COMS30127: Computational Neuroscience

The craft of computational modelling for neuroscience

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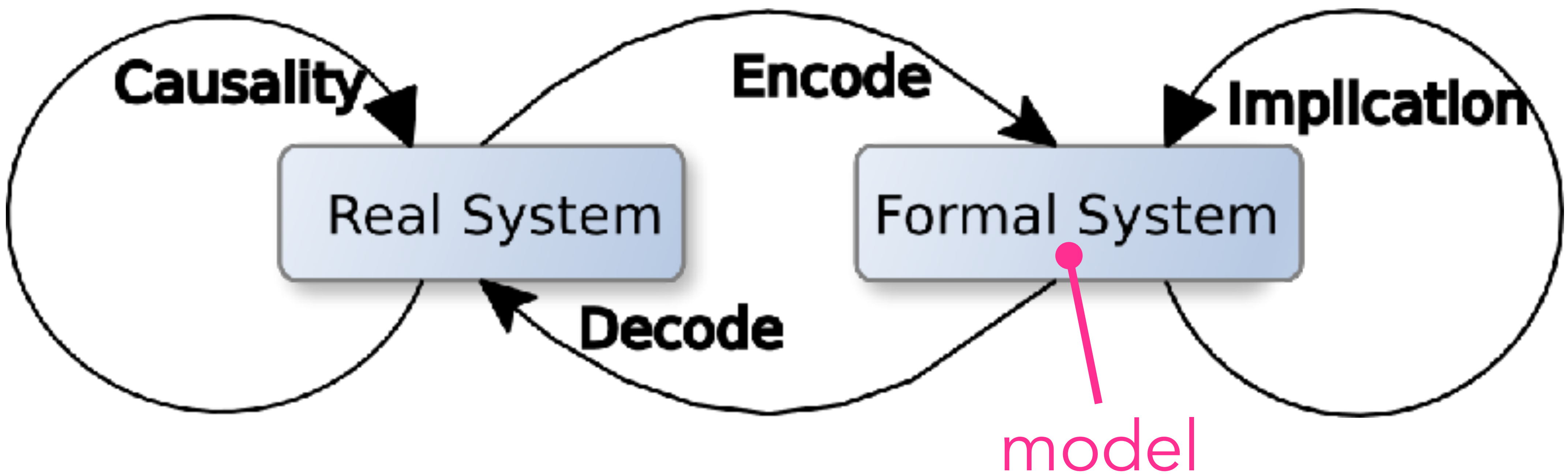
What we will cover today

- What is a model?
- What is the purpose of computational modelling?
- Levels of abstraction (spatial, temporal and conceptual)
- Compare models of single neurons.
- The Fitzhugh-Nagumo neuron model.
- How should we choose the 'correct' model for the problem at hand?

What is a model?

- A model is a simplified description of a real-world system.
- Models can be:
  - Physical (e.g. scale models of buildings)
  - Analogical (e.g. billiard-ball model of a gas)
  - Phenomenological (e.g. integrate-and-fire neuron)
- Models can be represented by:
  - A physical object
  - Words
  - Mathematical equations
- Overview of the philosophy of models in science: https://plato.stanford.edu/entries/models-science/

What is a model?



https://commons.wikimedia.org/wiki/File:MathModel.svg

What is a computational model?

- Fundamentally, a computational model is just a mathematical model that is programmed and then solved or simulated using a computer.

- Technically speaking all computational models are phenomenological (e.g. Hodgkin and Huxley ignored quantum mechanics).

- However in practice in neuroscience, most people consider phenomenological models to be those which abstract away all laws of (bio)physics.

What is the purpose of a computational model?

"All models are wrong, but some are useful."

