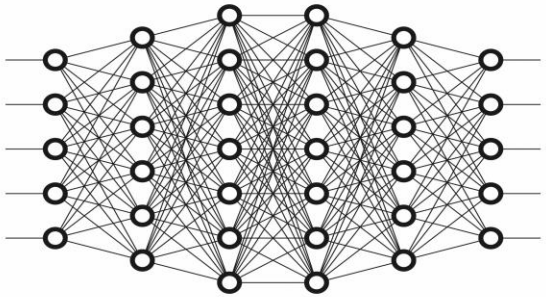
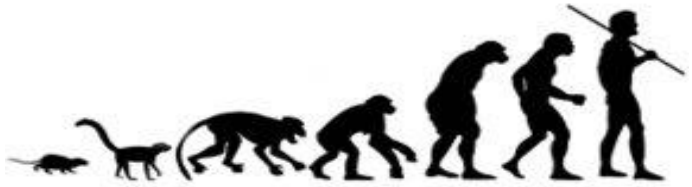
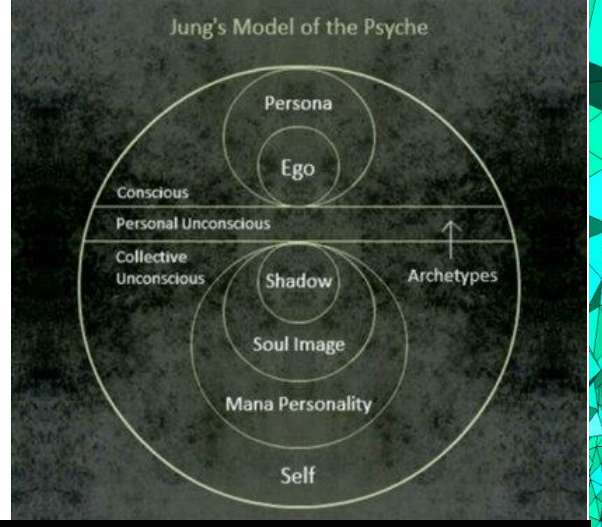
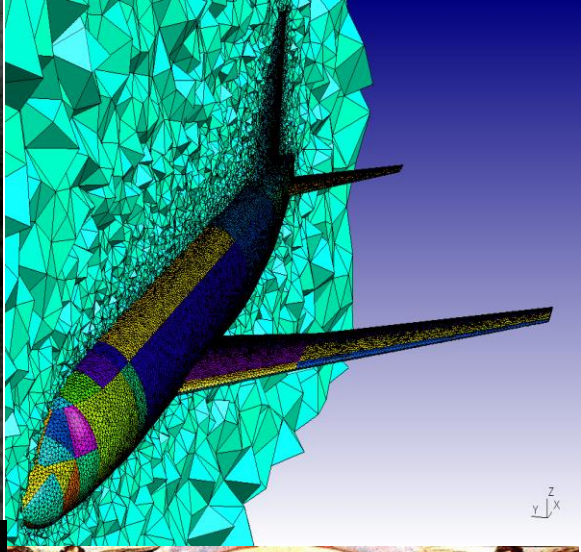
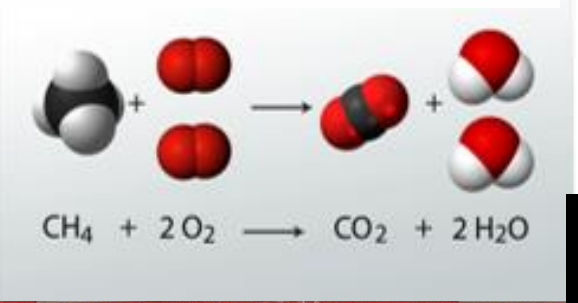




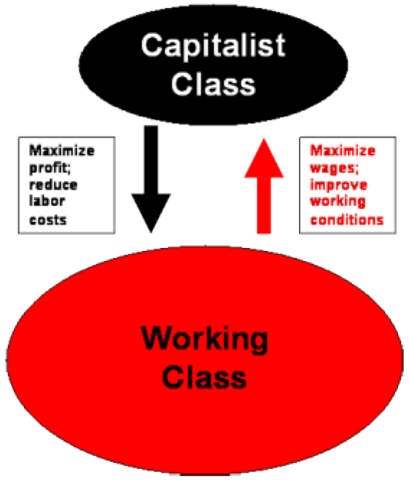




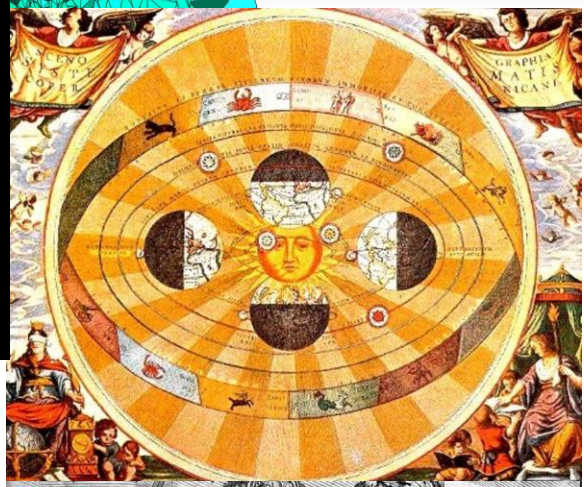


$$-\frac{\hbar^2}{2m}\nabla^2\psi + V(\boldsymbol{x})\psi = E\psi$$

What is a Model?

