDIENCE: [INAUDIBLE]

HAZHIR Something about the status. So these status perceptions, they have big lags. They move relatively slowly. So I
RAHMANDAD: would definitely have at least one stock and probably just one stock for this level of detail, not anymore, and a status value that is ascribed to having a thoroughbred horse.

Now, the status, we need to be a little bit careful about this definition as well because it's not a very well defined thing. And later on, I'll need to use the status signal to calculate something about demand or drive demand or put a pressure on demand. For now, I would call it a single stock.

But I also would have this worry in the back of my mind. How do I want to make this very qualitative, underdefined concept-- how do I turn it into something that plugs into my demand function? That, I don't have right now a solution for it, just by quick look at it. I need to think more clearly about the formulations. But that's not a problem to solve right now. It's OK to leave that a little bit ambiguous.

AUDIENCE: So just going back to the idea of using stocks for the trend in price, just as a question on presentation, obviously sociologists, in this case, would be able to follow what a trend is. But they probably wouldn't know the math behind us calculating this. So would you put the math in the main paper? Or would you have it in the appendix? Would you just say [INAUDIBLE]?

HAZHIR Yes. So for this, I would say, trend function, Sterman 2000 or whatever is the reference I want to use. And then I
RAHMANDAD: would have a technical appendix that is online and has all of the model equations. So it's fully documented. You also would include your actual simulation model with replication instructions. So that way, the people who are interested in the details can check it out and figure it out. But you are not wasting time and also creating more confusion and questions within the text of your paper.

OK, so I think those actually are probably covering the most important pieces. There is a question on the price itself. That is, when I'm thinking of formulating price, the most standard formulation of price has a stock in it, which is basically its current price as a stock. And then the indicated price changes based on the pressures of supply and demand.

And if you have more demand than currently there are horses-- and right now, I now know what is supply. I have the horses that are in the market and perhaps with an adjustment for the supply chain-- that is, the juvenile horses, the calves added to it. That gives me the expected supply in the marketplace that may put pressure on the price.

And then the demand side is less clear. Right now, I don't have a clear formulation for that. But usually, to formulate that, I would also think about one of these anchor and adjustment types of things. That is, this demand is coming from what? From a lot of qualitative factors about status, about expected growth in the prices, and so on.

So I can create a stock variable that is the anchor for the demand. And it adjusts towards these forces. That is, the status can push this demand up. The increasing trend in price can push this demand up, but also can bring it down. So that way, there would be another stock for modeling the demand. But that is a little bit less clear looking at this diagram. It is a choice about how I model demand that will determine that stock. So you may not know about it until you get into the modeling of demand. And you say, oh OK, the best way to model demand here would be an anchor and adjustment type of a formulation.

AUDIENCE: What about something about the money available for investing in horses?

HAZHIR Yes. So the money available is actually a physical thing. It's a good candidate for a stock. Money has the features
RAHMANDAD: of stock variables. But in these dynamics, we should ask, does it make a big difference? And it would have made a difference if this was the only good that people were investing in and trading. And therefore, they might put all of their savings or not.

But for the market we are looking at, the money that goes into the racing horses is tiny compared to the overall investments in this market. So I wouldn't be worried about money becoming a binding constraint in any of these interactions. So I would just leave that out. I'm not worried about that.

AUDIENCE: I feel like, I mean, something that I was thinking of is, would you want to have a stock between people who are currently owners of horses and those who are not but are considering it? And then you have word of mouth effect that the status propagates to the people who don't have horses.

HAZHIR So that's a good question. The way I'm thinking about that is demand is essentially that population. So if I'm
RAHMANDAD: modeling demand as number of people who have horses or own horses or want to own horses or something like that, it will be-- because the horses that are owned are already in the stock and flow for ourselves. So we don't need a separate thing for it. The number of people who want to have horses becomes the demand function.

Then there is the question do I want to capture the word of mouth type of dynamics here. I'm not seeing it in our diagram. There is a question of how fast people learn about the price changes. It's not hard to see that. Information is not the bottleneck in a sense here. That is, for people who might be into this, they probably will get their information if they want it. So the explicit word of mouth Bass diffusion type of thing is not, in my view, of high priority.