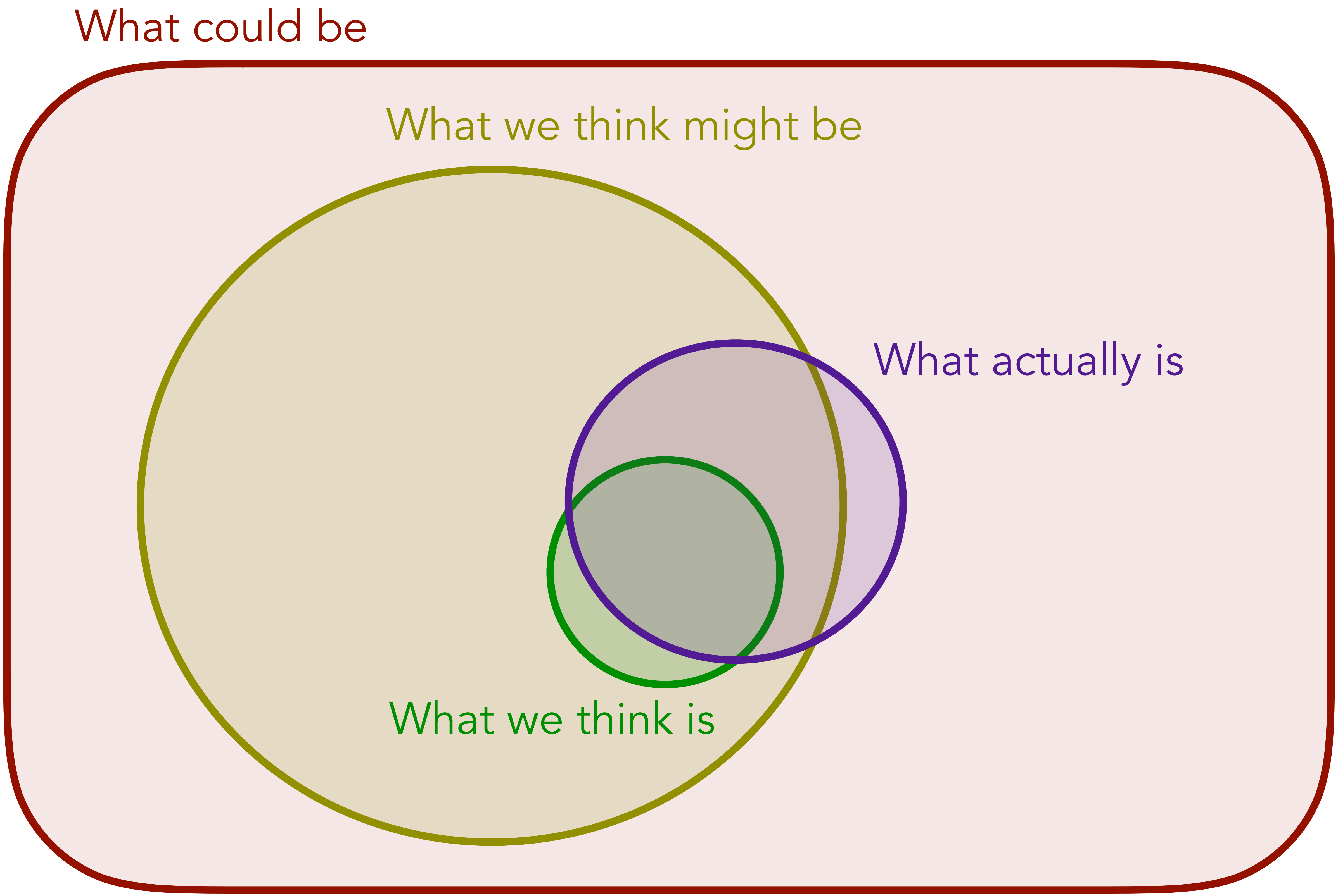
— George Box

What is the purpose of a computational model?

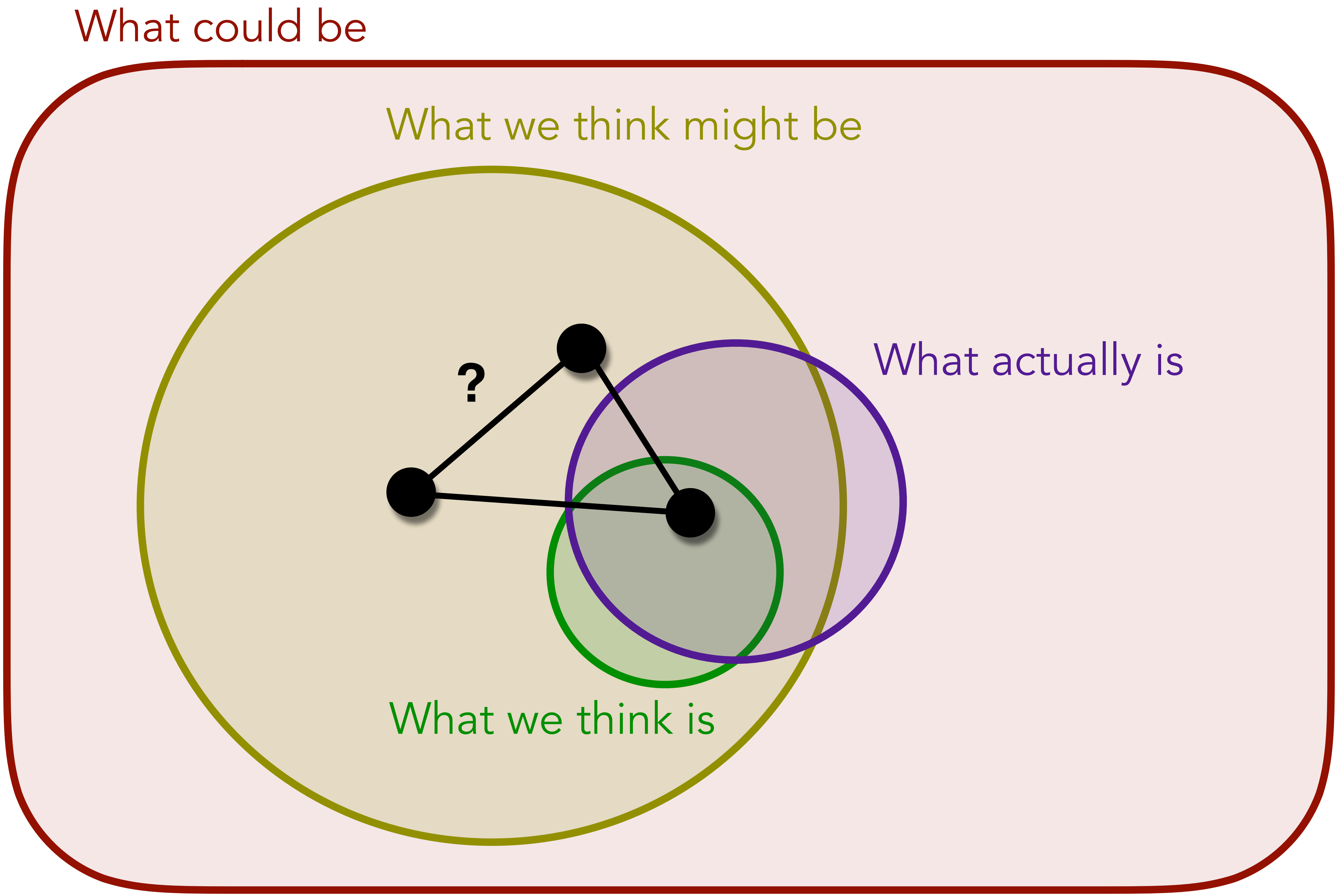
To gain an understanding of a system beyond what we could achieve via word models alone.

Computational models can be used to:

