# “Theory of Theory”

***On the role of theory and modeling in neuroscience. J Neurosci, 43(7):1074–1088; Feb 2023.***

Joseph Monaco

May 9, 2023

# NSF Future Theoretical Frameworks for Neuroscience

Feb 2019

1074 • The Journal of Neuroscience, February 15, 2023 • 43(7):1074–1088

Feb 2023

Viewpoints

## On the Role of Theory and Modeling in Neuroscience

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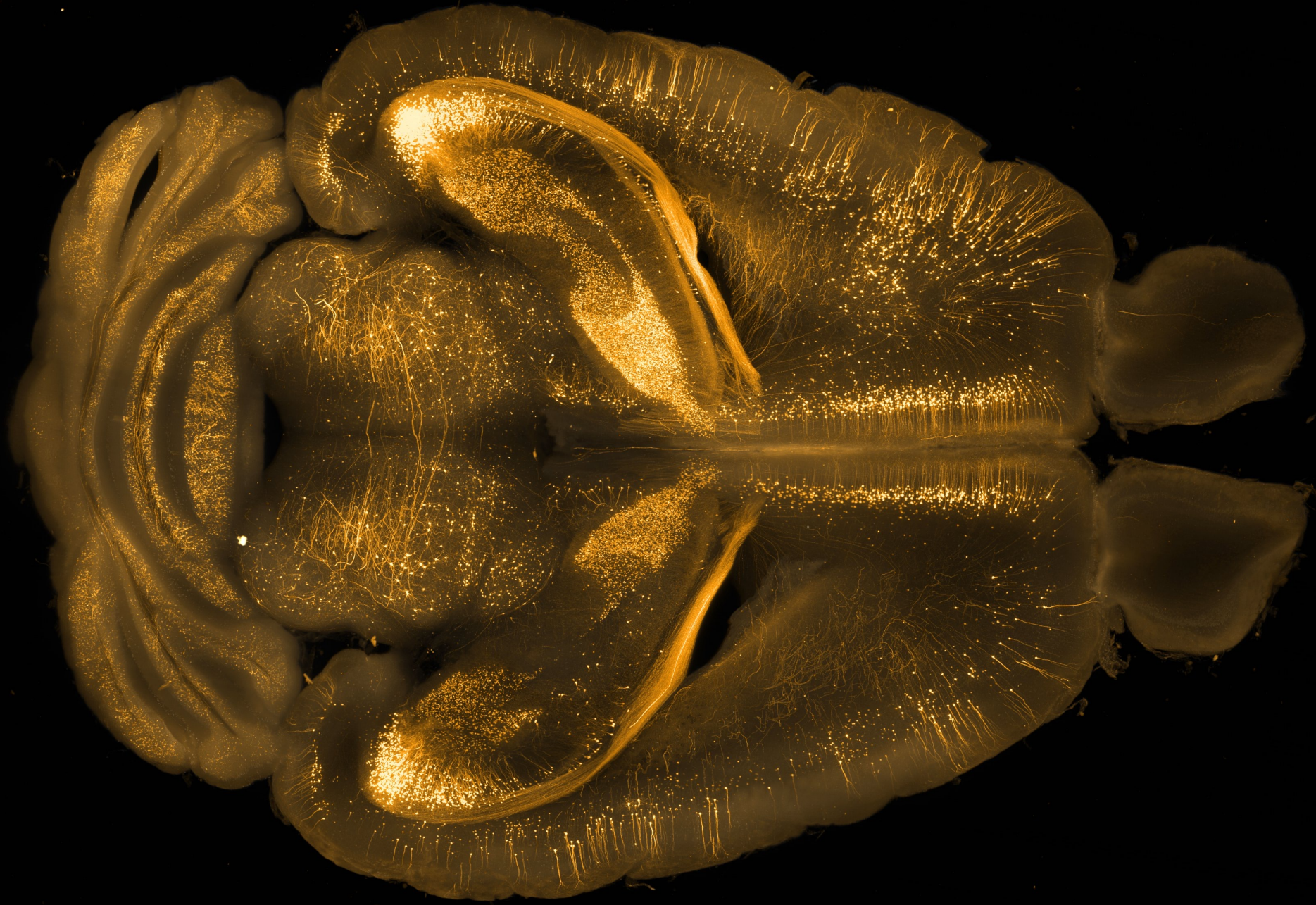
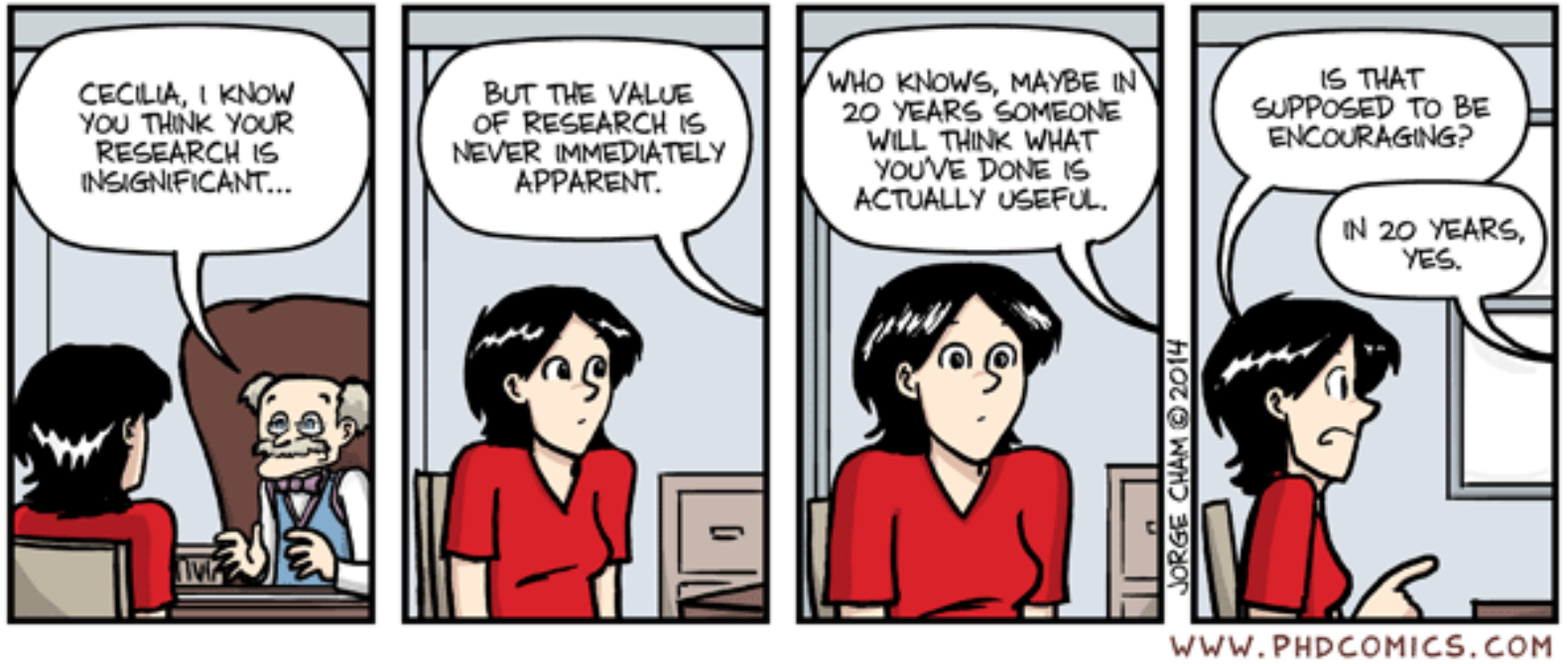
In recent years, the field of neuroscience has gone through rapid experimental advances and a significant increase in the use of quantitative and computational methods. This growth has created a need for clearer analyses of the theory and modeling approaches used in the field. This issue is particularly complex in neuroscience because the field studies phenomena that cross a wide range of scales and often require consideration at varying degrees of abstraction, from precise biophysical interactions to the computations they implement. We argue that a pragmatic perspective of science, in which descriptive, mechanistic, and normative models and theories each play a distinct role in defining and bridging levels of abstraction, will facilitate neuroscientific practice. This analysis leads to methodological suggestions, including selecting a level of abstraction that is appropriate for a given problem, identifying transfer functions to connect models and data, and the use of models themselves as a form of experiment.