It's actually one of those structures that drives a strong behavior inside the model. So if you want to put a Bass diffusion type of model into your formulations, really think hard because it will take over a whole structure in terms of dynamics. And if it is not the right fit for that problem, it will take your dynamics and your modeling in a direction that you may not actually want. So Bass diffusion, very solid, interesting classical model, but it is not a hammer to use for every nail. You need to be using it carefully.

OK, so I think this is a good conversation for what time we have for the horse market. Let's switch to the next one, which is looking at congestion and transportation. So this model is looking at dynamics of congestion in an urban environment. So think of travel time as your measure of congestion, which impacts attractiveness of driving and pressure to reduce congestion.

It is driven by the capacity of highways and the volume of traffic. And then these generate a variety of loops. On the supply side of highway capacity, the pressure to reduce congestion may lead to road construction, increases highway capacity. And then travel time impacts attractiveness of driving. So if driving becomes more attractive, people take more trips per day. They take longer trips. They may reduce their usage of public transit.

And all of those have impacts. So the public transit ripple effects go through the revenue side, which may change the quality of the public transit network and its adequacy. And then on the other side, the traffic volume is driven by these factors that were affected by the attractiveness of driving, things like trips, number of trips, average length of trips, and cars that are in the region. So the buying of cars and is also captured in this diagram.

Size of the region may also expand as you have more highways. And that can create interesting dynamics in terms of adequacy of public transit versus this people moving further out and therefore needing more cars. So those are the basic stories captured in the causal loop diagram-- again, coming from John's textbook from chapter 5. This one is discussed in detail in the text. So you can just read those as well. But I summarize those discussions in the assignment.

So for this one, given the time, let's more quickly converge to the discussion of inertial forces. Specifically, again, we could go with different audiences and get very different answers to the questions of level of aggregation and relevant stocks. These are really important dynamics if you are building an operational model for managing transportation infrastructure in a city.

So there are people building these types of models with really high levels of detail. They go into building models of public transit system that models the number of stations, all of the details of how many cars you have, and that you have models of highway capacity that are not a single capacity, but you actually have a network, and how that network creates traffic times, because it is really a very complex problem.

So we could go into a lot of detail in that direction within the scope of this causal loop diagram. For most system dynamics types of models, that's too much detail if you are looking at dynamics that are longer term, in the order of 20, 30 years, which really shows off the trade off between public transit versus private transportation and the side effects of building roads and then having too much congestion. So those are the types of things that may be more interesting qualitatively.

So that is a more theoretical high level strategic choice, which would be still relevant, for example, for a city mayor to think about their 10-year planning, but not for the transit commissioner for their next year planning. So these are two different audiences. If your audience is the city mayor in their strategic thinking or a transportation journal's high level theoretical conversations, what would be the right inertial concepts and stocks? So let's take five minutes, think about it independently. And then we will bring it back together in the class.

OK. Let's go back online and get some input from folks online. Zakie, why don't you go first this time?

AUDIENCE: [INAUDIBLE] about, for example, the time to build a new road to be a source of inertia because it will be slow, you need some time to do that.

HAZHIR So the travel time? The time you're on the road?

RAHMANDAD:

AUDIENCE: No. No, I mean the time delay for building new roads.

HAZHIR Oh, OK. Yes, so construction delay. OK. Zakie, you started, but you didn't get a chance to continue. You're muted.

RAHMANDAD: Please unmute yourself first, yeah.

AUDIENCE: Um, I don't--

HAZHIR You don't have any good candidates yet? That's all right, no worries. Anne, do you want to share any candidates

RAHMANDAD: you have for sources of inertia here?

AUDIENCE: I was thinking about cultural and social preferences for driving over taking public transport.

HAZHIR So that's preference for driving. So this is an interesting variable. So within a 20-30 year period, it can change.

RAHMANDAD: That is, the underlying preferences of people would change. So this would become an important stock. If we were doing the commissioners of transportation discussion, we may not even capture this as a stock because the time constant for this is in the order of several years for the underlying preference to change.