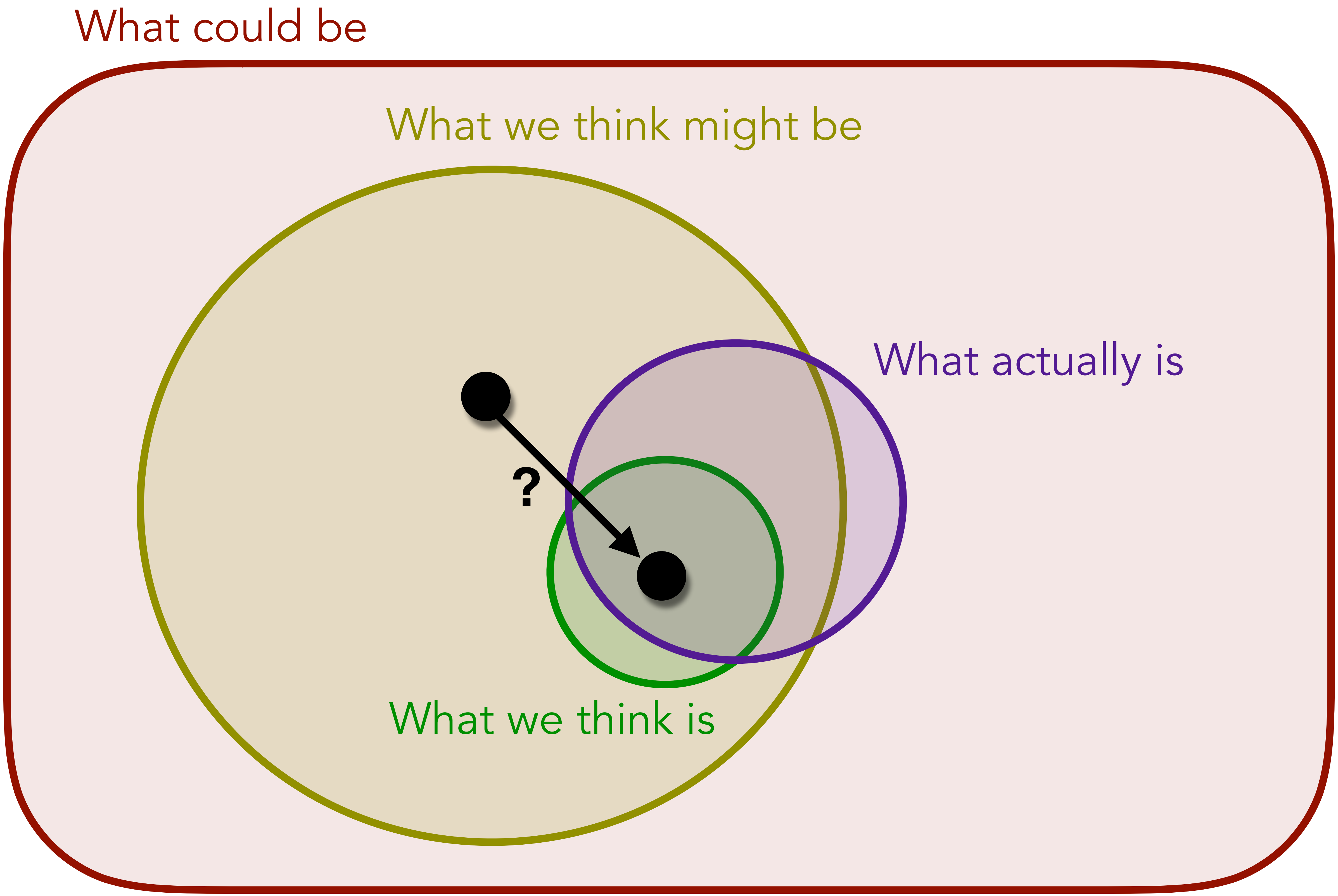
1. test if a set of concepts are mutually consistent. If not, why?
2. "link levels", i.e. to ask if a mechanism at one level of description can account for a phenomenon at another level.
3. simulate experiments that are technically difficult or impossible to do in the lab.
4. explore "what if?" scenarios that may never occur in the natural world.
5. validate a formal mathematical analysis.


What could be
What we think might be
What actually is
What we think is

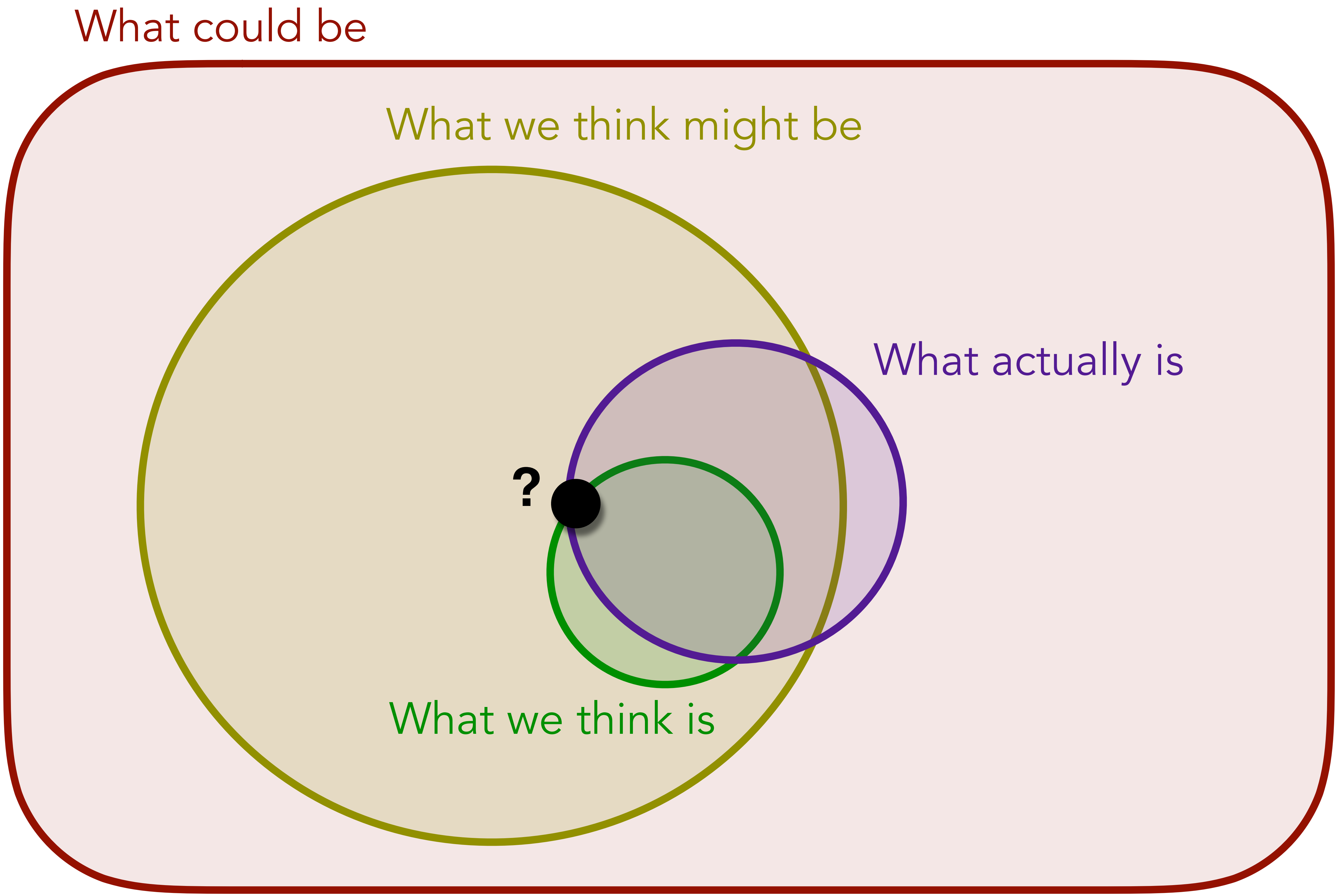
1. are these ideas mutually consistent?



