The Good, The Bad and The Ugly of Computational Modeling in (Cognitive) Neuroscience

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Outline

Taxonomy

Computational (cognitive) neuroscience

The Good

Beyond phenomena: what, why, and how

The Bad

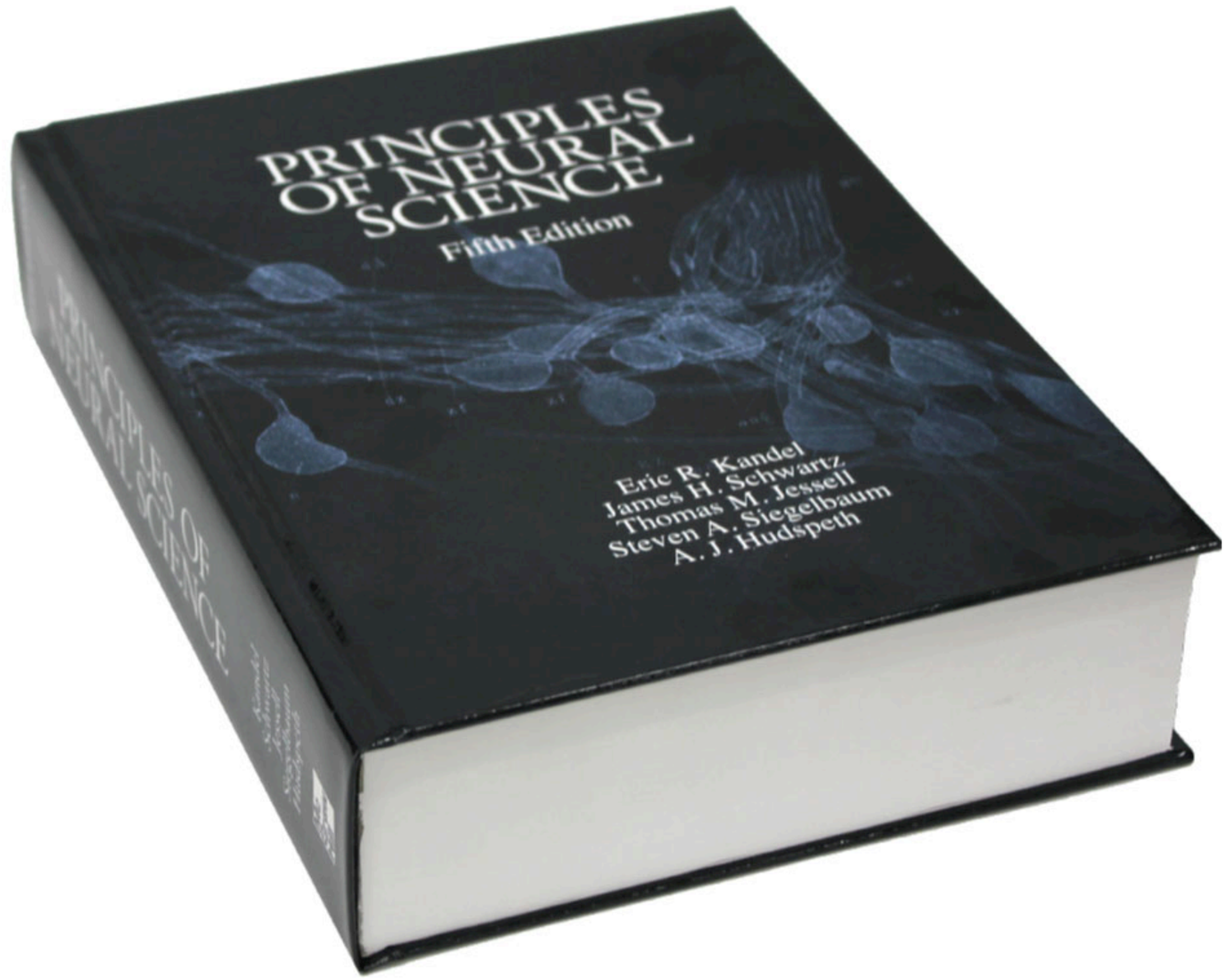
All models are wrong

The Ugly

Can we speak the same language?

Computational Neuroscience

… is prominently featured in this bible of neuroscience (1760 pages) :



Hello Theorists:

PNAS

Heavy use of equations impedes communication among biologists

Tim W. Fawcett[1] and Andrew D. Higginson

School of Biological Sciences, University of Bristol, Bristol BS8 1UG, United Kingdom

Edited[†] by Robert M. May, University of Oxford, Oxford, United Kingdom, and approved June 6, 2012 (received for review April 4, 2012)

Most research in biology is empirical, yet empirical studies rely fundamentally on theoretical work for generating testable predictions and interpreting observations. Despite this interdependence, many empirical studies build largely on other empirical studies with little direct reference to relevant theory, suggesting a failure of communication that may hinder scientific progress. To investigate the extent of this problem, we analyzed how the use of mathematical equations affects the scientific impact of studies in ecology and evolution. The density of equations in an article has a significant negative impact on citation rates, with papers receiving 28% fewer citations overall for each additional equation per page in the main text. Long, equation-dense papers tend to be more frequently cited by other theoretical papers, but this increase is outweighed by a sharp drop in citations from nontheoretical papers (35% fewer citations for each additional equation per page in the main text). In contrast, equations presented in an accompanying appendix do not lessen a paper's impact. Our analysis suggests possible strategies for enhancing the presentation of mathematical models to facilitate progress in disciplines that rely on the tight integration of theoretical and empirical work.

for enhancing the presentation of mathematical mo
tate progress in disciplines that rely on the tight i
theoretical and empirical work.

Results

To quantify the technical level of any theory pres
articles, we counted equations, inequalities, and
matical expressions (hereafter referred to simply as "e
the main text and any printed appendixes. We divided
the number of pages to give a measure of equation d
ranged from 0 to 7.29 equations per page (mean ±
0.04) and was uncorrelated with the length of the a
0.056, $P = 0.151$). To assess impact, we obtained cita
these articles from the Science Citation Index Expa
Thomson Reuters Web of Science in May 2011, exclu
citations (i.e., citing papers for which one or more
surnames matched one or more of the author surn
cited paper). The number of citations varied widely,
0 to 374 with a mean ± SEM of 44.80 ± 1.98 citatio
self-citations). Controlling for a significant positive e

Hey Experimentalists:

nature human behaviour

PERSPECTIVE

https://doi.org/10.1038/s41562-018-0522-1

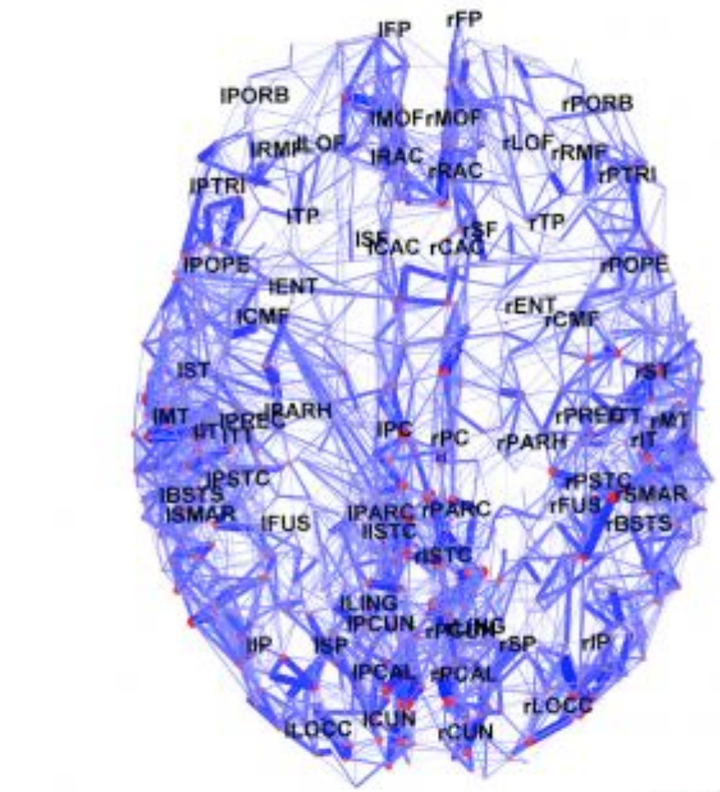
A problem in theory

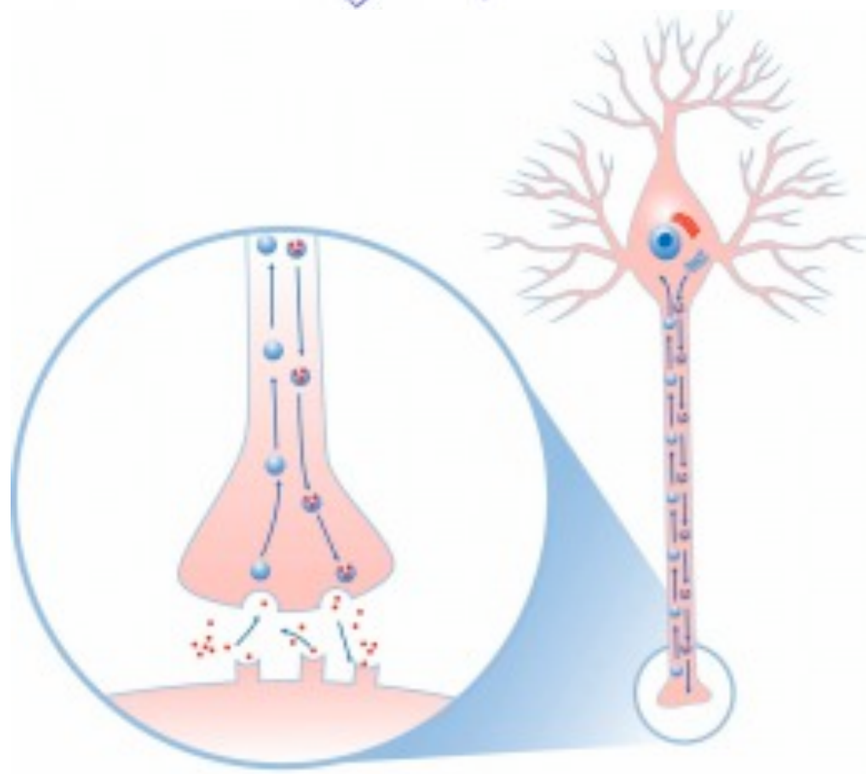
Michael Muthukrishna [1*] and Joseph Henrich [2,3]

The replication crisis facing the psychological sciences is widely regarded as rooted in methodological or statistical shortcomings. We argue that a large part of the problem is the lack of a cumulative theoretical framework or frameworks. Without an overarching theoretical framework that generates hypotheses across diverse domains, empirical programs spawn and grow from personal intuitions and culturally biased folk theories. By providing ways to develop clear predictions, including through the use of formal modelling, theoretical frameworks set expectations that determine whether a new finding is confirmatory, nicely integrating with existing lines of research, or surprising, and therefore requiring further replication and scrutiny. Such frameworks also prioritize certain research foci, motivate the use diverse empirical approaches and, often, provide a natural means to integrate across the sciences. Thus, overarching theoretical frameworks pave the way toward a more general theory of human behaviour. We illustrate one such a theoretical framework: dual inheritance theory.