Glazer/PEGASOS

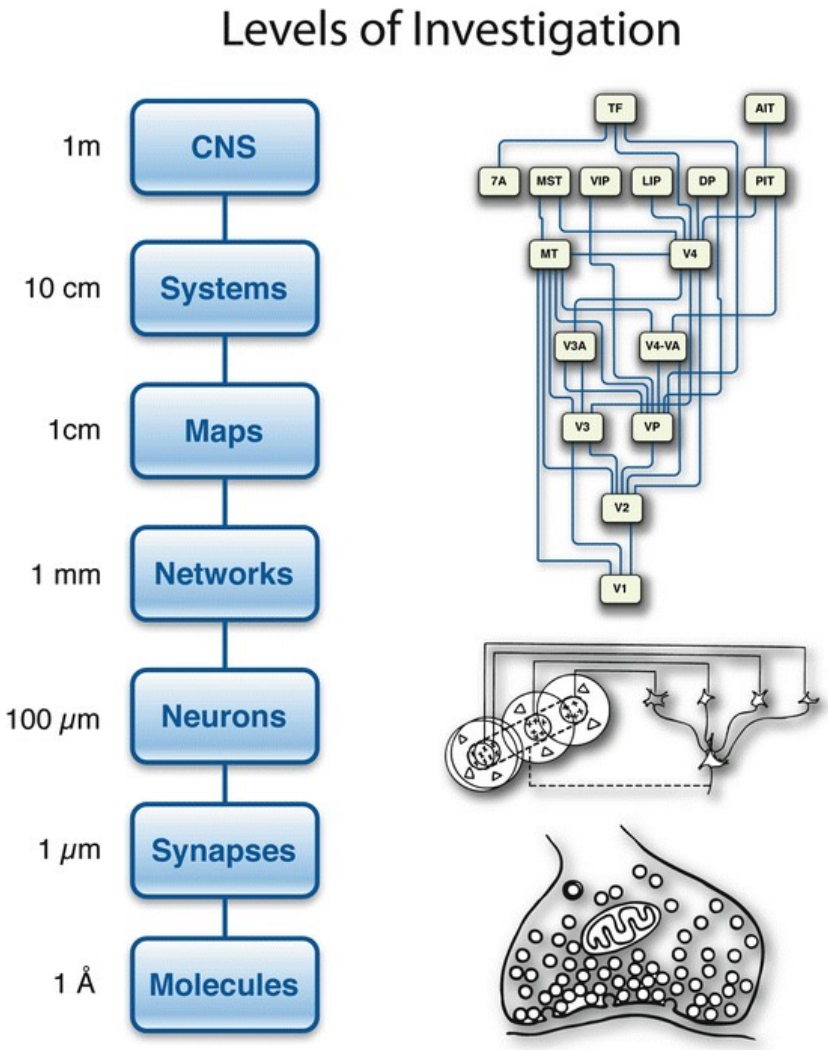
# A “pragmatic problem-solving” view of scientific progress

- Neuroscience as a field doesn’t agree on role of theory
- Let’s take a pragmatic view
  - Scientific progress as a landscape of evolving arguments, problems, solutions, and practices for evaluating all that



# Scientific questions as empirical problems

- Scientific questions about phenomena are empirical problems
  - Solutions require abstractions
  - Abstractions describe decisions about selecting certain aspects and ignoring others
    - Selection/exclusion at lower AND higher “levels” or scales
    - Decision can be implicit or explicit