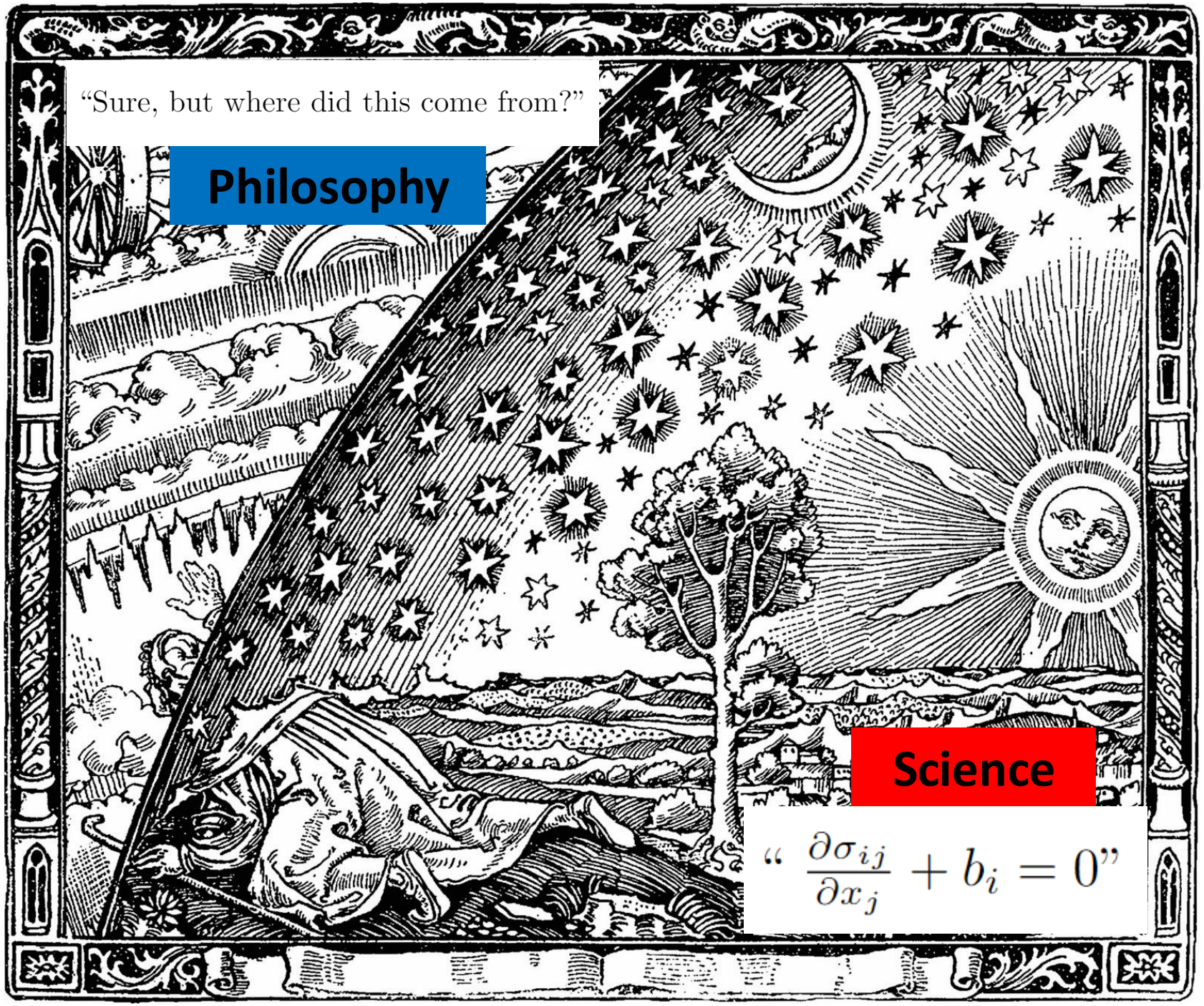


$$\sigma_{ij} = C_{ijkl}\epsilon_{kl}$$



Introduction

- Engineers in industry and academia use models all the time
- Models are used to understand and make quantitative predictions
- Can avoid experiments in the case of analysis, avoid trial-and-error in the case of design
- **How often we do think about what a model *really* is?**
- This question is straightforward from the perspective of engineering and science
- From an "outside" perspective, it is not so straightforward


"Sure, but where did this come from?"
Philosophy
Science
" $\frac{\partial \sigma_{ij}}{\partial x_j} + b_i = 0$ "

"Outside" Perspective Questions

- What defines a model? Are there different types?
- What are different models used for?
- How are they built? Are they invented or discovered?
- How is the goodness of a model assessed? Can a model be true?
- Can different models within a field be compared? Can models between fields be compared? If so, how?
- What is the difference between scientific models and non-scientific models?
- **Why has it taken most of human history to formulate scientific models?**

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Interdisciplinary Ethics Tech Competition

Event Summary

Held annually, the Interdisciplinary Ethics Tech Competition gives students a chance to wrestle with a real-world ethics problem in collaboration with a diverse team of students studying law, business, communication, journalism, engineering, ITP, information science, or computer science. Past case problems have featured a tech company grappling with ethical obligations related to its facial expression recognition product, and an online platform's efforts to address the challenges presented by "fake news."

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Herbst Program for Engineering, Ethics & Society

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Pursue answers to the great questions in an engineering context

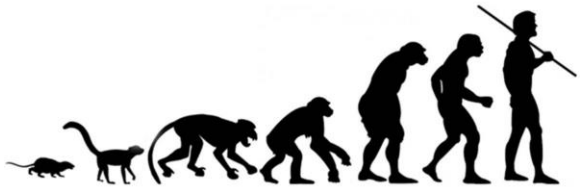
The Herbst Program for Engineering, Ethics & Society engages students with the essential questions of human existence, and links those issues with the ethical practices of science and engineering. As students read, watch and discuss great works of literature and film, they hone their critical thinking and communication skills—which are essential for tomorrow's professional engineers.

Our courses use foundational works of literature and film from various eras and cultures to address the complexities of the human condition, and find and develop meaning in the overlap between engineering, ethics and society.

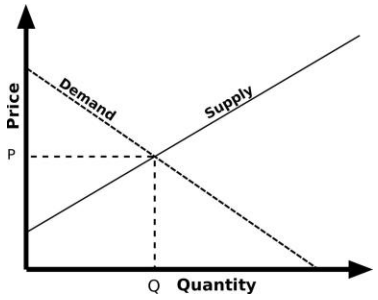
All Herbst Program courses count toward Humanities and Social Sciences requirements for students enrolled within the College of Engineering and Applied Science.

What is a Model?

- Want to consider myth, social science, psychology, biology, economics, chemistry, and physics all as dealing in models of different sorts
- Will use terms "model" and "theory" interchangeably
- **A model is a conscious or unconscious conceptual framework used to accomplish a goal**
- **Represents phenomena at some level of approximation, reduces complexity, endows the world with a sense of predictability, structure, meaning**
- Myths were human's original models of the world; not clear they had same goals as modern science
- Models exist in our minds, cultures, writing, etc.
- Consider models existing on spectrum of "scientificness"



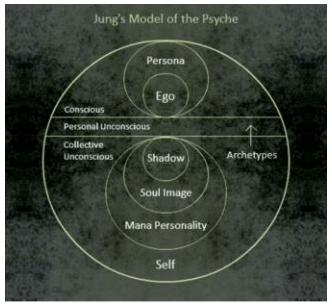
Darwinian evolution



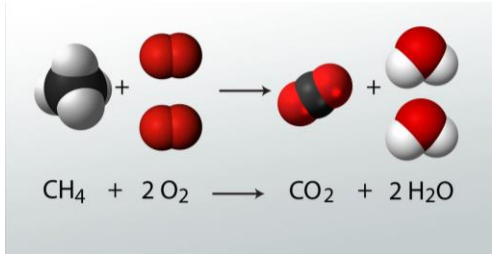
economics

$$\sigma_{ij} = C_{ijk\ell}\epsilon_{k\ell}$$

linear elasticity



Jungian psychology



chemistry

Religion

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V(\boldsymbol{x})\psi = E\psi$$

quantum mechanics

Less scientific

↑ scientific = ↑ experimentally validated, ↑ quantitative, ↑ predictive, ↓ simplifications, approximations or assumptions

More scientific

Models are Goal-Oriented

"But in point of epistemological footing the physical objects and the gods differ only in degree and not in kind. Both sorts of entities enter our conception only as cultural posits. The myth of physical objects is epistemologically superior to most in that it has proved more efficacious than other myths as a device for working manageable structure into the flux of experience."

— *Two Dogmas of Empiricism*, W.V. Quine

Unconscious Models

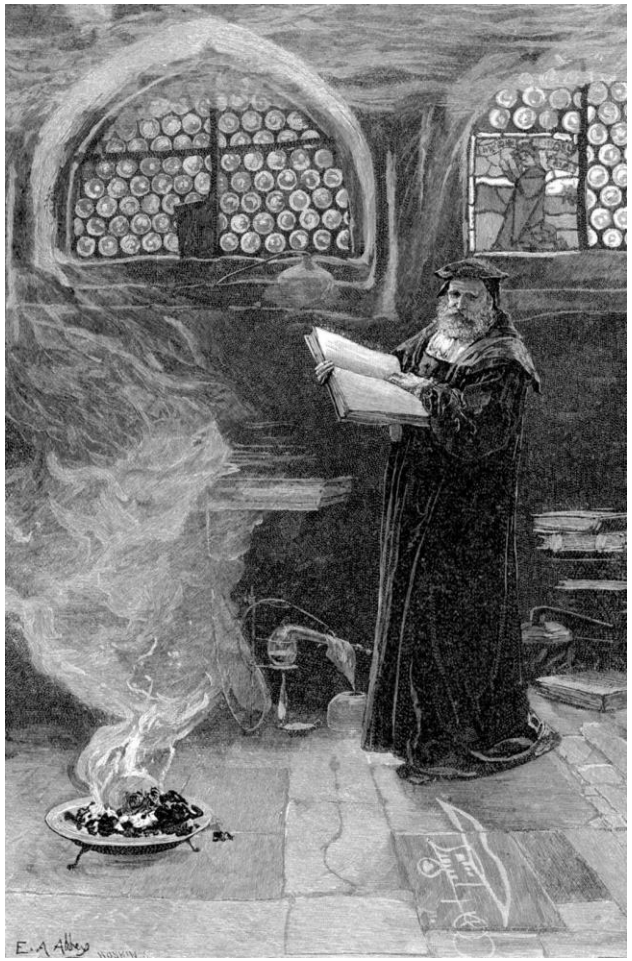
- To explore how many hardwired models humans have, consider the problem of computer vision
- If raw video footage is to be processed and used by computers, models for object detection, object permanence, depth, motion tracking and prediction, etc. are required
- The struggles of self-driving cars has shown this is not simple to do!
- Convolutional neural networks were a revolutionary invention and simply build stronger connections between neighboring pixels
- Our visual systems do all this naturally
- These hardwired biological models have developed to serve the goal of survival

What is this thing? What to pay attention to?