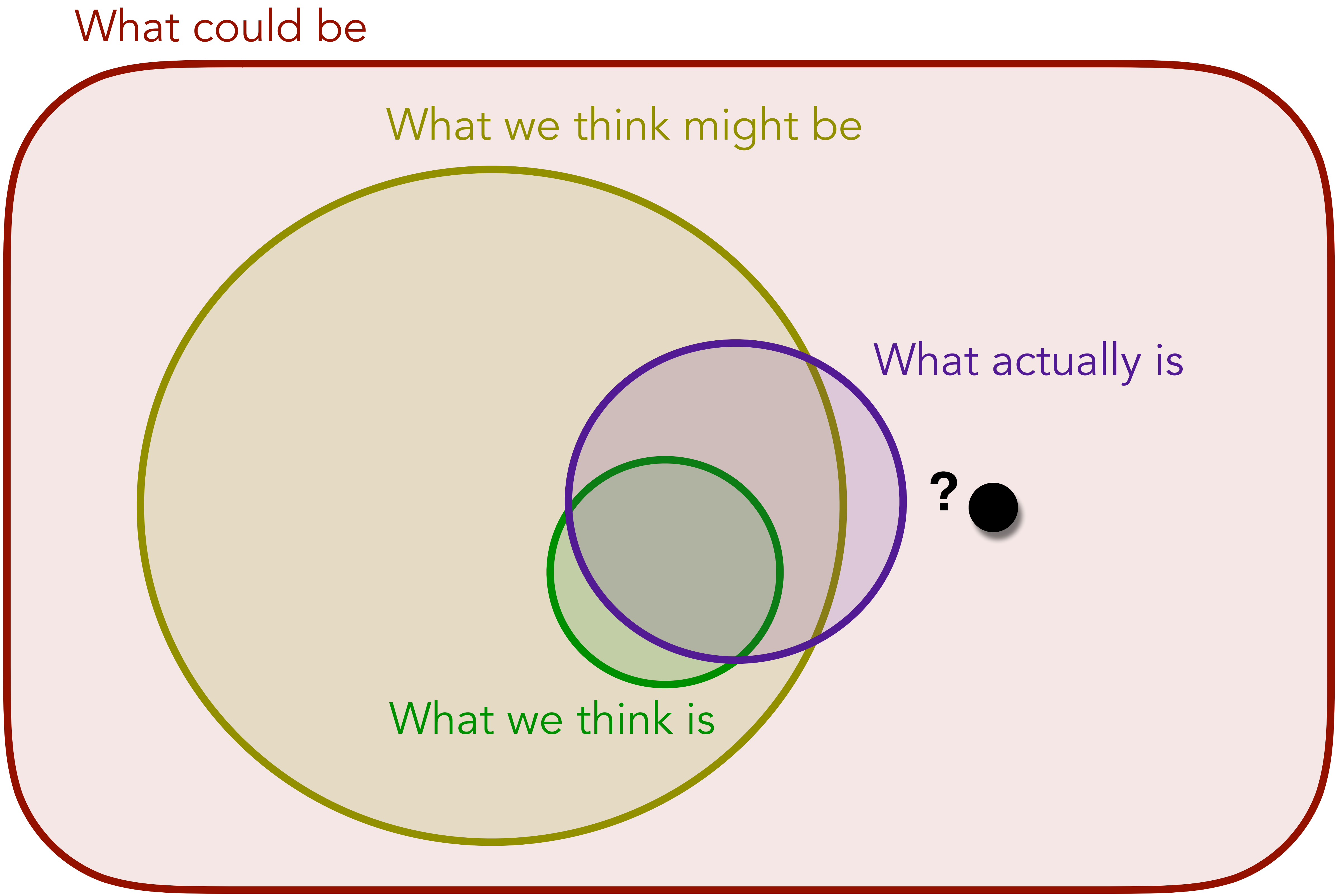
2. can ‘this’ explain ‘that’?



3. simulate difficult experiments



4. *simulate 'what if?' scenarios*



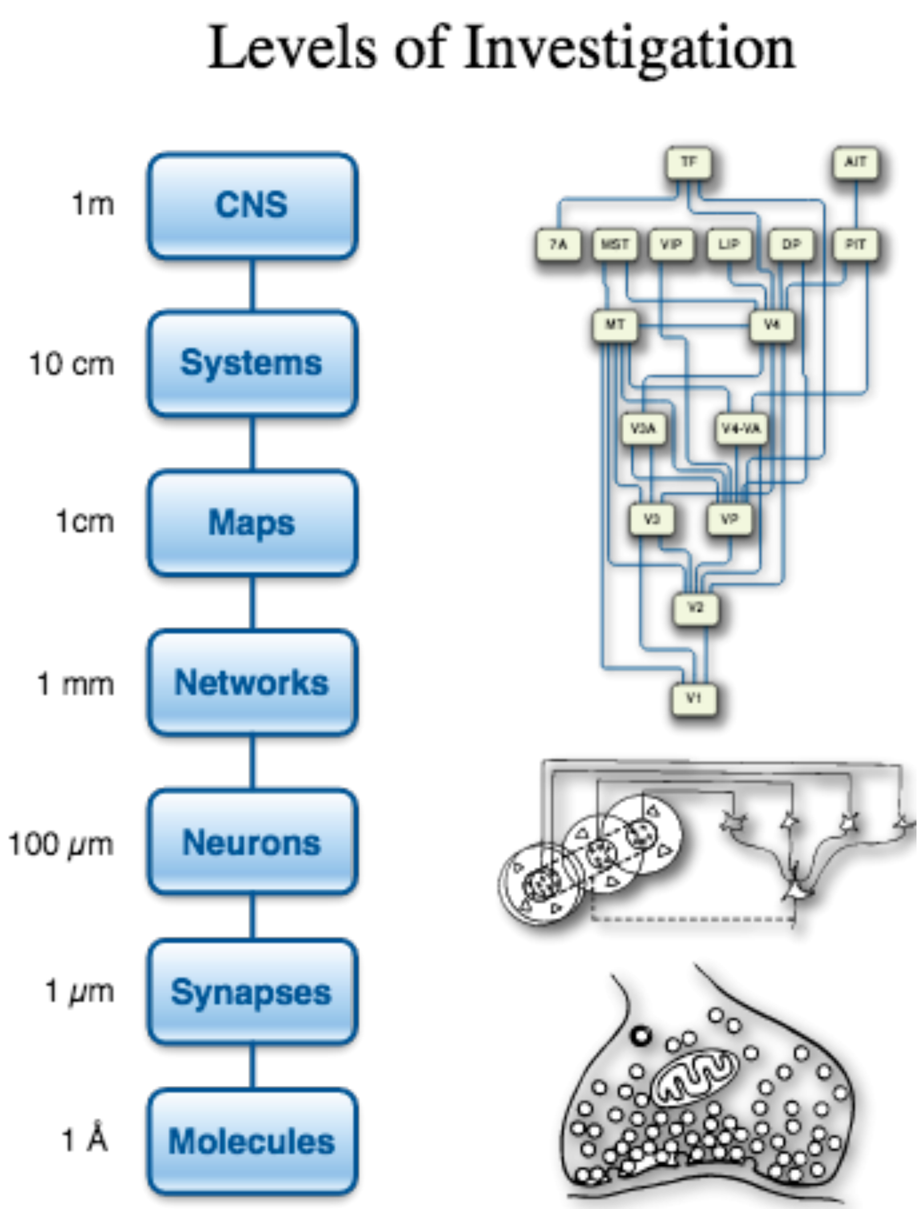
What is the purpose of a computational model?