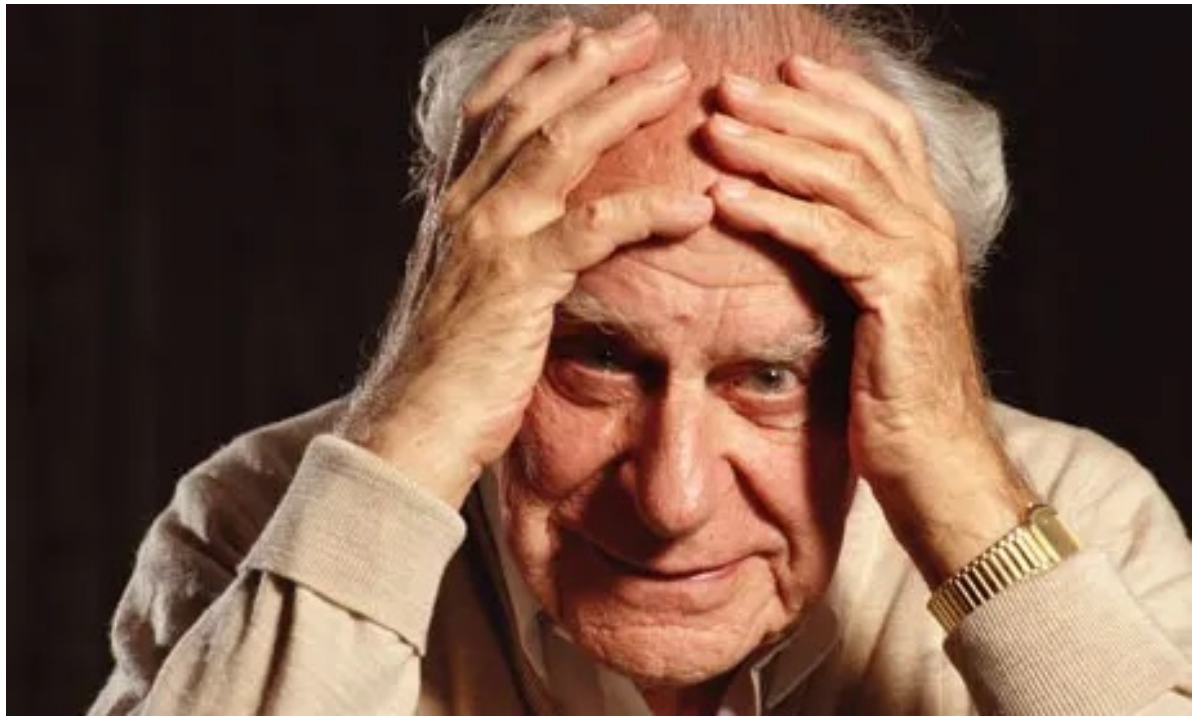





Sejnowski (2016)

# What is a theory & what is it *good* for?

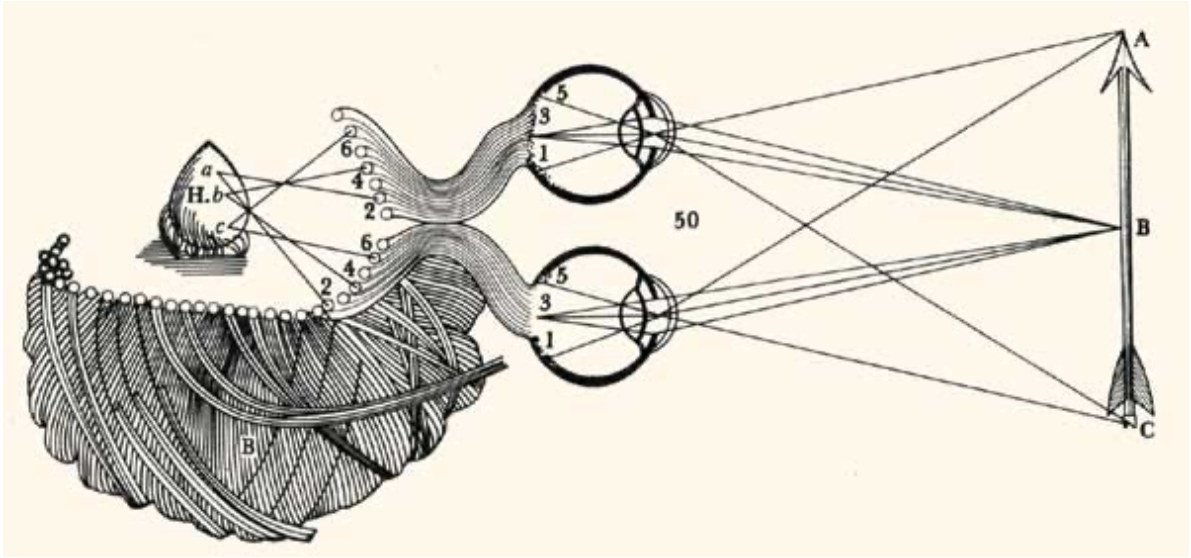
- Theory is how we make sense of scientific work
  - Yet poorly served in training, methodologies, and incentives
- The Popperian tradition
  - Theories are universal propositions whose truth value must either be *falsified* or *corroborated*
  - It is not a pragmatic view and it does not reflect the history of science
- Why? Because scientific questions are ill-defined search problems with unclear success state. *Agreement is required.*



Karl Popper, head in hands.

# What is a theory & what is it *good* for?

- Definition
  - Theories are the sets of ideas that we/scientists use to propose solutions to empirical problems about observed phenomena
- The pragmatic view…
  - Theories are imbued with the epistemic, sociological, and historical context surrounding a phenomenon and its problems



