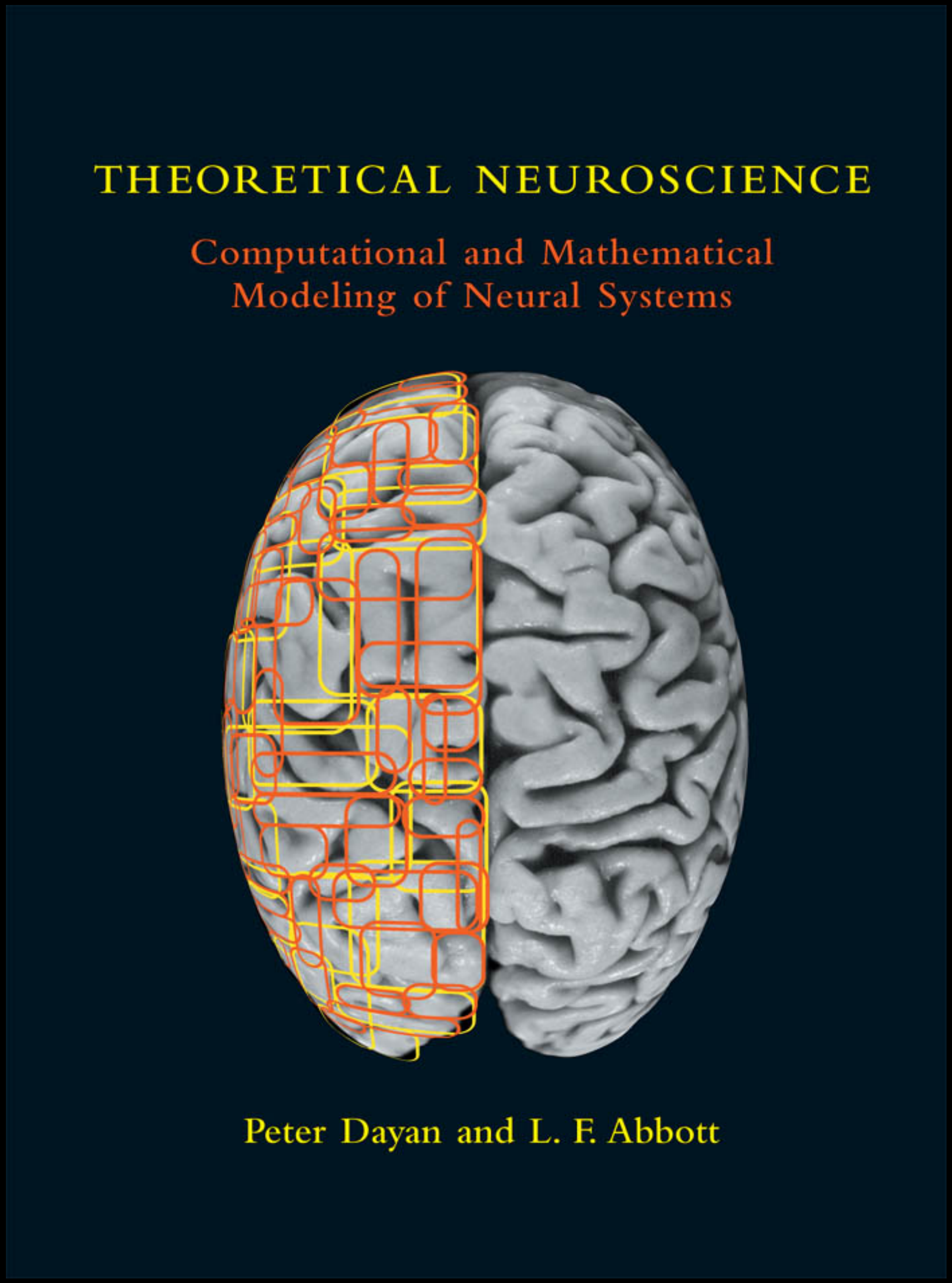
An Introduction to Computational Neuroscience

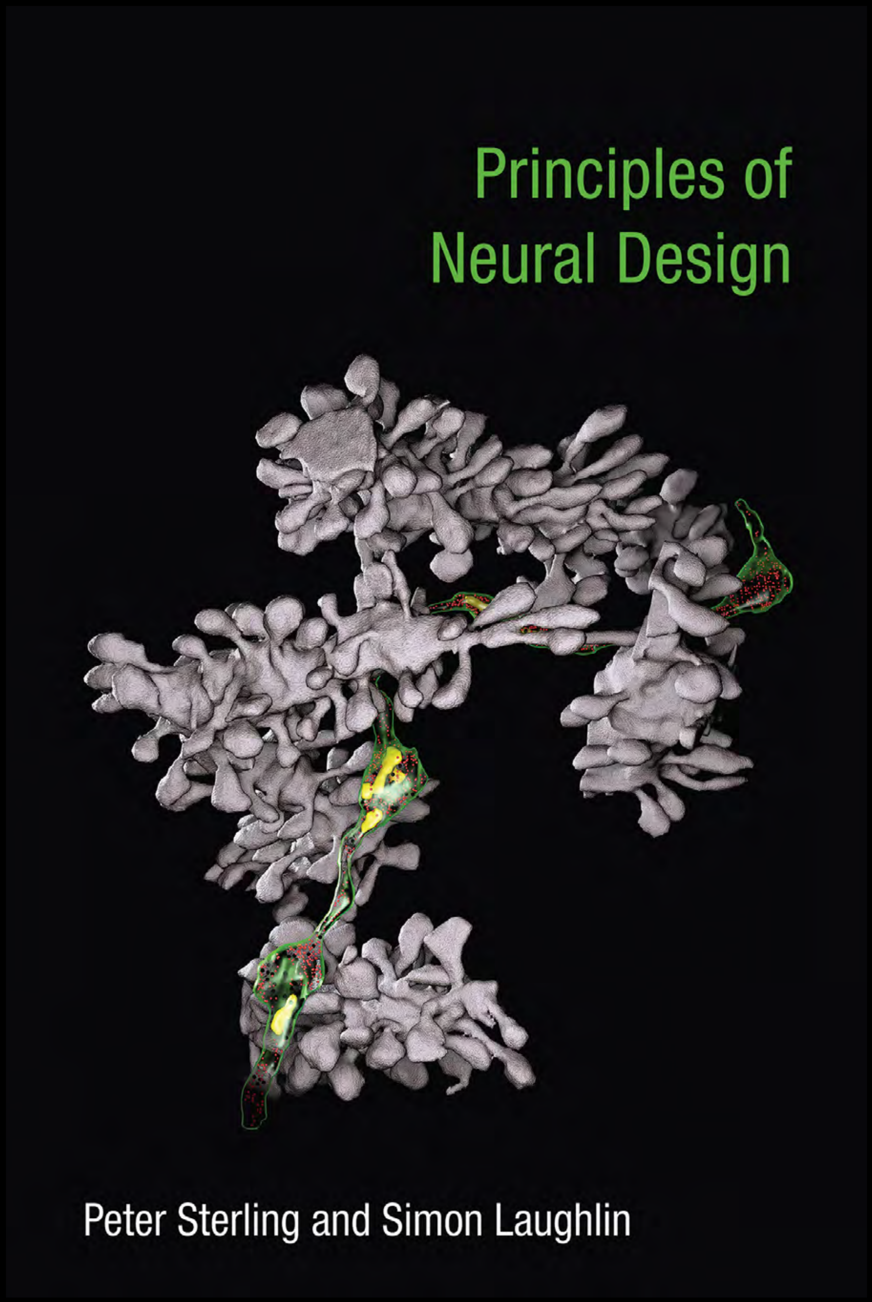
WEN quan (温泉)
University of Science and Technology of China

September 2 2024

Recommended textbooks

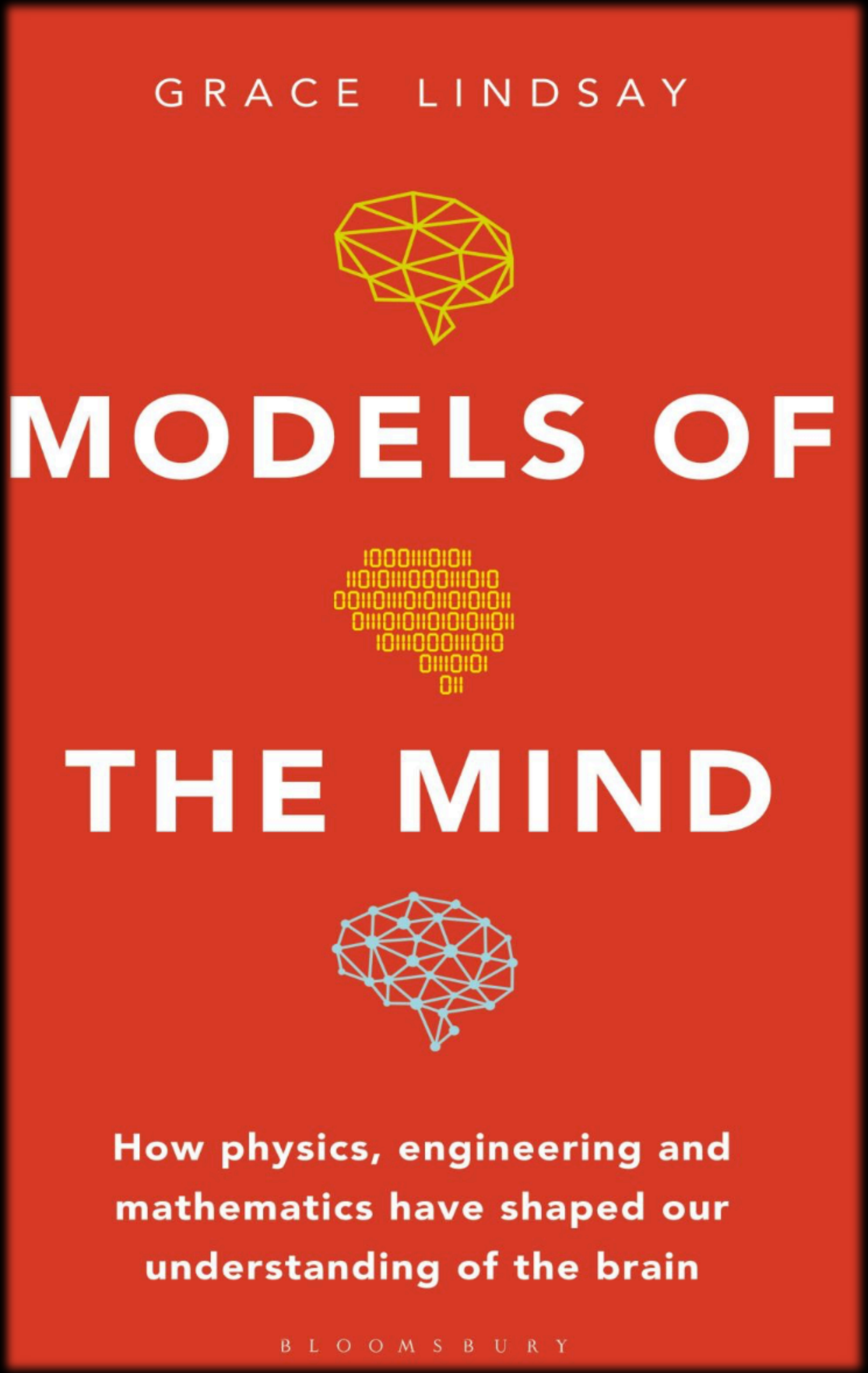


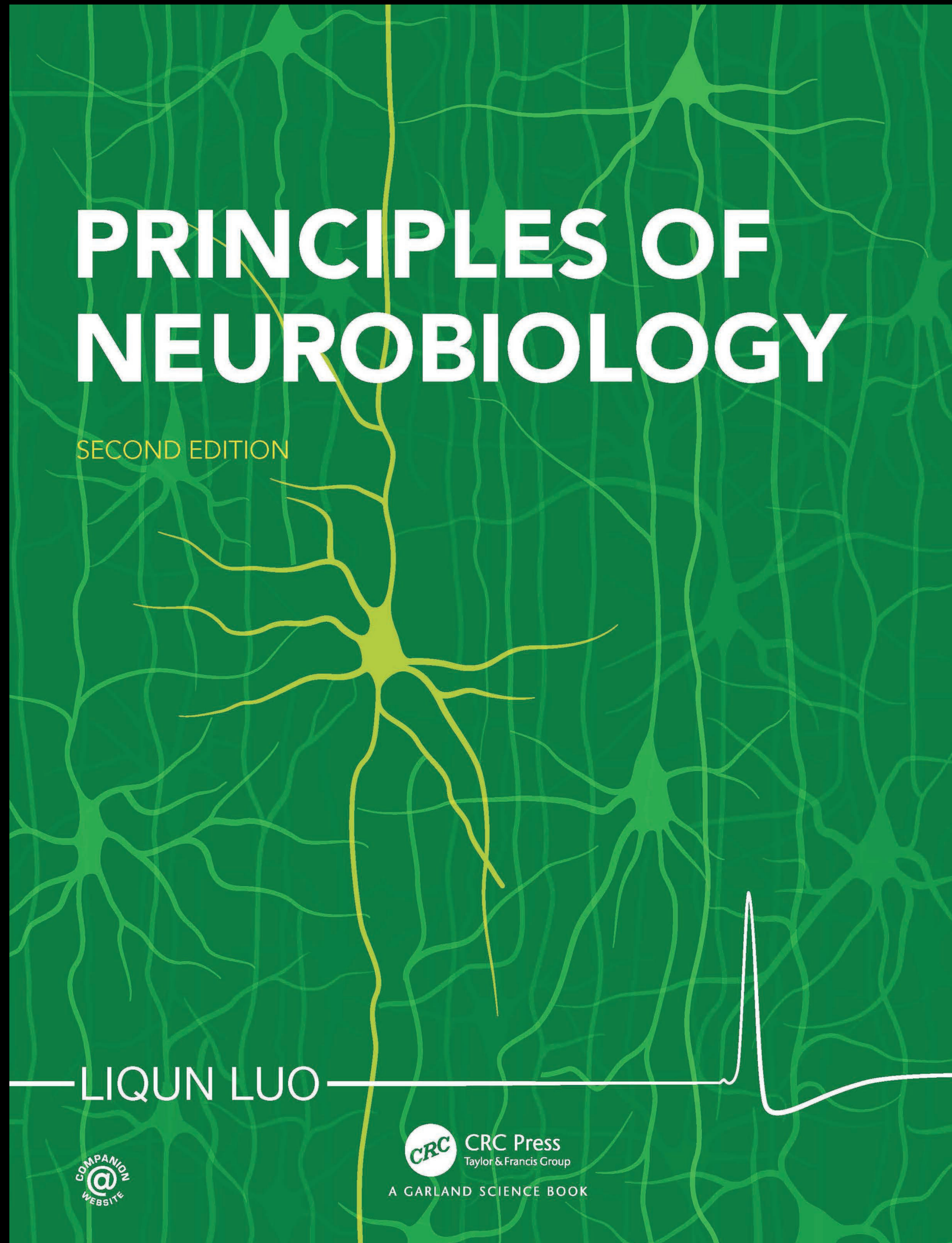
How questions



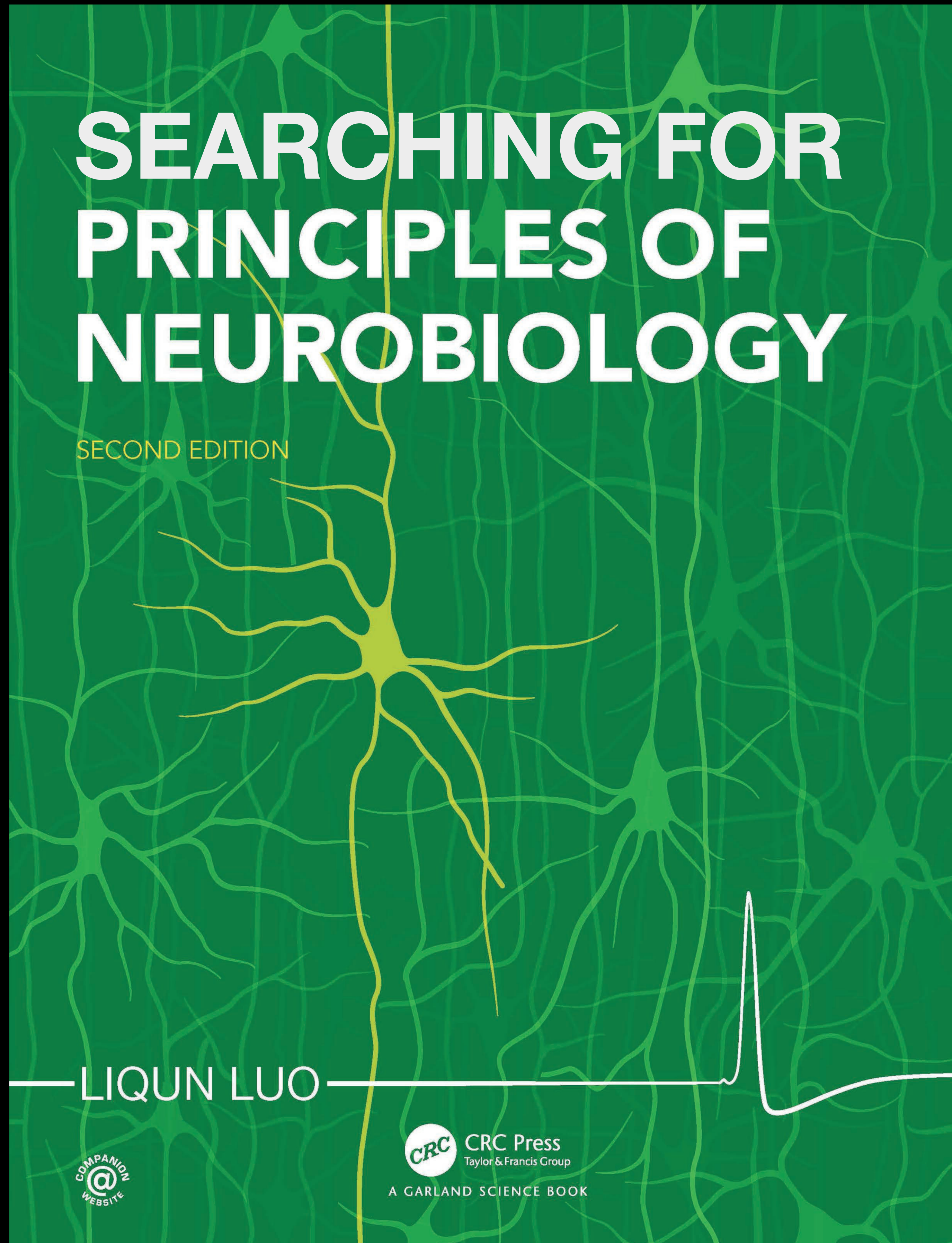
Why questions

Recommended book for a general audience




PRINCIPLES OF NEUROBIOLOGY
SECOND EDITION
LIQUN LUO
CRC Press
Taylor & Francis Group
A GARLAND SCIENCE BOOK
COMPANION
WEBSITE

666 pages



SEARCHING FOR PRINCIPLES OF NEUROBIOLOGY

SECOND EDITION

LIQUN LUO

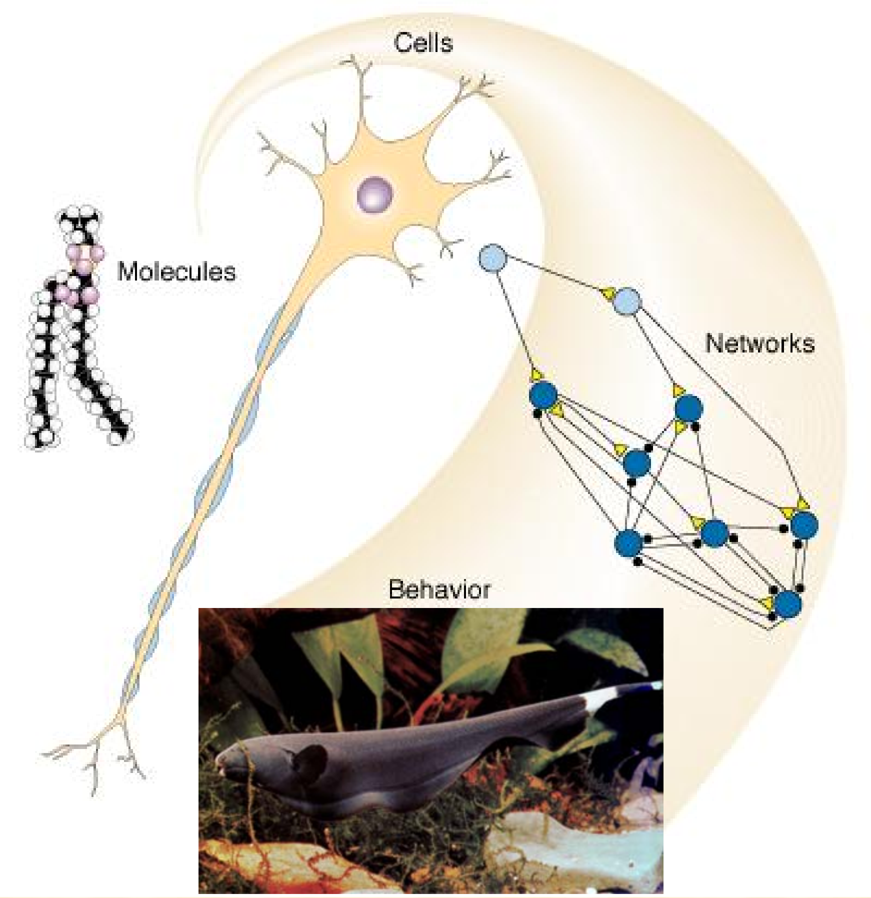
COMPANION WEBSITE

CRC Press
Taylor & Francis Group
A GARLAND SCIENCE BOOK

A general impression of the brain

- The brain is squishy and messy. It may be impossible to understand the brain from a small number of principles just like in physics.
- There are too many (interesting) facts! And almost every rule has an exception.