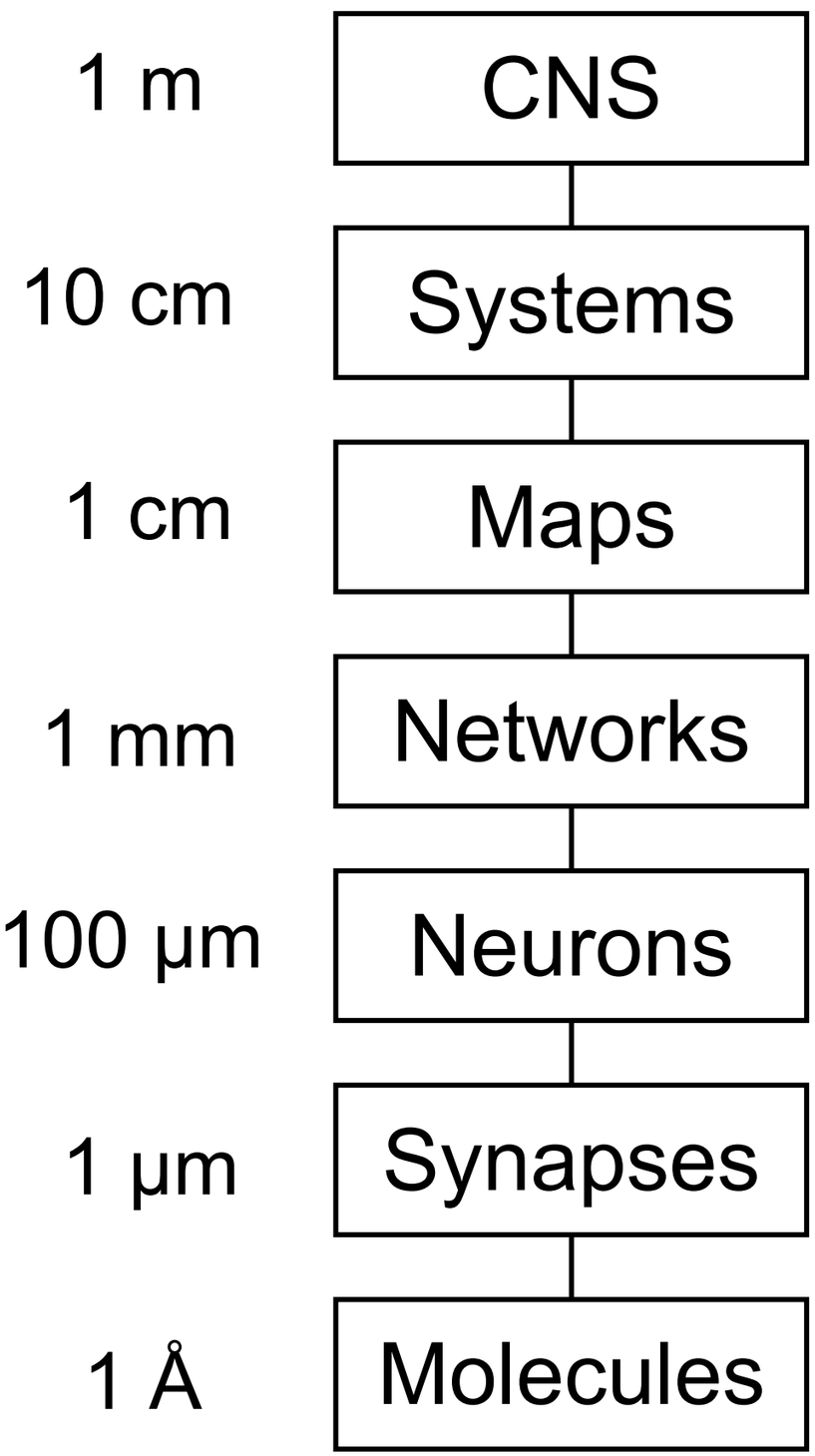
Research Scales

1 m	CNS
10 cm	Systems
1 cm	Maps
1 mm	Networks
100 µm	Neurons
1 µm	Synapses
1 Å	Molecules





Research Scales



Computational Cognitive Science

Bayesian perception
Diffusion models

Computational Cognitive Neuroscience

Connectivity analysis
Neural networks

Computational Neuroscience

Neural coding
Neuronal models

Computational Neuroscience

Pros

Offering good insights about neural processes

Providing specific testable predictions

Cons

Modeling neural correlates rather than behavior per se

Often not characterizing inter-cortical dynamics

Computational Cognitive Neuroscience

Pros

Modeling neural correlates and behavioral data

Characterizing inter-cortical dynamics

Cons

Simplifying underlying neurobiology

Increasing model complexity

Computational Cognitive Science

Pros

Simple & Straightforward

Providing good insights about cognitive processes

Cons

Often lumping different underlying processes

Neural plausibility is unclear

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All models are wrong

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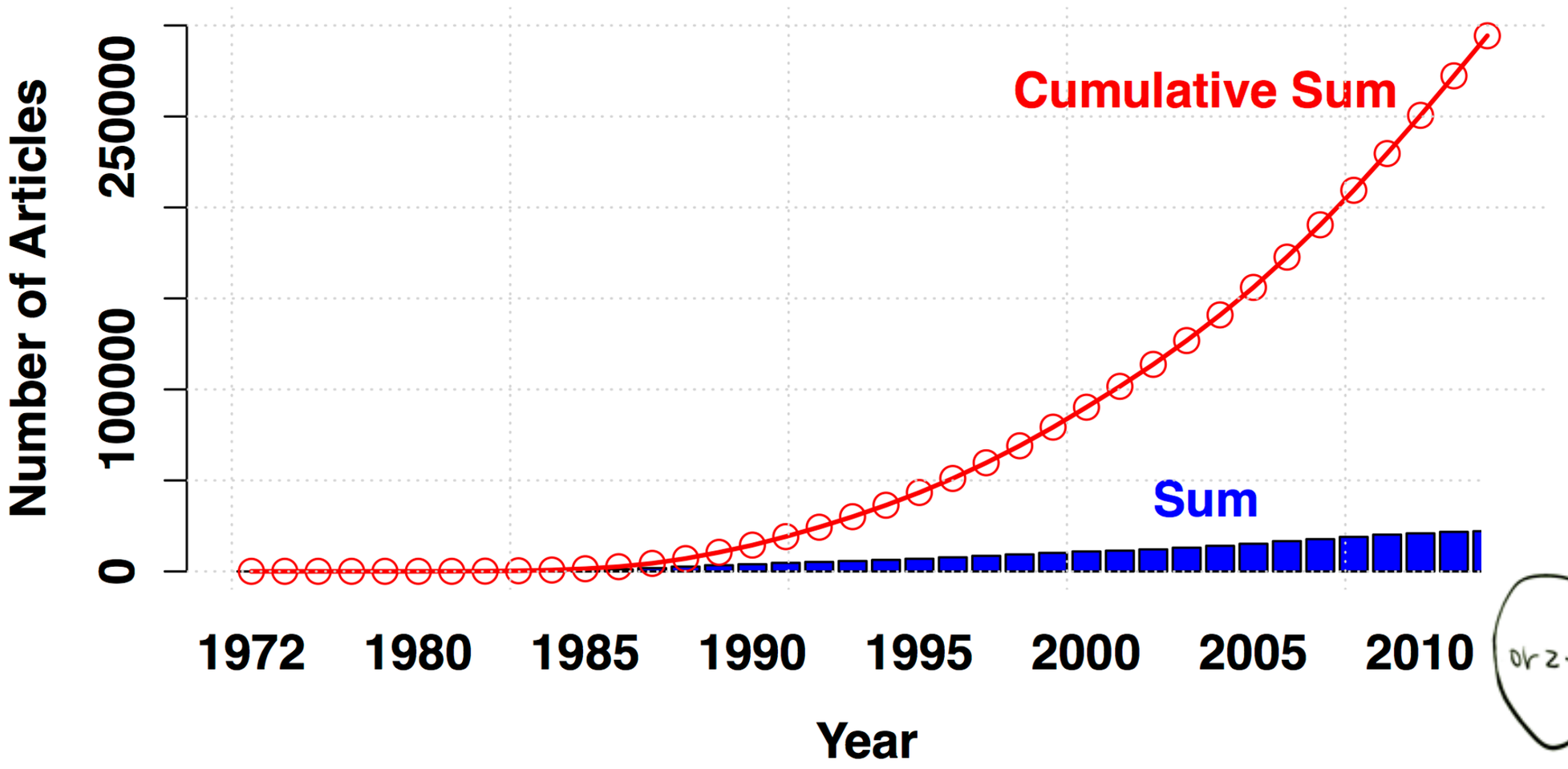
Can we speak the same language?

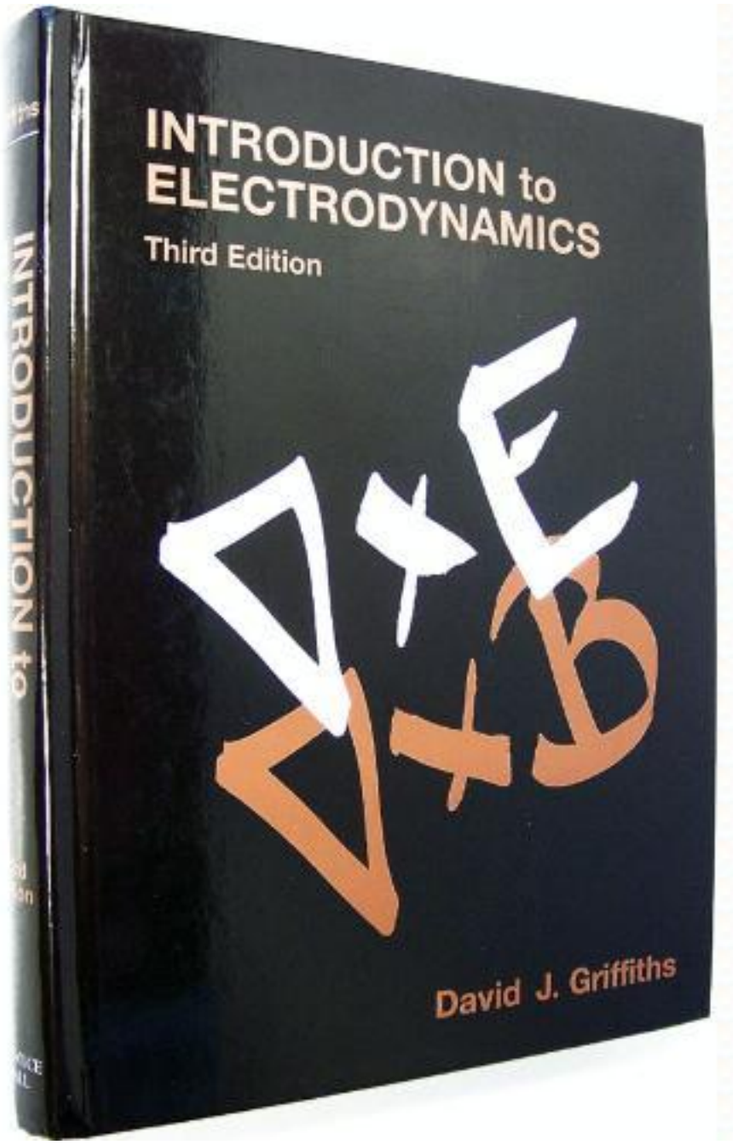
Data in (Cognitive) Neuroscience

Too much data to digest



Why modeling? Data reduction!