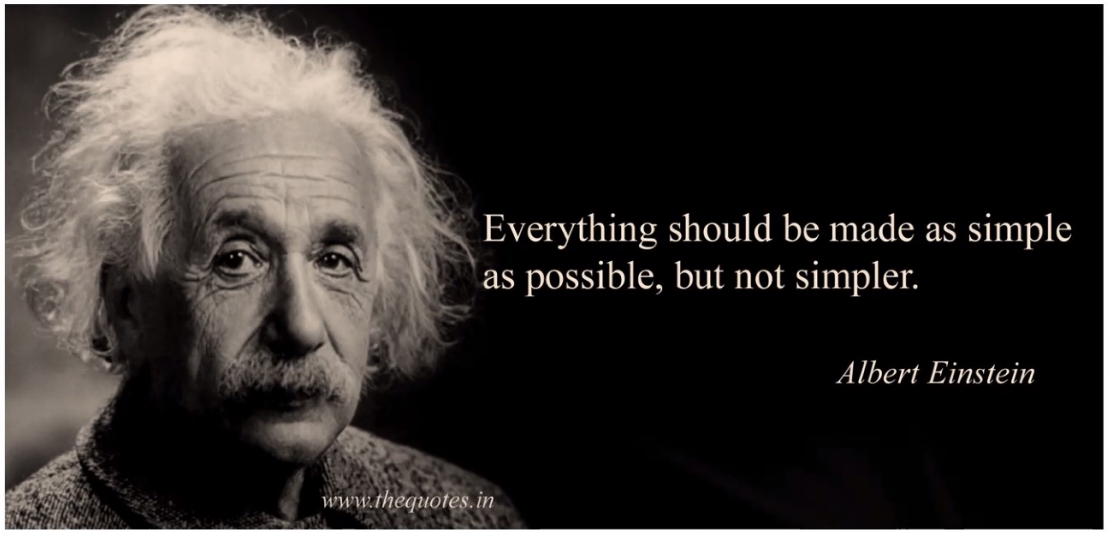



Descartes' problems with the pineal gland became moot.

# What is a theory & what is it *good* for?

- Theories are almost always implicit in practice
  - They are only rarely formalized, yet most scientists think of formal theories and models given the word "theory"
- Theories are good when they are effective and useful for solving empirical problems
  - I.e., they provide *explanations*
- Considerations
  - Accuracy, simplicity (parsimony), falsifiability, generality, reproducibility, specificity, degree of empirical content…

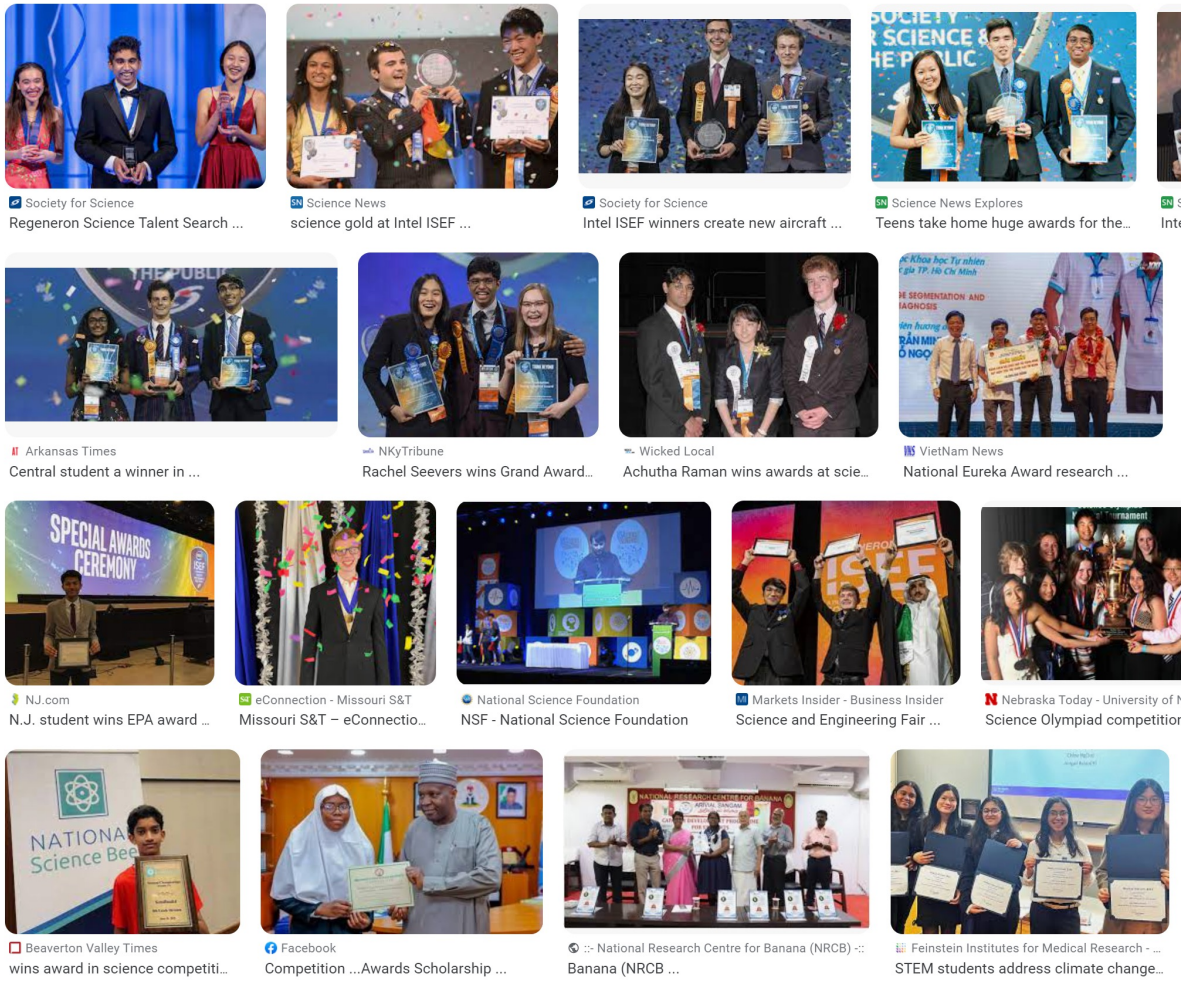
$$F = \underbrace{D[Q(s_\tau) \| P(s_\tau)]}_{\text{simplicity}} - \underbrace{E_{Q(s_\tau)}[\ln P(o_\tau \mid s_\tau)]}_{\text{accuracy}} \geq \underbrace{-\ln P(o_\tau \mid m)}_{\text{evidence}}$$