Example usages of computational models in neuroscience:

- Hodgkin-Huxley model
  (to ask if the squid axon action potential can be explained by the voltage gating dynamics of sodium and potassium conductances).
- Simulation of recurrent hippocampal networks with synaptic plasticity
  (to ask if synaptic plasticity could mediate memory recall from partial cues).
- Simulating the biophysics of calcium signalling at a synapse
  (to explore what happens during synaptic stimulation).

Levels of abstraction

Spatial

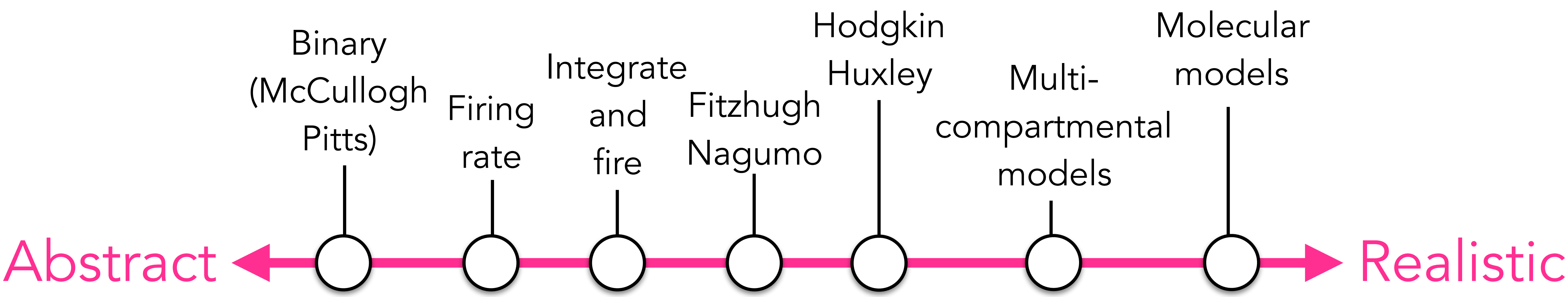


T. Sejnowski
http://cnl.salk.edu/

Temporal

years	Memories
weeks	Brain development
hours	Gene expression
mins	Cellular signalling
s	Neural circuit dynamics
ms	Action potential

Models of single neurons



Abstract models		**Realistic models**
Simple	vs	Detailed
Hard to relate to biology	vs	Contains stuff you could measure
Few parameters	vs	Lots of parameters
Fast simulation	vs	Slow simulation
Mathematical analysis	vs	Intractable
Generic	vs	Specific

The Fitzhugh-Nagumo neuron model

- The Fitzhugh-Nagumo neuron is a reduced mathematical model of the original HH model (proposed in 1961-2).
- Its 2D form permits dynamical systems analysis (much loved by mathematicians).

Neurons as dynamical systems

Figure 1.8: Neurons are dynamical systems.

Dynamical Systems in Neuroscience: The Geometry of Excitability and Bursting.
Izhikevich E.M. (2007)