Maxwell's equations for
all electromagnetic phenomena:



$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

Types of Models

Conceptual Models

Making sense of data qualitatively; guiding new experiments

Mathematical Models

A compact and precise summary of data

- **Descriptive (What)**
- **Interpretive (Why)**
- **Mechanistic (How)**

Computer Simulations

Allowing concrete visualization of abstract mathematics

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Stats on Nobel Prizes

Table 2. Categorization of Nobel Science Awards, 1991–2011

	Medicine	Chemistry	Physics	Total
Theory	2	4	8	14
Method	21	22	20	63

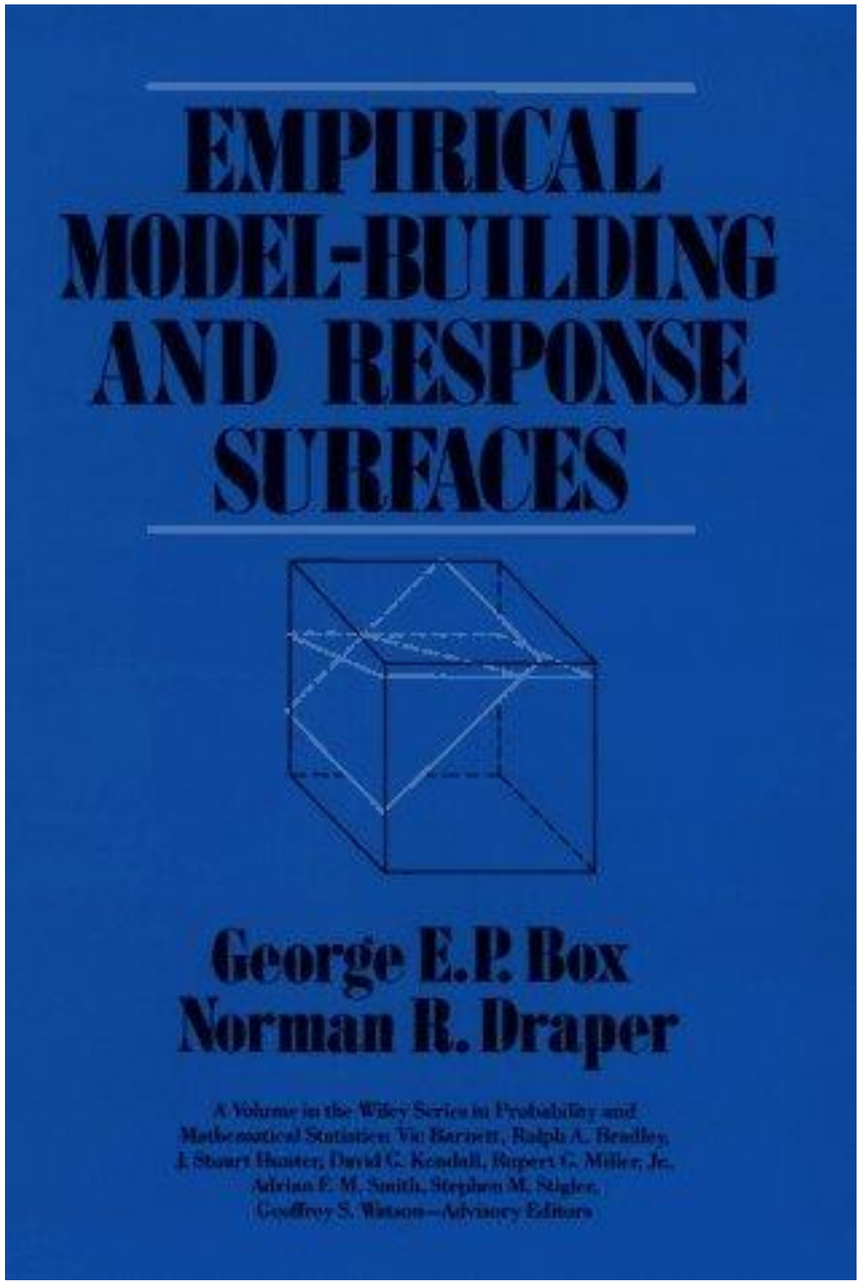
Greewald, 2012, *Perspectives on Psychological Science*

Theory will always get blown away by data.

- Jack Gallant

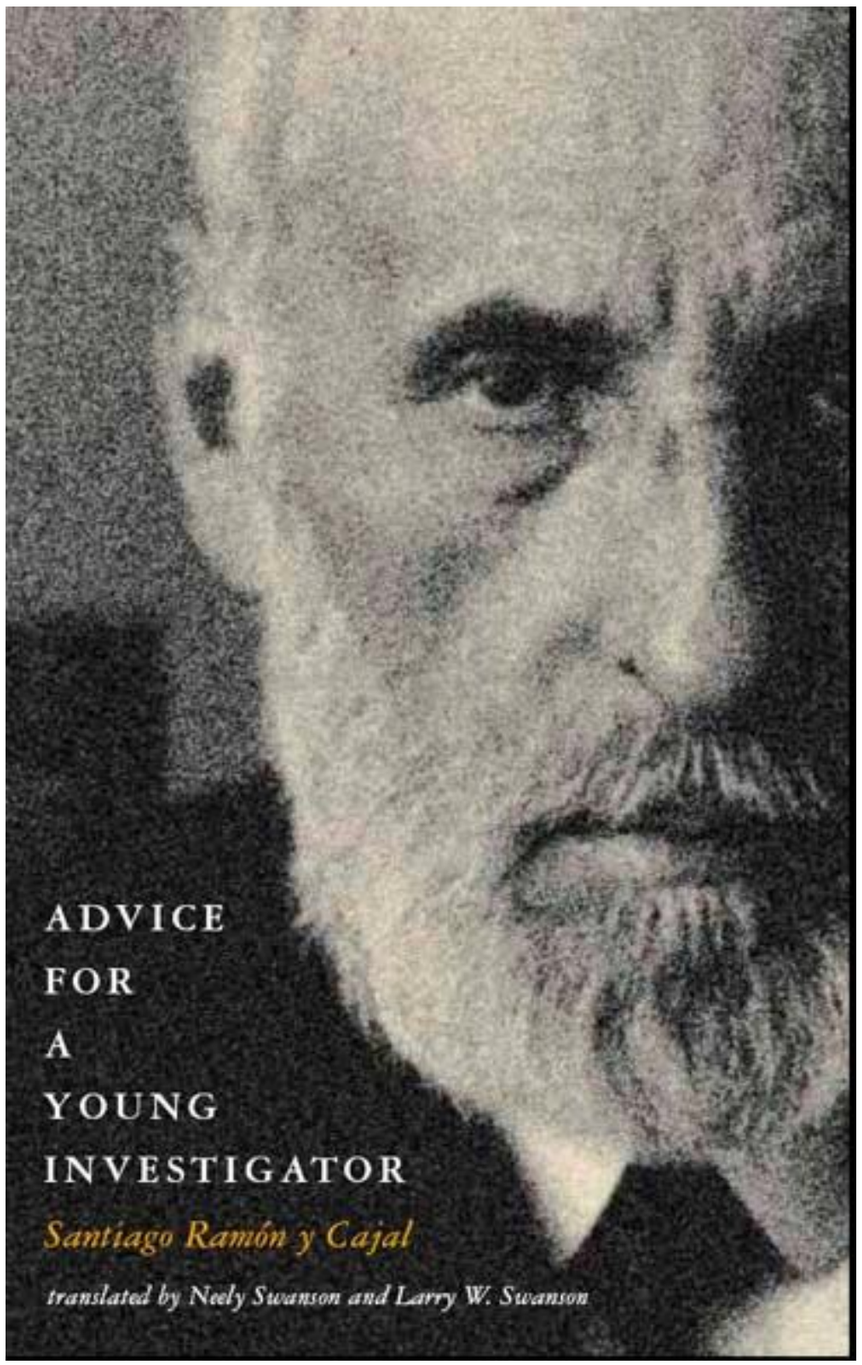
Here is the reason:

All models are wrong, but some are useful.



Box & Draper, 1987

Advice for the Young



"A scholar's positive contribution is measured by the sum of the original data that he contributes. Hypotheses come and go but data remain. Theories desert us, while data defend us."

"The beginner should devote maximal effort to discovering original facts by making precise observations, carrying out useful experiments, and providing accurate descriptions."

Ramón y Cajal, 1897

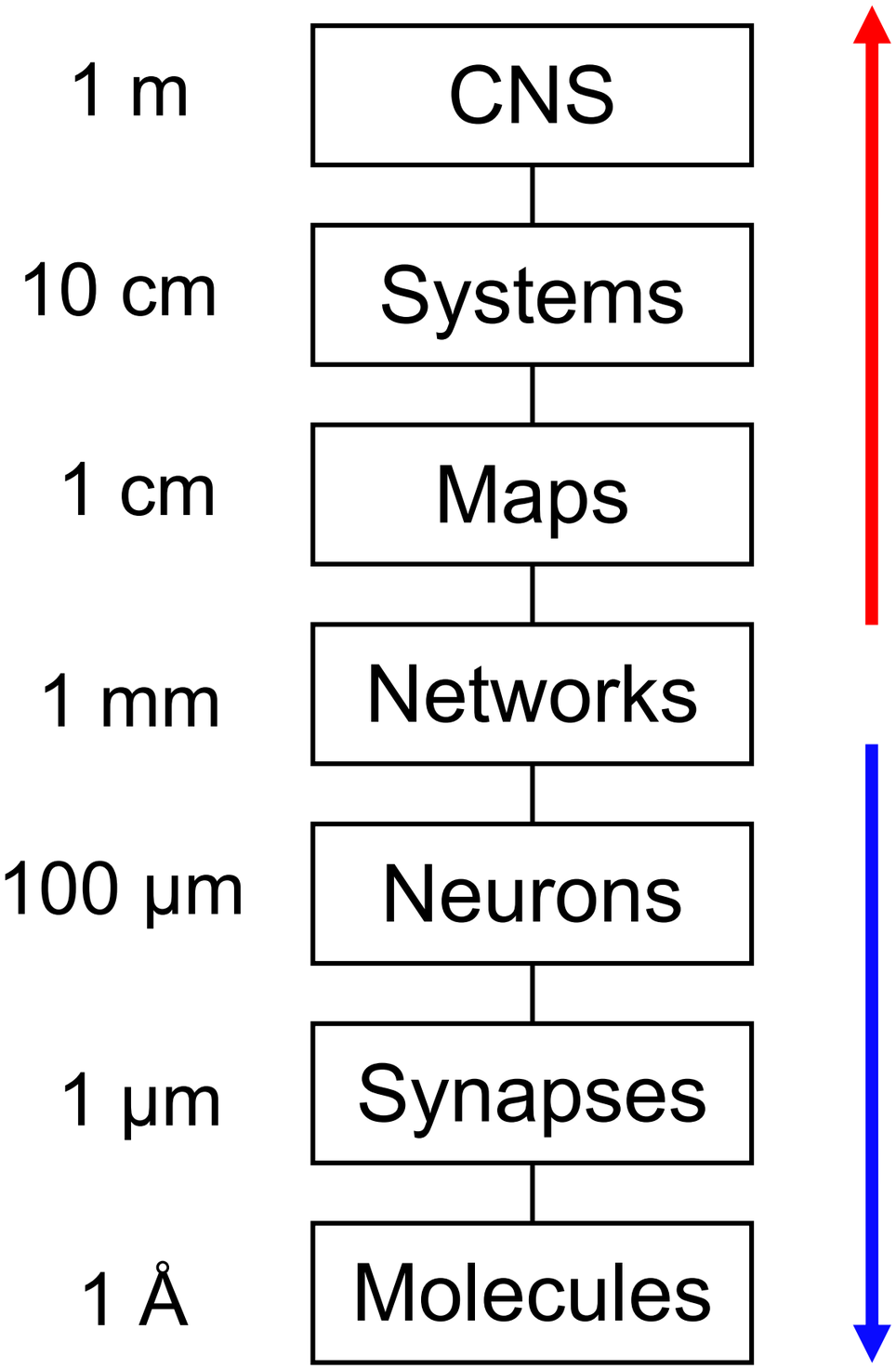
Theories = Interpretations

Portrait source: U.S. Centennial of Flight Commission
http://www.centennialofflight.gov/essay/Dictionary/newton/DI36.htm