- Electrical engineer—how the hardware works
- Manufacturing engineer—how it is made
- Computer scientist—how to give it instructions
- Political scientist—how it is used, how it changes society
- Historian—where did it come from
- Child—source of entertainment
- Old person—how to avoid using it
- Most people—how to use it
- Machine learning people—God Incarnate
- Skeptic—a threat to traditional ways of life

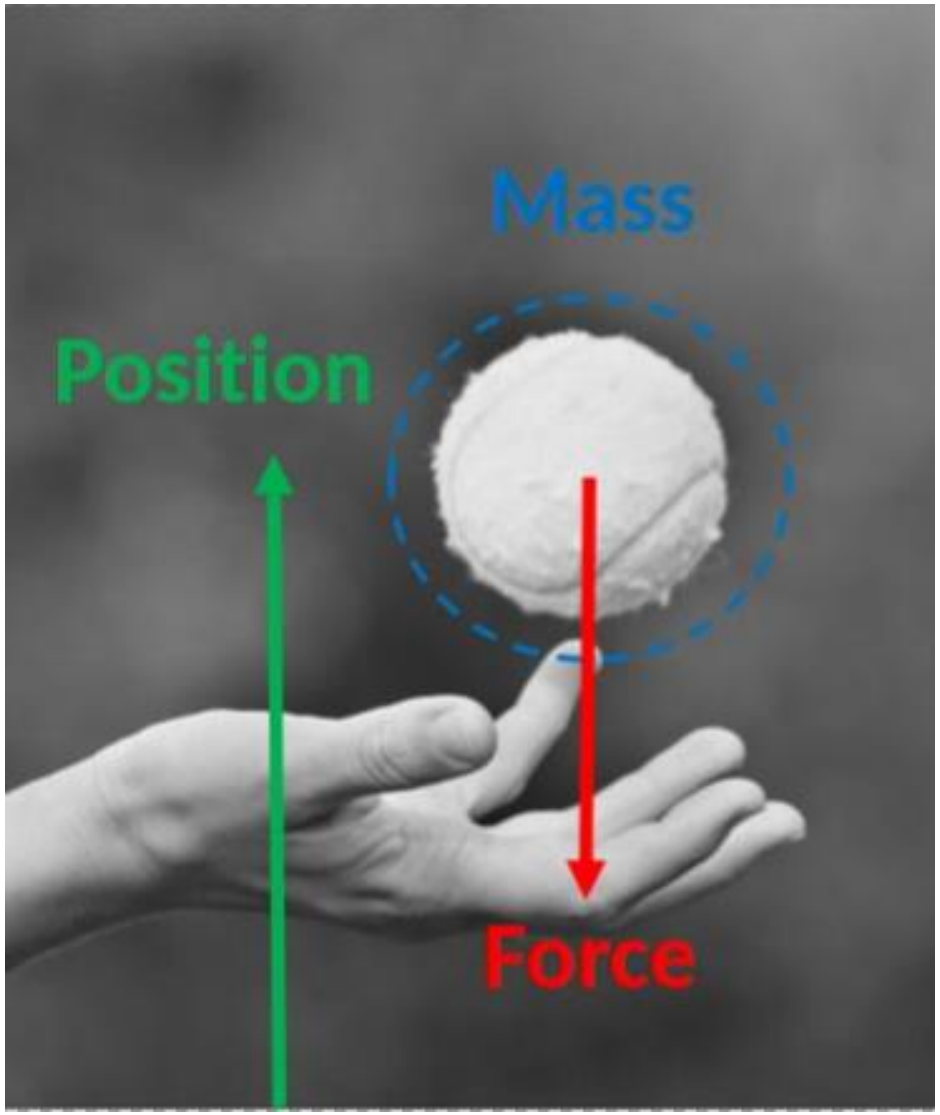
Machinery of Scientific Models—A Roadmap

1. What are models made of?
2. How are models built in practice?
3. How are models validated?
4. Why thinking about this stuff matters



Identifying Concepts

- With a goal in mind, the **first step of modeling process is to identify the relevant "concepts"** (entities, moving parts, nodes)
- What you see and pay attention to is conditioned by the goals of the model
- Identifying the right concepts is not a simple task
- Sometimes the right concepts are not directly observable!
- But, there must be an account of how unobservable concepts are connected to measurable quantities



"The beginning of wisdom is to call things by their proper name."

— Confucius

"History suggests that the road to a firm research consensus is extraordinarily arduous. History also suggests, however, some reasons for the difficulties encountered on that road. In the absence of a paradigm or some candidate for paradigm, all of the facts that could possibly pertain to the development of a given science are likely to seem equally relevant. As a result, early fact gathering is a far more nearly random activity than the one that subsequent scientific development makes familiar . . . early fact gathering is usually restricted to the wealth of data that lie ready to hand."

— *Origins and Structures of Scientific Revolutions*, Thomas Kuhn

What are the right concepts to model a country?

Individuals are basic unit of society

- **Institutions**
- **Companies**
- **Social groups**
- **Individuals**
- **Biological structures**
- **Molecules**
- **Elementary particles**

Money controls behavior of country

- **Power**
- **Class**
- **Distribution of wealth**
- **Relation between labor and capital**
- **Economic policy**