Neurons as dynamical systems

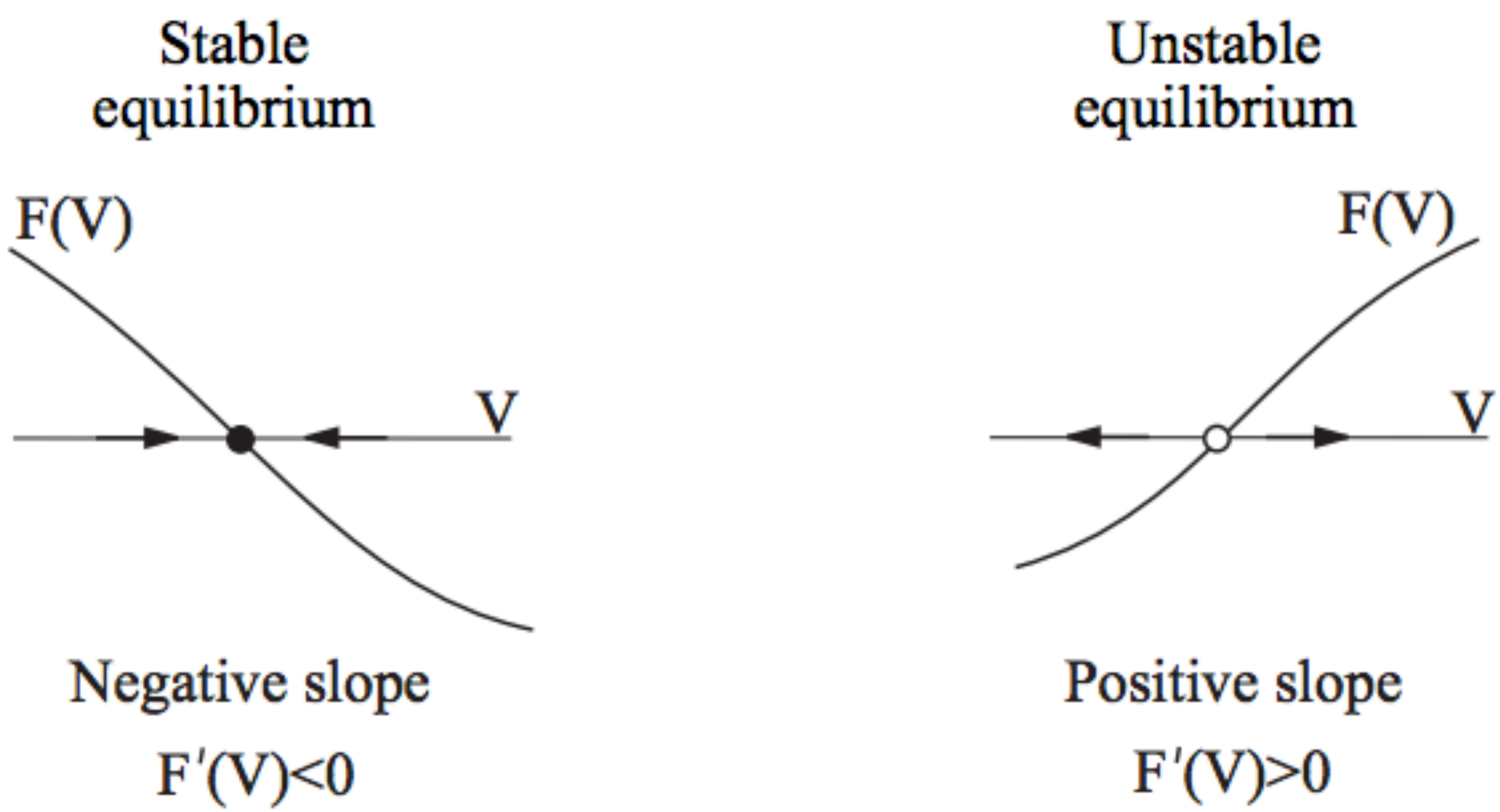


FIGURE 3.9. The sign of the slope, $\lambda = F'(V)$, determines the stability of the equilibrium.

Izhikevich E.M. (2007)

Neurons as dynamical systems

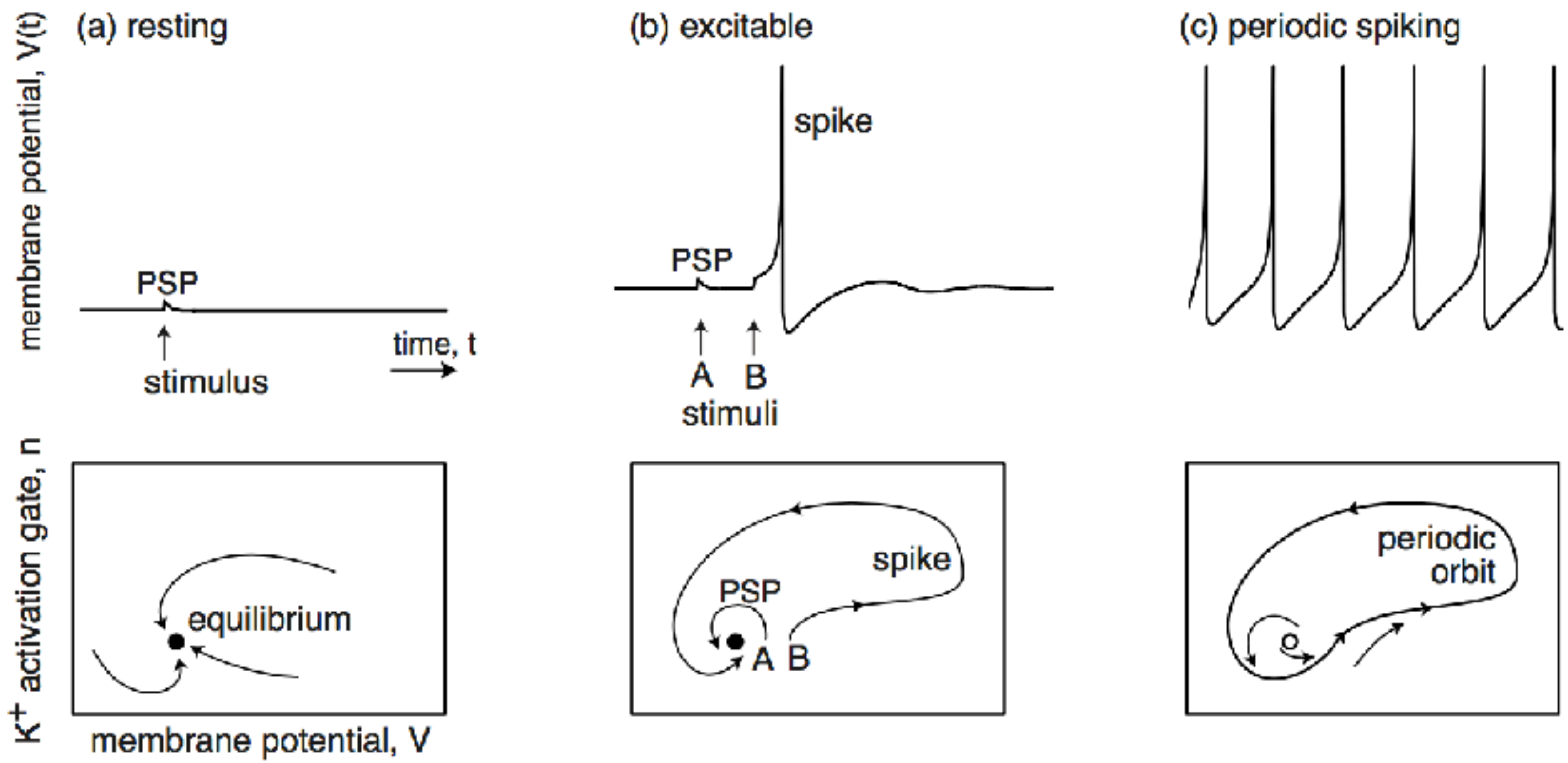


Figure 1.9: Resting, excitable, and periodic spiking activity correspond to a stable equilibrium (a and b) or limit cycle (c), respectively.

Izhikevich E.M. (2007)

The Fitzhugh-Nagumo model

Consists of two coupled ordinary differential equations for:

1. the voltage *V*, and
2. the 'recovery' variable *W*.