Speed →

Size: Near or less than 10^{-9} m	Far less than 3×10^8 m/s	Comparable to 3×10^8 m/s
Far larger than 10^{-9} m	Classical Mechanics	Relativistic Mechanics
Near or less than 10^{-9} m	Quantum Mechanics	Quantum Field Theory

Scale Issue in Neuroscience



Computational Cognitive Science

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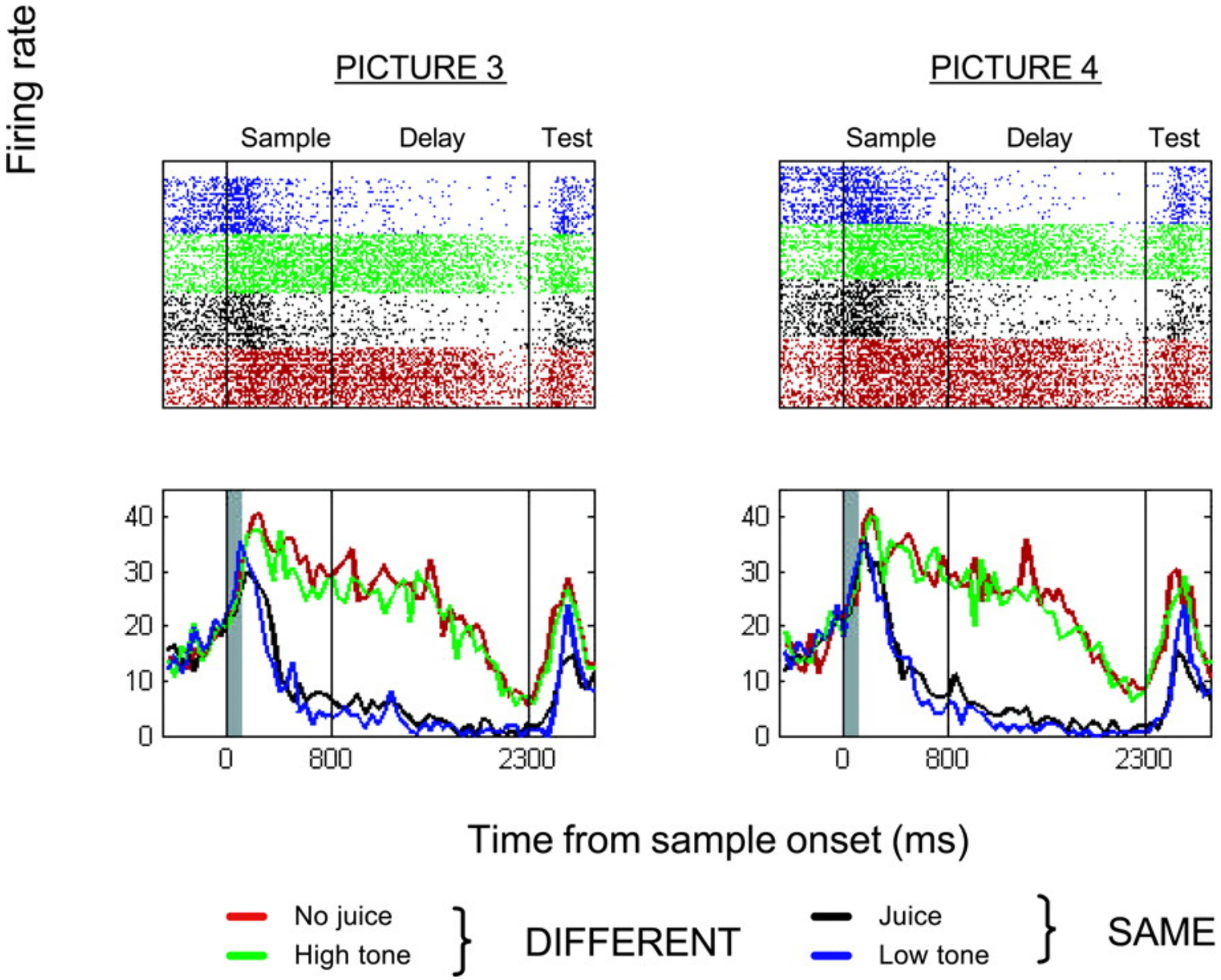
Neural coding
Neuronal models

Lacking Biological Details?

We can model the dynamics of firing rates



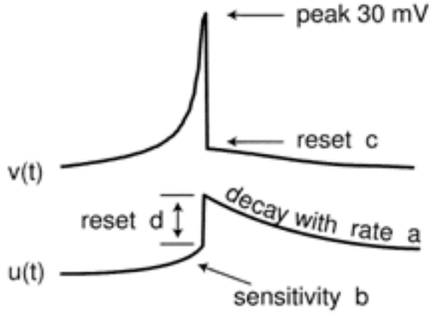
Wallis & Miller, 2003, *Journal of Neurophysiology*

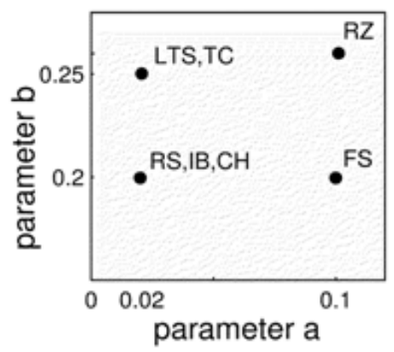
Lacking Biological Details?

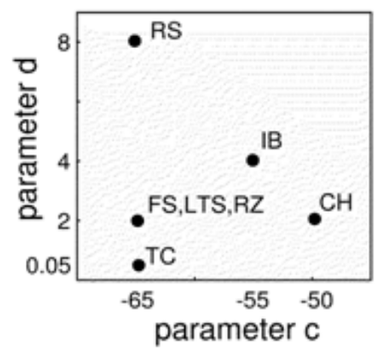
Firing-rate models cannot produce spikes:

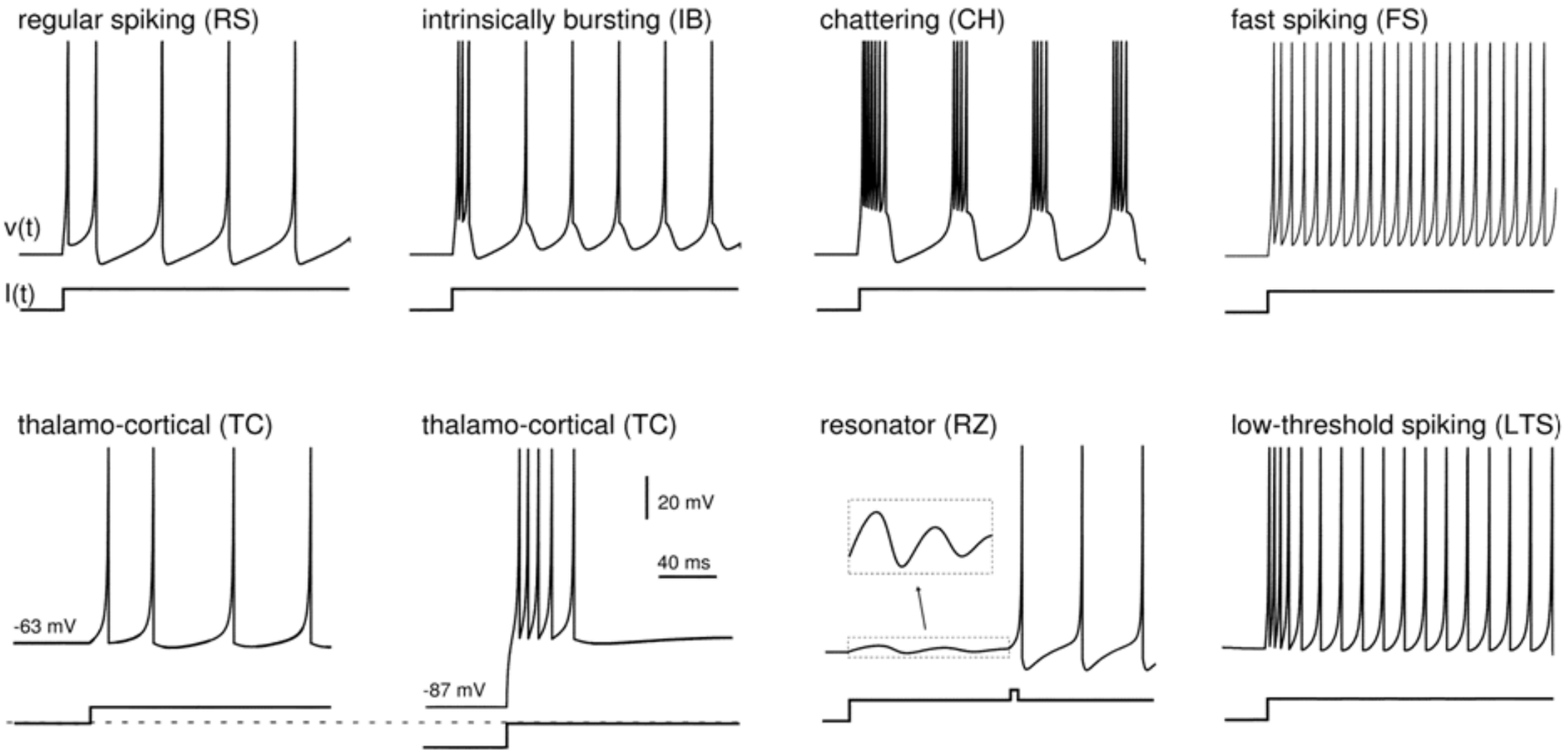
$$v' = 0.04v^2 + 5v + 140 - u + I$$
$$u' = a(bv - u)$$

if v = 30 mV,
then v ← c, u ← u + d





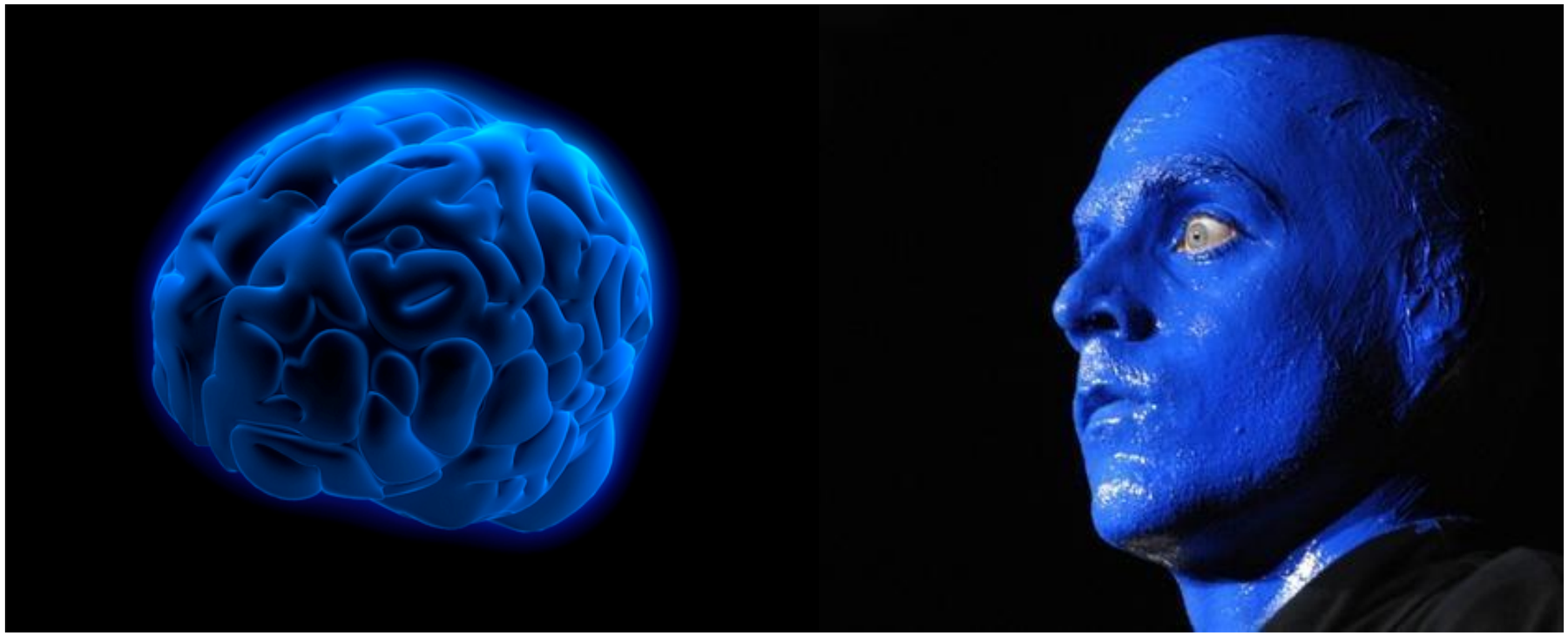




Izhikevich, 2003, *IEEE Transactions on Neural Networks*

The Blue Brain Project

Very detailed simulations of coupled neurons



What do we learn from it?