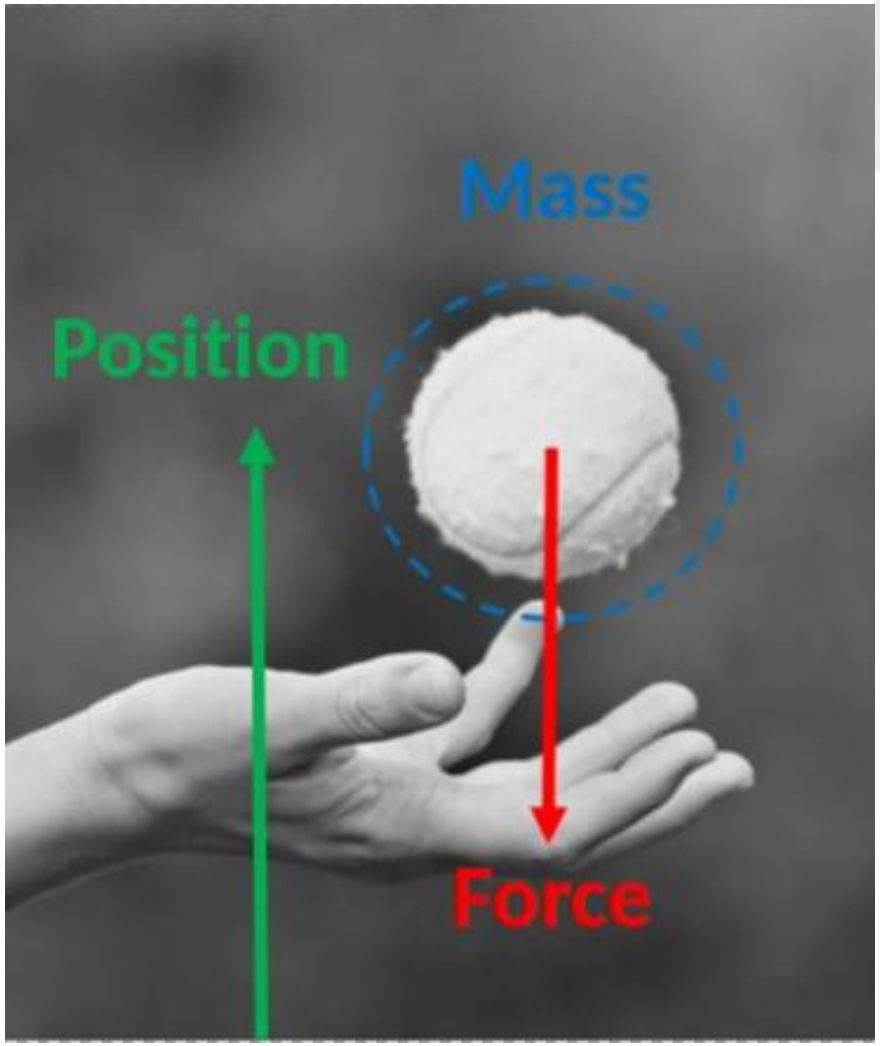
Politics is downstream of culture

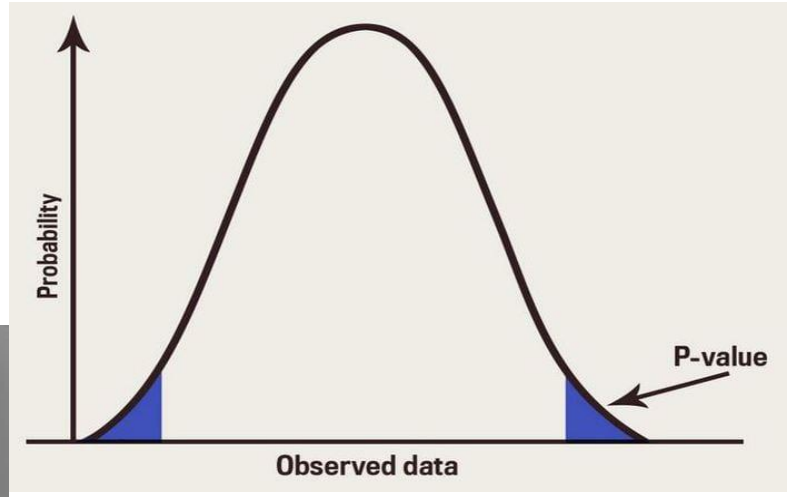
- **Culture**
- **Art**
- **Ideas**

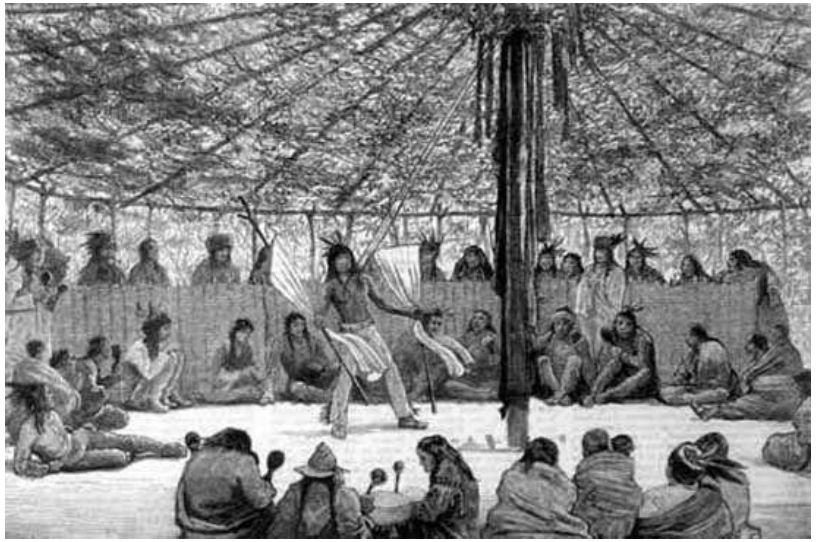
Interaction Rules

- Next step in modeling process is to **propose interaction relationships between the identified concepts**
- Some models may be descriptive/explanatory, others predictive, many somewhere in between
- Taxonomical models do not go so far as to propose interaction laws
- **Scientific models are the ones which posit mathematical relationships between concepts**
- Usually there is some basis in fundamental physical principles, as direct fitting to data is not as common in "hard" sciences

$$F = m\frac{d^2x}{dt^2}$$







Constitutive relation

Strain tensor ⟺ **Stress tensor**

Continuum model

Displacement field

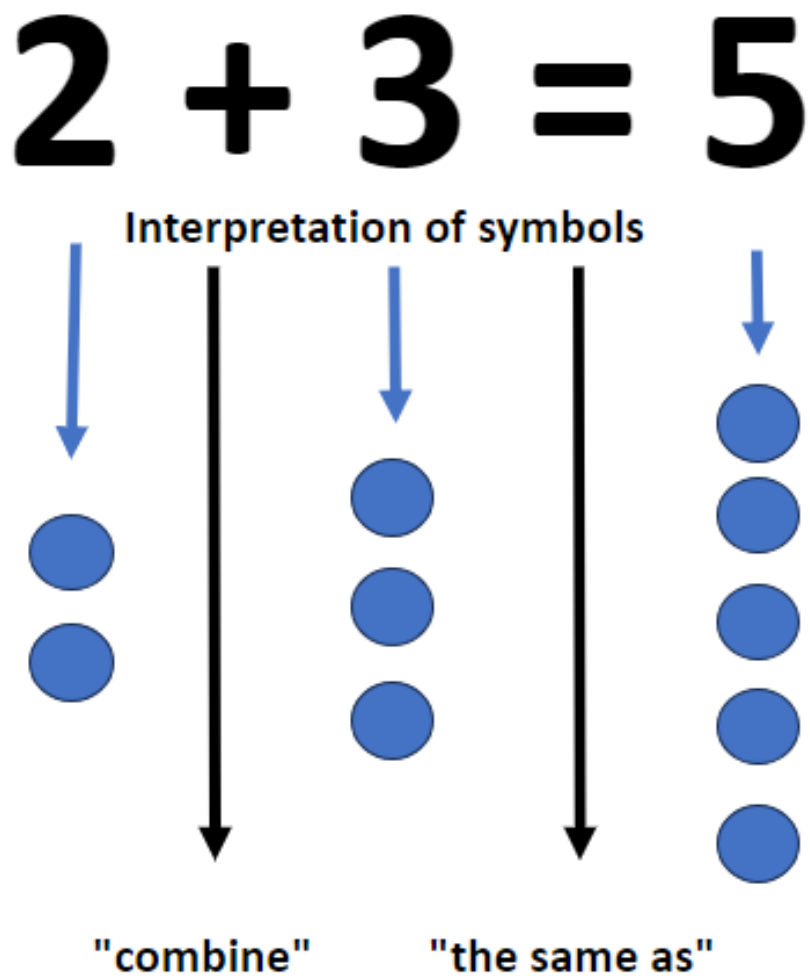
Deformation

Traction

Force

Scientific Models

- **Scientific models are powerful because math can be "mined" to deductively produce new truths about the system**
- **Math is a formal system, not a model**
- Formal systems outline procedures for the manipulation of written symbols with given interpretations
- Axioms act as allowed starting points for the application of rules of symbol manipulation; this process produces "theorems" of the system
- Mathematical manipulations of interaction rules can be used to discover the best concepts or level of description of a system