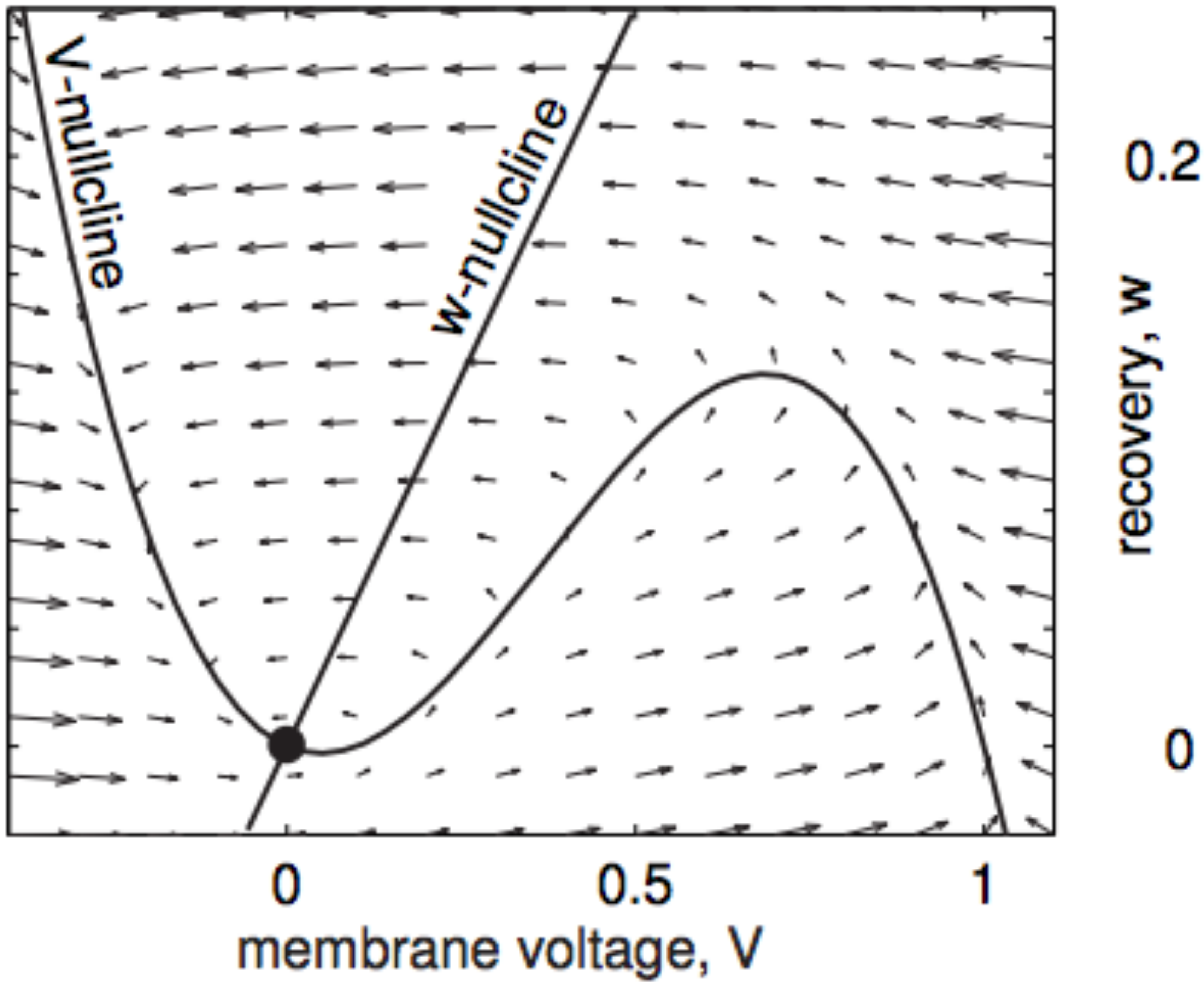
Self-excitation via nonlinear positive feedback

$$\frac{dV}{dt} = V - V^3/3 - W + I_{stim}$$

$$\frac{dW}{dt} = 0.08(V + 0.7 - 0.8W)$$

Slower linear negative feedback

The Fitzhugh-Nagumo model



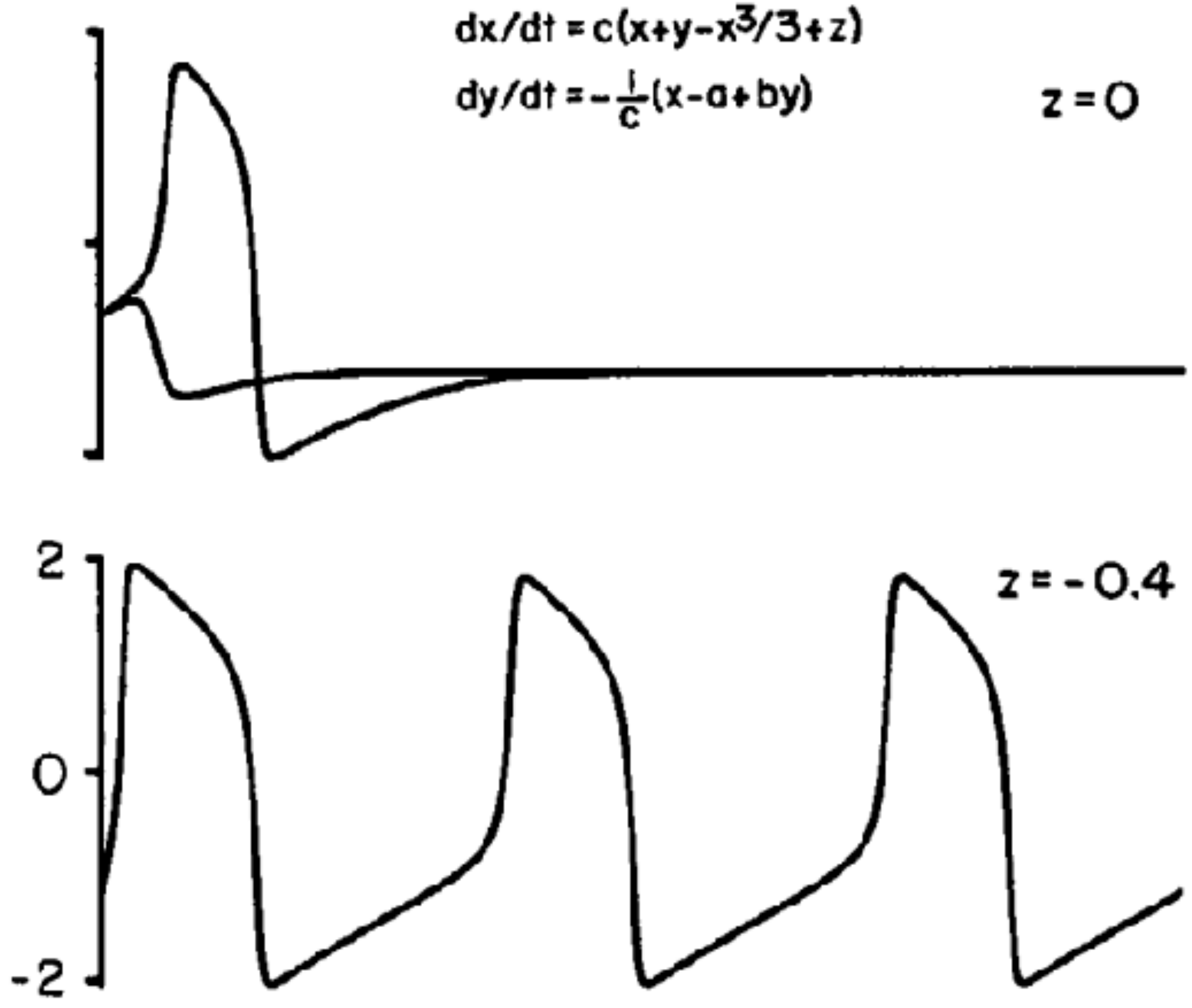
Izhikevich E.M. (2007)