The Blue Brain Project

SCIENCE

The Human Brain Project Hasn't Lived Up to Its Promise

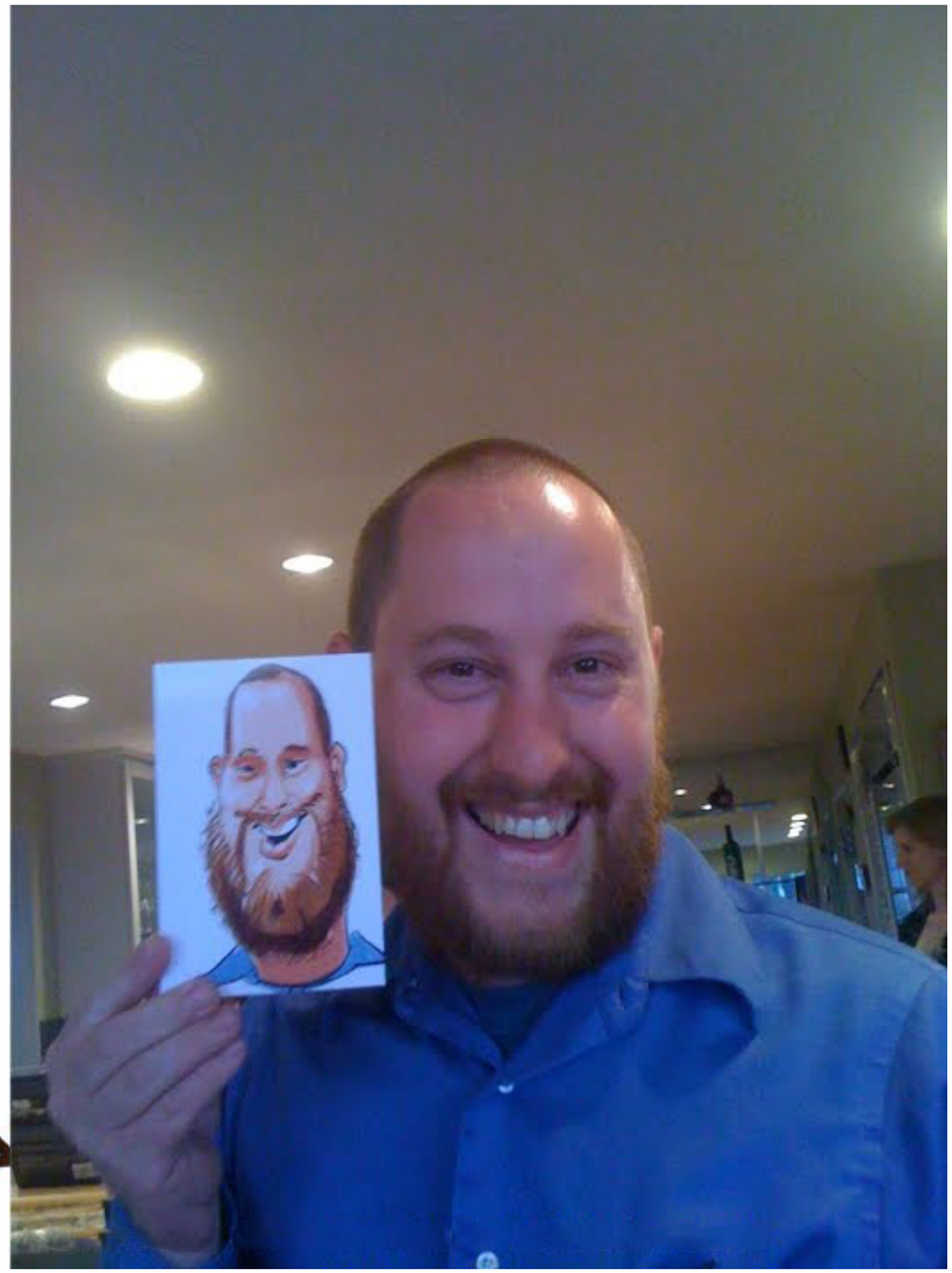
Ten years ago, a neuroscientist said that within a decade he could simulate a human brain. Spoiler: It didn't happen.

ED YONG JUL 22, 2019

The HBP, then, is in a very odd position, criticized for being simultaneously too grandiose *and* too narrow. None of the skeptics I spoke with was dismissing the idea of simulating parts of the brain, but all of them felt that such efforts should be driven by actual research questions. For example, Xiao-Jing Wang from New York University has built models that show how neurons, if connected in a certain way, can hold on to electrical activity even if they're not being stimulated—the essence of what we call working memory, or the ability to hold on to thoughts. Meanwhile, Chris Eliasmith from the University of Waterloo has built a model called Spaun, which uses a simplified set of 2.5 million virtual neurons to do simple arithmetic and solve basic reasoning problems.

The Point of Modeling

To characterize defining features



1:1 Map

1:1 Map

Too big to be useful

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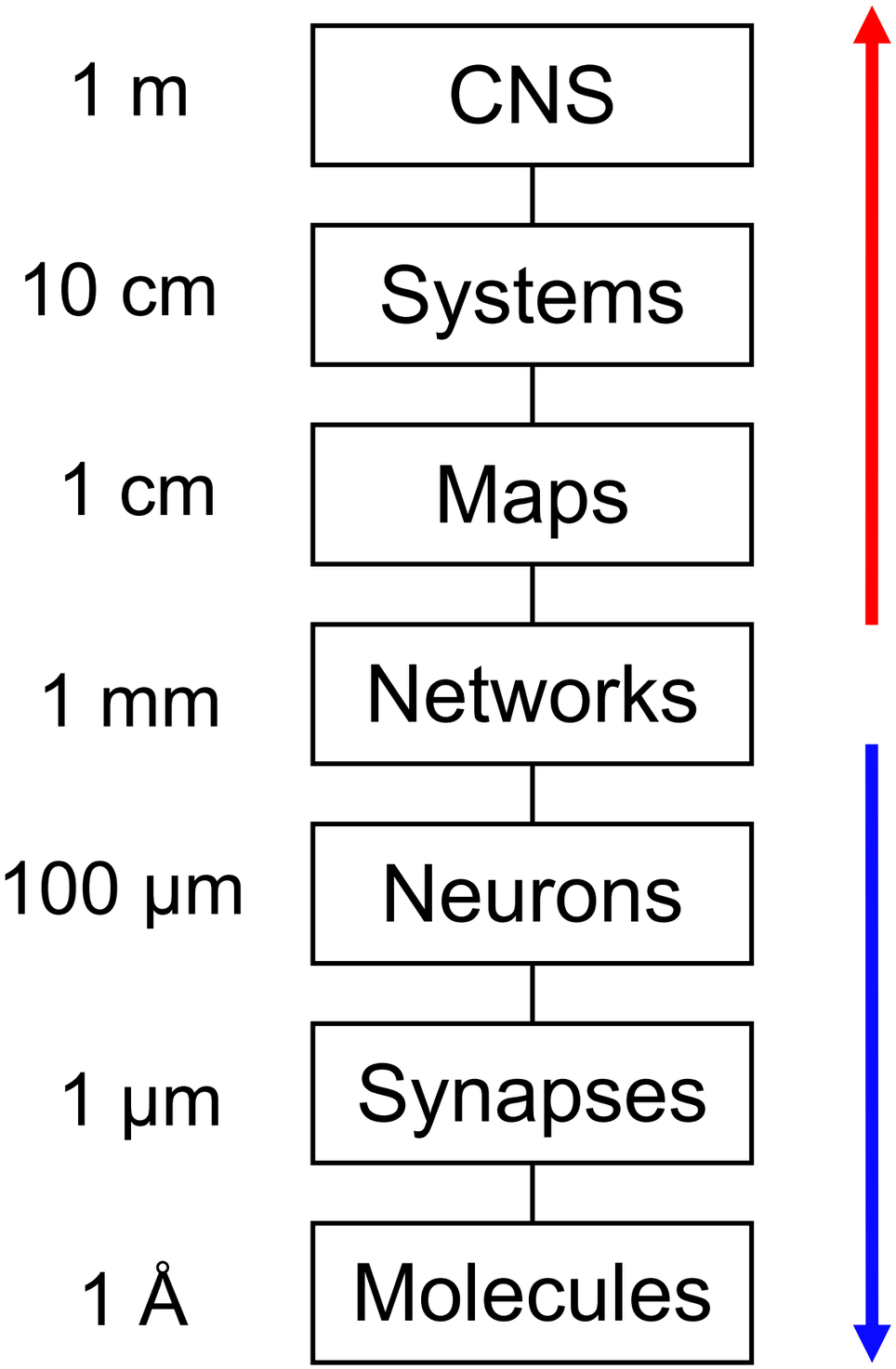
Governing Equations?



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Neuronal models

A Less Integrated Community

OPEN ACCESS Freely available online

PLoS COMPUTATIONAL BIOLOGY

Review

Why Are Computational Neuroscience and Systems Biology So Separate?

Erik De Schutter[1,2]*

1 Computational Neuroscience Unit, Okinawa Institute of Science and Technology, Japan, **2** Theoretical Neurobiology, University of Antwerp, Antwerp, Belgium

Abstract: Despite similar computational approaches, there is surprisingly little interaction between the computational neuroscience and the systems biology research communities. In this review I reconstruct the history of the two disciplines and show that this may explain why they grew up apart. The separation is a pity, as both fields can learn quite a bit from each other. Several examples are given, covering sociological, software technical, and methodological aspects. Systems biology is a better organized community which is very effective at sharing resources, while computational neuroscience has more experience in multiscale modeling and the analysis of information processing by biological systems. Finally, I speculate about how the relationship between the two fields may evolve in the near future.

cosyne.org). Alternatively, computational neuroscience is about the use of computational approaches to investigate the properties of nervous systems at different levels of detail [8–10]. Strictly speaking, this implies simulation of numerical models on computers, but usually analytical models are also included (e.g., the material covered in [9]), and experimental verification of models is an important issue [11]. Sometimes this modeling is quite data driven and may involve cycling back and forth between experimental and computational methods [12]. A typical venue is the Computational Neuroscience Meeting (http://www.cnsorg.org/) and user meetings of specific neural simulator packages. Although these two opposing views are often swept under the carpet, and many scientists attend both conferences mentioned, they are reflected in partially separate communities and sometimes lead to heated debate about how the field should be defined.