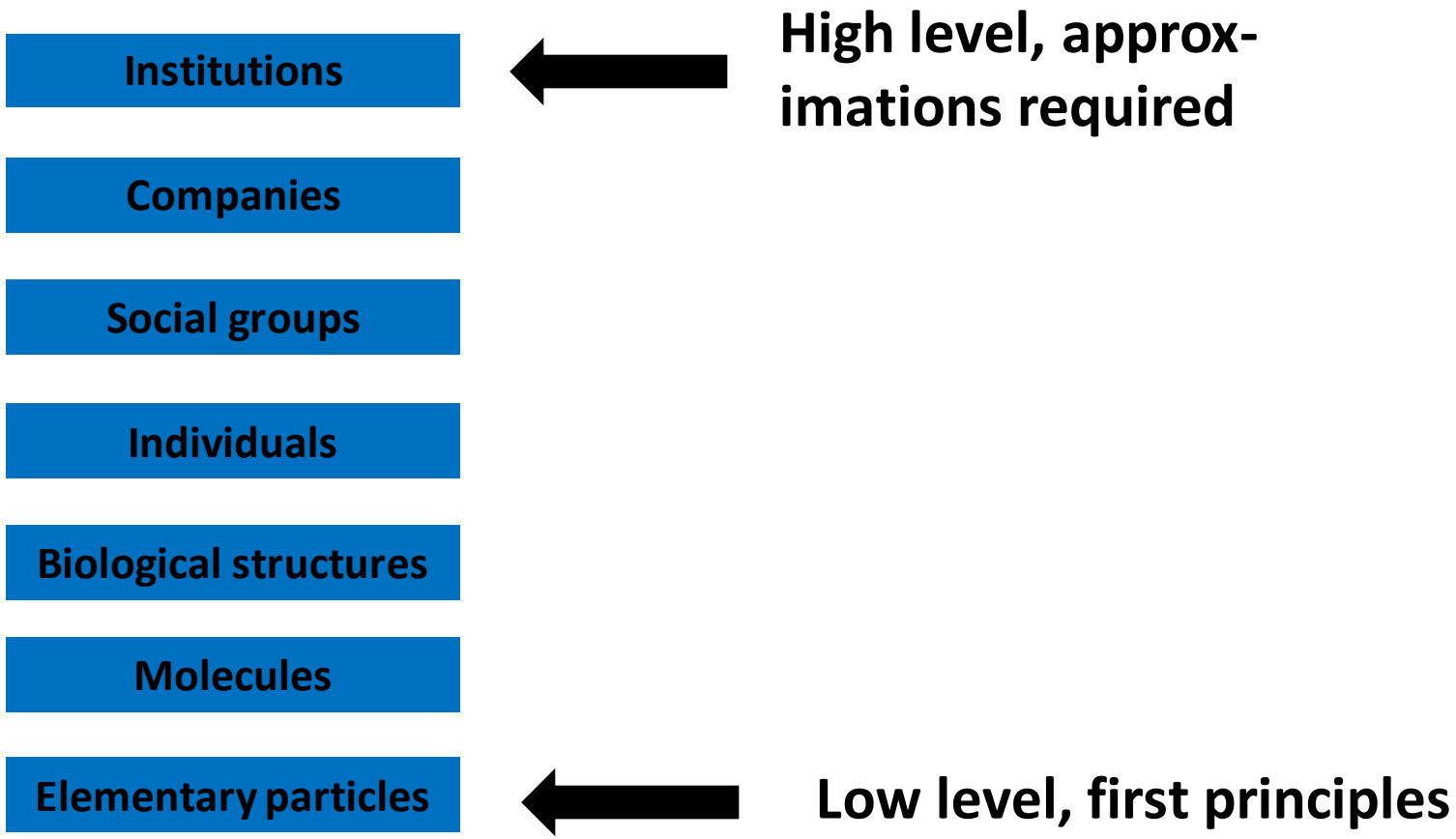
"All that the geometry itself tells us is that if anything can be brought under the definitions, it will also satisfy the theorems"

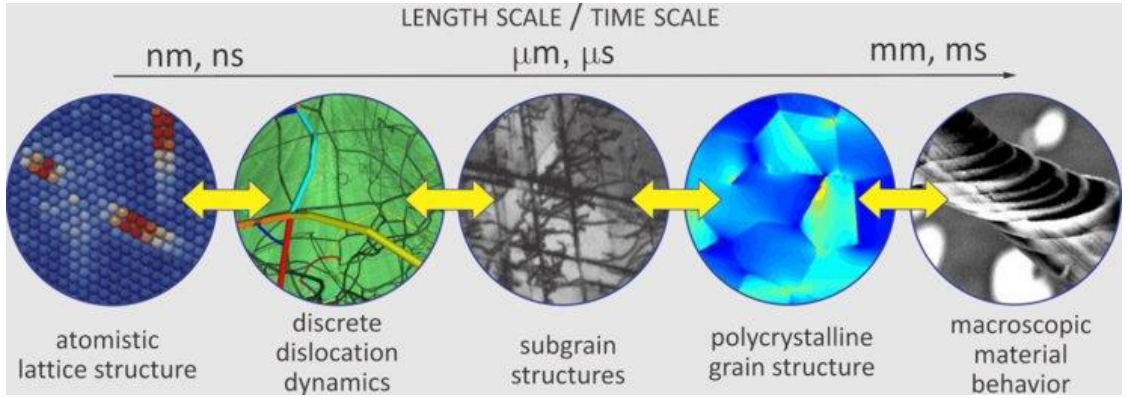
— *Language, Truth, Logic*, A.J. Ayer

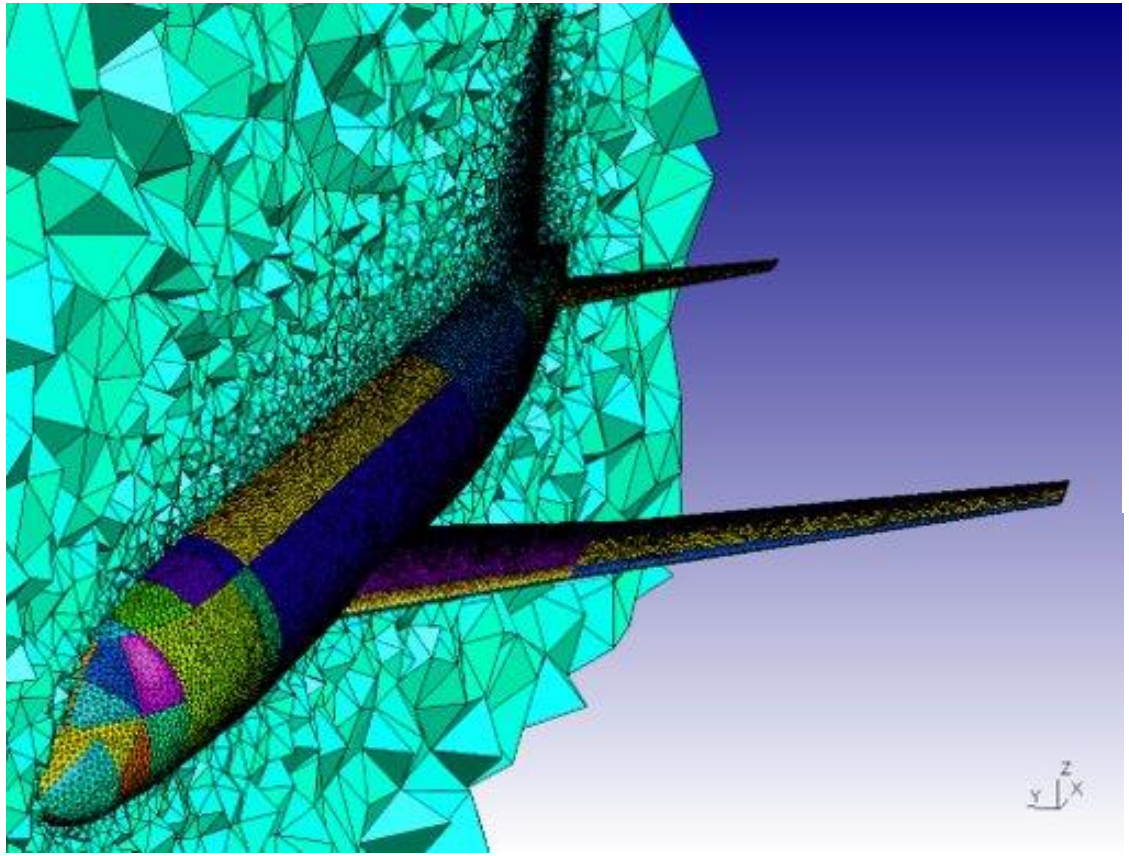
Difference Between "Pure" Science and Engineering