Multiscale Organization of the Nervous System



Delcomyn 1998

Organism	1 m
System	10 cm
Map	1 cm
Column	1 mm
Neuron	10 μm
Synapse	1 μm
Molecule	10 Å

"To pile speculation on speculation, I would say that the next stage could be hierarchy or specialization of function, or both…. with increasing complication at each stage, we go on up the hierarchy of sciences. We expect to encounter fascinating and, I believe, very fundamental questions at each stage in fitting together less complicated pieces into the more complicated system and understanding the basically new types of behavior which can result."

P. W. Anderson, Science1972
condensed matter physicist

More is different

Fitzgerald: The rich are **different** from us.

Hemingway: Yes, they have **more** money.

a conversation somewhere in Paris in 1920s

“I never had to use an equation after high school”

David Hubel

What has theoretical component bought to neuroscience?

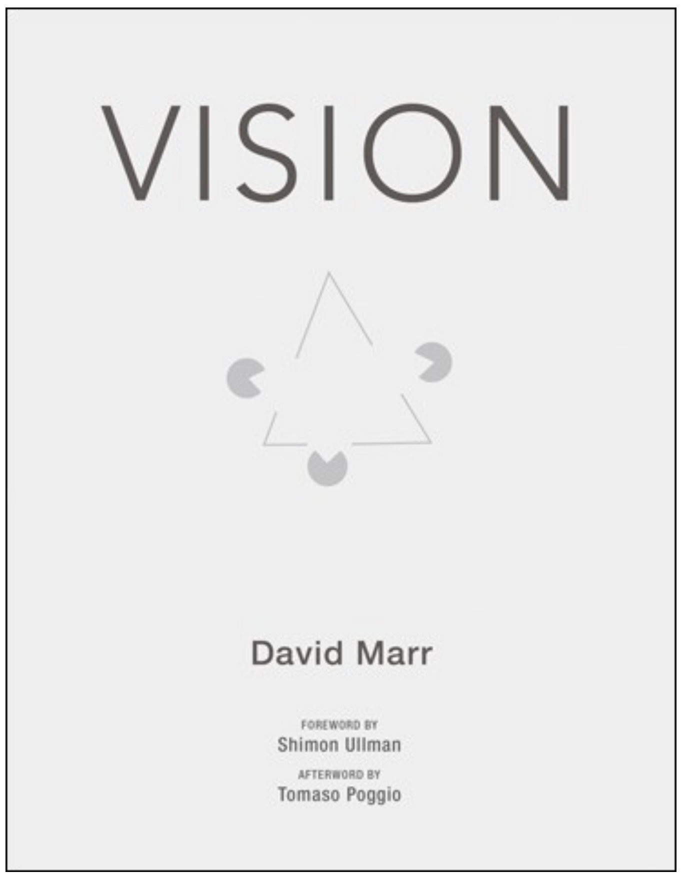
- The brain is squishy and messy. It may be impossible to understand the brain from a small number of (say 3?) principles just like in physics.
- There are too many facts! And almost every rule has an exception.
- However, most interesting facts are not singular. Instead, they must and can be connected to achieve a deeper understanding. And to build such a connection requires an integral approach, and mathematics are crucial during this process.

“…Equations force a model to be precise, complete, and self-consistent, and they allow its full implications to be worked out. It is not difficult to find word models in the conclusions sections of older neuroscience papers that sound reasonable but, when expressed as mathematical models, turn out to be inconsistent and unworkable. Mathematical formulation of a model forces it to be self-consistent and, although self-consistency is not necessarily truth, self-inconsistency is certainly falsehood.”

Larry Abbott
Theoretical Neuroscience is rising
Neuron 2008

David Marr
1945-1980

Henry Markram
1962 -



blue brain project

David Marr's three level theory

- **Computational level**: Identify the computational problem and task that the brain solves.
- **Algorithmic level**: Find the mathematical procedures that solve the problem.
- **Implementation level**: How the algorithms are realized by the nervous system.

top-down

Henry Markram's three level theory

- **Systems level**: describe how population neural dynamics and behaviors emerge from ensembles of neurons.
- **Cellular level**: develop biophysically accurate models to describe input-output relationships of different cell types.
- **Structure level**: identify how neurons are statistically connected to each other in a circuit.

bottom-up

The structure of an information processing machine does not tell you what computation it performs

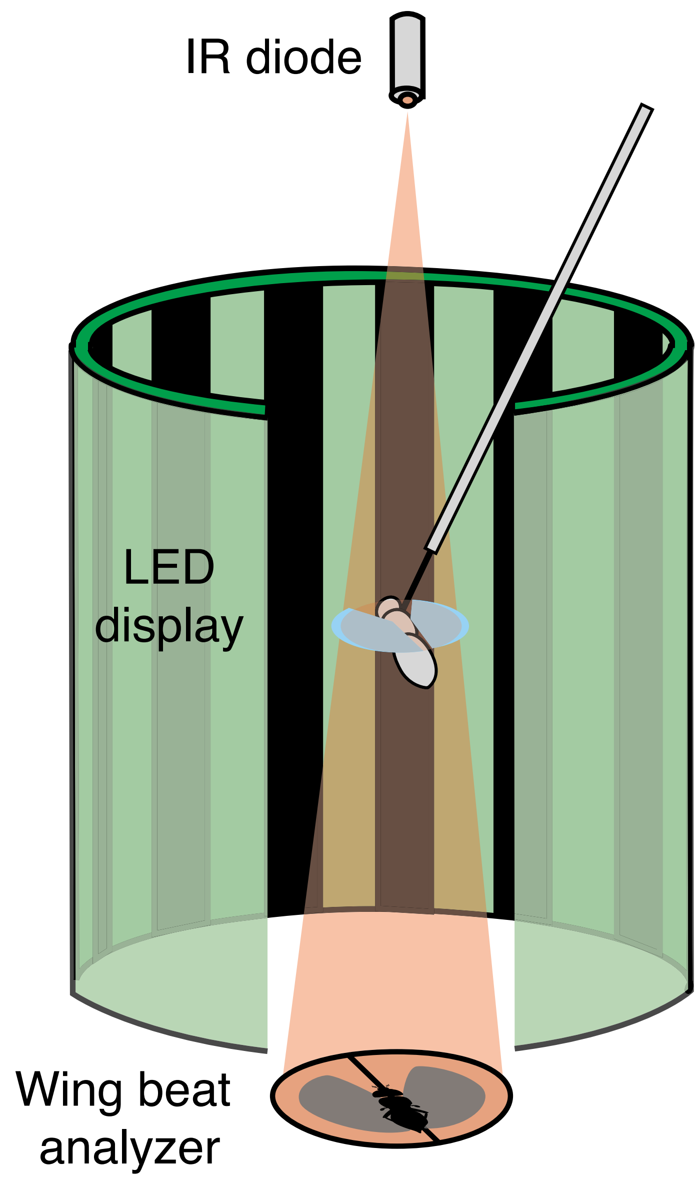
Anthony Movshon

Circuit diagrams or connectomes are *absolutely* necessary but *completely* insufficient for understanding nervous system function.

Eve Marder

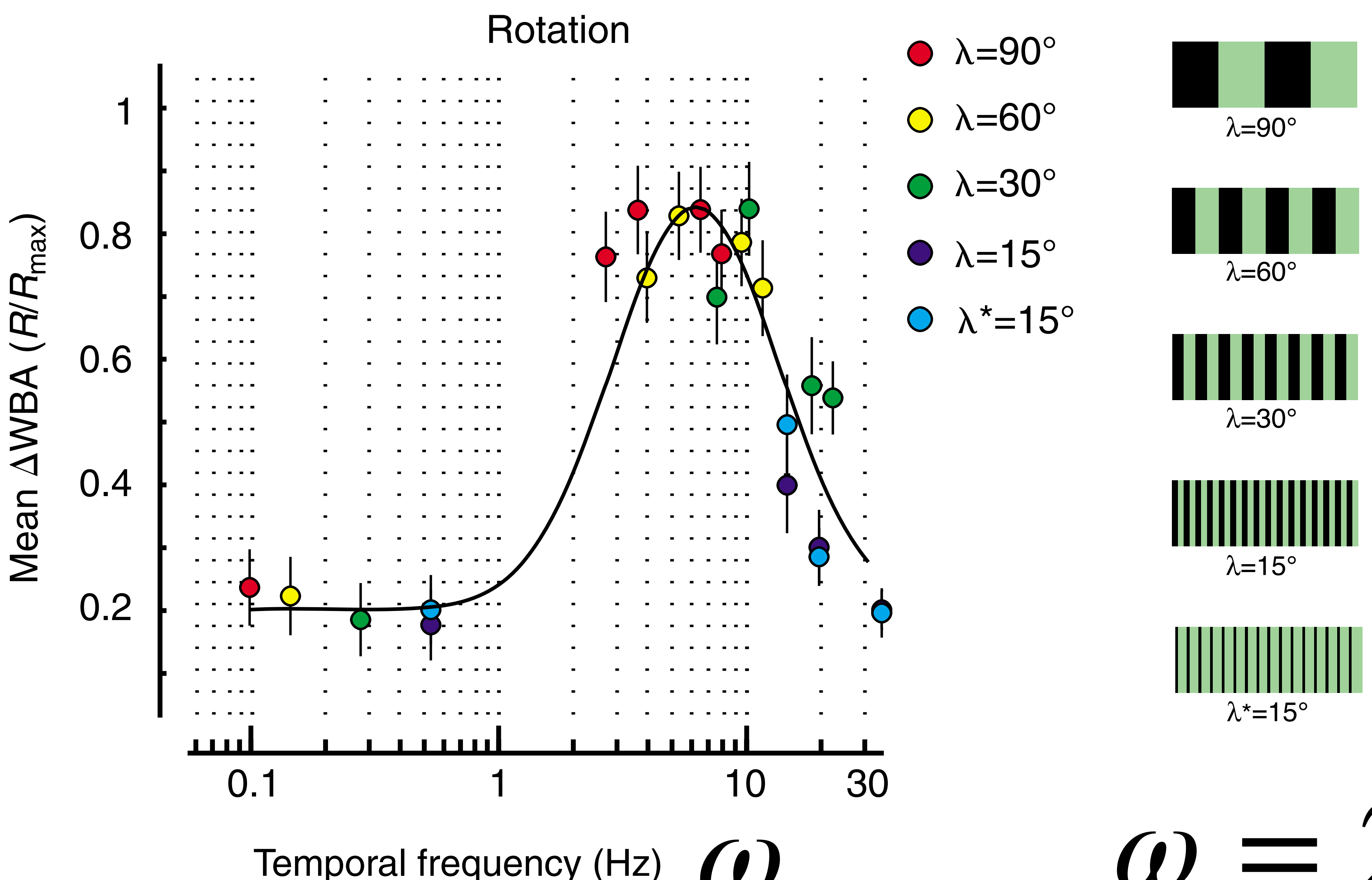
Motion detection, an example

Optomotor response in fly



Duistermars B et. al., Journal of Experimental Biology 2007

Optomotor response in fly

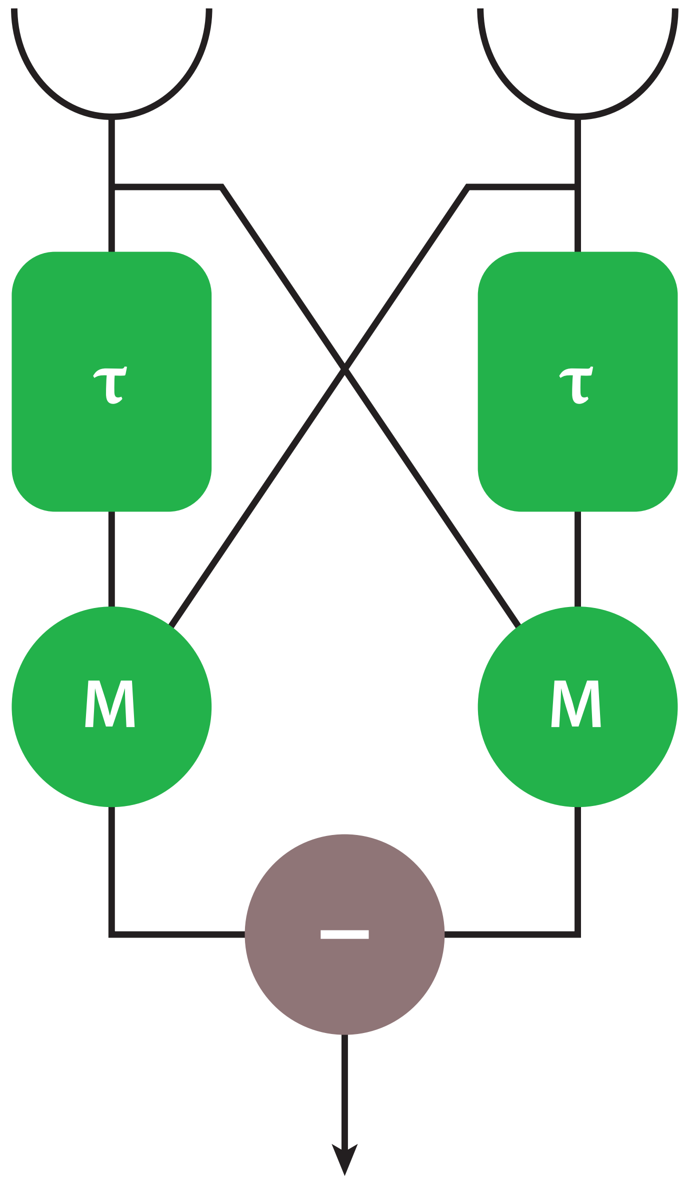


ω

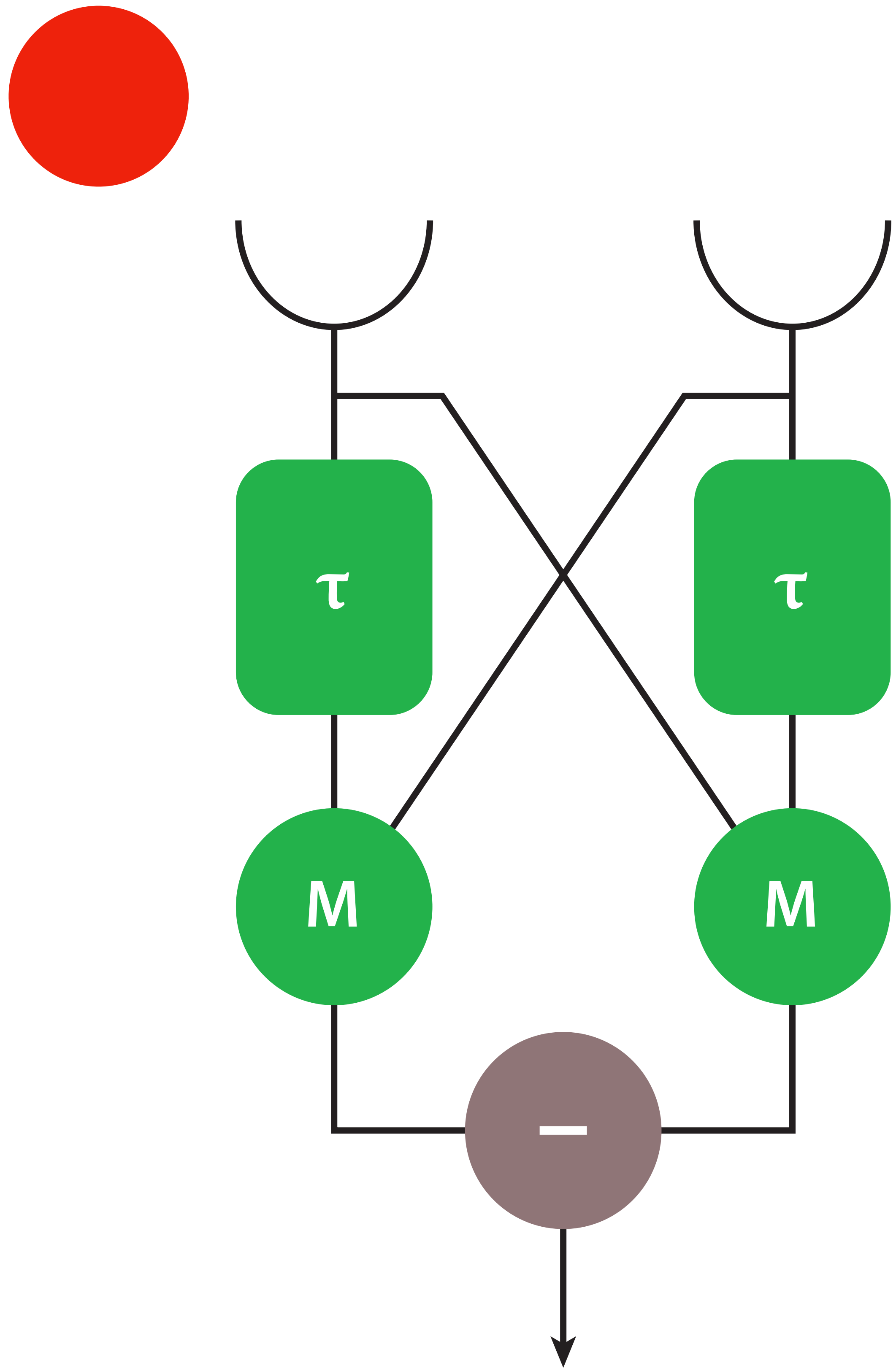
$$\omega = 2\pi v/\lambda$$

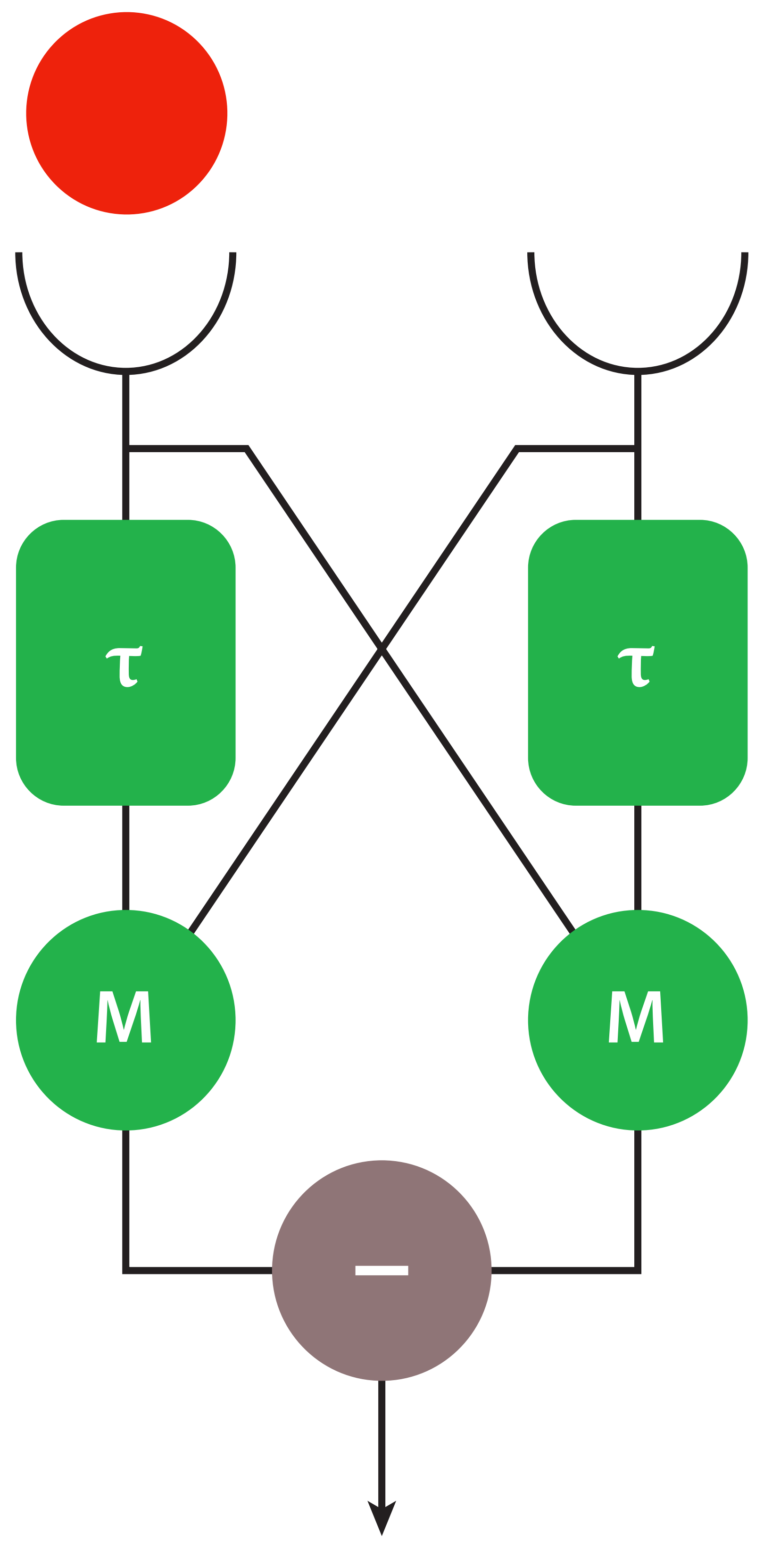
Duistermars B et. al., Journal of Experimental Biology 2007