And therefore, in a one to five-year planning period, you cannot count on enough cultural change to be meaningful, so you can use it as a parameter. So this is a way to think about what counts as a good stock or not or a good source of inertia really depends on the time horizon. So very good item to bring up. Great. Others? Anybody?

AUDIENCE: I guess highway capacity.

HAZHIR Highway capacity. Yeah, so that's a pretty physical, clear stock relevant to the dynamics. So we do want to have

RAHMANDAD: that.

AUDIENCE: Public transit capacity.

HAZHIR Public transit capacity as well.

RAHMANDAD:

AUDIENCE: I would say the urban versus suburban population and the movement between the two.

HAZHIR So something about where the houses are-- that is, how much of the population is in the urban versus suburban.

RAHMANDAD: And if you are going with this high level of aggregation model, in terms of stocks, you may just stick to two-- urban residents versus suburban residents in households, but yeah.

This is important because the preference to go to the suburban areas does depend to the highway capacity. It is an endogenous choice within the time horizon of a couple of decades. Again, for a three or four-year time horizon, it may not be as big a deal. But much of the transportation models don't explicitly model this feedback that people change their residence based on the transportation feedbacks. Good.

AUDIENCE: Besides highway capacity, we have the number of cars on the road.

HAZHIR Absolutely, so something about cars on the road, car ownership.

RAHMANDAD:

AUDIENCE: [INAUDIBLE]

HAZHIR So we have the capacity, but we don't have the rider. So there is this question of how the population is split

RAHMANDAD: between using public transit versus using private transportation. There is a question whether we want to think of that as a stock variable or not. It is not obvious.

So why is it not obvious? As a physical thing, yes, people in the trains are obviously a stock variable. But people in the trains today, their time constant is in minutes. It's not relevant for our dynamics. So it could easily be an auxiliary variable. So the question is, what is the source of inertia that is more longer term in the context of this choice of public versus private transit?

This is one of those places where you need to trace the source of inertia. Go always to the root of the source of inertia. So what is the source of inertia? One important source of inertia here is people's assessment perception of how good is public transit versus how good is private transit.

So if I have perception of quality of public transit and perception of driving time, travel time as the major driver of congestion, if I have those two, I have already captured the core driver of inertia in how people change their mode-- their usage of different modes of transportation.

So as such, I would be hesitant, for a simple model, to add another source of inertia for number of people who are using public transit, for example. This is actually a good conversation because this is not the most intuitive candidate stock. You would think of, OK, people on public transit, we're very intuitive. But it is not necessarily the right choice here. So let's add those perceived quality of public transit and congestion as important stocks.

Sepideh

AUDIENCE: I was wondering how you can measure the perceived quality of public transit.

HAZHIR Very good. So at this stage-- that is, deciding on good stock variables-- it is legitimate to not worry about it and
RAHMANDAD: say, I'll come back to it. But it is an important question. So thinking about this, I would think about some measure of time per mile of travel. That is, if I have a trip of typically one mile, what would be the time I need to be on the train and how much money it costs me.

And the money part is easier. It's out there as a parameter. So I would focus on the expected time, which includes the waiting for the trips, the potential for-- and then that is not all of the quality. Then you may adjust that based on physical quality-- how clean it is, how safe it is, and so on. So I would incorporate all of it into a single measure. So it would be normalized travel time, normalized for the quality of my time spent there, something along those lines.

AUDIENCE: So if for people who the audience of this model, maybe this is part of [INAUDIBLE] public transit cost or travel time is part of this perception for that.

HAZHIR Yes, so the perceived quality for a high level model should aggregate all of these components into a single
RAHMANDAD: construct. So that is why this conversation would be needed later on to how you operationalize it.

AUDIENCE: I have a question of sorts. Is it reasonable to assume the public transit fare is some sort of stock?

HAZHIR It is, but we don't need to worry about it too much unless we are trying to have a formulation that says public
RAHMANDAD: transit fare responds endogenously to what is happening in the rest of the model, which is part of it. So the fare increase feedback loop is exactly capturing that. So if you want to endogenize public transit fare, because it takes time, it is a negotiation process and so on, and it may actually be something that takes months to a year, then, yes, then it would be a good stock candidate. Yeah?