- Pure science works with formulating first principles with less regard for application
- First principle = "basic proposition or assumption that cannot be deduced from any other proposition or assumption"
- **Engineers tend to work with models at much "higher" level than first principle physical phenomena**
- **Modeling assumptions often used to carefully ignore all the details of lower level behavior**
- Engineering models use heuristics and apply principles from pure science to solve problems of interest
- Pure scientific models do not tend to do well on phenomena which are far removed from first principles
- Engineering models can combat this to some extent but eventually also break down (especially on level of biological and social systems)

Levels of Analysis







"There is, however, perhaps one significant negative feature of a chunked model: it usually does not have exact predictive power. That is, we save ourselves from the possible task of seeing people as collections of quarks (or whatever is at the lowest level) by using chunked models; but of course such models only give us probabilistic estimates of how other people feel, will react to what we say or do, and so on. In short, in using chunked high-level models, we sacrifice determinism for simplicity"

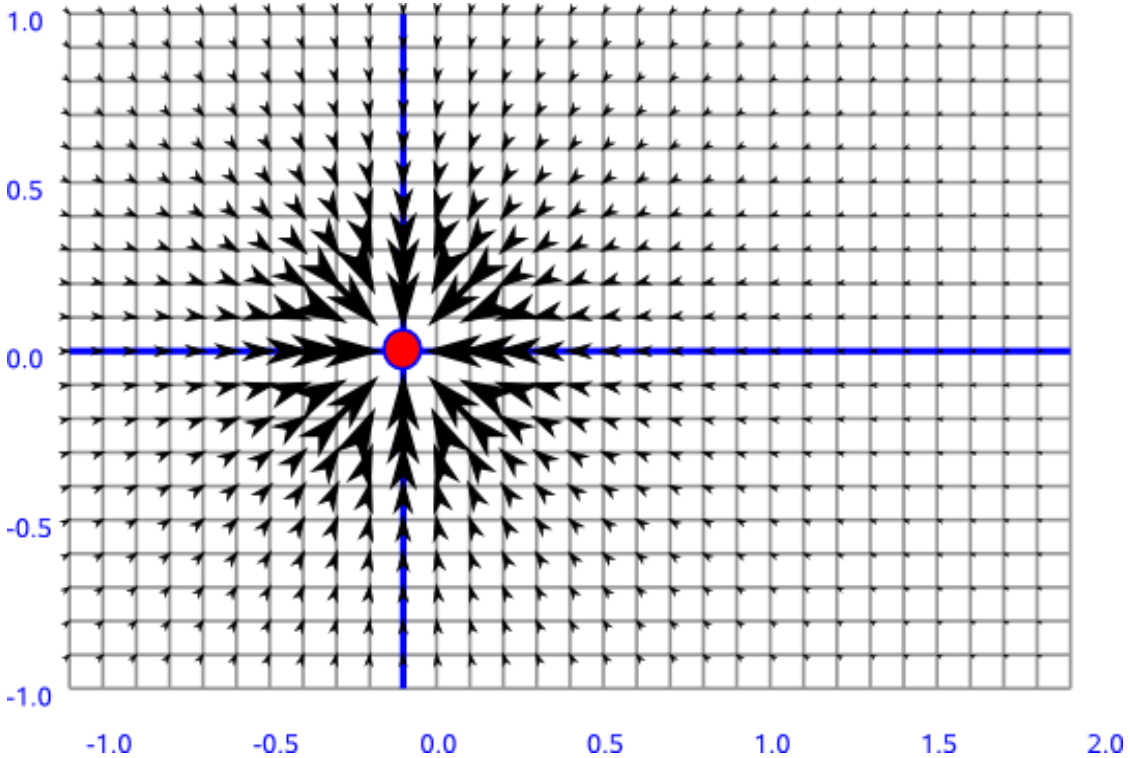
— *Godel, Escher, Bach*, Douglas Hofstadter

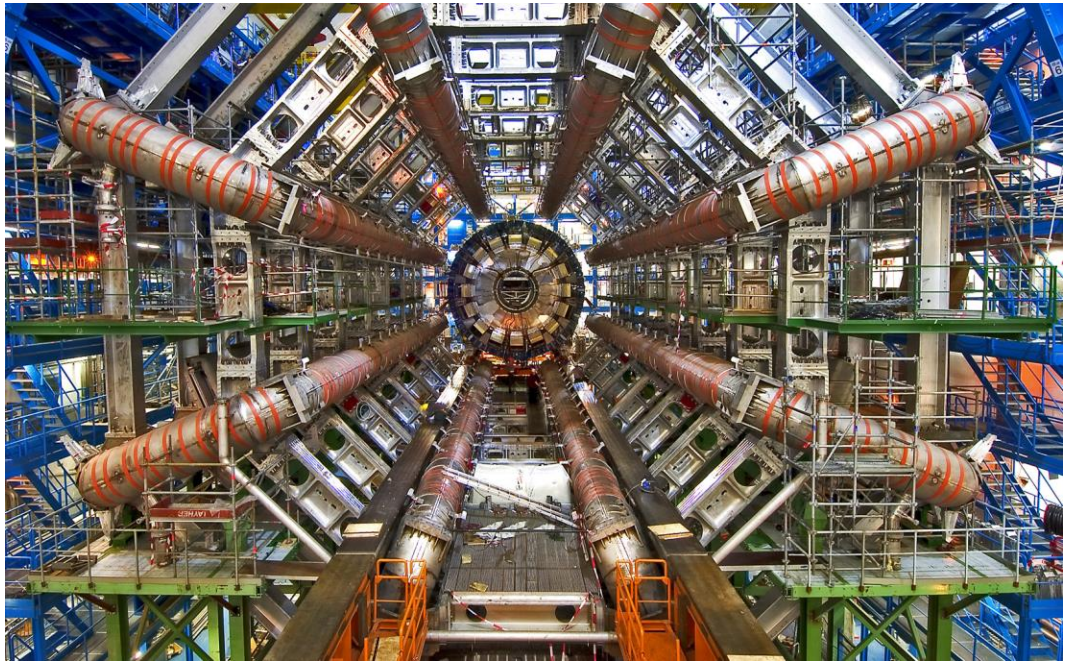
Building a Model in Practice

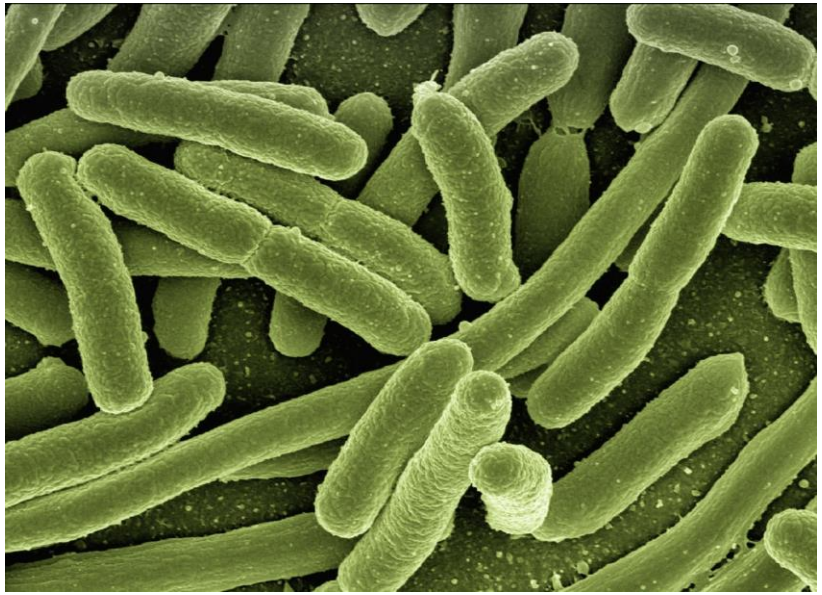
- In 1620, Francis Bacon's "Novum Organon" is published, which outlines inductive approach to natural philosophy and lays groundwork for modern scientific method
- Challenges deductive logic put forth in Aristotle's "Organon" by arguing that phenomena are best studied through experiment and observation
- Bacon saw the reasoning faculties of the mind as limited and fallible, thereby discrediting metaphysical explanations by saying they were not based on observations
- **With his empirical and inductive methodology, Bacon was confident that knowledge flowed directly from sense data aided by scientific instrumentation**

