MEEM 3501
Product Realization I
HO3: Fundamentals of Modeling and Analysis — The System Concept

No man is an island entire of itself; every man is a piece of the Continent. John Donne (1572-1631), English poet.

The systems concept is one of the "great ideas" of mechanical engineering (and every other kind of engineering and science). It enables designers to deal with the complexity of real designs. It is a network of interconnected ideas:

> ***Idea 1: For specific modeling purposes, "things" can be isolated from the world by boundaries, and their important behaviors and relationships with the rest of the world identified.***

Donne was arguing for a richer view of the relationships among people — we naturally see ourselves as individuals, much less a part of humanity than a field is part of the land. But the boundaries around things form a spectrum of naturalness, from human skin and the surface of a car, through state borders and the boundaries of "the automotive transportation system", through the line we might draw around a mountain or a welded beam in a structure, to the boundaries of a stress element isolated within that beam.

The last example illustrates the power and difficulty of the system concept. Nothing except our purpose separates the stress element from the beam; its boundary is completely artificial. We also decide that the stresses imposed by the rest of the beam are its only important interactions with the world, ignoring heat flows and the gravitational attractions of the Earth and Arcturus. Of course, the stresses themselves are only *modeling abstractions*, the "reality" is only forces among electrons — or is it the exchange of virtual particles, or the interactions among quarks, or vibrations of "strings", or . . .? And certainly our stress analysis of the element ignores grain boundaries, etc. The fact is, we can never completely know the reality. We can only form more or less detailed models.

Because we so easily mentally isolate parts of the world, we often forget this is only a modeling strategy. The world is one piece. There are no "things" until we decide to see them as separate — no boundaries until we decide to draw them. This modeling strategy — predicting the important (to us) parts of the world's behavior by isolating some special parts of it — is so powerful that our ancestors acquired it long ago. Most mollusks certainly appear to simply react to stimuli, without forming concepts of "things". But there are octopi that build "houses" of stone, and it is hard to imagine them doing so without perceiving the stones as separate "things". And anyone who has owned a dog is quite sure that dogs recognize not only living things but emotional states.

In most engineering classes, students deal only with problems in which the boundaries have already been drawn. In all real design problems, designers must draw their own boundaries and decide what behaviors to analyze and for what interactions to design. Judgment in formulating systems is a key design skill.

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Exercise 1: *Drawing Boundaries and Identifying Interactions* — Suppose you were writing regulations for the Federal Aviation Administration on how many passengers an airplane could carry. You need to determine how much the average passenger weighs. Where would you draw the boundary around a passenger?

a. At the skin.
b. Around the clothes.
c. Around the clothes plus average carry-on baggage, purses, etc.

Idea 2: Behaviors and interactions can often be described by constitutive laws, states, boundary conditions and conservation laws.

The simplest models of objects are *static constitutive* laws/relations that require relationships among *boundary conditions*, or between boundary conditions and internal conditions. (I have generalized the term constitutive law from the commonly known example, Hooke's law: stress = strain · elastic modulus, $\sigma = \varepsilon \cdot E$.)

Exercise 2: *Static Constitutive Laws* — Match the purpose (question to be answered), the imaginary object being used as part of the model, and the appropriate equation. (Warning: the models provide only part of the answers to these questions.)

Purpose (question)?	**Object**	**Equation**
1. ____ How much force must the tank mounting bolts of the space shuttle endure?	a. Rope	w. $torque = \frac{voltage - speed \cdot K_1}{resistance} K_2$
2. ____ How much force is applied by the load to the winch of a crane?	b. Spring	x. $force = deflection \cdot stiffness$
3. ____ How far will a beam deflect if I stand on it?	c. Electric motor	y. $force = mass \cdot acceleration$
4. ____ Can this starter motor start this engine?	d. Point mass	z. *equal tension at each end*

More complex behavior models are *dynamic* and require knowledge of *states* and *conservation laws*. The state variables of an object describe its current condition, for example, its temperature or velocity. Conservation laws all say that the value of some state variable after a period of time equals the value at the start plus the amount that comes in minus the amount that goes out. For example, the rate of change in kinetic energy U_k of an isolated object equals the product of its velocity and the net force on it

$$\frac{\partial U_k}{\partial t} = \left(\sum \vec{f}\right) \cdot \frac{\partial \vec{x}}{\partial t}. \tag{1}$$

Exercise 3: *Conservation Laws* — Match the purpose, name of the law, and form of the equation.

Purpose (question)?	Law	Equation
1. ____ How much water is in a city water tank?	a. Conservation of energy	w. $mg\mu x = \frac{1}{2}mv^2$
2. ____ How far will a diving board deflect if I bounce on it, three feet in the air?	b. Conservation of mass	x. $mgh = \frac{1}{2}kx^2$
3. ____ If a 1500 kg car is traveling 60 miles per hour, how long (in secs) will it take to stop?	c. Conservation of momentum	y. $M = \int(\dot{m}_{in} - \dot{m}_{out})dt$
4. ____ If a 1500 kg car is traveling 60 miles per hour, how long (in feet) will it take to stop?	[redacted]	z. $mg\mu\Delta t = m\Delta v$

Incidentally, the static constitutive laws are often special cases of conservation laws.