Similarly, systems biology has also been described in multiple

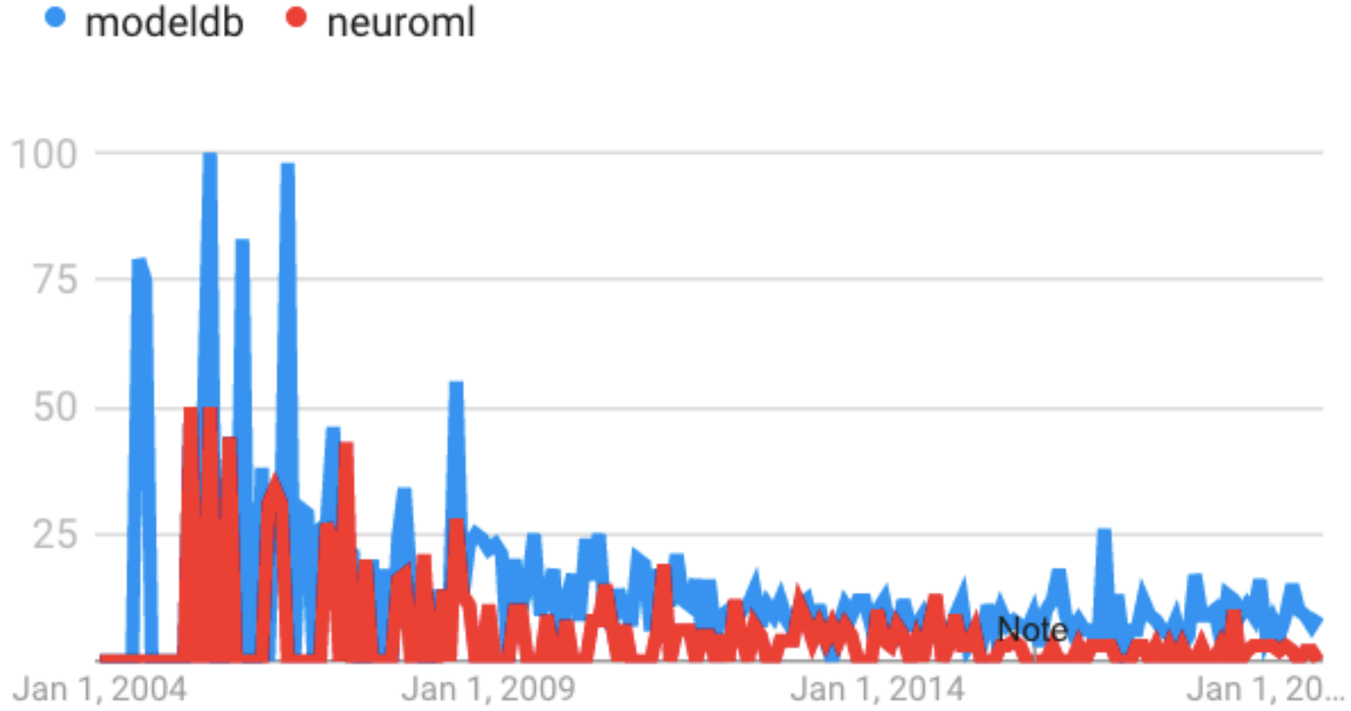
A Common DB & Language

ModelDB

[NeuroML]

Interest over time

Worldwide. 1/1/04 - 9/10/19. Web Search.



Google Trends

Scale Issue in Physics

Correspondence Principle:

Quantum Mechanics → Classical Mechanics

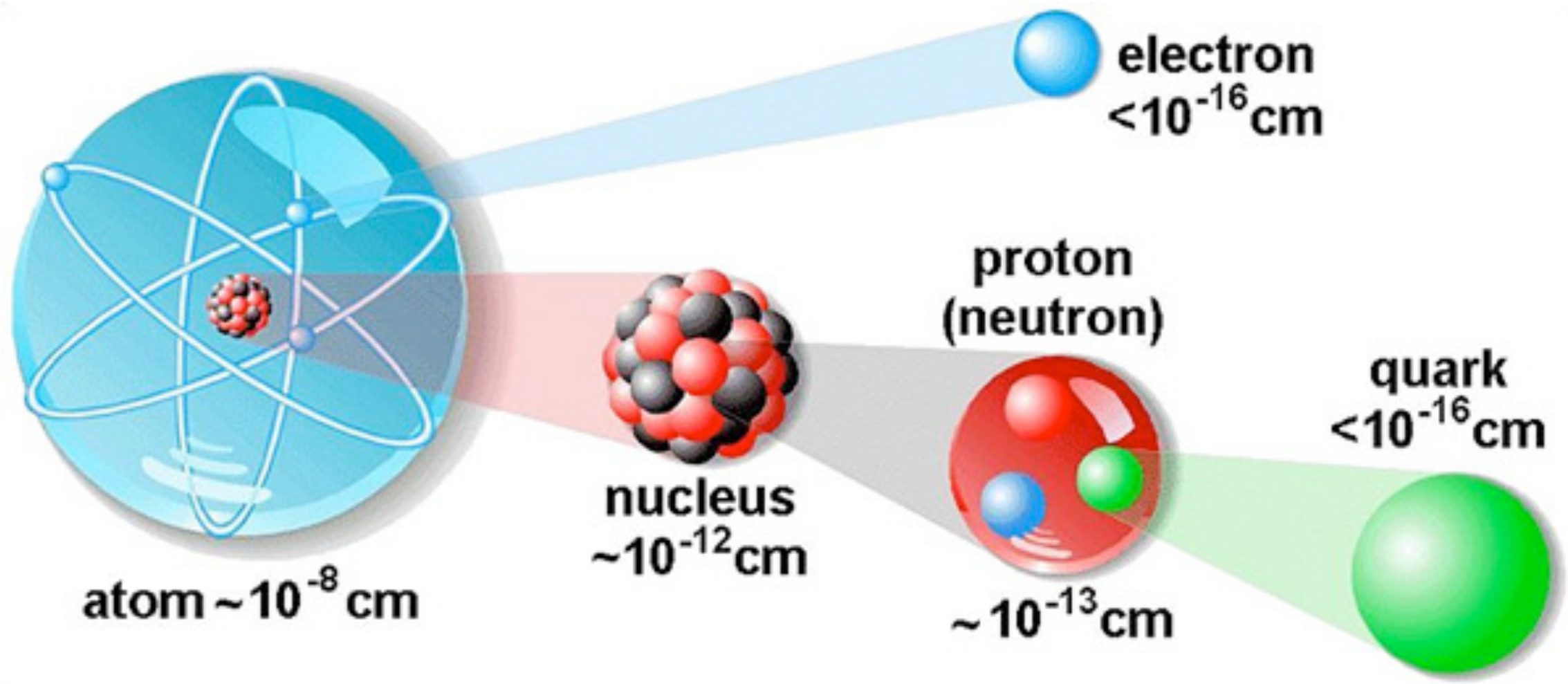
Planck's constant

de Broglie wavelength $\lambda = \frac{h}{p}$ $\quad p >> h \quad \longrightarrow \quad 0$

Momentum

Scale Issue in Physics

Renormalization and Effective theories:



Toward a Unified Theory

Correspondence Principle:

Molecules/Ion-Channels→Neurons→Networks→Behavior

Toward a Unified Theory

Correspondence Principle:

Molecules/Ion-Channels→Neurons→Networks→Behavior

Mechanistic

↓

Descriptive→Mechanistic

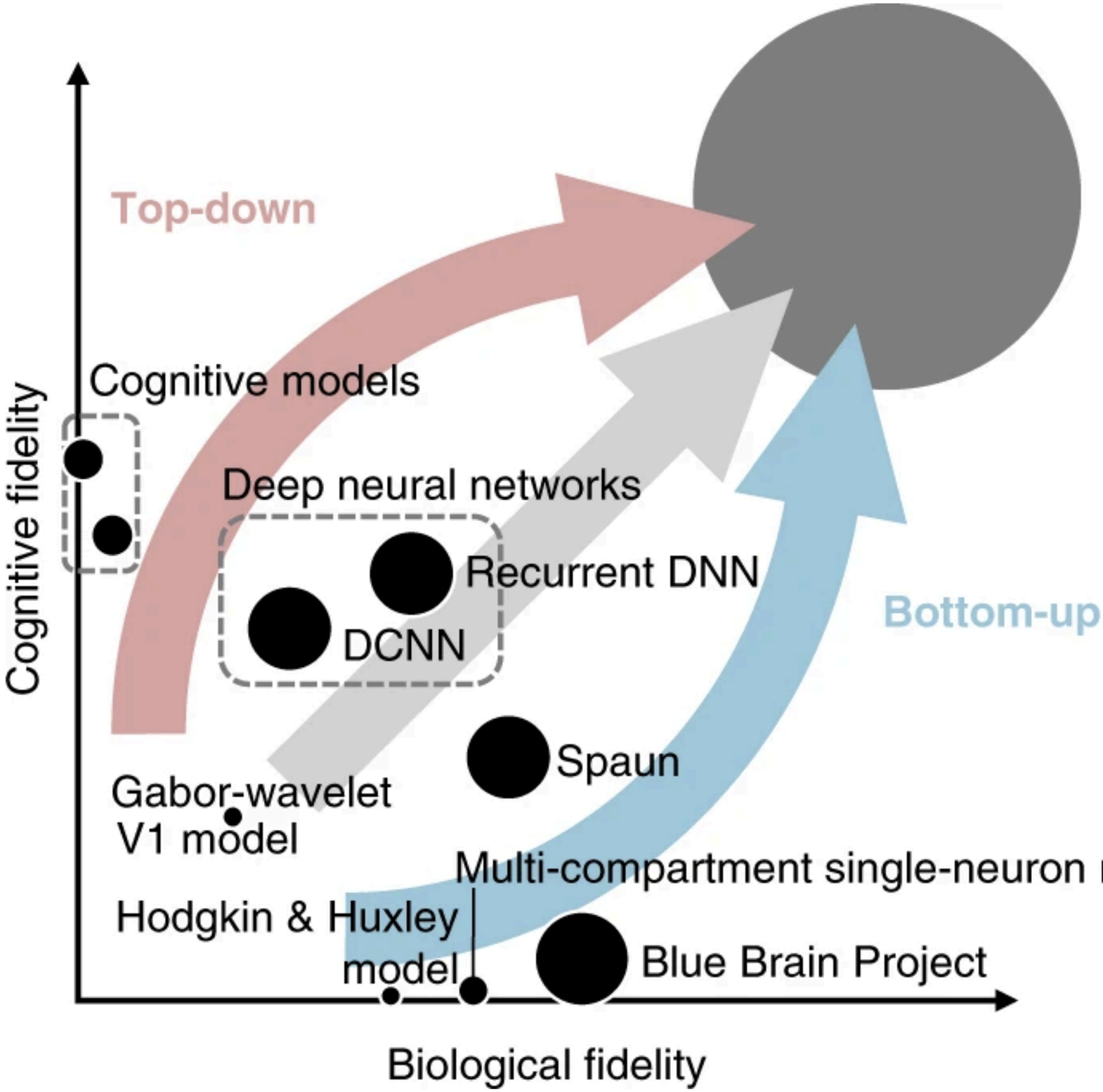
Toward a Unified Theory

Correspondence Principle:

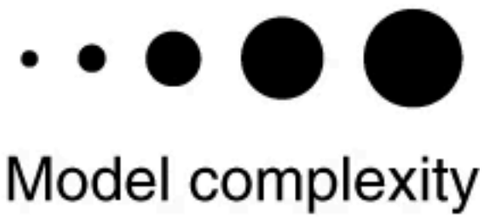
Molecules/Ion-Channels→Neurons→Networks→Behavior