Karl Friston's free-energy formalization of the Bayesian brain theory

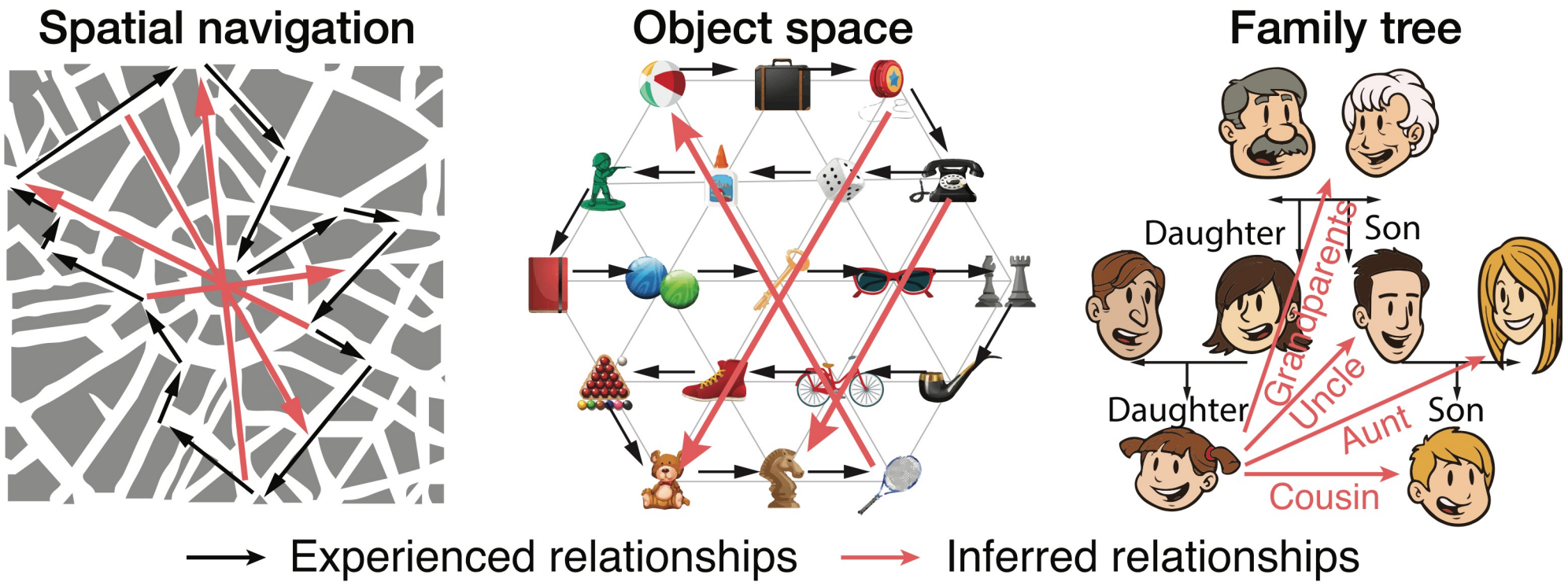
# What is a theory & what is it *good* for?

- How is scientific progress made if theories are implicit, sociological constructs?
  - Community-maintained standards of scientific explanations for observed phenomena
  - Overarching drive to control the world in ways that achieve societal goals
  - Scientists *compete* to solve problems, so explanations evolve toward increasing utility



# Frameworks and constructs

- Frameworks provide conceptual constraints on the forms that theories can take
  - They provide a language (terms, objects, relations) from which theories can be described and constructed






Cognitive mapping framework (ref. TK)

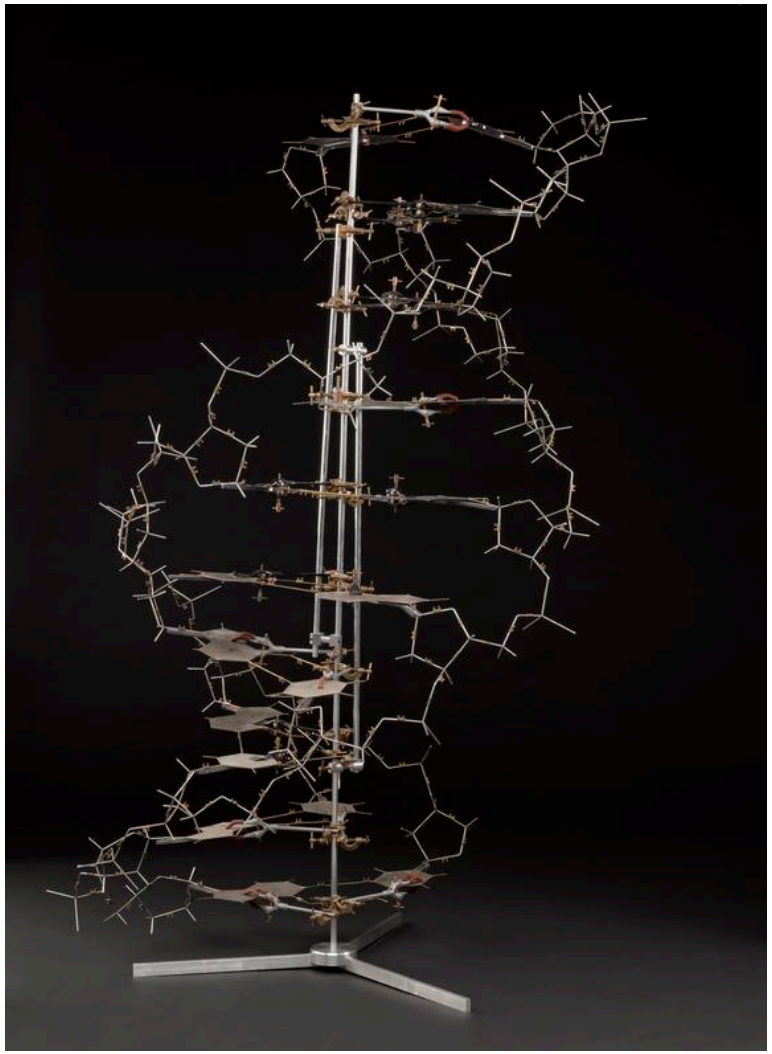
# Frameworks and constructs

- Theories derived within different frameworks are not (directly) comparable
  - E.g., theories in *neuropsychiatry* are not usefully comparable to those in *psychoanalytic* traditions
- However, their utility for problem-solving *can* be compared
  - Prediction accuracy
  - Level of control attained