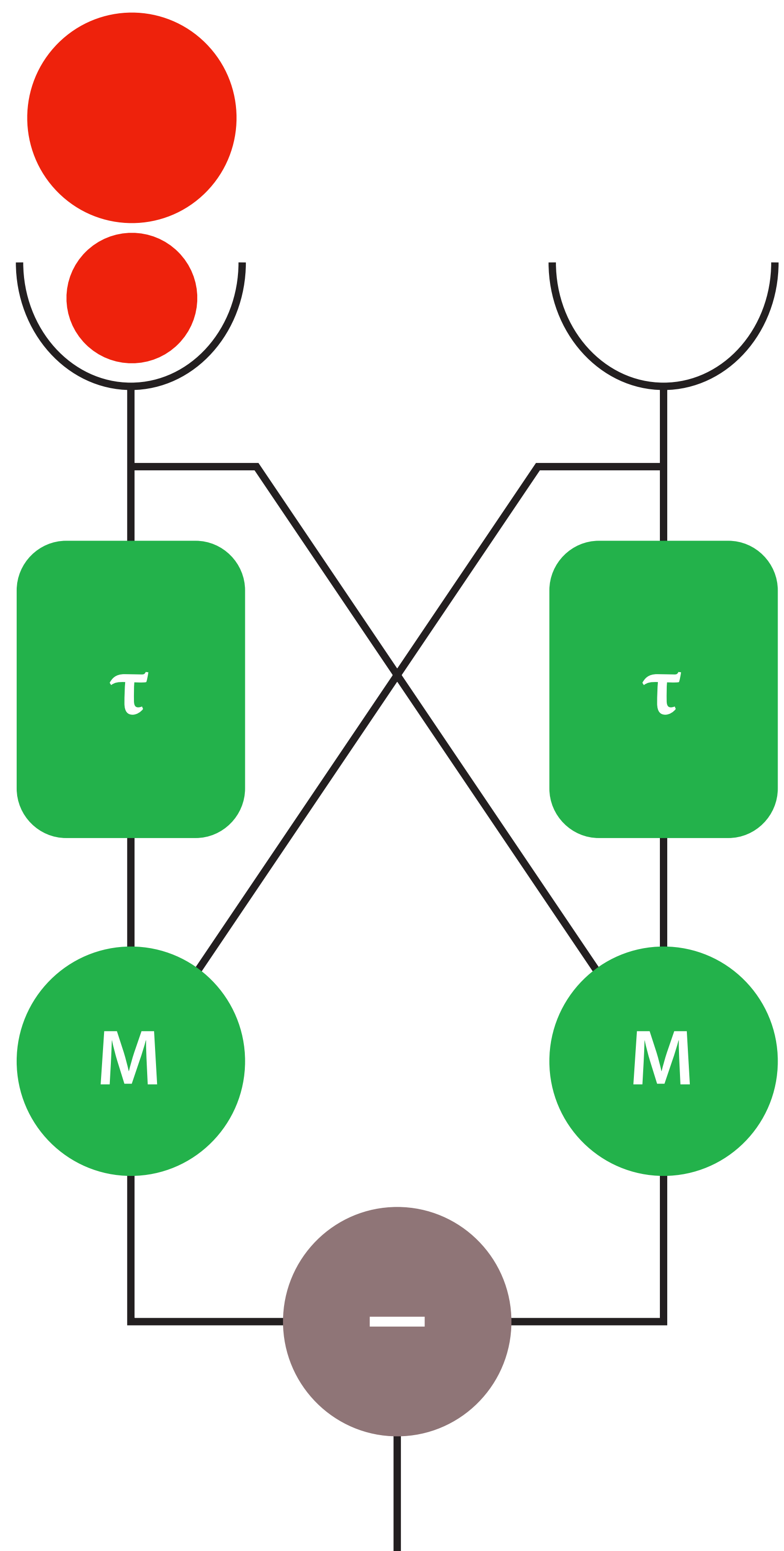
Hassenstein-Reichardt Detector Model

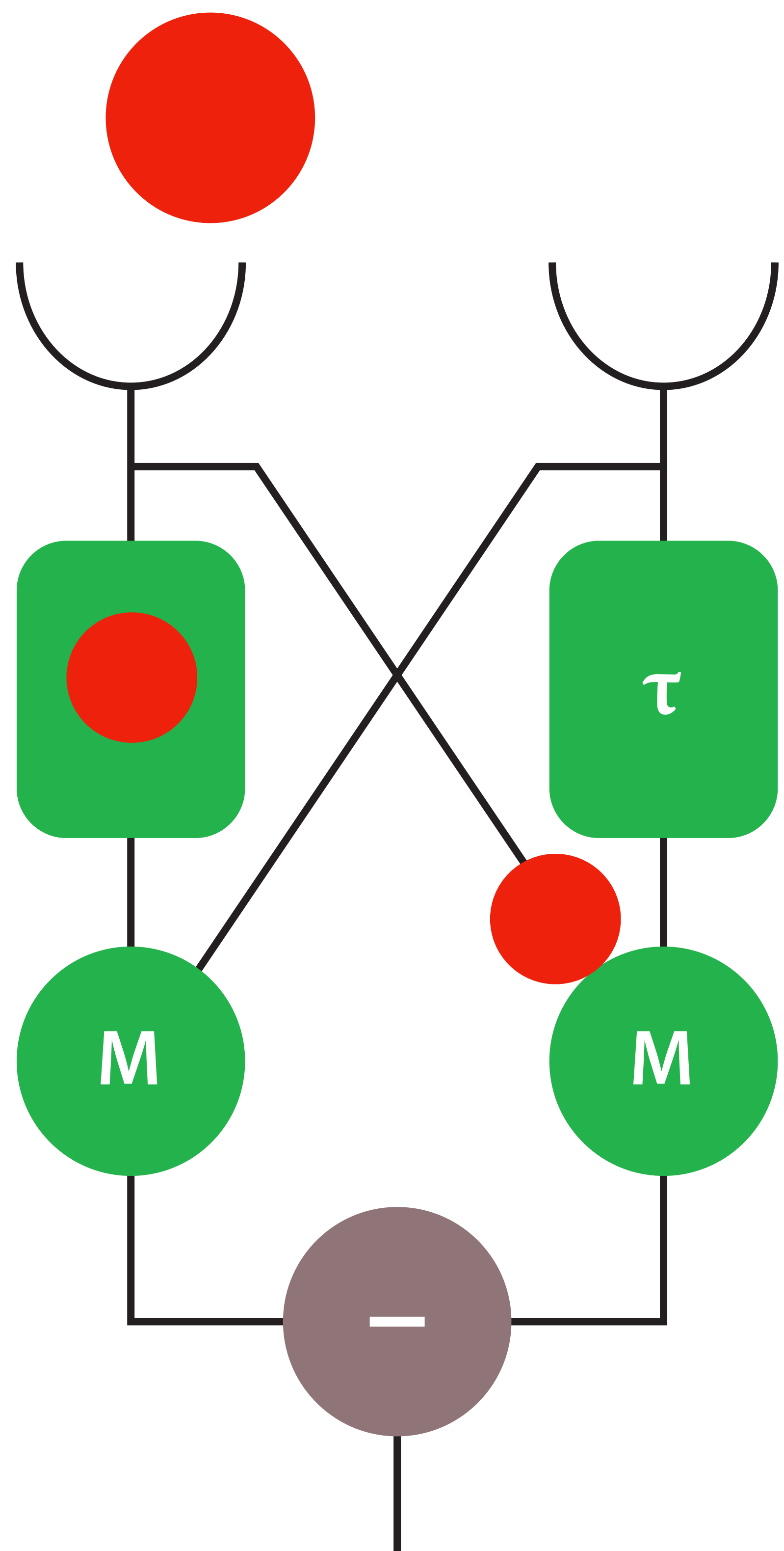


Werner Reichardt

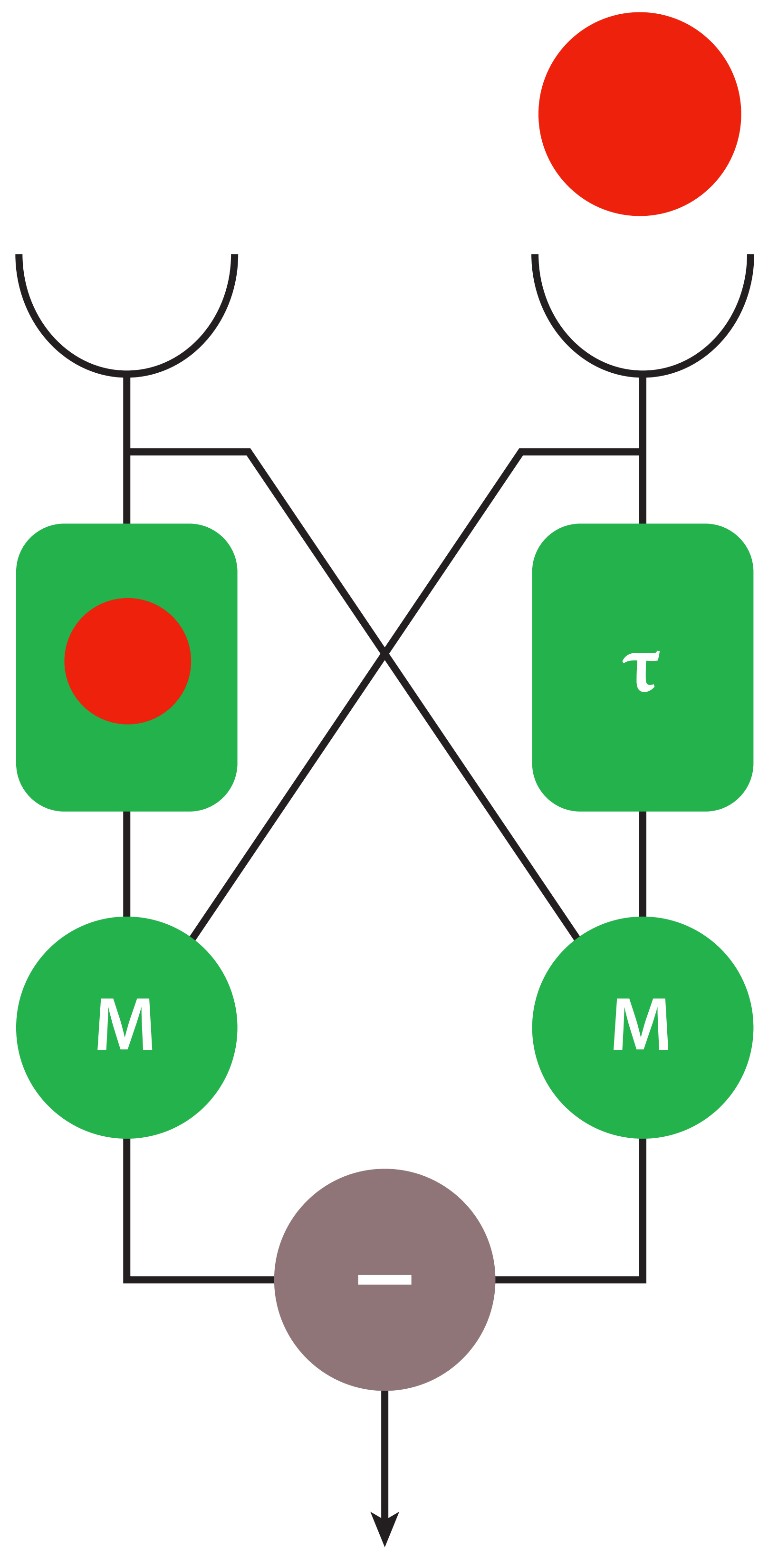

τ
τ
M
M
−


τ
τ
M
M
−

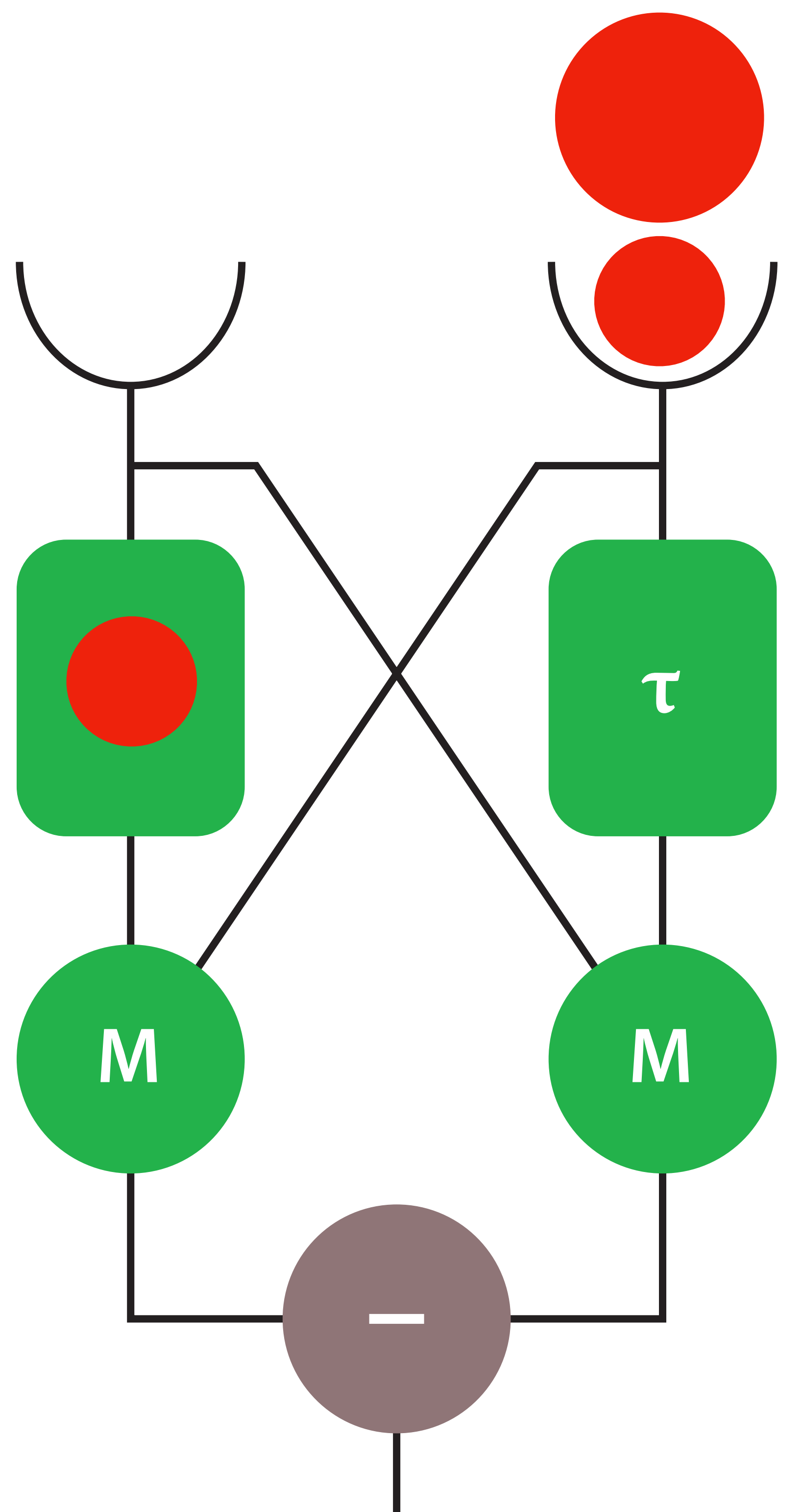

τ
τ
M
M
−

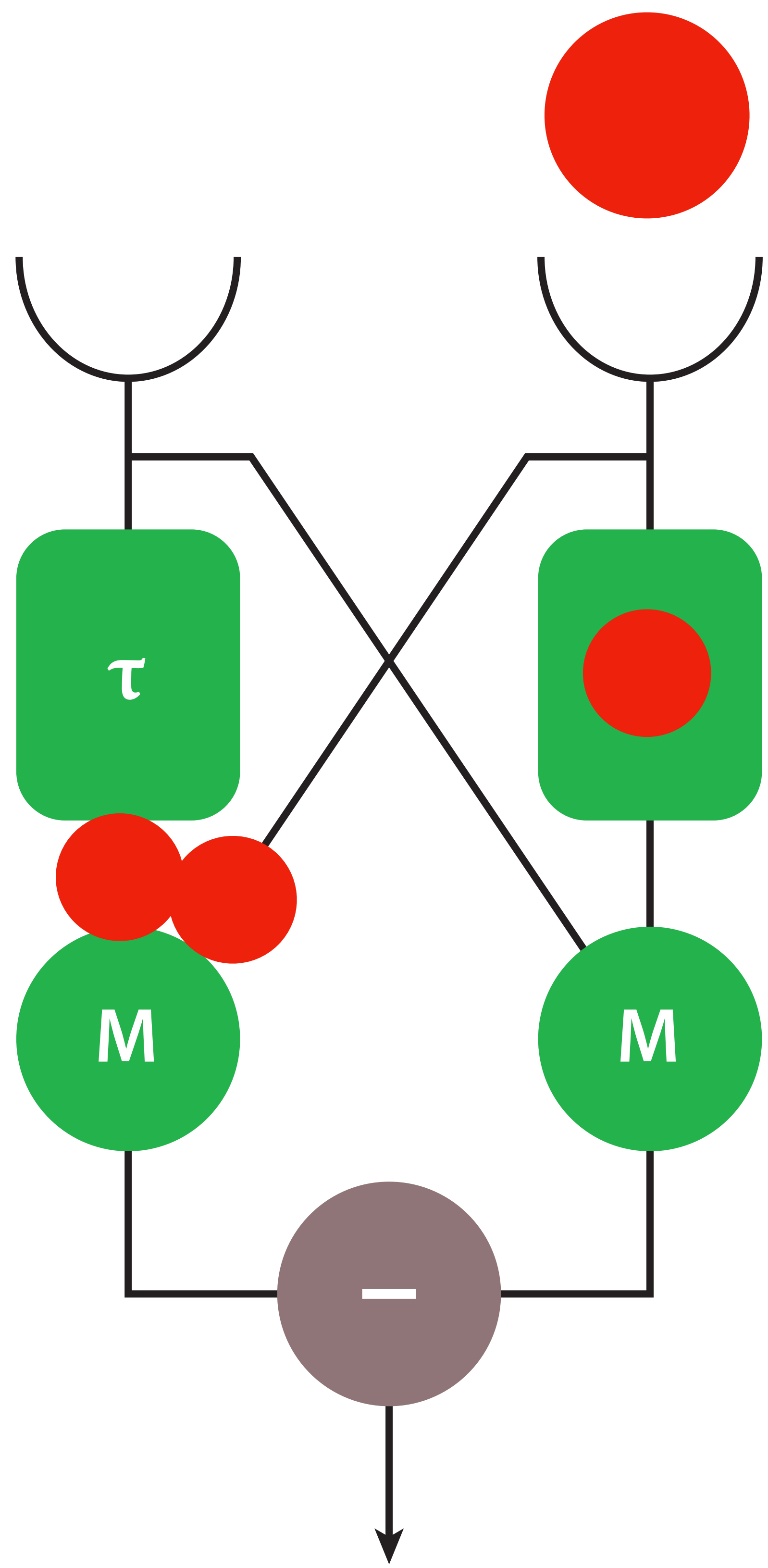


τ
M
M
–

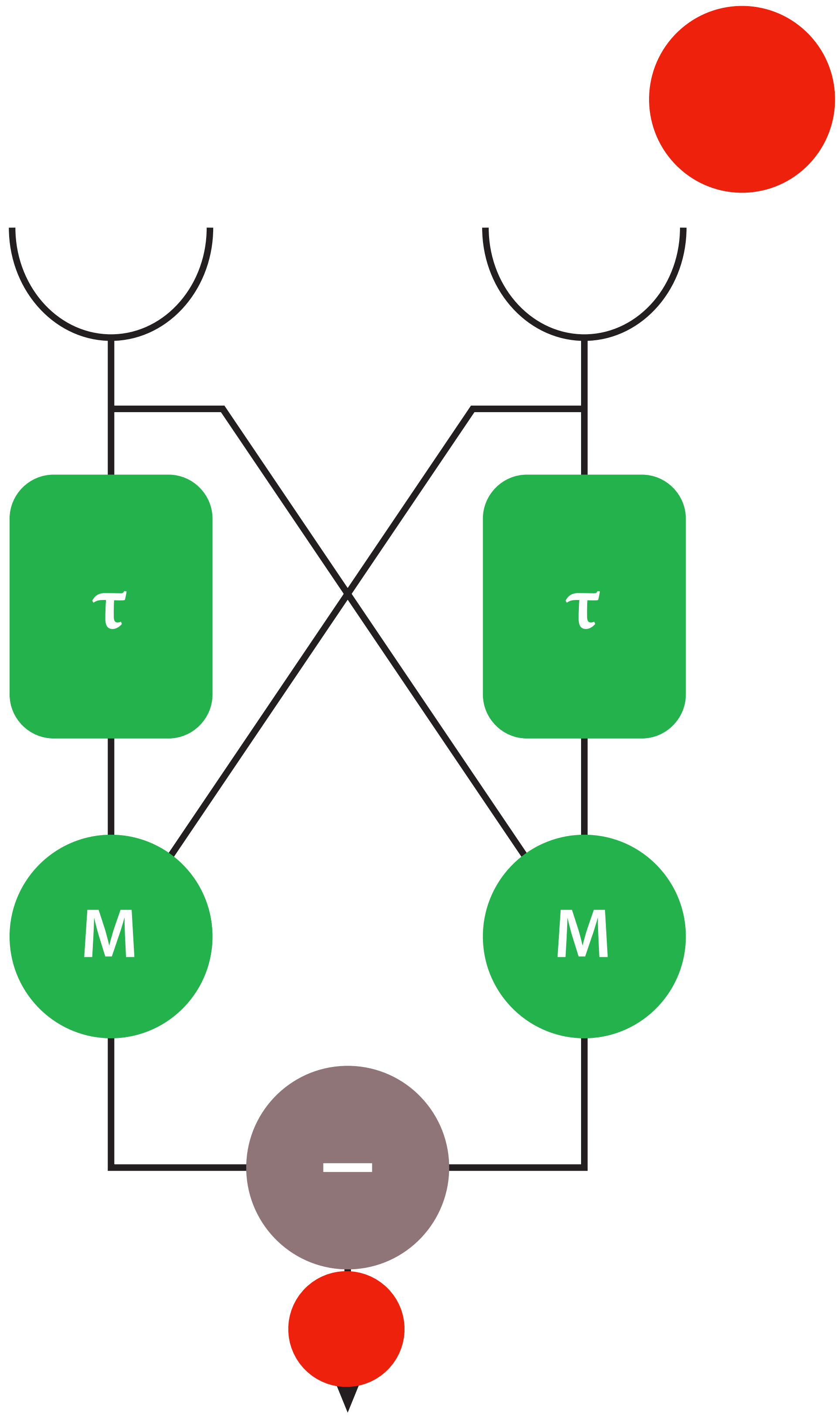


τ
M
M
−

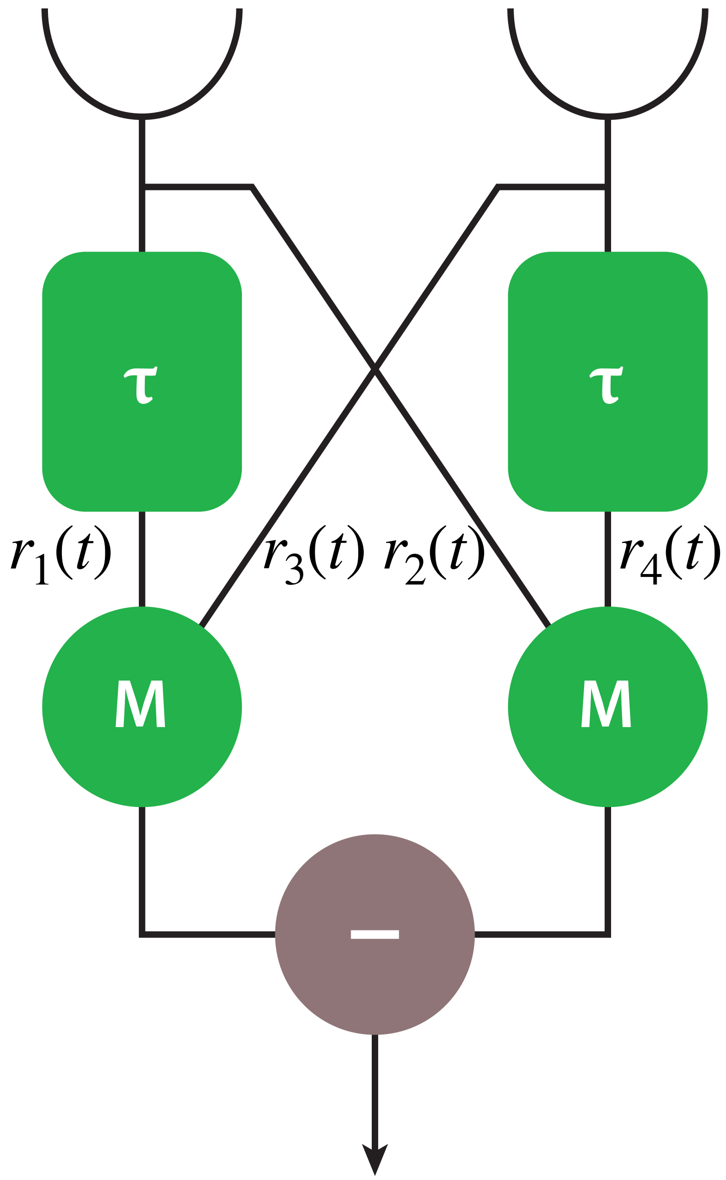

τ
M
M
−



τ
M
M
−


τ
τ
M
M
−

Hassenstein-Reichardt Detector Model