The Problem with Bacon's Induction

- 20th philosophers have argued that sense data and observation do not uniquely determine scientific models
- Data to form a hypothesis is necessarily limited and is guided by prior commitments
- Scientific models are often phrased in terms of entities which cannot be observed (e.g. bacteria, fields of force, energy, complex numbers)
- What is observable is a function of technology (current theory, measurement equipment)
- **Models are informed and constrained by observation but require goals, technology, insight, imagination, and creativity to formulate—they are thus partially subjective and not uniquely determined by sense data as Bacon hoped**







$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + V(x)\Psi(x,t)$$

Validating Models—Problem of Induction

- In the mid 1700's, philosopher David Hume argued that no amount of observation could conclusively verify a scientific model
- His argument was that at best, extensive experimental confirmation of a model could suggest that it was likely to be true
- **Pointed out that no theoretical guarantee can exist that future evidence won't disagree with the model**

x10000000

But still...

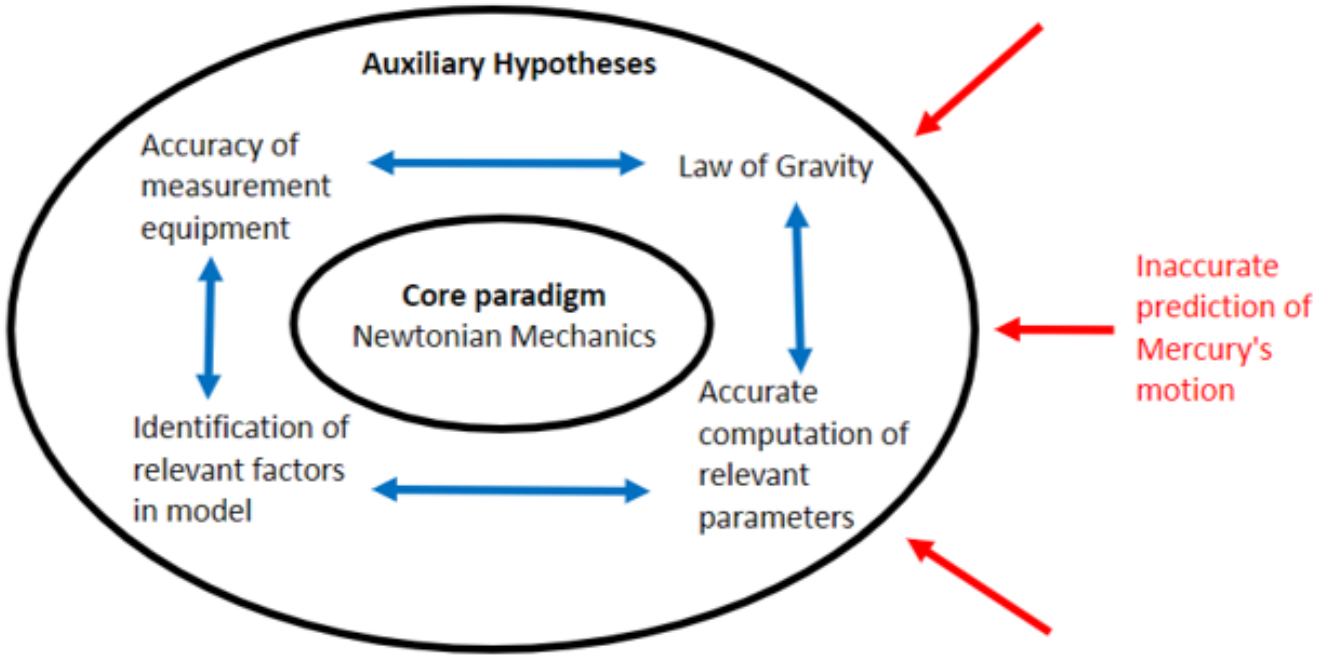
Popper and Falsification

- In the mid 1900's, Karl Popper responded to Hume's problem of induction by saying that scientific theories were never verified, but they could be falsified
- It is a deductive process to check whether the predictions of a model agree with experimental evidence
- Theories should be subject to "risky" tests in attempts to falsify them
- A theory is rendered more trustworthy when it agrees with an abundance of experimental evidence
- **This is a framework to "weed out" bad theories as opposed to confirm good ones**

Duhem-Quine Thesis

- Soon after Popper's theory of falsification, Pierre Duhem and W.V. Quine independently wrote about a set of ideas which have been called the "Duhem-Quine Thesis"
- This states that it is uncommon and sometimes impossible to test a single hypothesis against evidence—rather, **many hypotheses are used to make a prediction, and counter-evidence does not indicate which hypothesis may be at fault**
- By stating that falsification is not a straightforward deductive process, the Duhem-Quine thesis refutes Popper's falsification framework
- Of course, history has shown it is possible to refute hypotheses, but it takes many falsifications of a "body" of theories used to make predictions in different domains to "triangulate" the incorrect hypothesis

Apparent Falsification of Newtonian Mechanics



"My countersuggestion . . . is that our statements about the external world face the tribunal of sense experience not individually but only as a corporate body . . . Total science is like a field of force whose boundary conditions are experience . . . but the total field is so underdetermined by its boundary conditions that there is much latitude of choice as to what statements to reevaluate in the light of any contrary experience."

— W.V. Quine, *Two Dogmas of Empiricism*

Kuhn and the Status of Scientific Models

- Scientific knowledge is frequently thought to accumulate steadily over time
- In the 1960's, Kuhn observed that fields undergo occasional "revolutions"
- Famously argues that **progress in science is hard to measure because scientific theories before and after revolutions make use of "incommensurable" concepts**
- Also claims that revolutions are motivated primarily by sociological factors
- Kuhn believes that **science is socially constructed, provisional, and does not approach truth in any straightforward way**
- Sounds radical, but his arguments are taken very seriously

Recap

- Models help us understand the world; they are ubiquitous and come in a variety of forms
- Models are fundamentally driven by goals
- Scientific models identify relevant entities and prescribe mathematical relationships for how they interact
- There are unavoidable subjective aspects of the model building process and inherent difficulties in validating these models
- **Different models answer different questions in different ways**

How Can a "Philosophy of Models" Be Applied?

"These smug pilots have lost touch with regular passengers like us. Who thinks I should fly the plane?"