Freud has questions

# Models at the interface

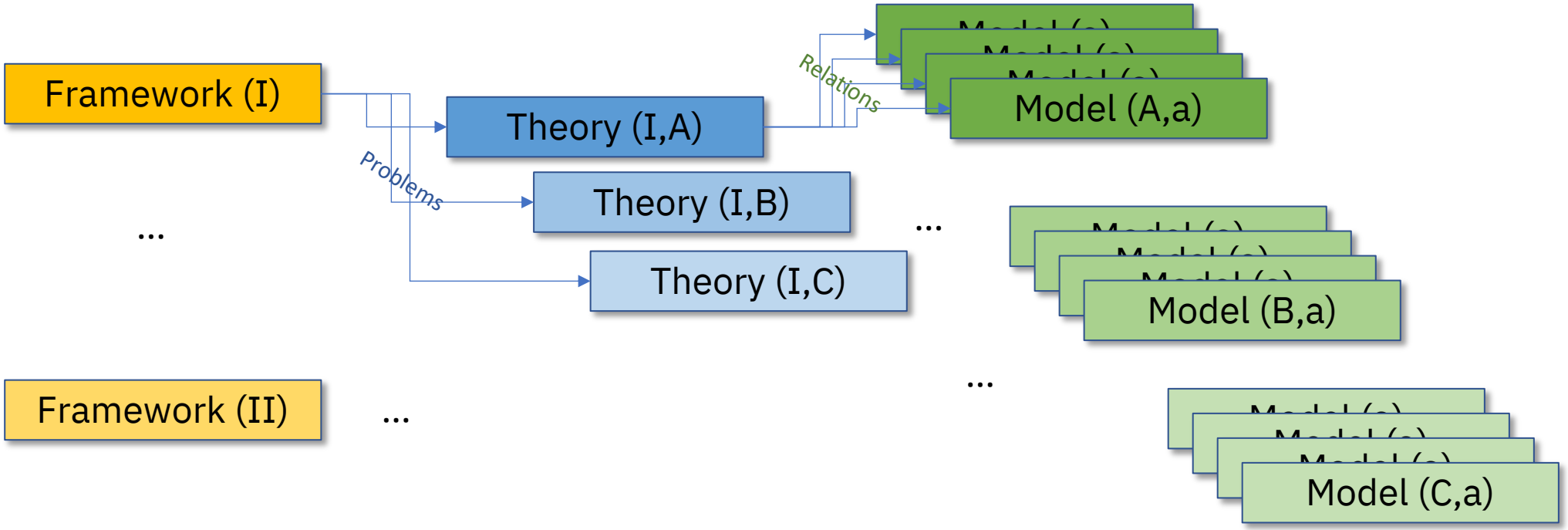
- Definition
  - A model is a *construct* and an *interpretation* (or, *construal*) for how its structure relates to an observed phenomenon
- Formal models can be analytical or computational
- Other kinds of models can also operate at the interface of theory and phenomenon
  - Conceptual models
  - Physical models
  - Animal models



Physical model of nucleic acid conformations underlying the structure of DNA

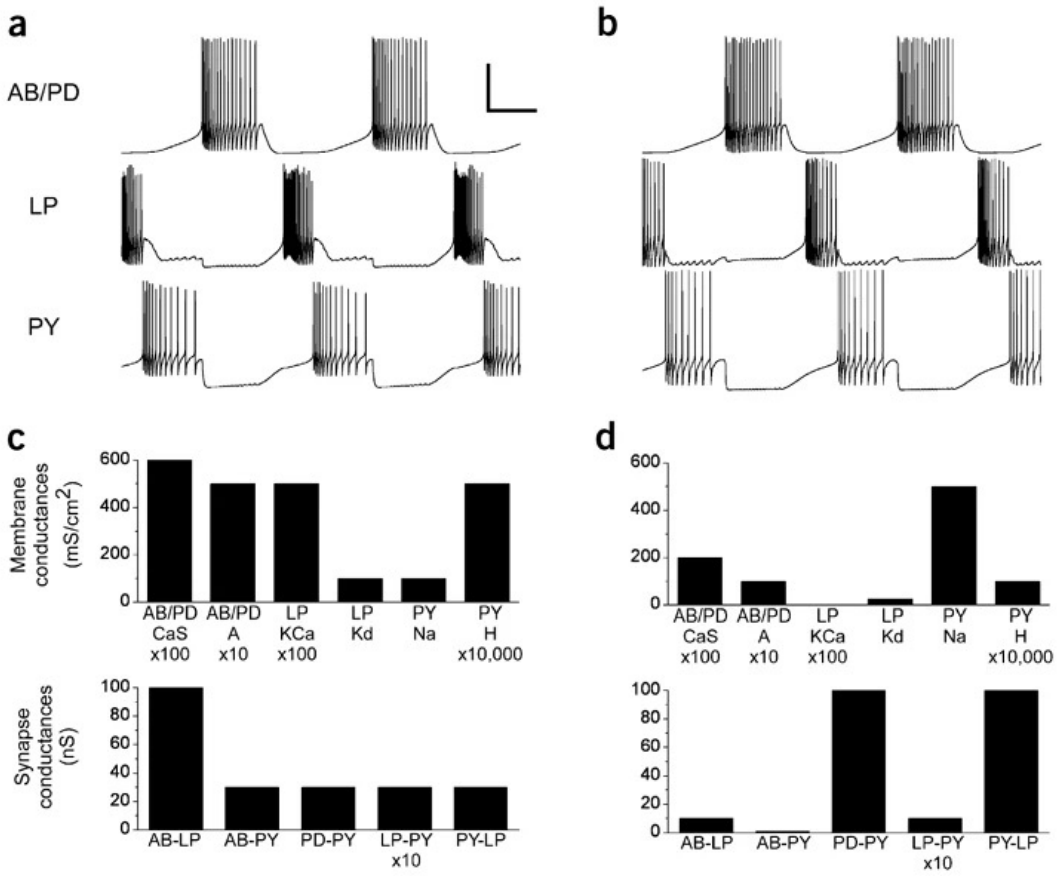
# Frameworks, theories, & models

- Frameworks constrain theories
  - Theories are constructed to solve research problems
    - Models provide *experimental apparatus* to test theory against observation