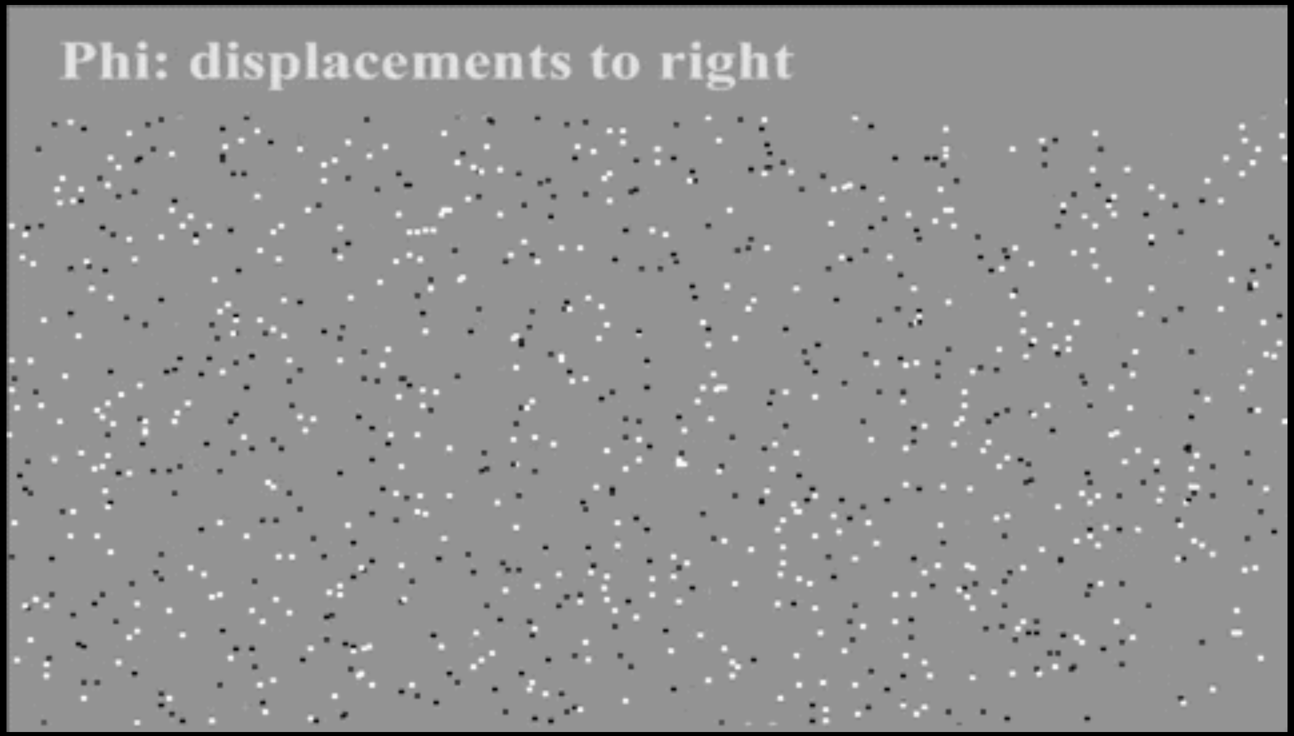
$$r_1(t) = \int_0^\infty s_1(t-\tau)D(\tau)d\tau;\ \ r_2(t) = \int_0^\infty s_1(t-\tau)\delta(\tau)d\tau$$

$$r_3(t) = \int_0^\infty s_2(t-\tau)\delta(\tau)d\tau;\ \ r_4(t) = \int_0^\infty s_2(t-\tau)D(\tau)d\tau;$$

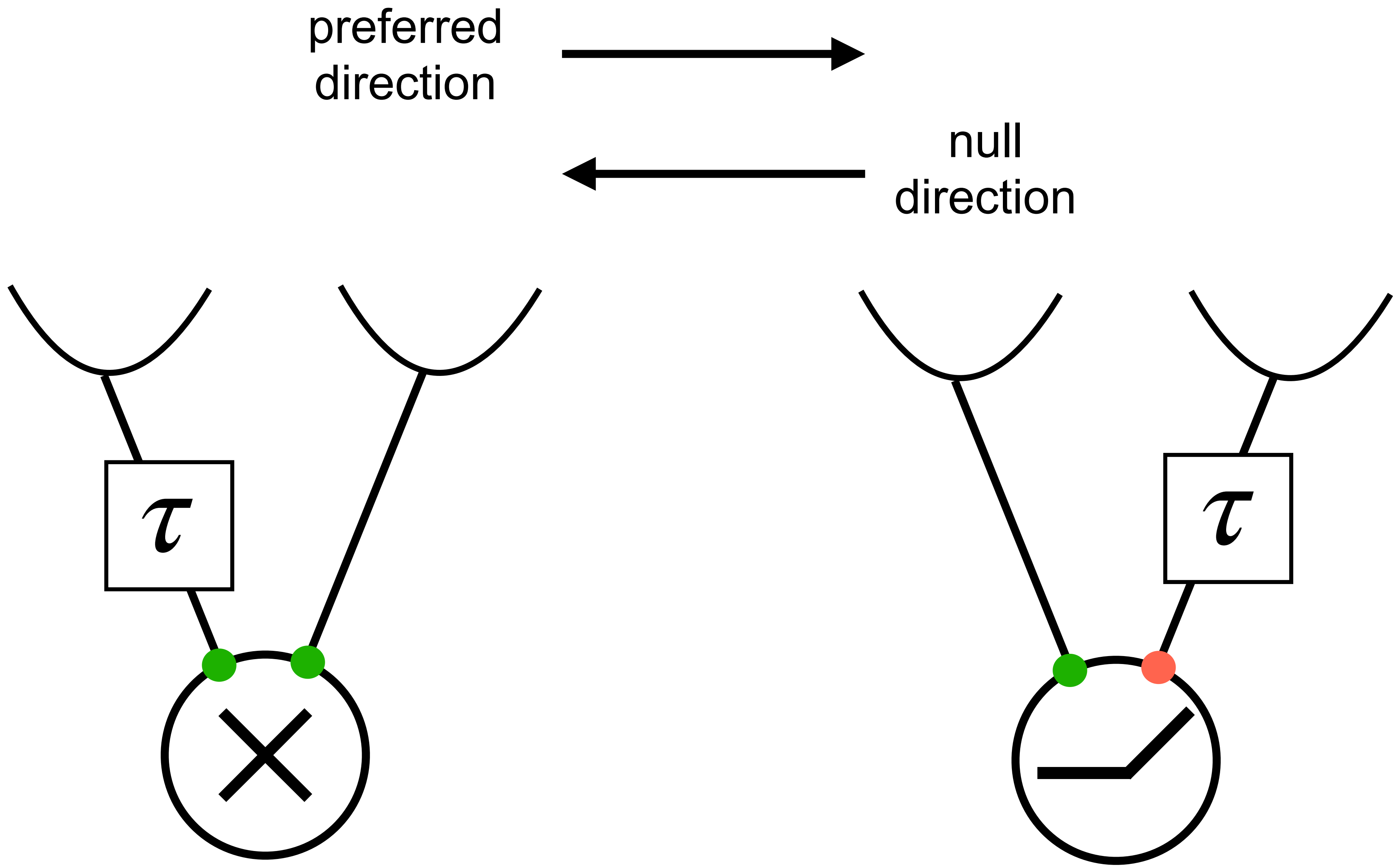
$$R(t) = r_1(t)r_3(t) - r_2(t)r_4(t)$$

$$D(\tau) = \frac{1}{\tau_0}\exp(-\tau/\tau_0)$$

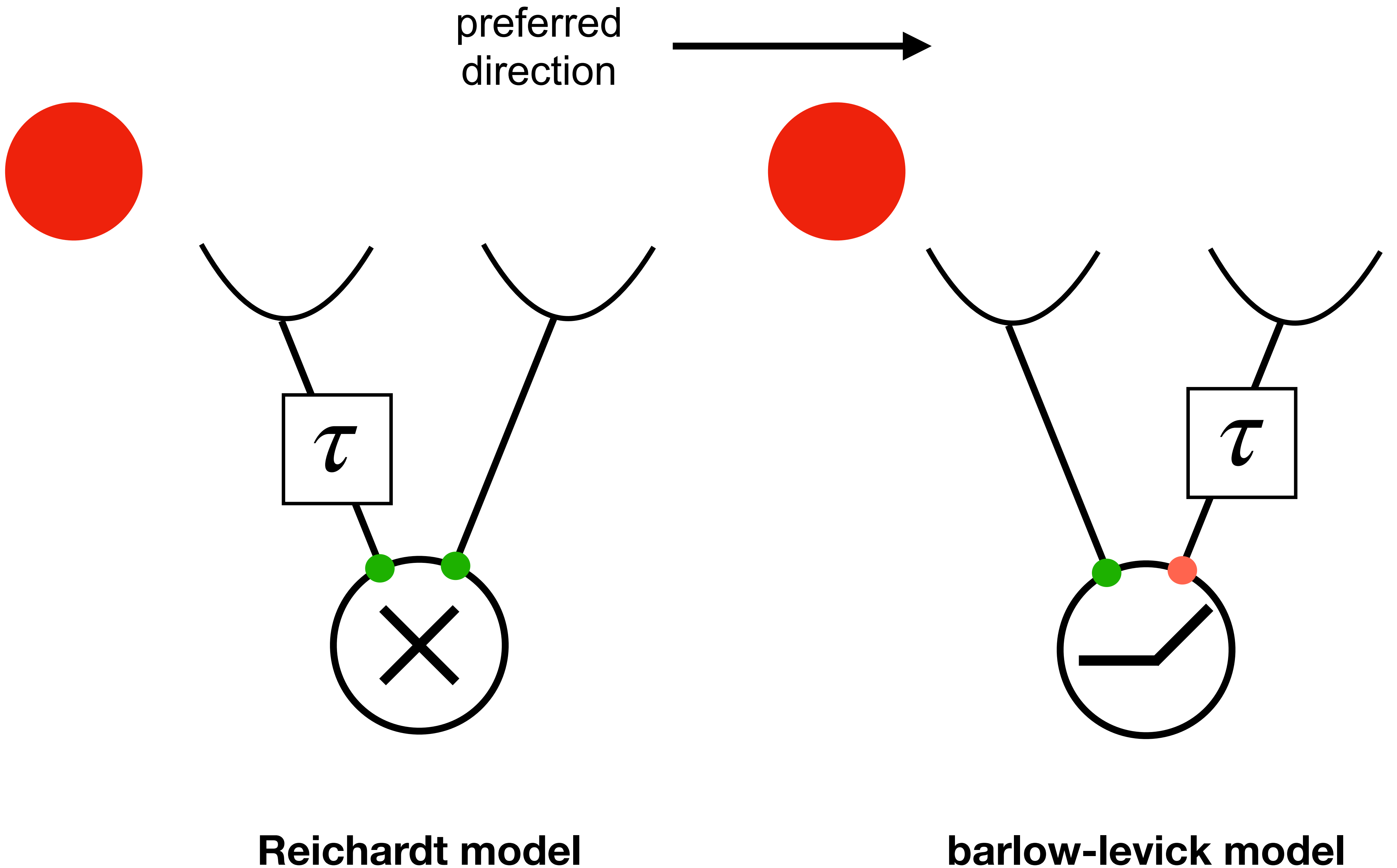
$$\langle R \rangle = \frac{\omega\tau_0}{\omega^2\tau_0^2 + 1}$$