Mechanistic
↓
Descriptive→Mechanistic
↓
Descriptive→Mechanistic
↓
Descriptive→Mechanistic

Evolution of Models

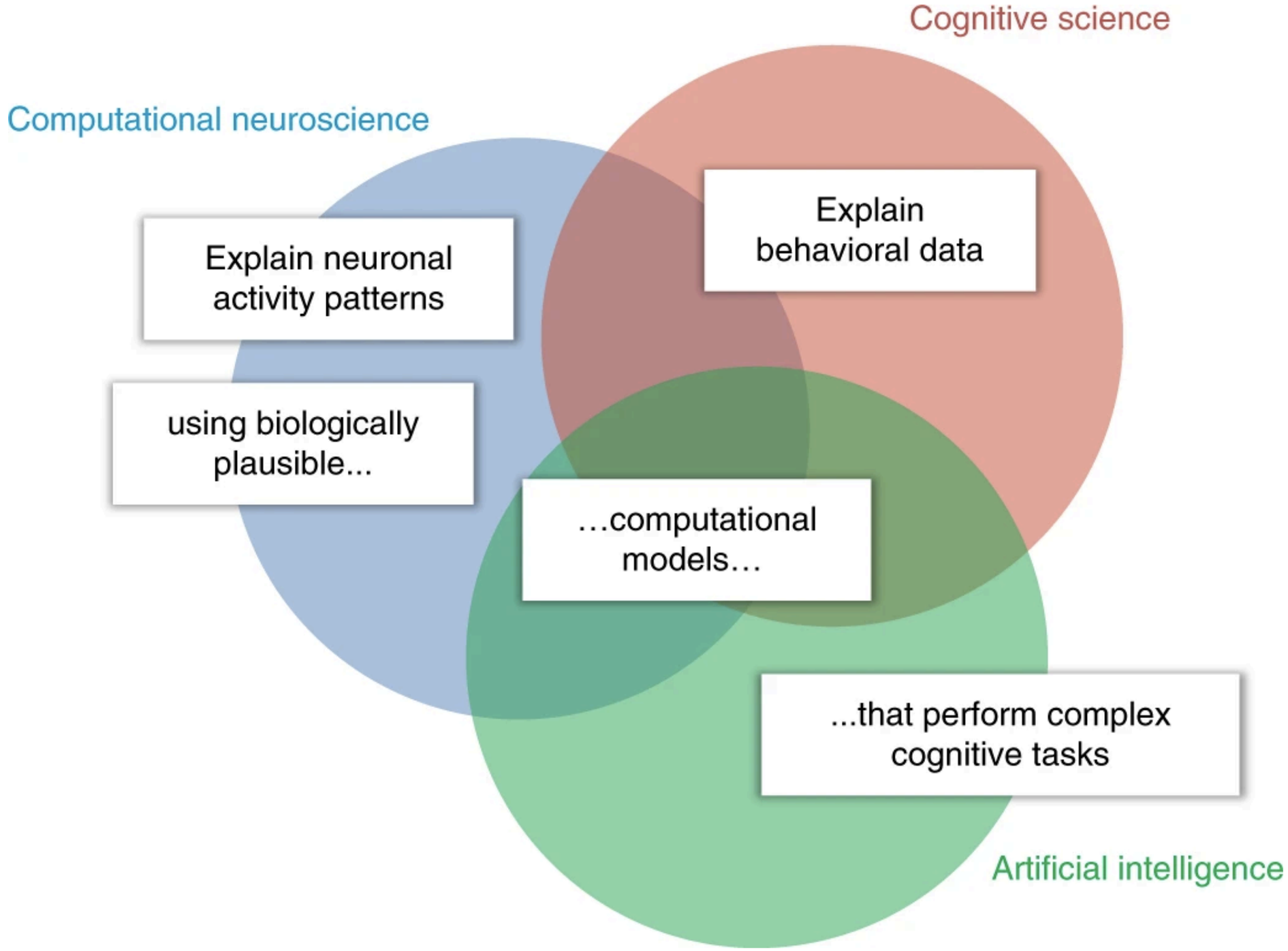


Getting more & more complex!