# Models make theoretical assumptions explicit

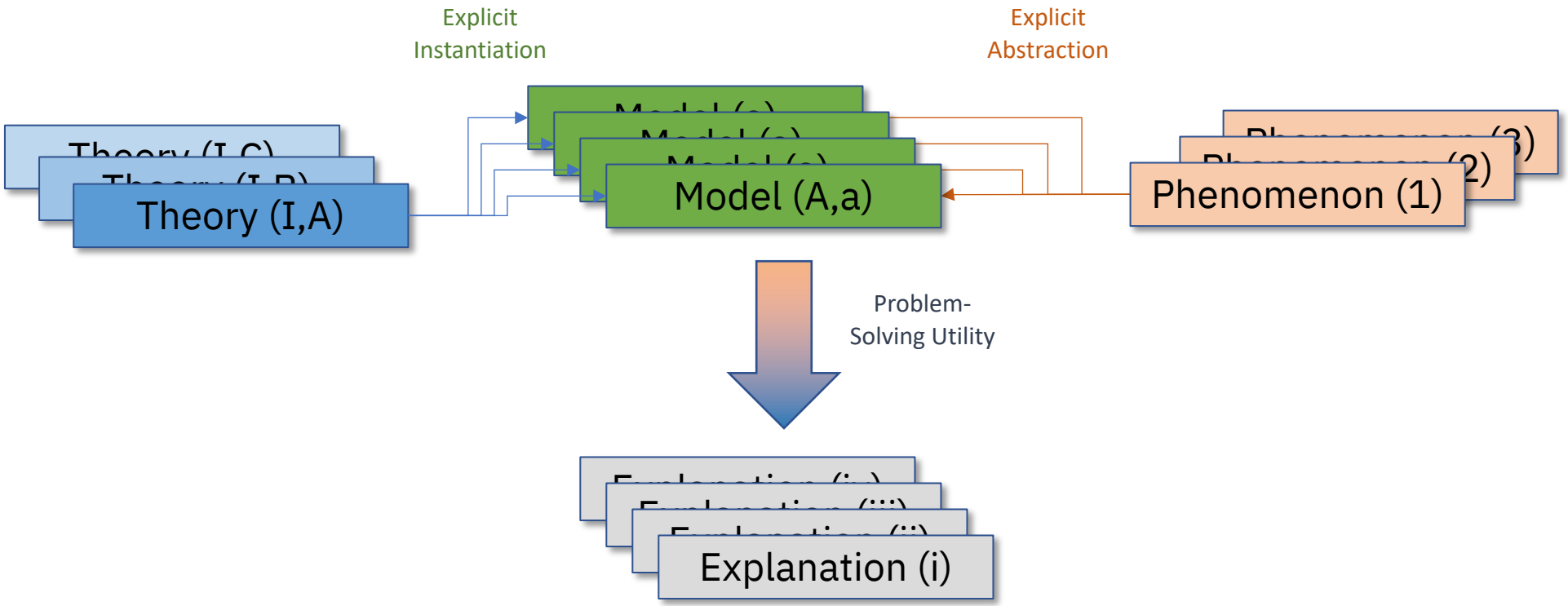
- Problem-solving progress requires “experiments” in diverse types of models
  - Implicit assumptions must be confronted and made explicit to achieve transparency and utility of theories and models across research domains
    - Marder (2000)
  - Problem of degeneracy
    - Structural
    - Parametric
      - E.g., Prinz/Marder (2004)




Prinz/Marder (2004)