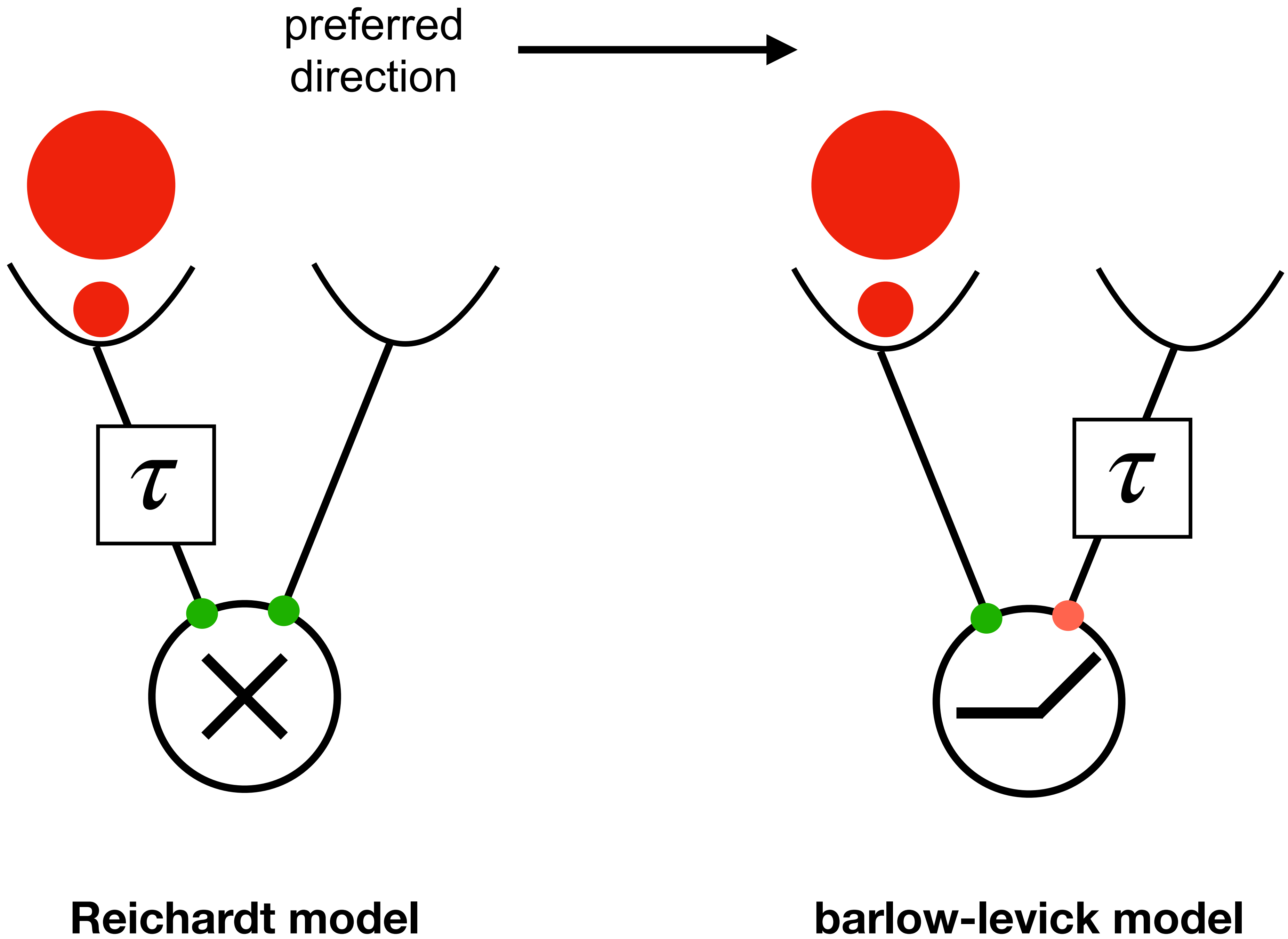
adapted from Damon Clark's slide

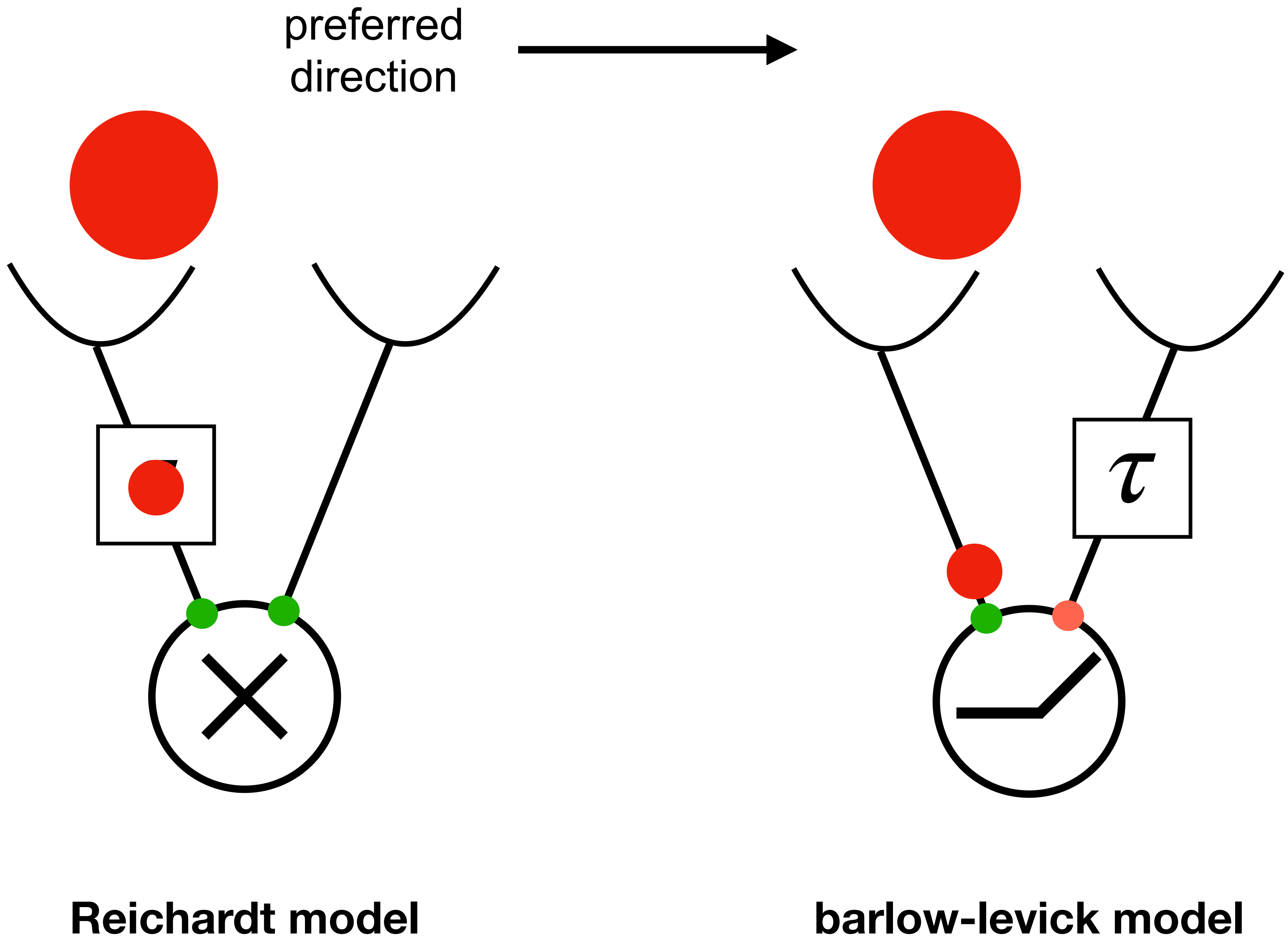


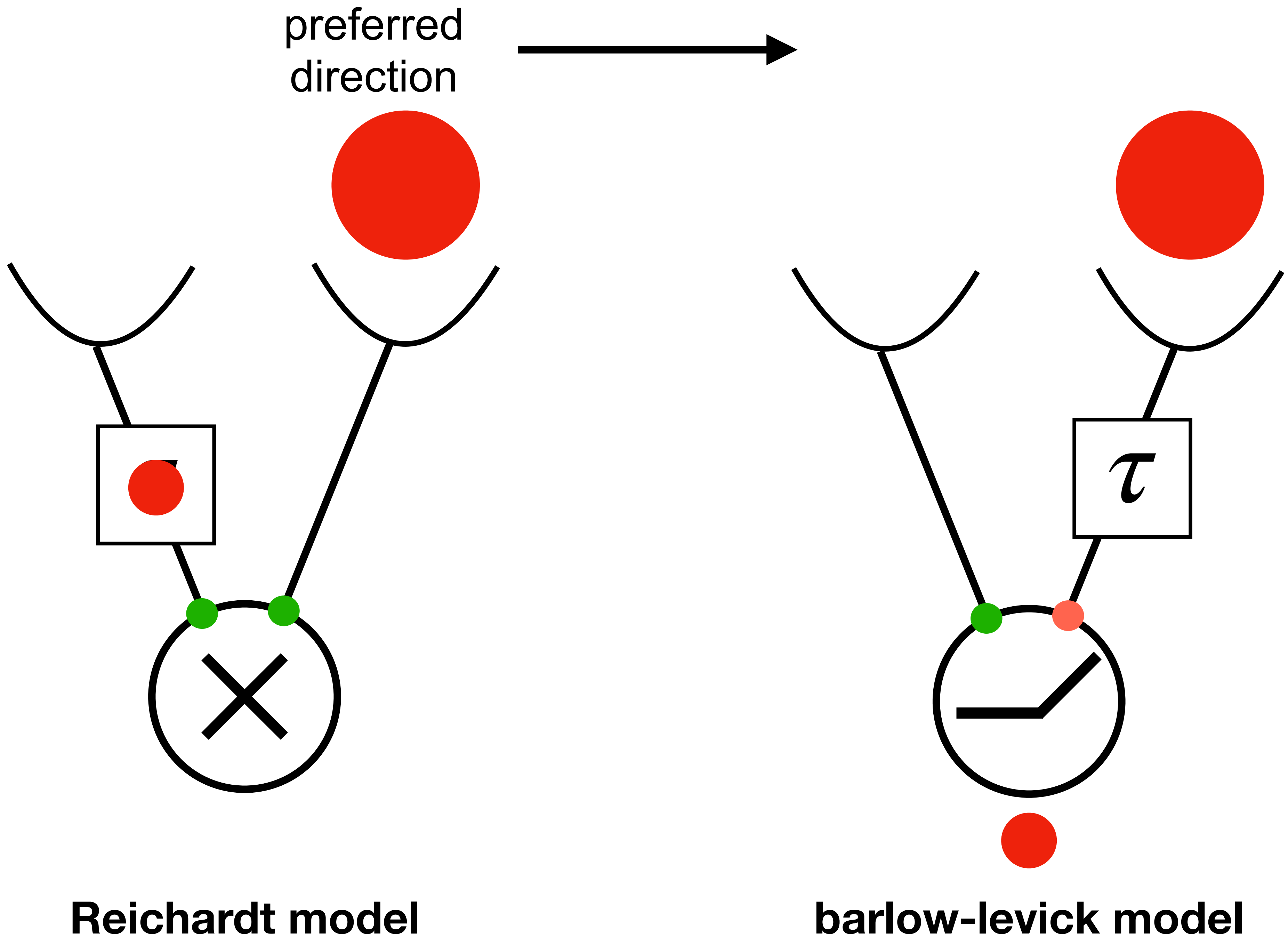
Reichardt model **barlow-levick model**

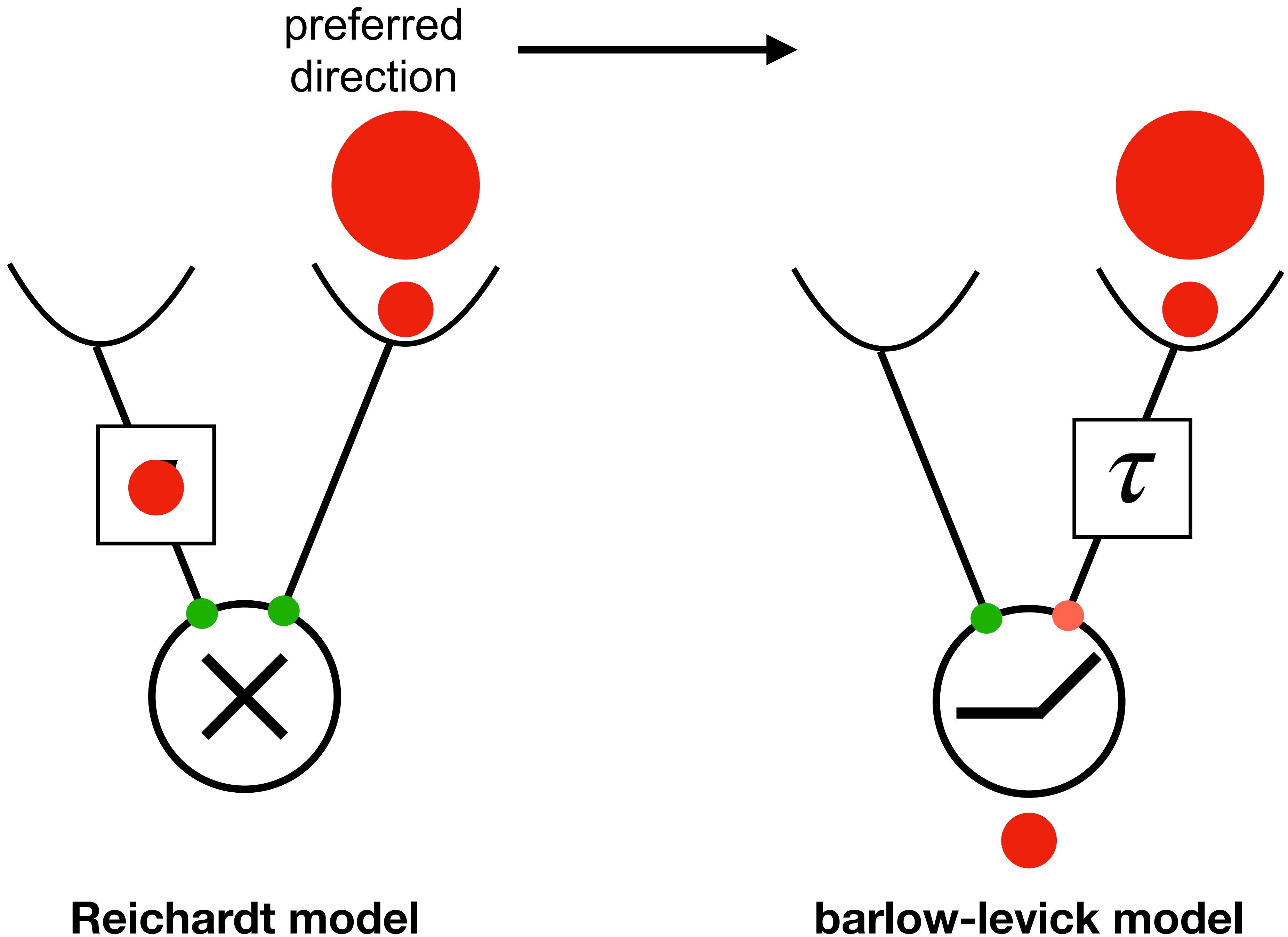


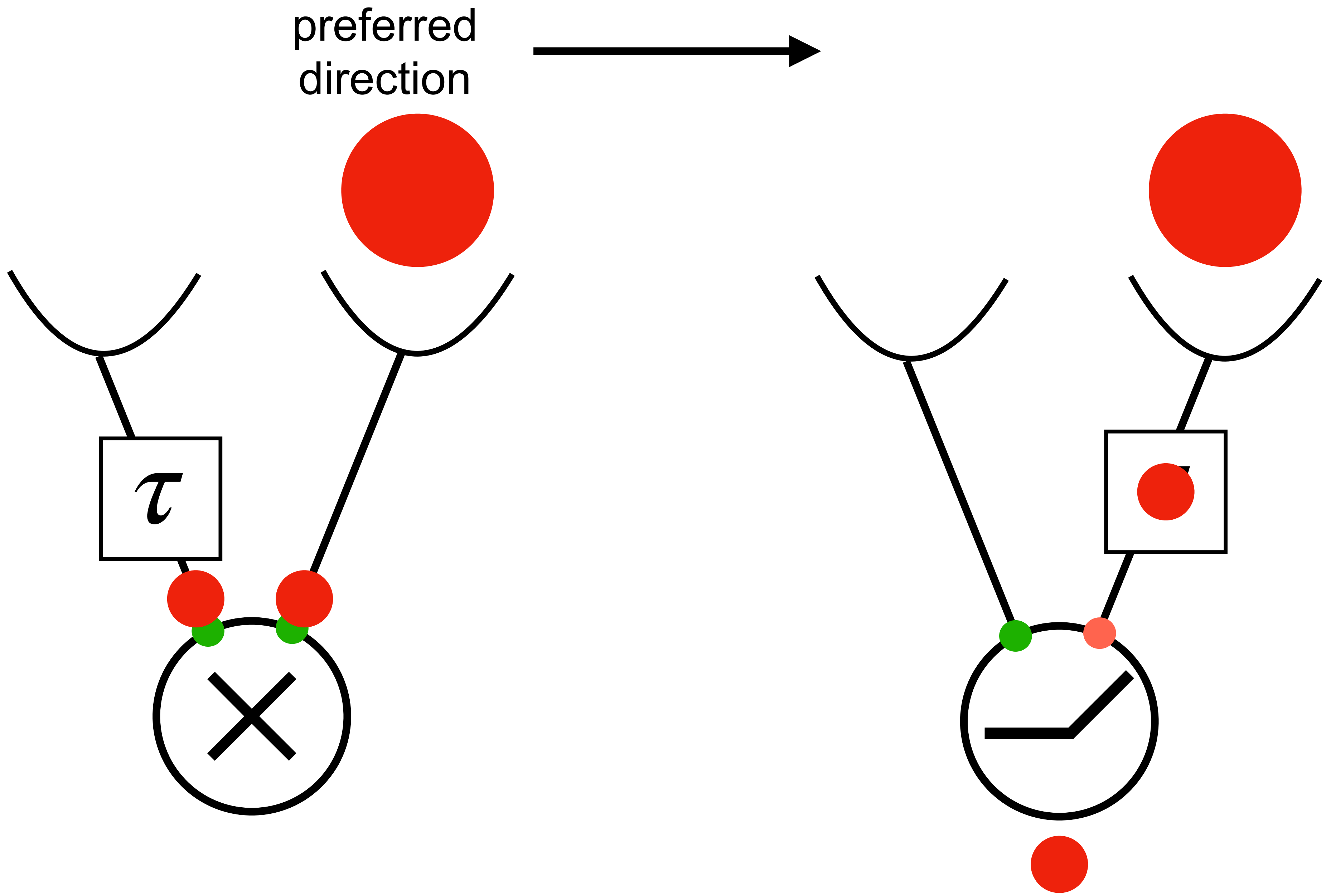
preferred
direction
τ
τ
Reichardt model
barlow-levick model