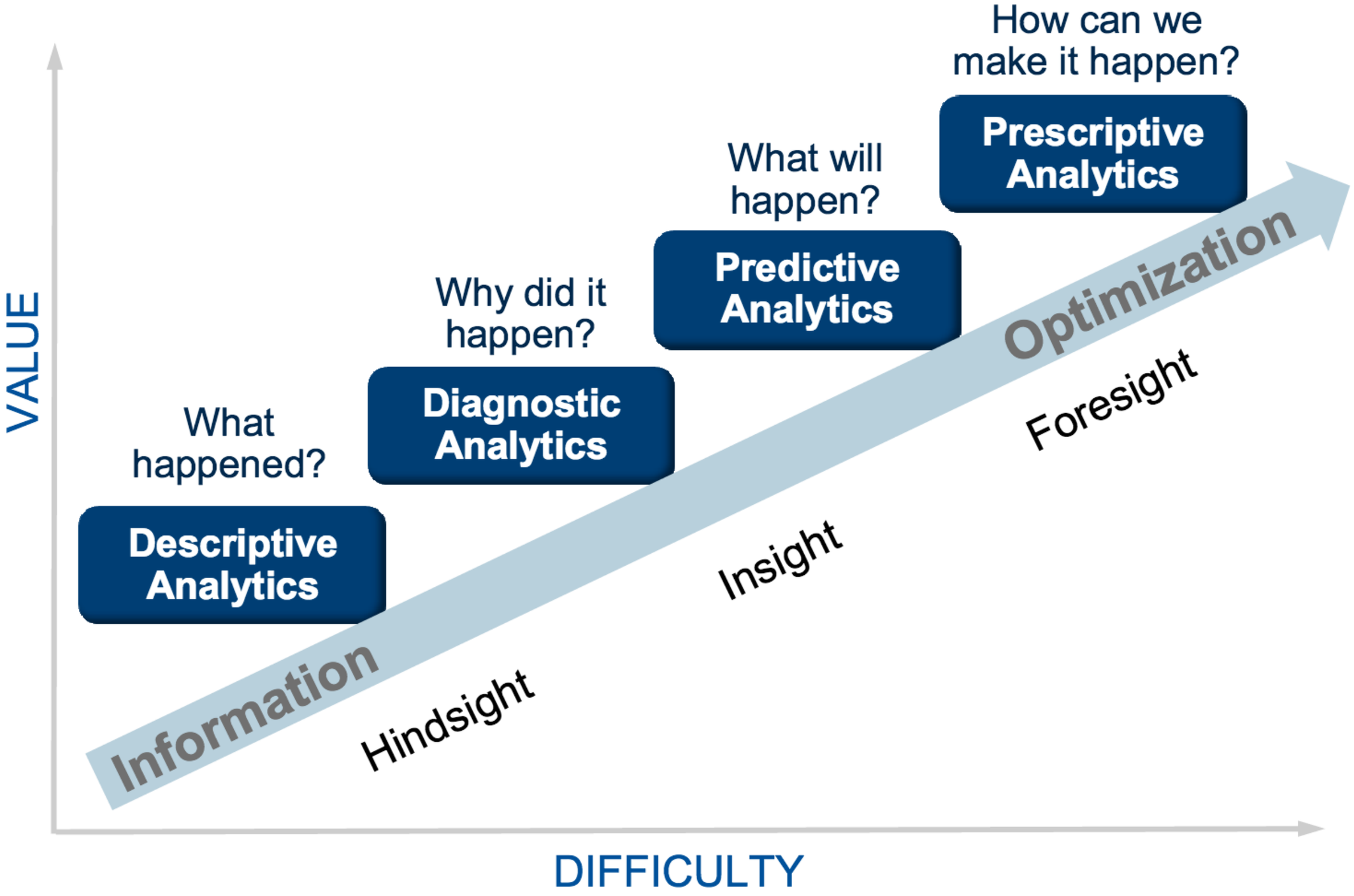
Beyond Explanations

AI models are good at predictions



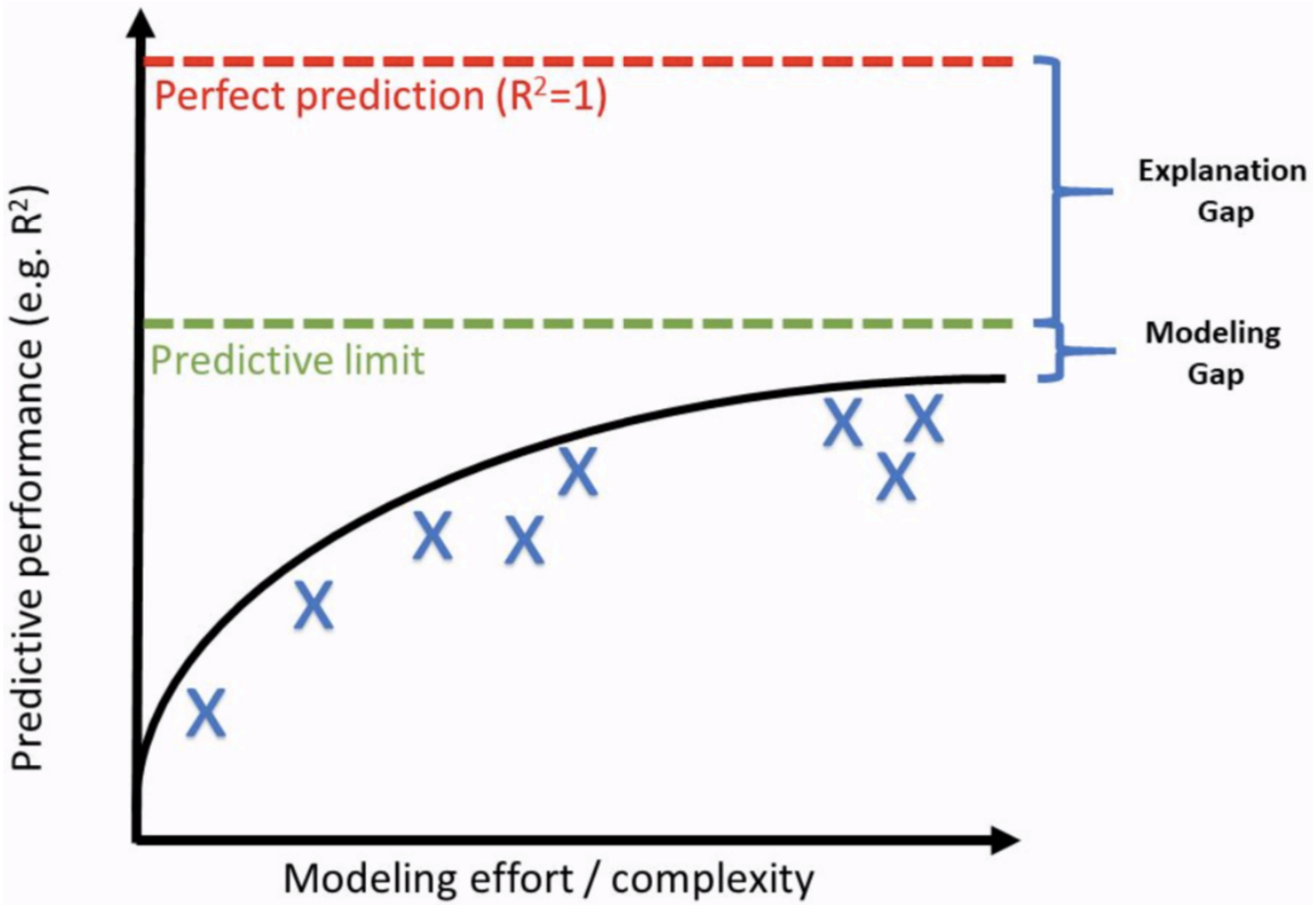
Beyond Explanations

As a natural progress of science



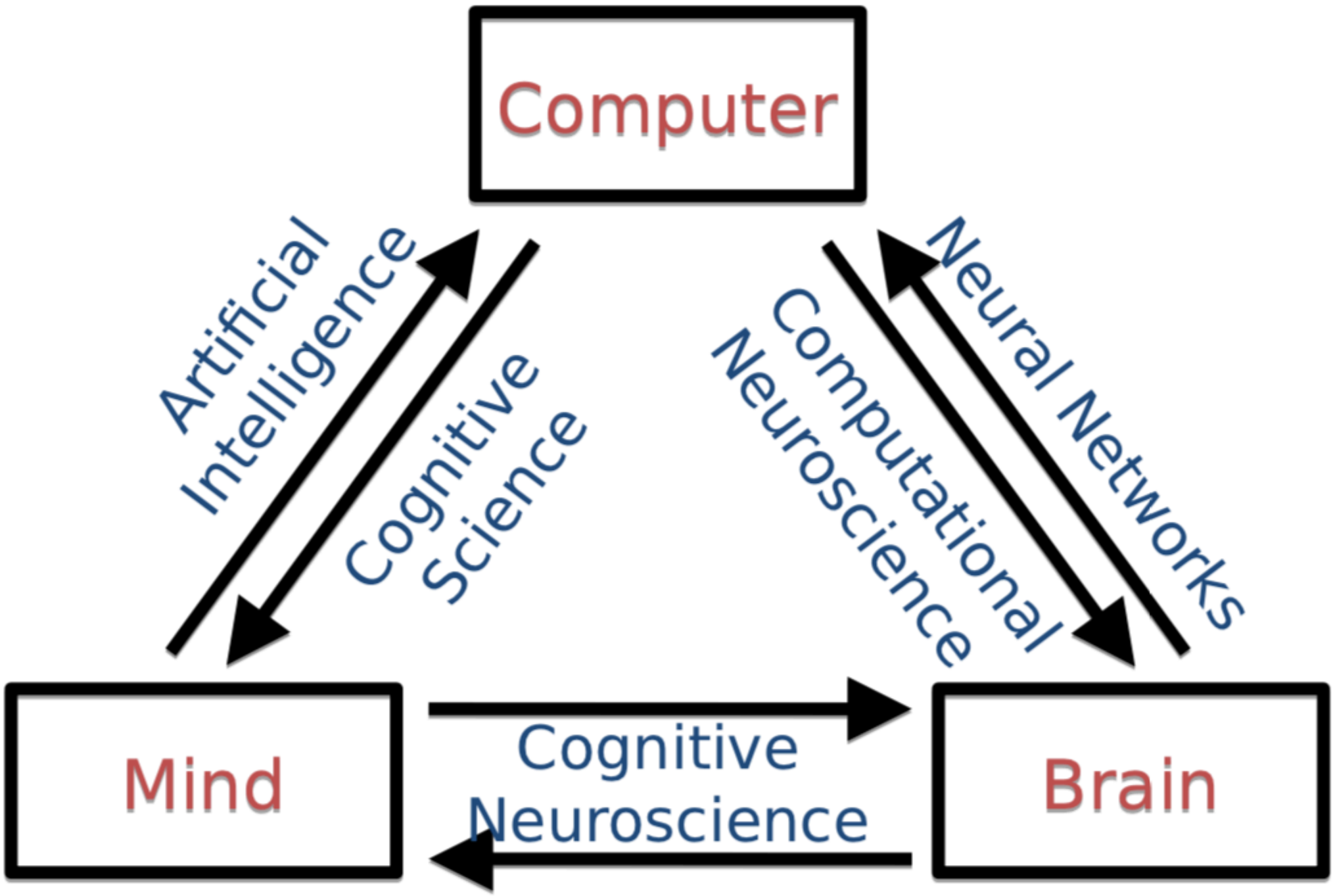
Beyond Explanations

Explanation & prediction: Two sides of the same coin!



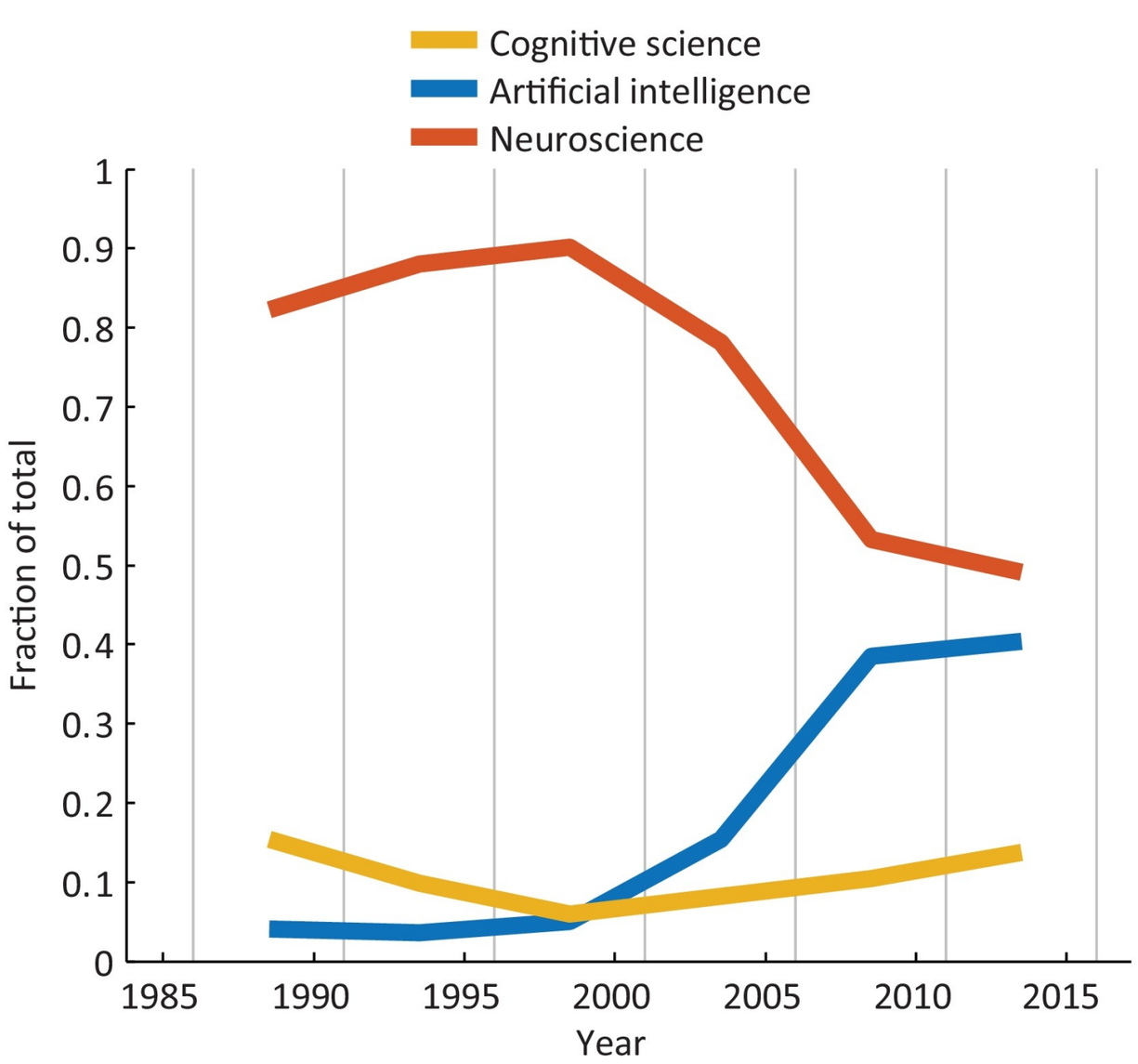
Closely Related Fields

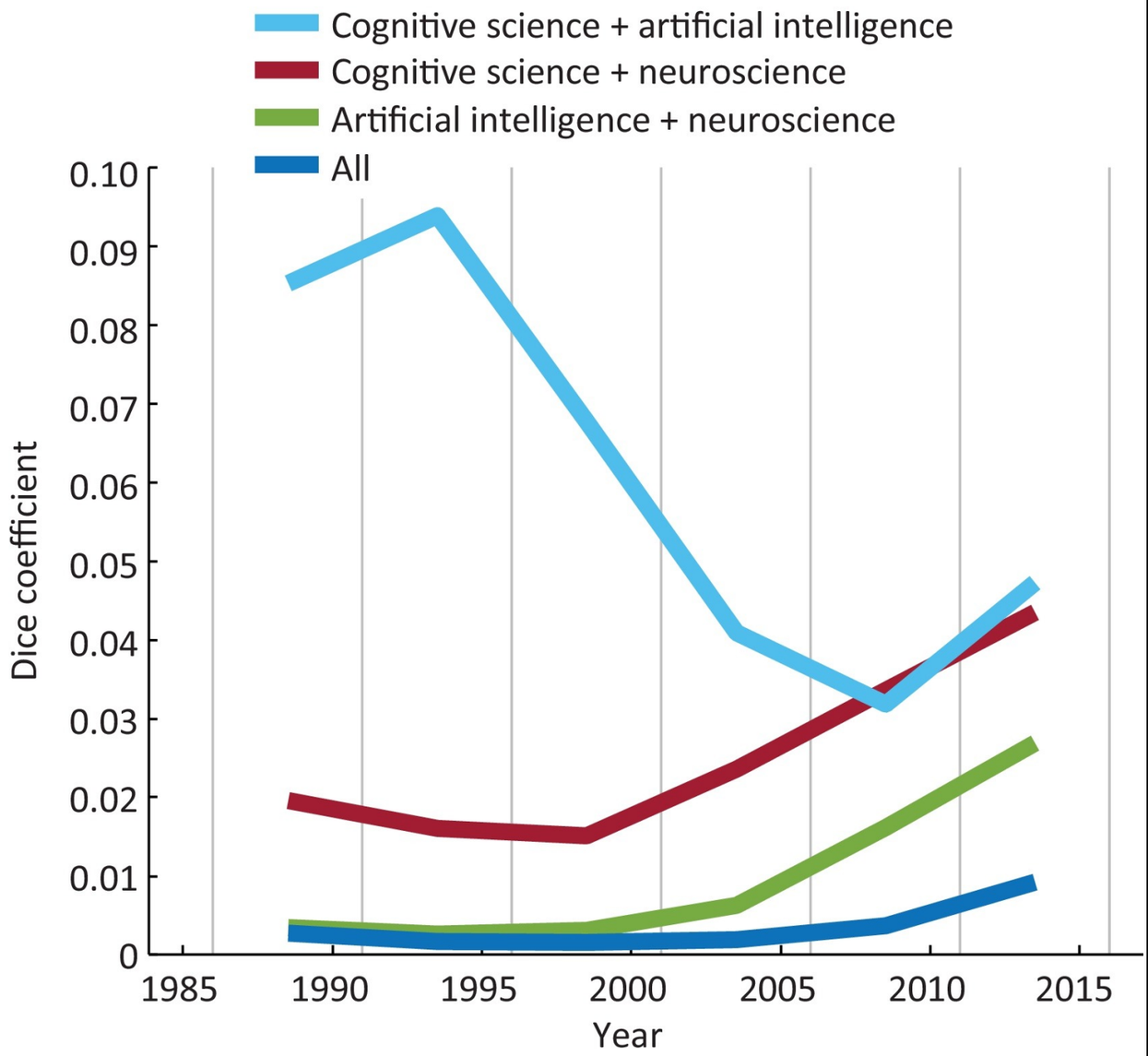
All discussed in this course



Closely Related Fields

Note the trend





I want to study how the brain works from a theoretical perspective.