# Dual role of models in scientific explanation

- Models provide *instantiation* and *abstraction*

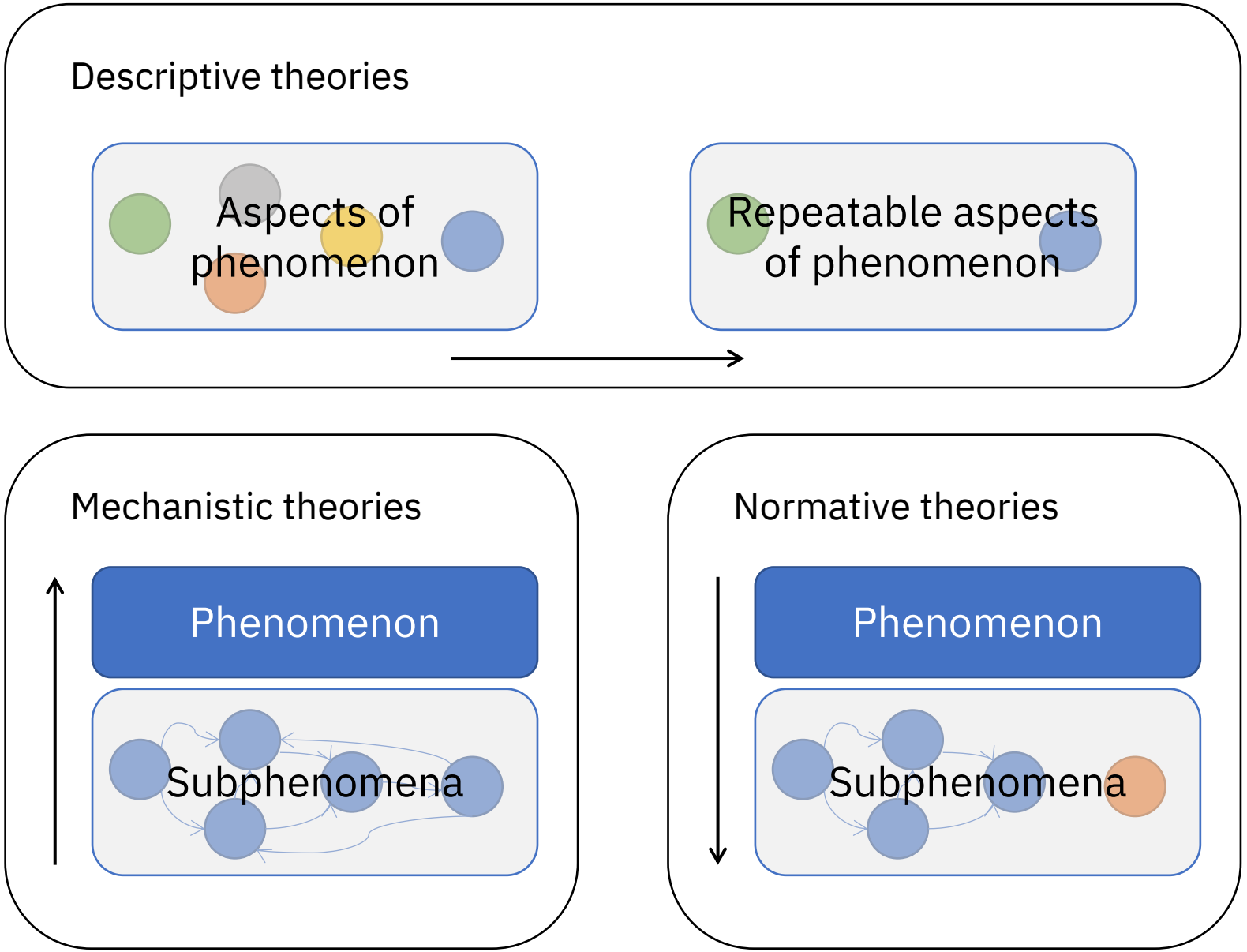


# Levels of abstraction

- Solving empirical problems requires selecting which aspects of a phenomenon are relevant to the question
  - Some aspects must be ruled in, while others are ruled out
  - Disagreement can arise around what to include/exclude in models or theories, but decisions *must be made*

- Descriptive
  - Selection of components within a level of abstraction
- Mechanistic
  - Asking a “how” question requires linking components at a lower level to a phenomenon described at a higher level
- Normative
  - Asking a “why” question requires positing a function and finding system components that can satisfy that higher-level goal

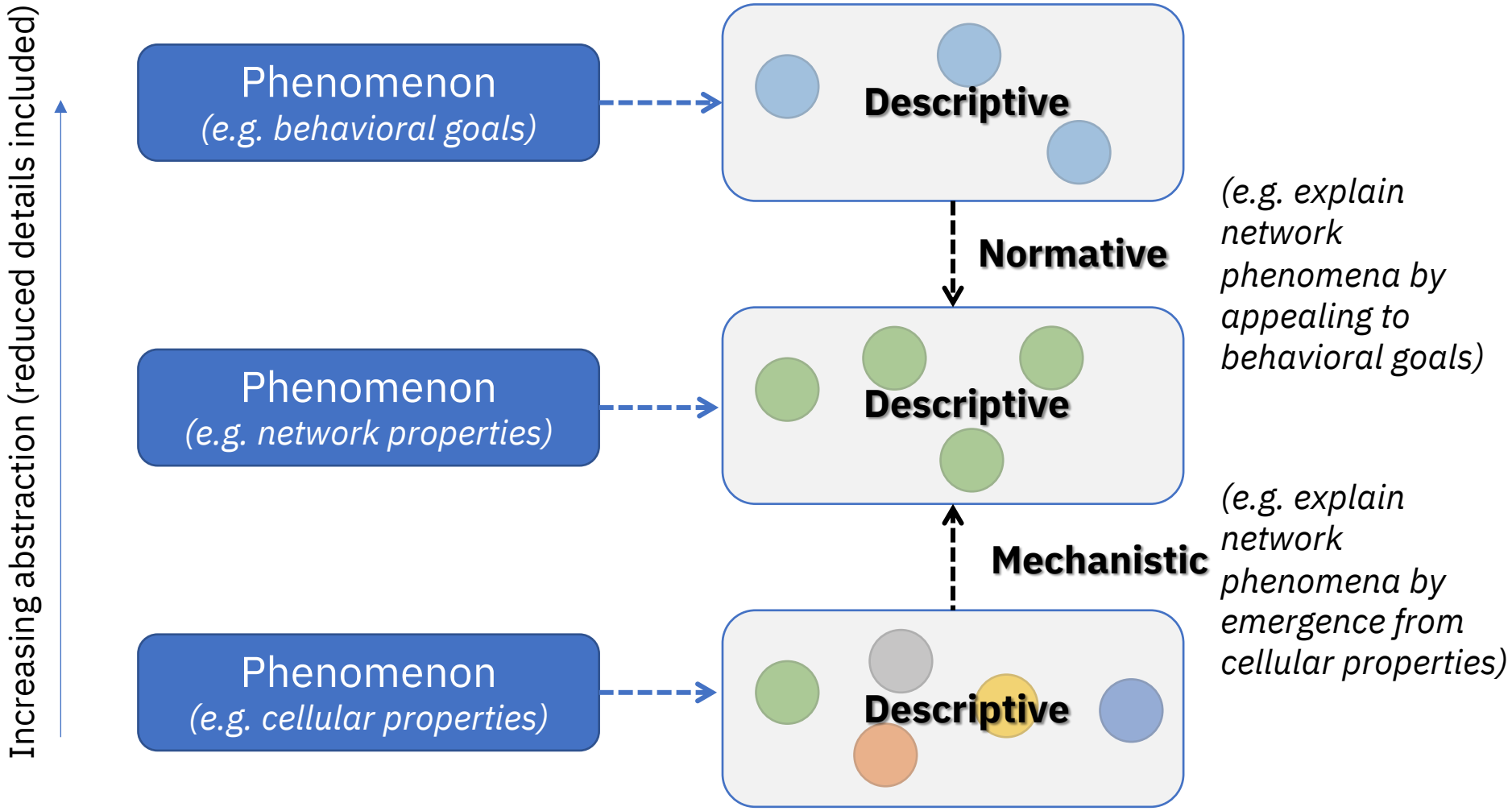
# Descriptive, Mechanistic, Normative






Levenstein, et al (2023). Figure 1

# Descriptive, Mechanistic, Normative






Levenstein, et al (2023). Figure 2

# How to build a theory and a model

- How is the phenomenon defined? What's in/out?
- What kind of question is being asked? What/How/Why?
- How were decisions made about the utility of explanations at the resulting level of abstraction?
- Causal mechanistic models: Are phenomena 'emergent' or deductive?
- Are degenerate structures or parameter spaces evaluated?
- How will predictions *compete* against existing models?
- Which functional/normative assumptions are driving the evaluation of model-based explanations?
- Is an underlying optimization process assumed? How is it justified?