> ***Idea 3: A system is a collection of systems, plus their interconnections, that we mentally isolate from the environment. We understand the whole system by establishing behavior laws for the sub-systems, and analyzing their important interactions.***

For example, if I am trying to determine how well a car will perform on a race track, I don't need to know the timing of the ignition spark. I need to know how much torque the engine produces at various speeds, how quickly it responds to throttle inputs, and how much it weighs. Later, I may want to think about the timing in order to improve the engine performance, which will improve the race performance. At that point, I am looking at the engine system, not the car/track system.

Exercise 4: *Interaction Types* — Match the appropriate connection types to the subsystem pair (there may be more than one).

Subsystem Pair	Connection Type
1. ____ engine, transmission	a. supplies information to
2. ____ bearing, shaft	b. locates
3. ____ pipeline, oil	c. supplier power to
4. ____ oxygen sensor, engine control computer	[redacted]

Notice what a wonderful trick we have discovered — the cure for the "I don't know where to start" syndrome. We can organize our design process "from the top down and the outside in". First, we isolate our problem. We look at its connections with its environment in order to formulate specifications. Then, we can break it into smaller problems, or "decompose" it. If those sub-problems are still too complicated, we can break them down again, watching carefully the connections between them, until we reach problems we can handle. Then, we can put the solutions together. Computer scientists call this approach "divide and conquer", or "recursion." But, there is a catch — the way we break down the problem determines the kinds of solutions we get.

Exercise 5: *The Trouble with Dividing* — If we divide an airplane design into fuselage, wings and tail, engines, and avionics, will we ever find a flying wing as a solution? (A flying wing is an airplane that doesn't have a body: the cockpit, cargo area, etc. are built into the wing. The B-2 stealth bomber is an example.)

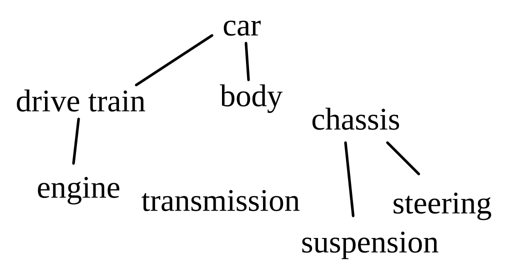
Yes No

Idea 4: We can show the connections among subsystems with outlines, connection graphs, and matrices.

Outlines are good for showing the connections between systems, subsystems, sub-subsystems, etc.

Exercise 6: *Outlines, Tree Graphs and System-Subsystem Connections* — Draw in the missing lines of the tree graph to the right so that it is equivalent to the outline to the left.

- car
  - body
  - chassis
    - suspension
    - steering
  - drive train
    - engine
    - transmission



There is a whole mathematical science of graphs. This is a “tree” graph because is has a “root” (the car: sorry that it is on top), and branches. The drive train is a “child” of the car. The words are “nodes”, and the lines are “edges” or “links”. One node of a tree has no “parent”; the rest have only one parent.

Matrices are good for showing connection graphs that are not trees, with more complicated interconnections. Graphs can have directions, and we can label the links to show what kind they are. But, if the links are of only one kind, and go both directions, then we don’t need arrowheads and labels.

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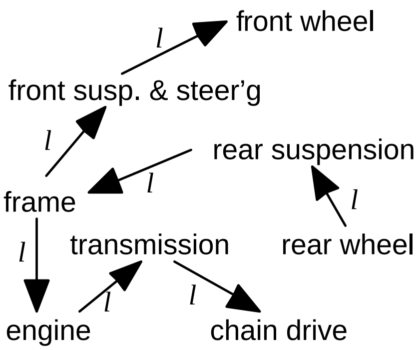
Exercise 7: *Matrices, Directed Graphs and Labeled Links* — Add arrows to the graph at right showing the flow of power through a motorcycle: the result should match the matrix at left.

component v **component >** **contacts**								
frame		*l*					*l*	
engine			*p,l*					
transmission				*p,l*				
chain drive						*p*		
rear suspension	*l*							
rear wheel					*l*			
front susp. & steer'g								*l*
front wheel								



p = transmits power to

l = locates

Note that if we just wanted to show connections, we could get rid of the labeling letters and the arrowheads, and put all the matrix entries in the upper (or lower) triangle.

Idea 5: We can model the design process as one in which we:

1. ***Separate the thing to be designed from the rest of the world.***
2. ***Understand its important interactions with the rest of the world.***
3. ***Generate ideas about what its main subsystems should be, and how they should be arranged.***
4. ***Pick such an arrangement.***
5. ***Design each of the subsystems in the same way.***

We will return to this model again.