preferred direction
τ
τ
Reichardt model
barlow-levick model


preferred
direction
τ
Reichardt model
barlow-levick model

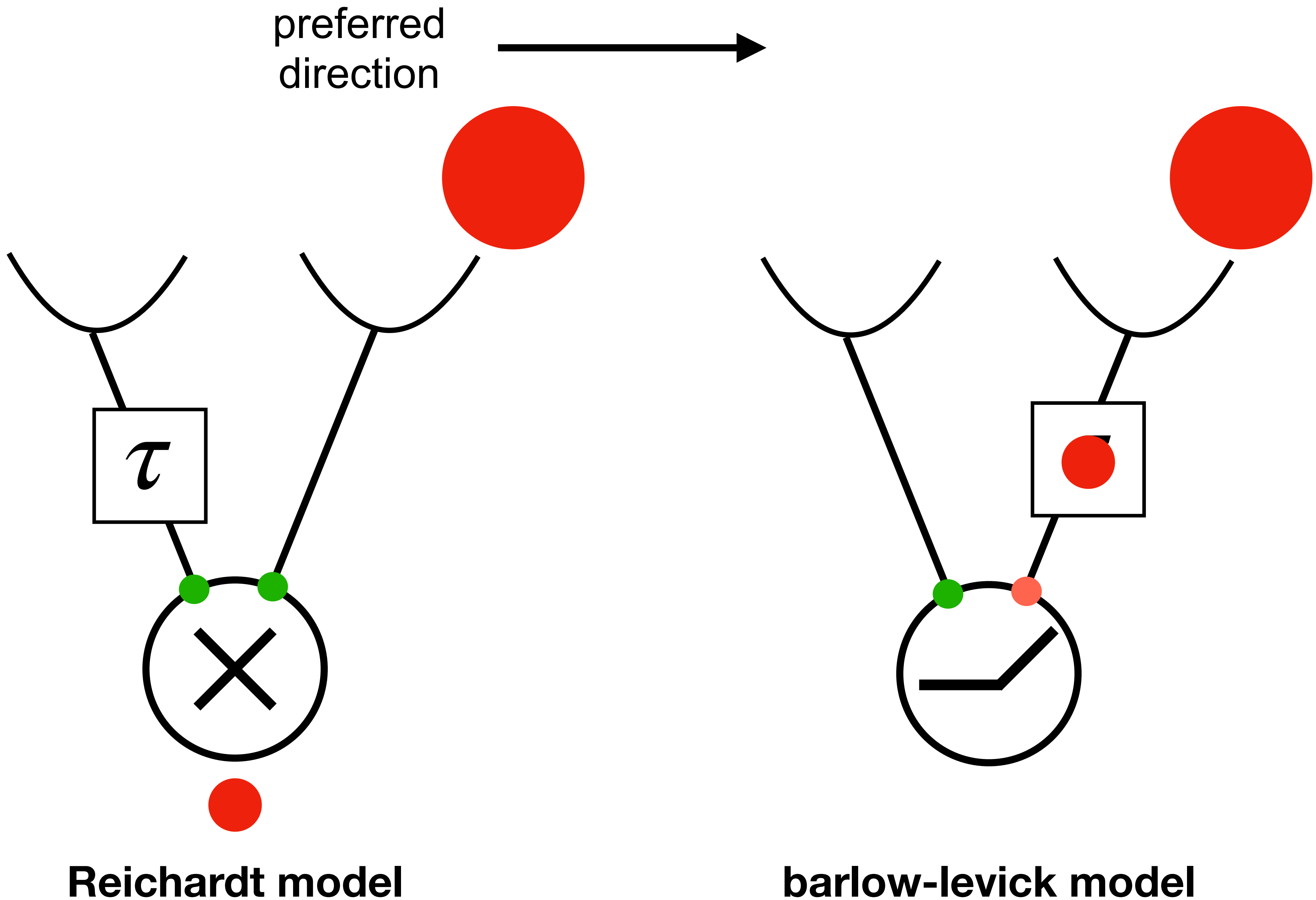

preferred
direction
τ
τ
Reichardt model
barlow-levick model


preferred
direction
τ
Reichardt model
barlow-levick model

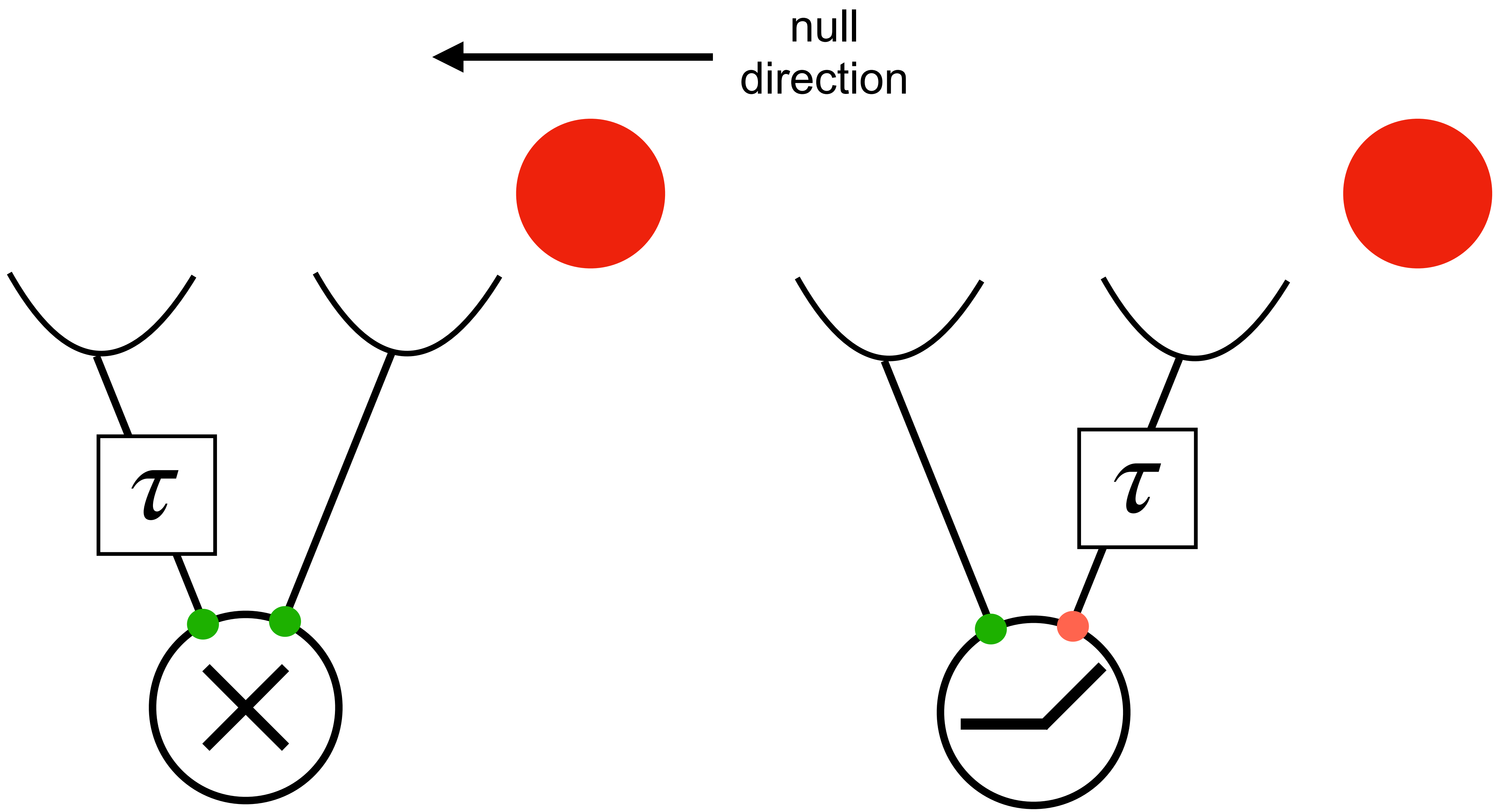


Reichardt model

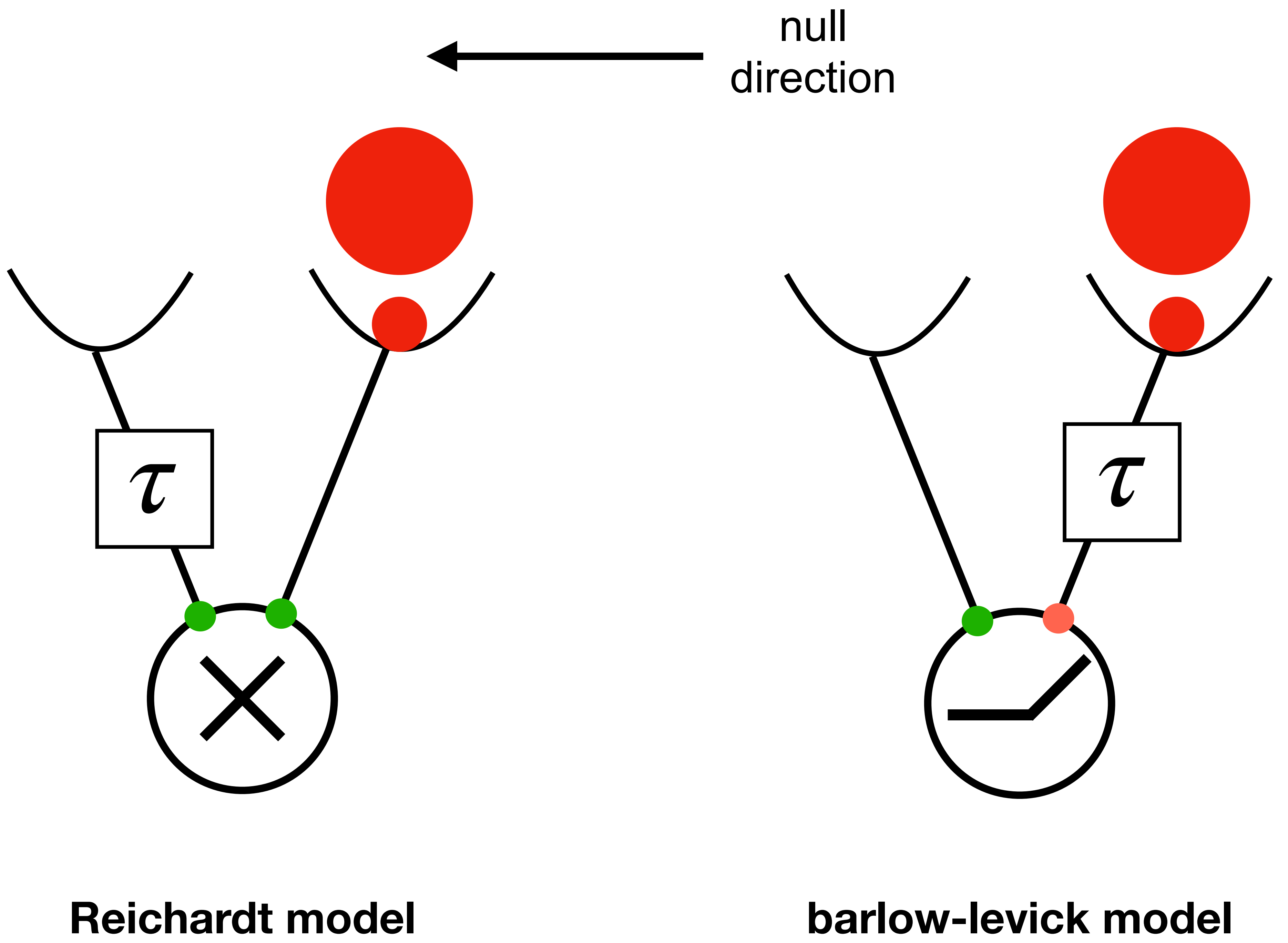
barlow-levick model

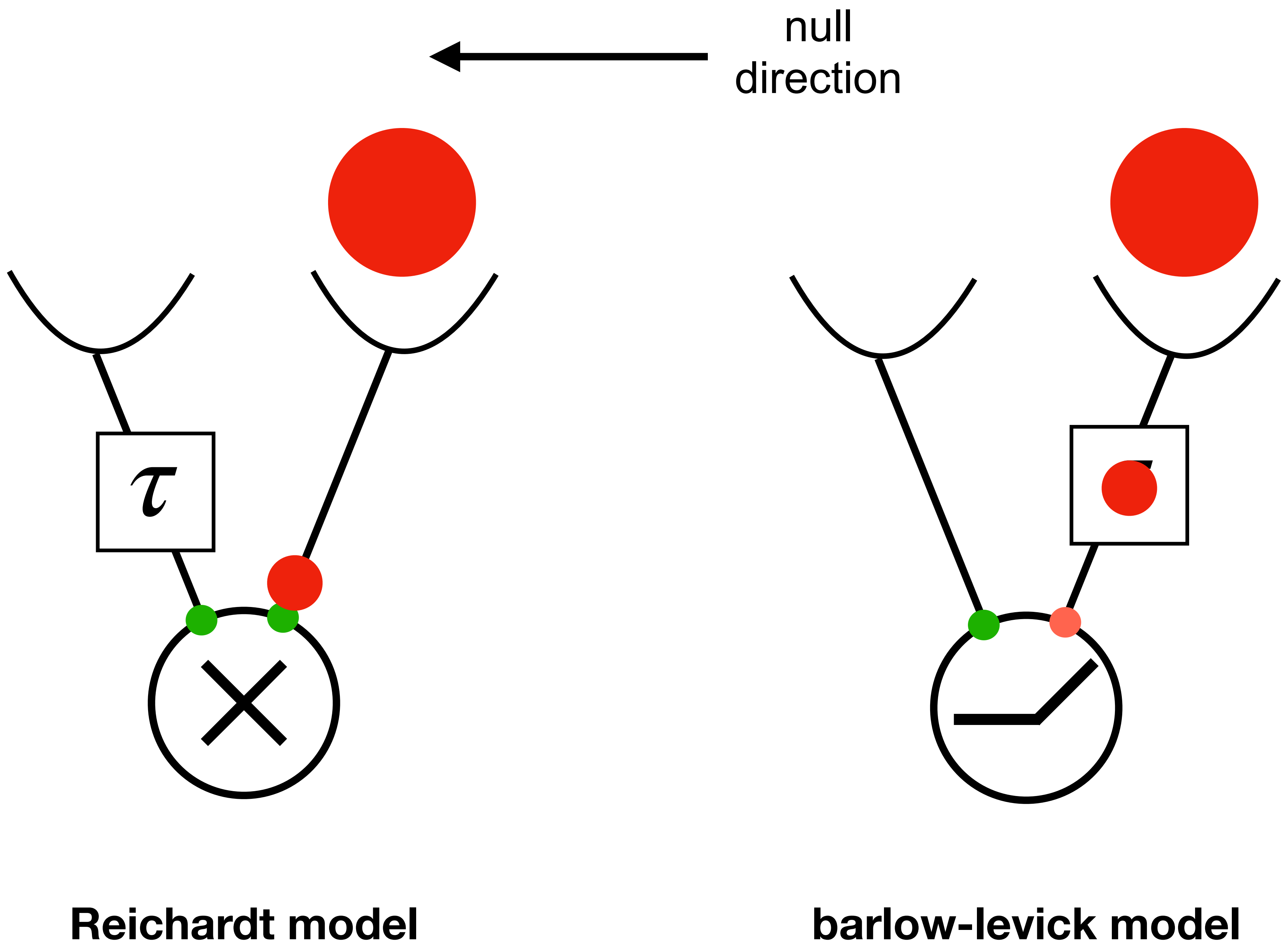


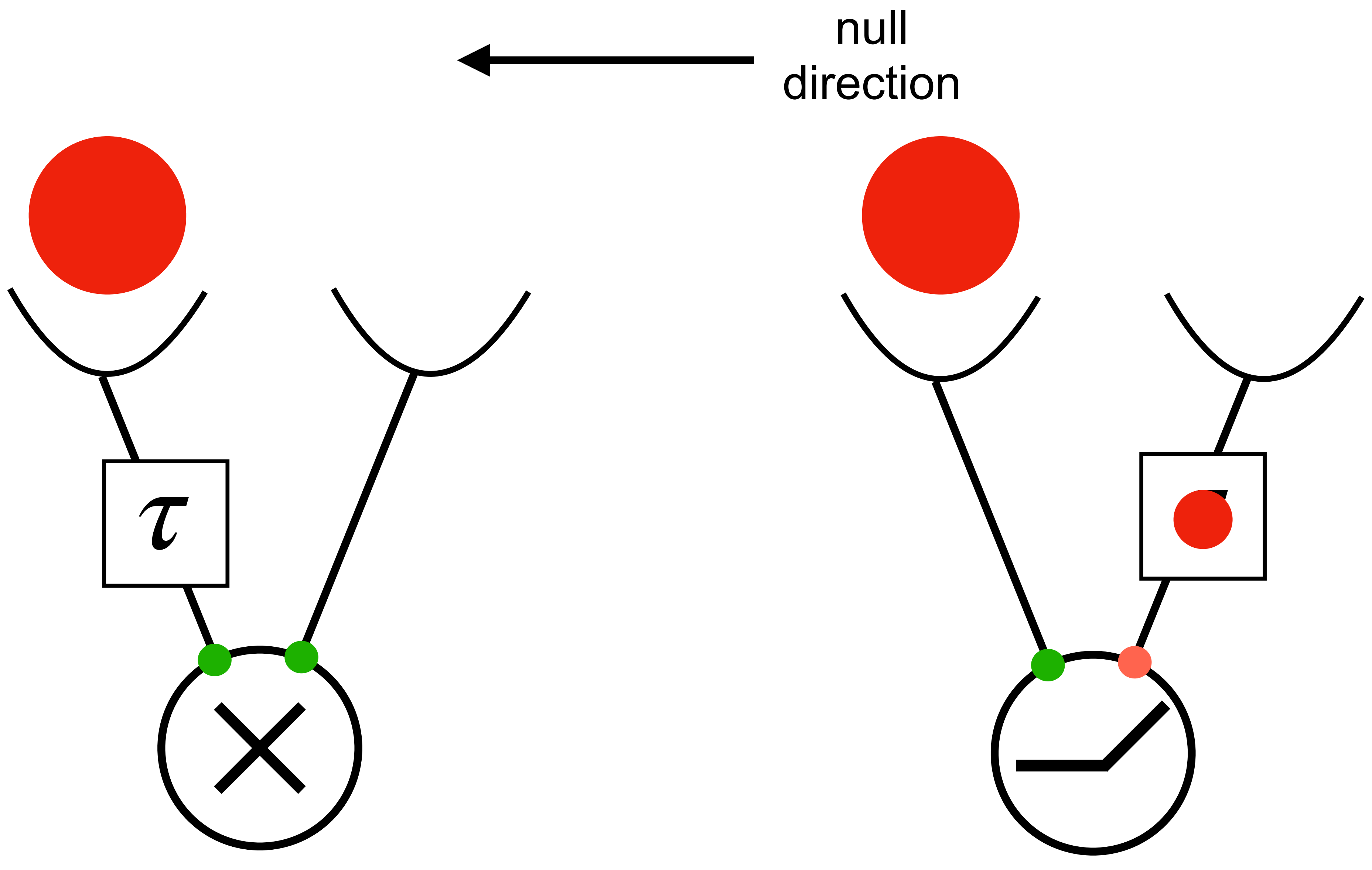
preferred
direction
τ
Reichardt model
barlow-levick model