My interpretation

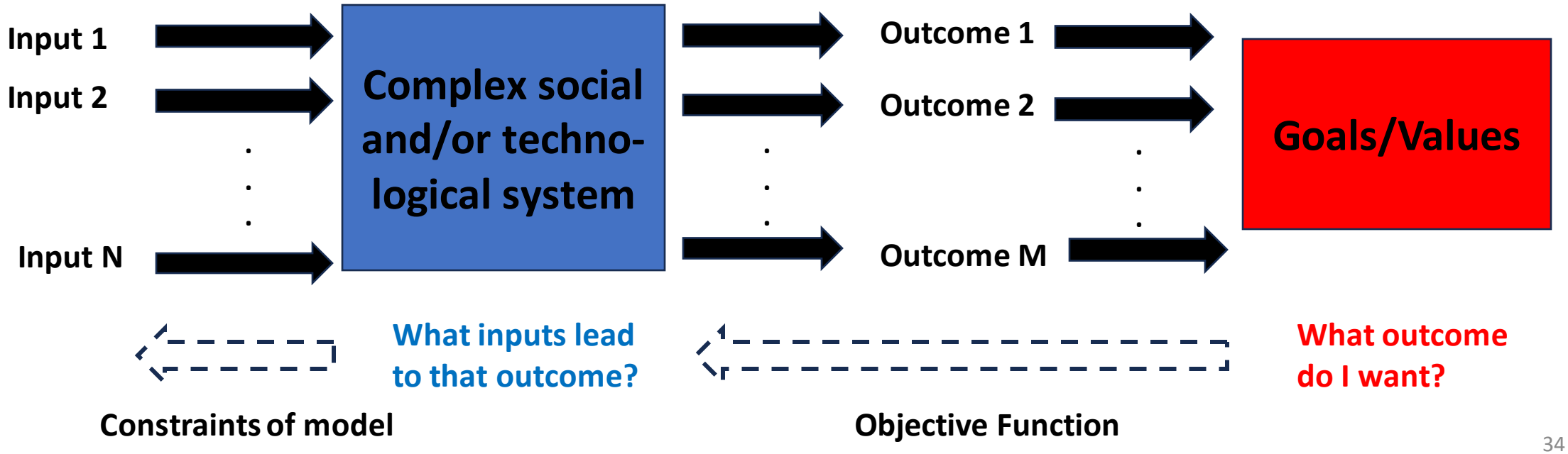
- Cartoonists are equating operating an airplane to governing a society
- Flying an airplane is a metaphor for technical knowledge of complex systems
- Critique of people who question the authority of experts on social, scientific, and political questions
- **While everyone agrees that safely landing a plane constitutes success, not everyone agrees what constitutes successful social/political outcomes**

What does this have to do with models?

- **Just like building models is goal-oriented, using models is also goal-oriented**
- **Desired outcomes are often highly contested!**
- Making social/political decisions could be conceptualized as constrained optimization problem: user-specified objective is optimized with respect to design variables which satisfy constraints of underlying complex system
- Thus, technical expertise does not equate to knowing what "should" be done when goals are contested
- Can illustrate this with made-up economics example

System where everyone agrees on objective

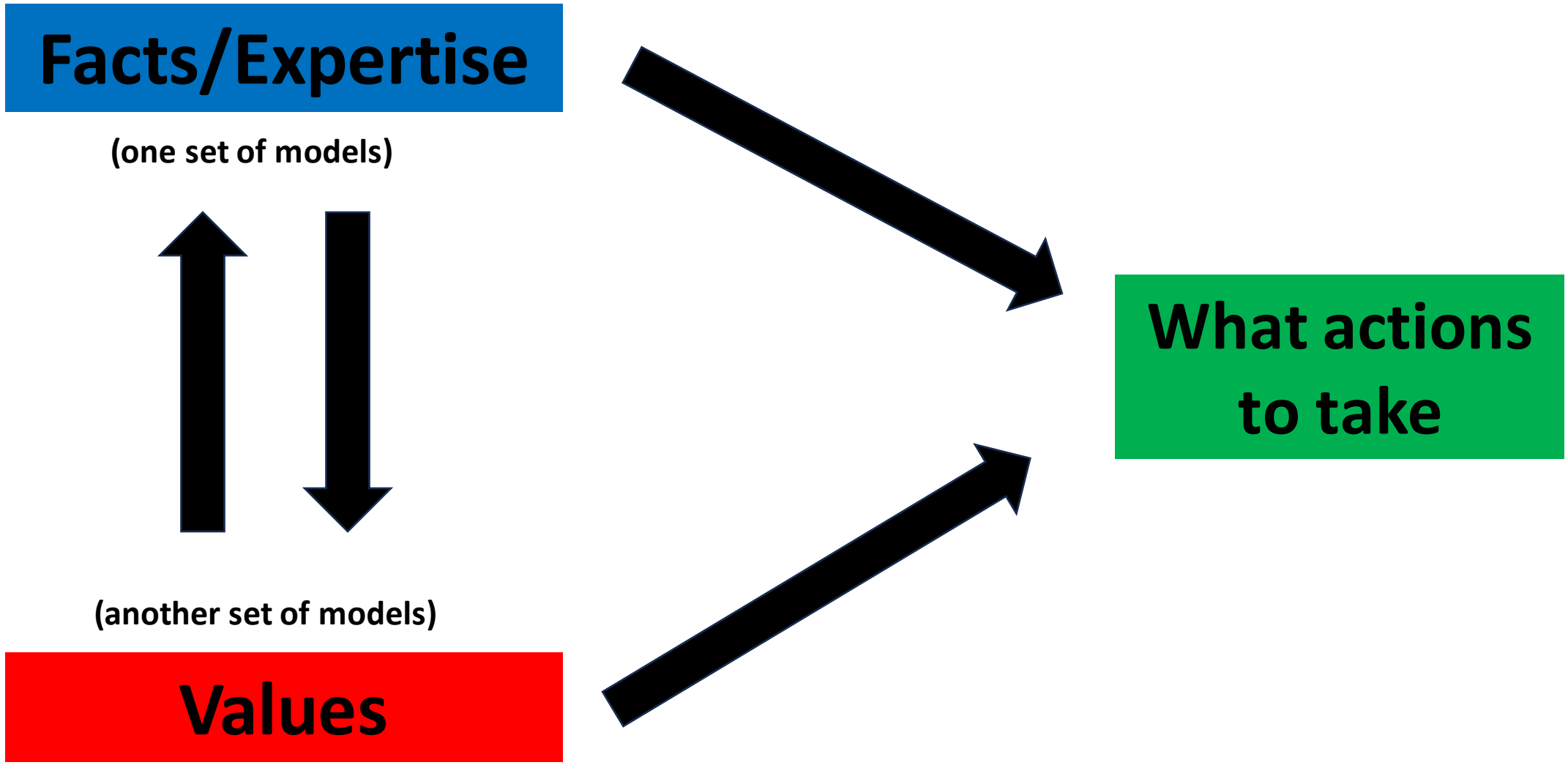
System where objective is not well-defined



Goals and Values

- First principle commitments specifying what is good
- Values may be functions of religious, spiritual, philosophical, or political models of the world
- **Scientific models can tell us what will happen if we take certain actions, but values are used to judge/interpret these outcomes**
- Think of engineering optimization problems—values provide objective function, scientific models provide constraints

So maybe more like this...



Conclusion

- Models produce knowledge about the world
- Different models answer different questions in different ways
- Decisions can be made when goals/values and scientific models come together
- PhD students are future experts, science communicators, and intellectual authorities
- Misunderstanding "philosophy of models" leads to inaccurate assessment of a model's power and scope
- In climate of distrust of technical expertise and politicization of science, **it is especially important to communicate wisely, humbly, and thoughtfully about what scientific models do**
- **There are always goals driving model development and use**

"You can be a good empiricist only if you are prepared to work with many alternative theories rather than with a single point of view and "experience." . . . Theoretical pluarlism is assumed to be an essential feature of all knowledge that claims to be objective . . . The function of such concrete alternatives is, however, this: they provide means of criticizing the accepted theory in a manner which goes beyond the criticism provided by a comparison of that theory "with the facts."

— *How To Be A Good Empiricist*, Paul Feyerabend

The End. Thanks!

More Fun Questions…

- Where do conservation laws come from? Are these arrived at deductively or inductively?
- What quantities can be measured directly in science? Force, temperature, energy, stress, strain? How does this influence how you think about the "truth" of scientific models?
- What is the difference between building machine learning and physics-based models? Does this influence the use-cases of the two types of models?
- Can negative numbers be observed? Can zero be observed? What about irrational or complex numbers?
- What questions did pre-scientific models answer if they weren't explicitly predictive?
- How often are political disagreements about facts vs. values?