AUDIENCE: I don't know if it's important. But for example, also I was thinking about the time to improve the public transit capacity.

HAZHIR Yes, so the delays in PT construction delay needs something, exactly. Jake?

RAHMANDAD:

AUDIENCE: I feel like there's something-- I don't know exactly-- but something about transit volume per person because we have trips per day and average trip length up there, but we're not capturing that.

HAZHIR Yes. So once we have determined the total demand for transportation, which you get from the population stocks--
RAHMANDAD: so you need-- actually, those residents in suburban versus urban captures that. So you have the sources of inertia. Then you have the total demand for transit. Then you break it between public and private.

So all of those can be done without a stock. So you have the demand in place. You have also the capacity, which we have a stock for. And so then you can see how well that demand is served. It creates also crowding. It creates your revenues. All of those will be endogenously created. So I don't think we actually are missing something there.

AUDIENCE: [INAUDIBLE]

HAZHIR Demand, we have it. The stocks for demand are captured in the residents in that center of the city versus the
RAHMANDAD: suburbs. That's part of it, and then in their perceptions of the quality. So those together would allow you to calculate the demand explicitly. So that's how you go to the source of the inertia. Don't add more new variables. One more comment, and then--

AUDIENCE: There's a spatial element to this, which are hard to capture with our models. I don't know if we need it, but the geographic size of the catchment area.

HAZHIR Yeah, that's fair. And actually, that determines a bunch of parameters that translates how many people you have
RAHMANDAD: in suburban area into how much demand for traffic you have. So you could have the area of the city, in a sense, as a stock that expands. And then it changes those parameters endogenously through some function that is not trivial and it's nonlinear, but it can be done. Good. I think this is kind of a nice conversation about thinking about stocks. And hopefully, you can get some of these ideas into the next steps.

So next, week what we are doing is-- let me just quickly go through that-- is extending the SIR model. So SIR model, well known, I hope everybody is familiar with it. It is susceptible infectious recovered or removed. It goes back to the 1920s. Simple but very powerful model, also overlaps with the Bass diffusion model in many ways.

You're adding three things-- behavioral responses to risk-- that is, you have an ongoing epidemic. More death, as a result of the epidemic, leads to people staying home, reducing their interactions, becoming more cautious in terms of their interactions. Waning of immunity-- not waving, it should be waning.

Waning of immunity-- that is, people lose immunity after some time, when they get the disease. So once you have recovered from the disease, you wouldn't remain immune forever for many diseases. For some, you remain immune almost forever. But for COVID, for example, you don't. So it's good to have a case in mind. In this case, COVID-19 is a good example to keep in mind to inform your decision making.

And then vaccination, how would you capture vaccination? So there is more details on how to capture these or the assumptions you need to make and those judgment calls. So basically, you go through adding these three. And these are your three iterations-- add the first behavioral response, then the waning of immunity, then the vaccination.

In fact, for the part with the waning of immunity, if you want to challenge yourself, try to put that model not only in equilibrium, but also calculate some of the equilibrium features of the model if you felt comfortable. And it depends on how you formulate the behavioral response. Depending on the nonlinearity that you capture there, you may or may not be able to do that with the analytical equilibrium.

And then in terms of stocks and flows, the SIR parts are pretty well established. So there is no other stock that you need for that. But when you think about waning of immunity and other features that are introduced, there are additional architectural choices. And how can you keep it simple?

So for the audience in this case, again, this is a model that you could actually turn into a policy oriented or decision support oriented model with more details or keep it fairly aggregate for a more conceptual, insight based model. Go with the latter. Keep it as aggregate as you can, as long as you can address those requirements that are discussed in the exercise description.

So I think that's all we have time for today, except that if there are any questions, especially on minor clarifications or administrative items, let's get those addressed. And I think a couple of you still don't have video releases. If you can just sign those or let me know if you have a concern, we can figure that out. That would be great. And that's that. Any questions? OK. So then thank you, folks. Folks online, we'll see you next week. And have fun.