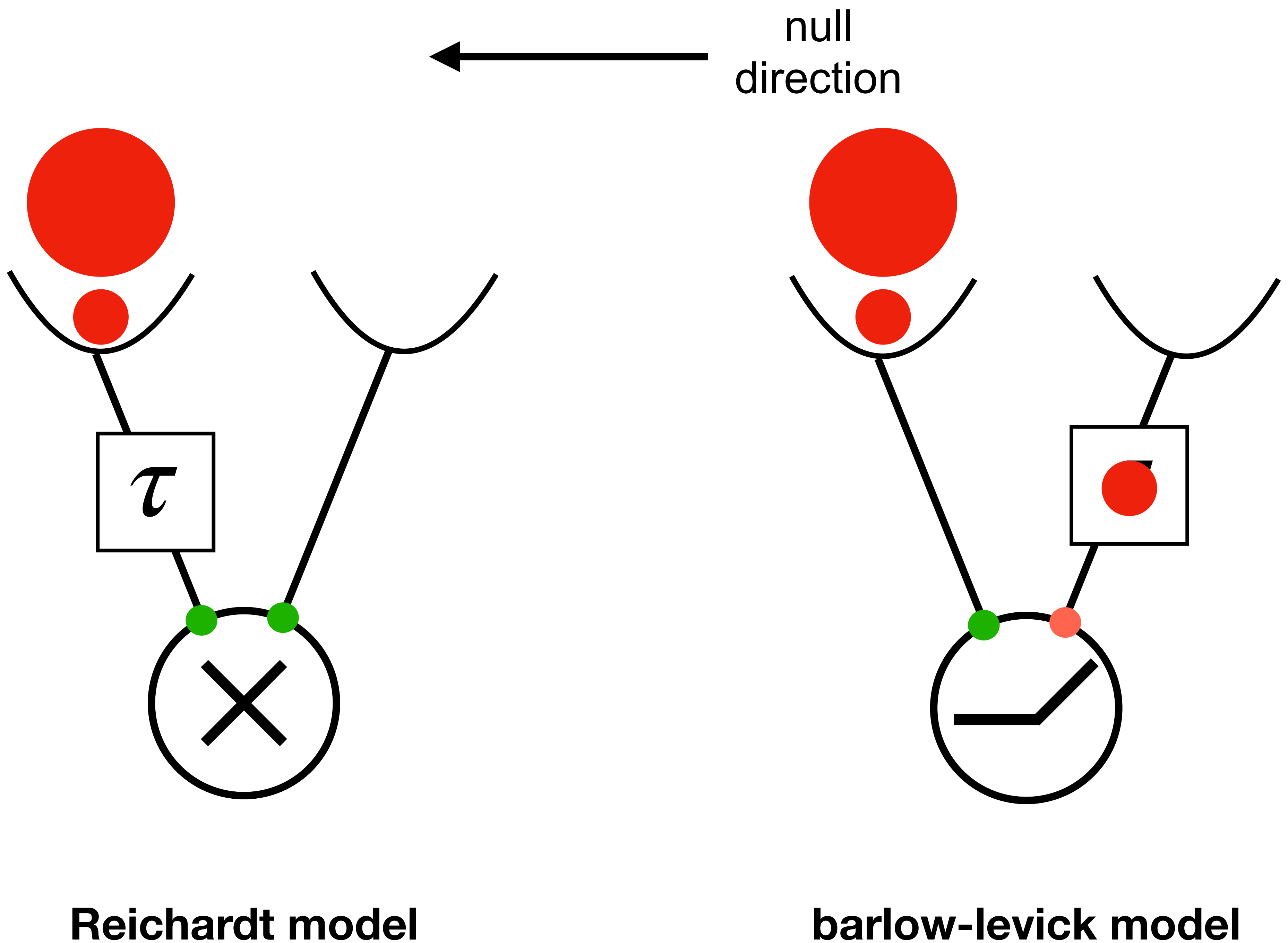
Reichardt model **barlow-levick model**

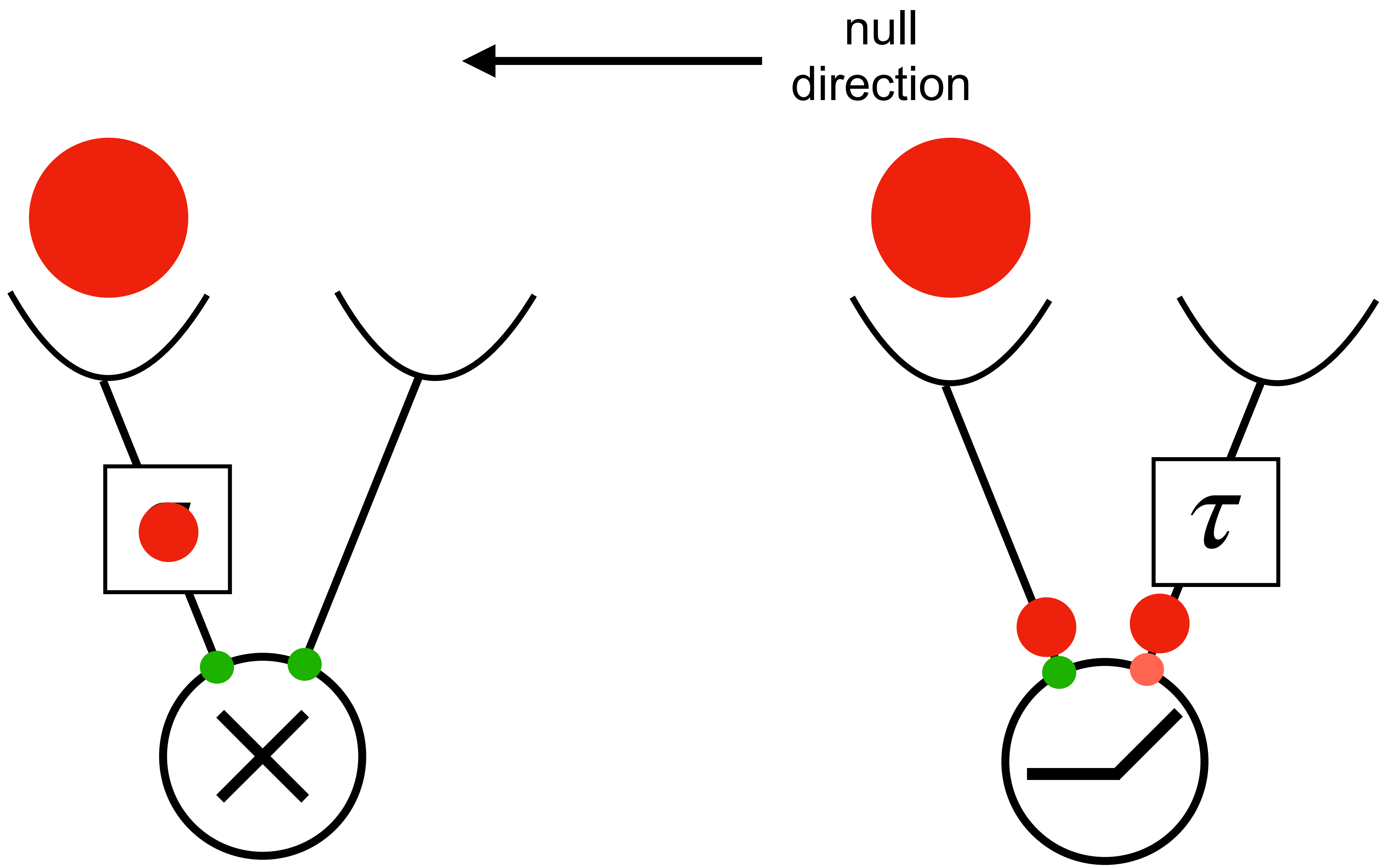

null
direction
τ
τ
Reichardt model
barlow-levick model


null
direction
τ
Reichardt model
barlow-levick model



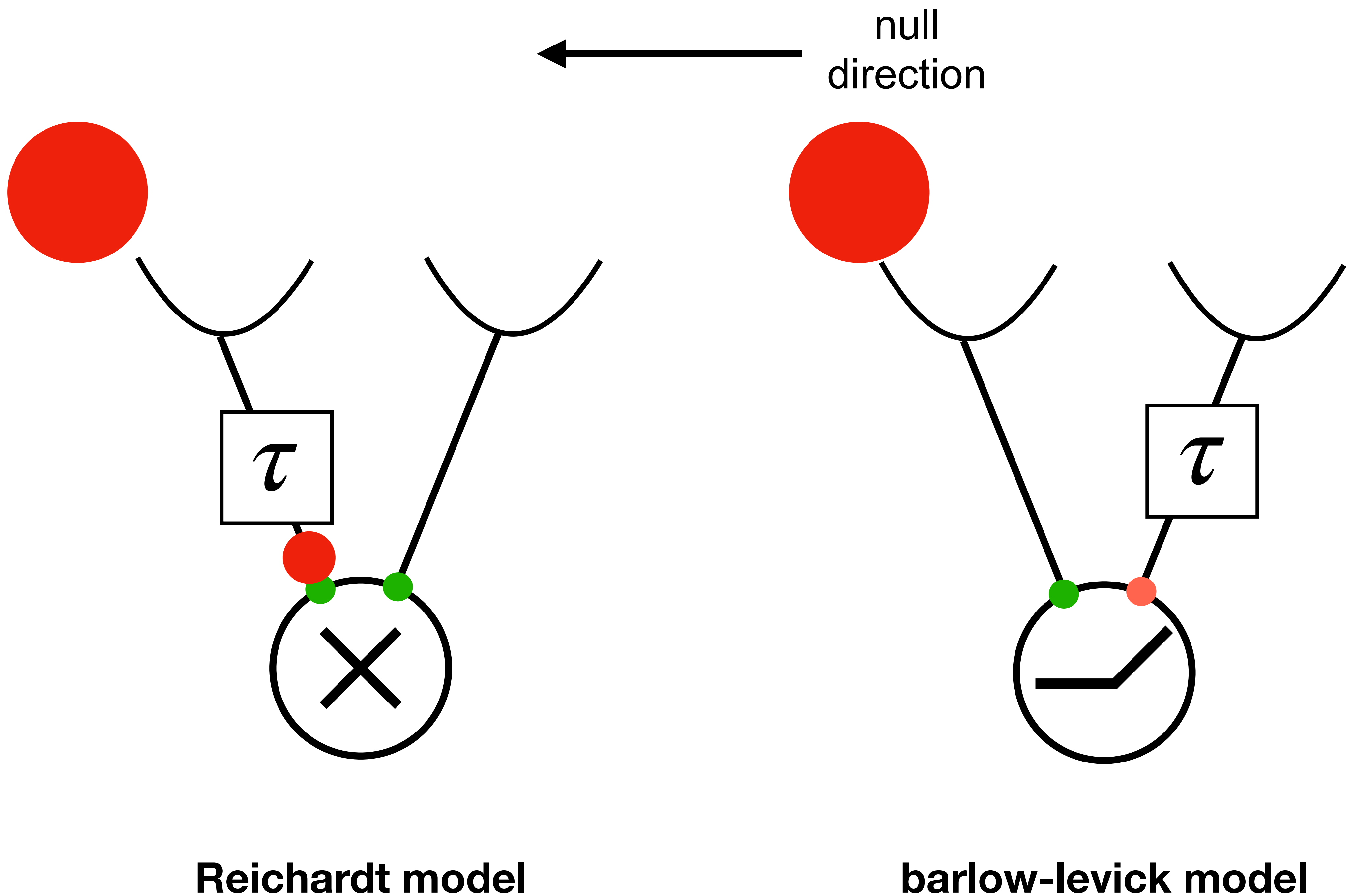
Reichardt model **barlow-levick model**

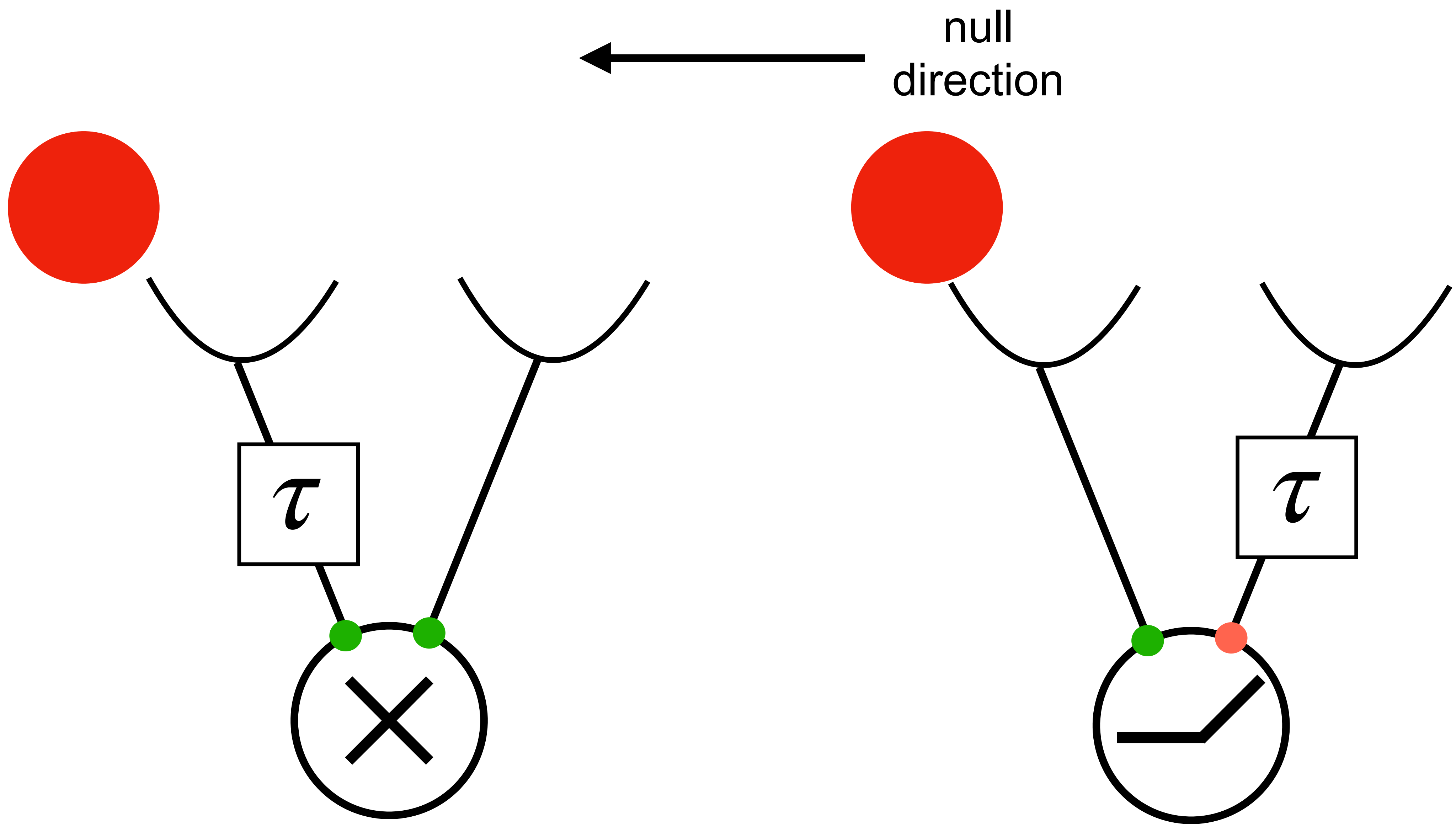

null
direction
τ
Reichardt model
barlow-levick model



Reichardt model

barlow-levick model


null
direction
τ
τ
Reichardt model
barlow-levick model



Reichardt model

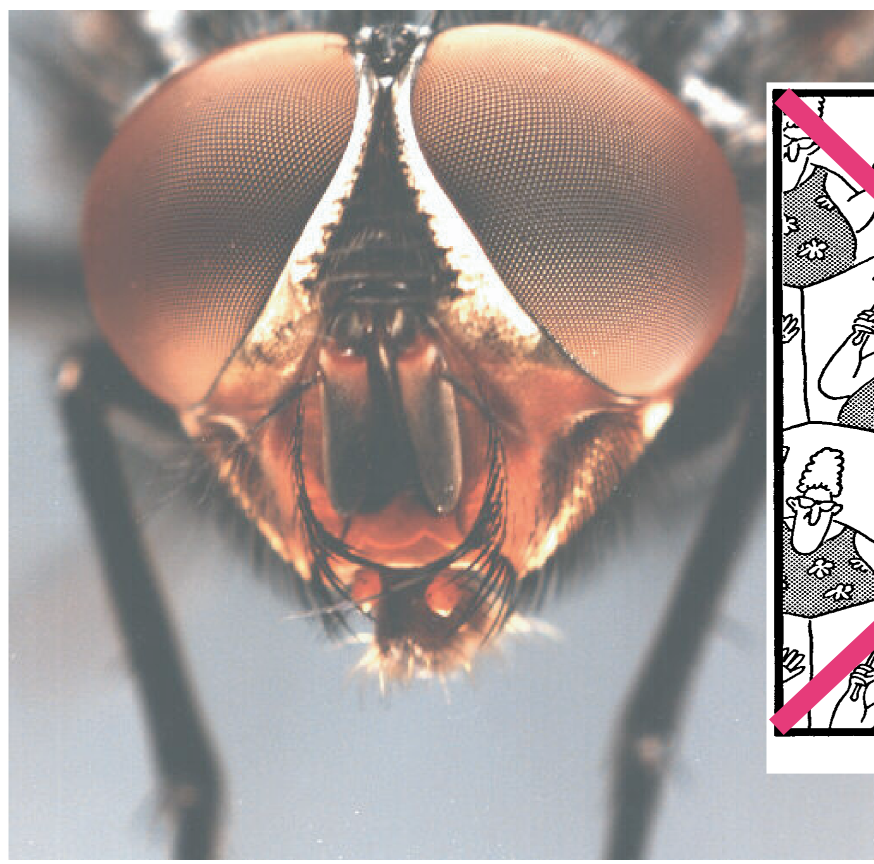
barlow-levick model

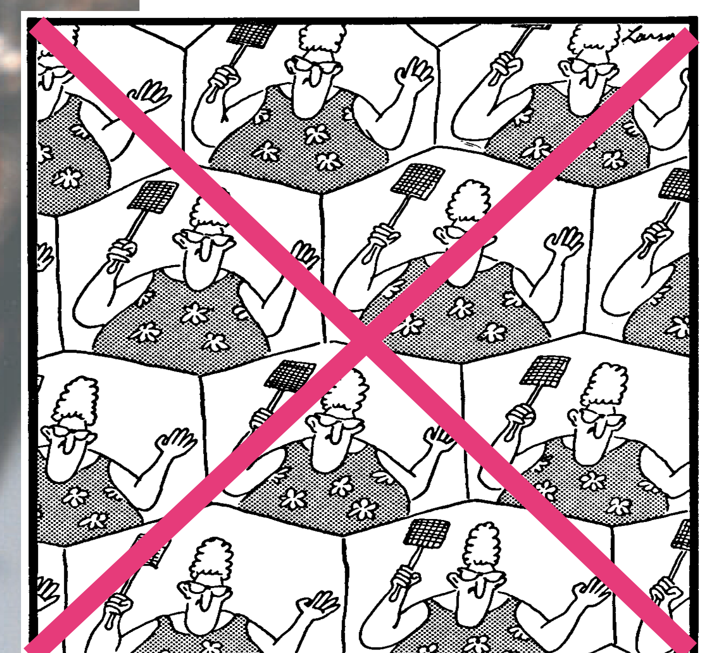
- **Computational level**: Identify the computational problem and task that the brain solves.

- **Algorithmic level**: Find the mathematical procedures that solve the problem.

- **Implementation level**: How the algorithms are realized by the nervous system.