The Fitzhugh-Nagumo model

This simple model can recapitulate:

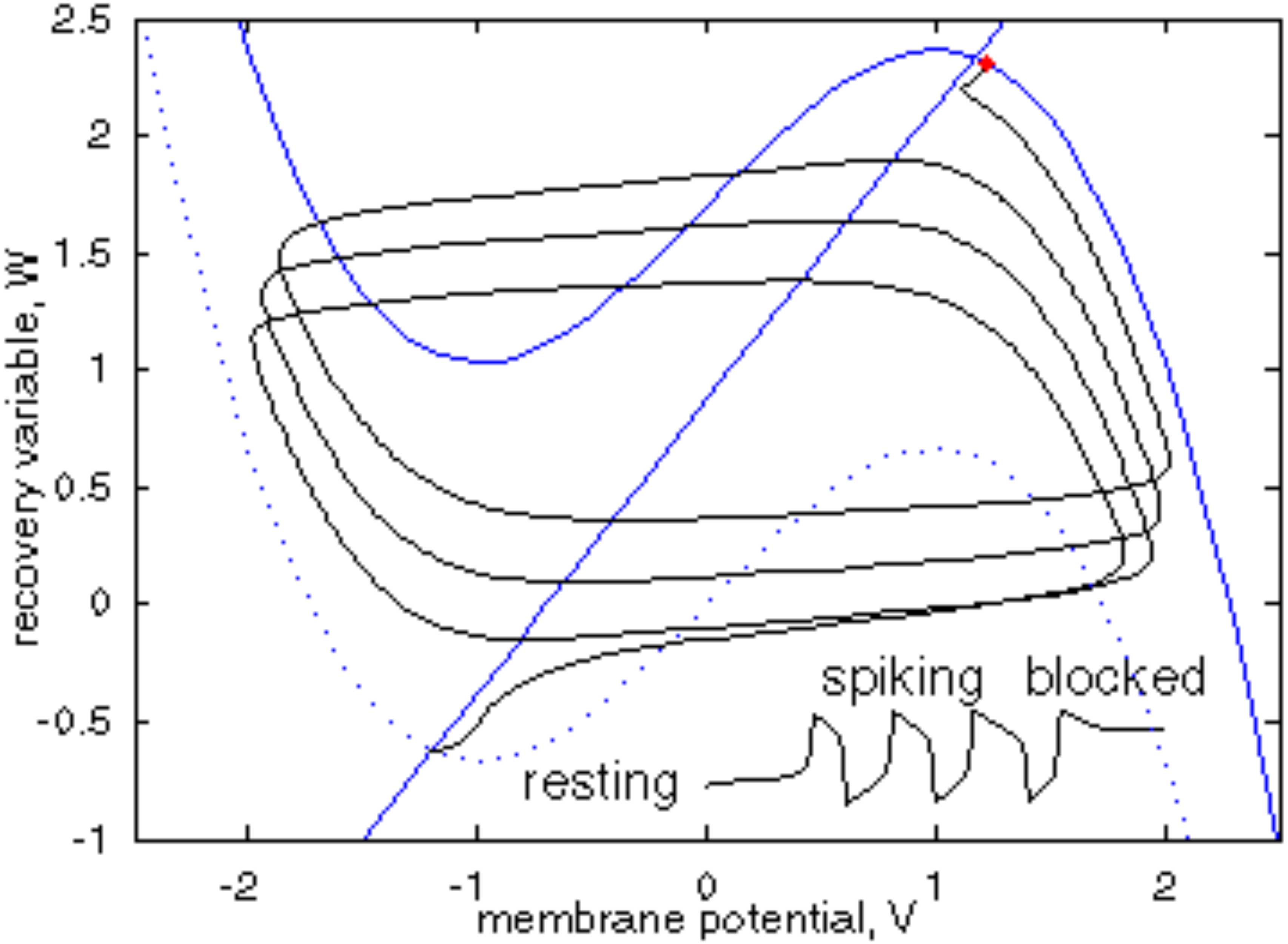
- Appearance of all-or-nothing spike threshold
- Periodic spiking from a constant input current
- Refractory period
- Excitation block

Prediction of spiking dynamics by the Fitzhugh-Nagumo model



FitzHugh, *Biophys J* (1961)

Prediction of excitation-block by the Fitzhugh-Nagumo model



http://www.scholarpedia.org/article/FitzHugh-Nagumo_model

The Fitzhugh-Nagumo model

This simple model ***cannot*** recapitulate:

- Bursting
- Chaotic dynamics
- Type 1 neural dynamics
- The spiking behaviour of many mammalian neurons

As a result, many other dynamical neuron models were developed (Hindmarsh-Rose, Morris-Lecar, Izhikevich…)

Which model is best for my problem?

- Choose the form of the model that best matches the granularity of your scientific question.

- *"A model should be as simple as possible, but no simpler"*
  — Albert Einstein

- Often this choice is dictated by:
  - the data you have to constrain the model
  - the phenomenon you wish to explain
  - the computational resources you have available
  - how much maths/programming you know
  - ~~what someone else did previously~~

End