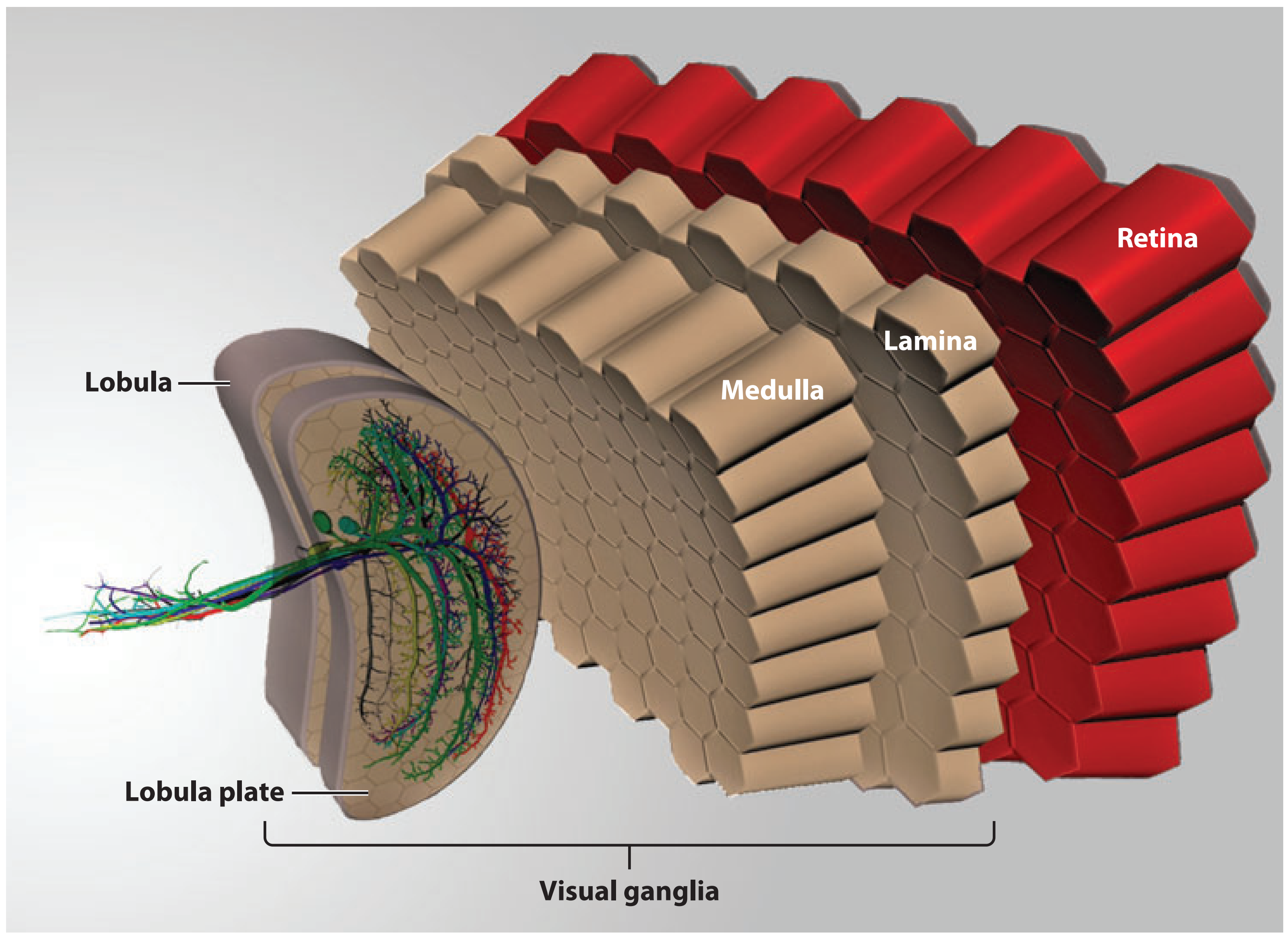
The Fly Visual System



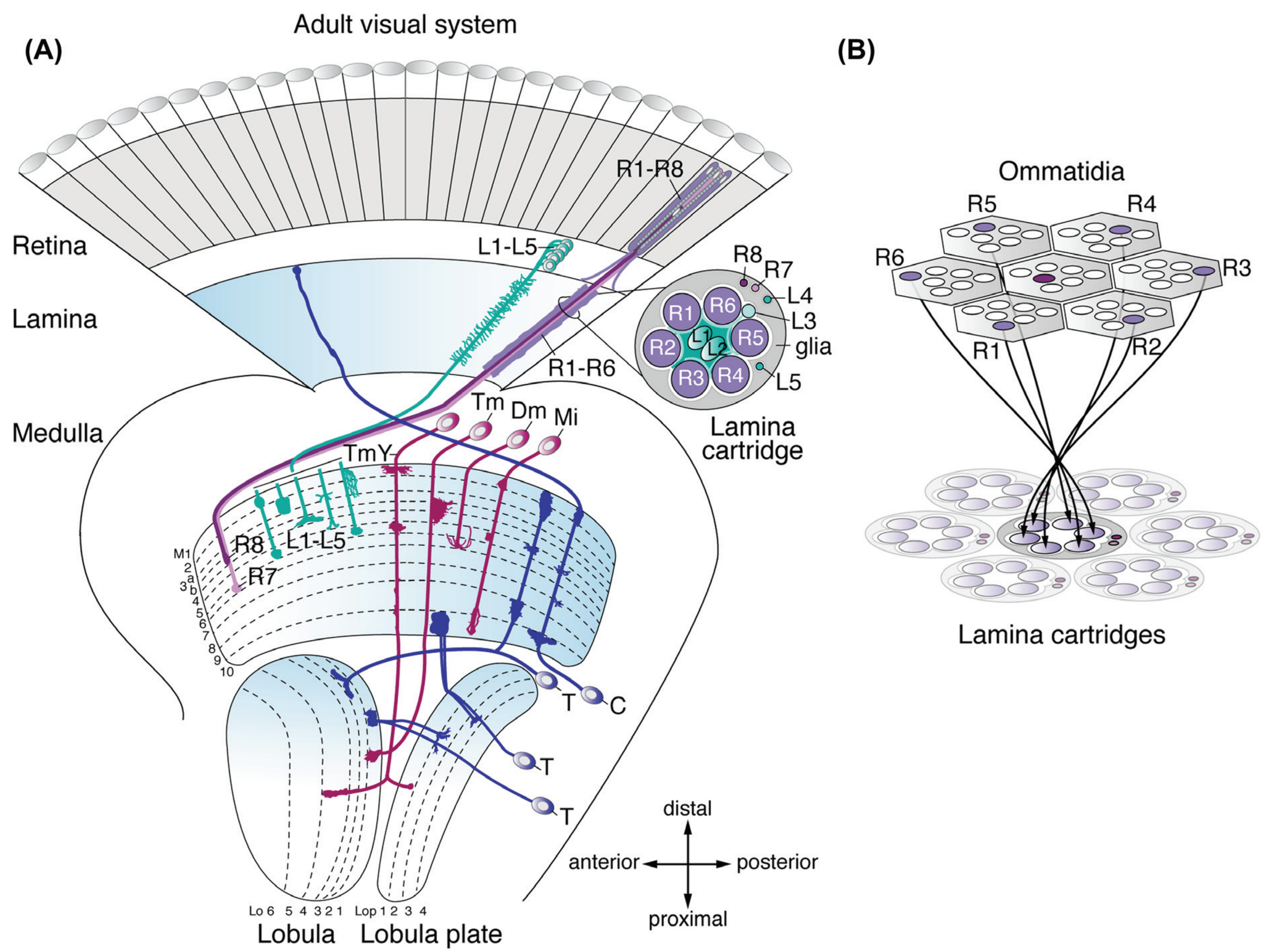


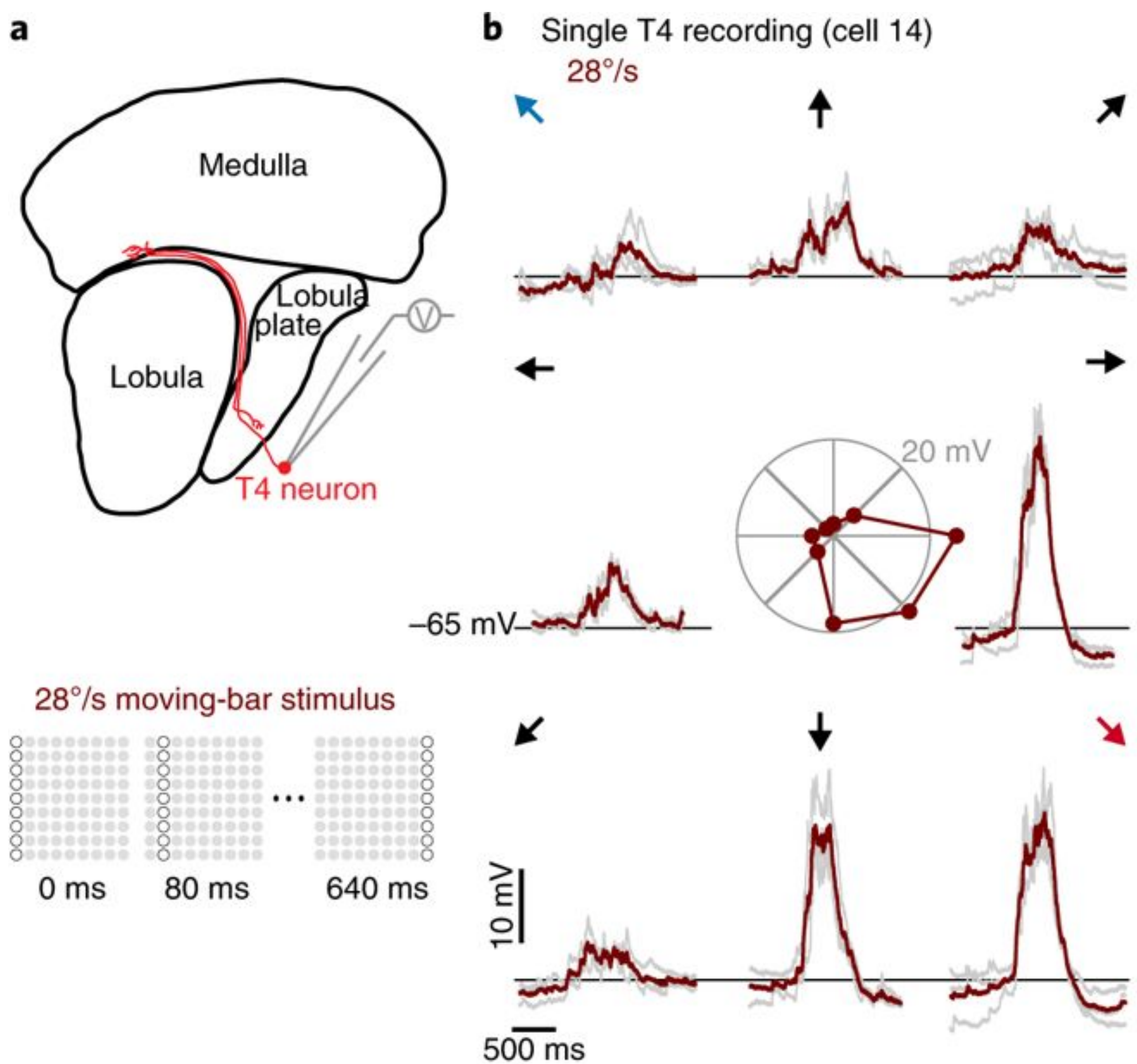
The last thing a fly ever sees

The Fly Visual System

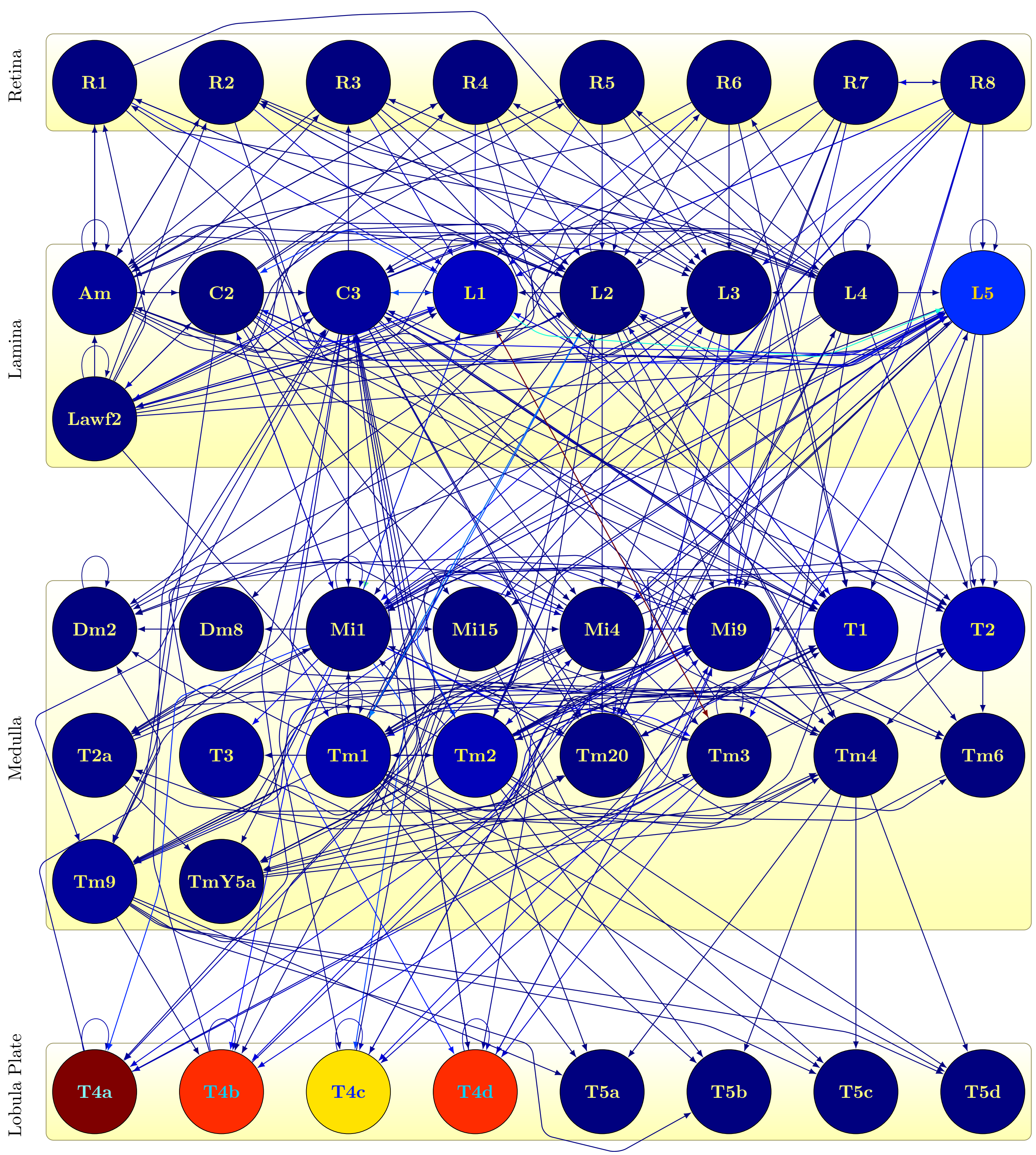


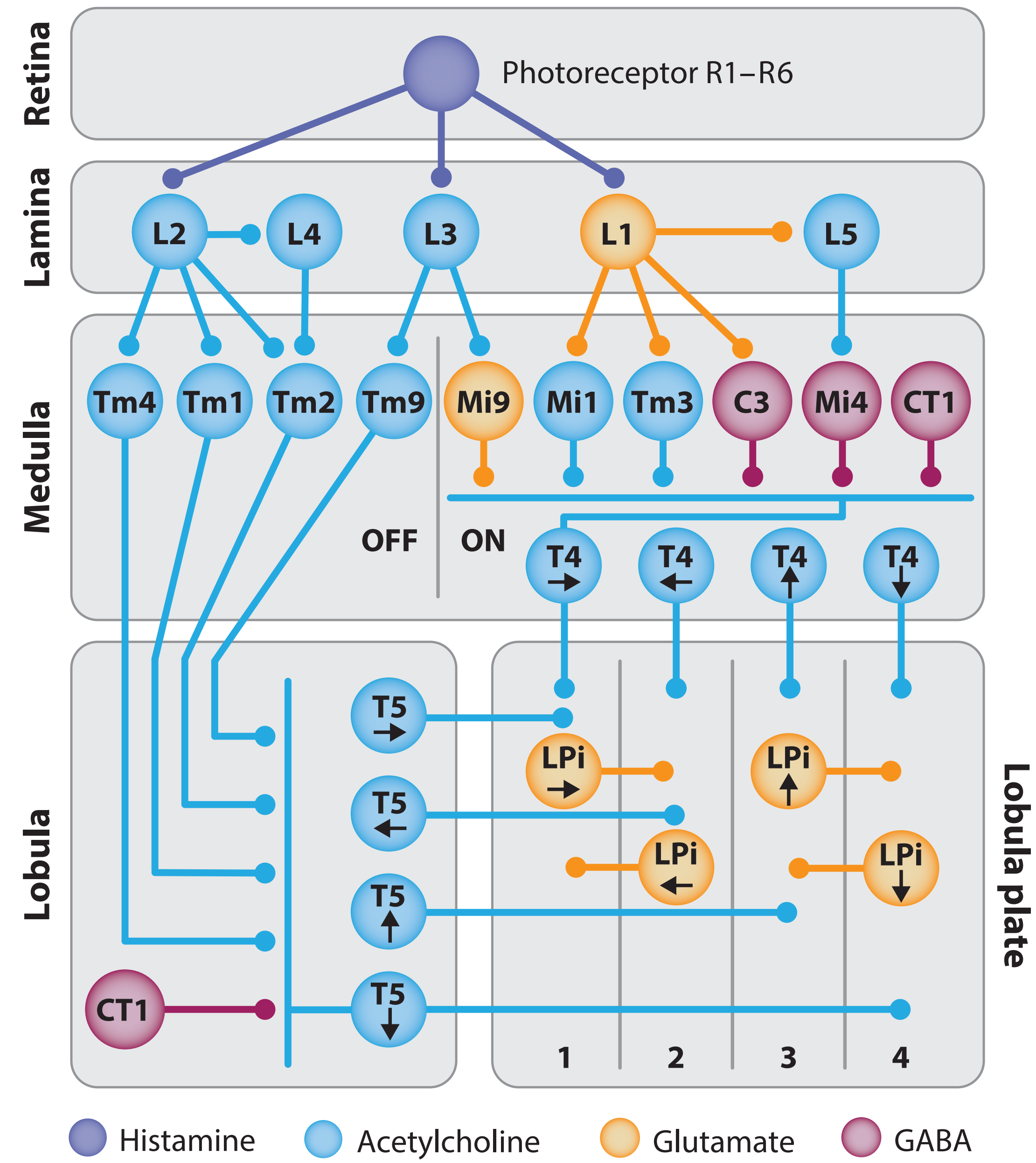
The Fly Visual System



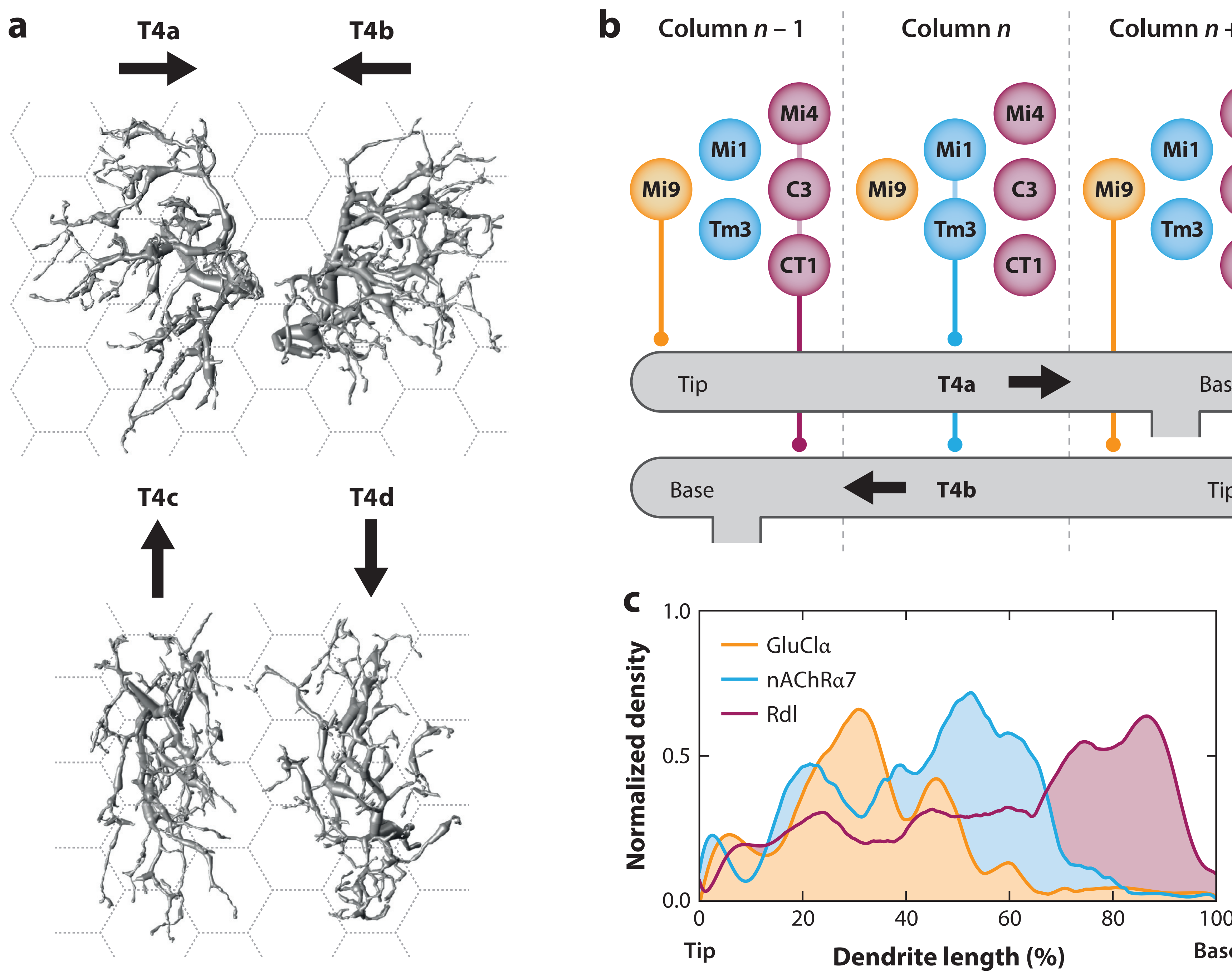


Gruntman, Romani and Reiser et. al., Nature Neuroscience 2018

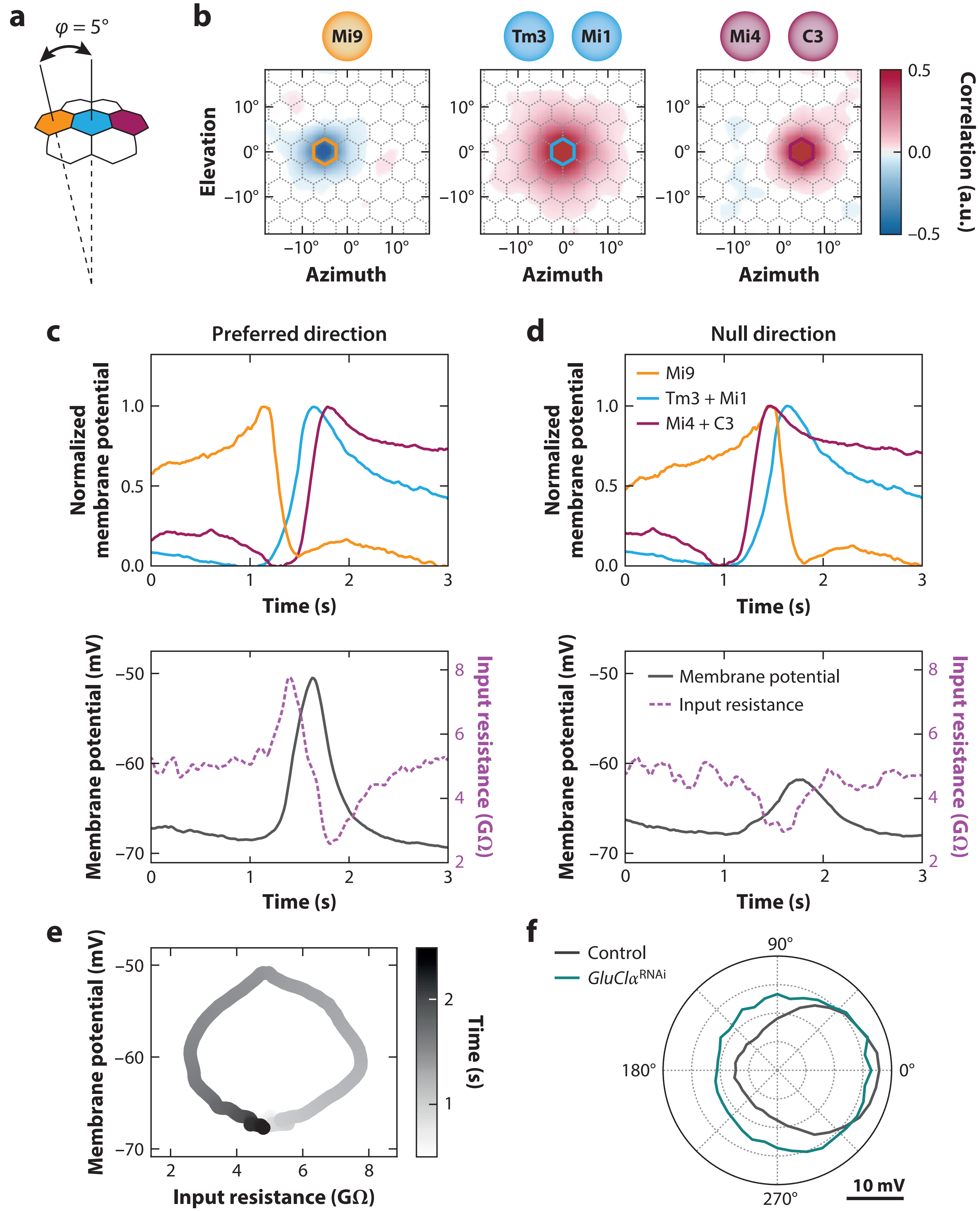




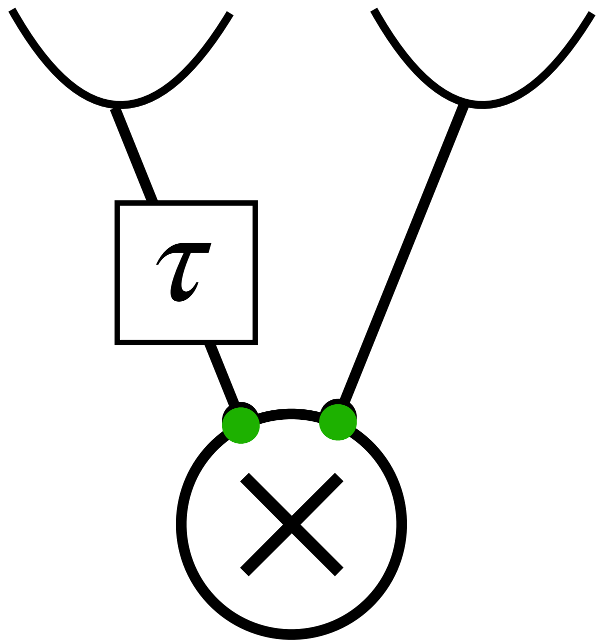
Takemura et. al., Nature 2013 & elife 2017



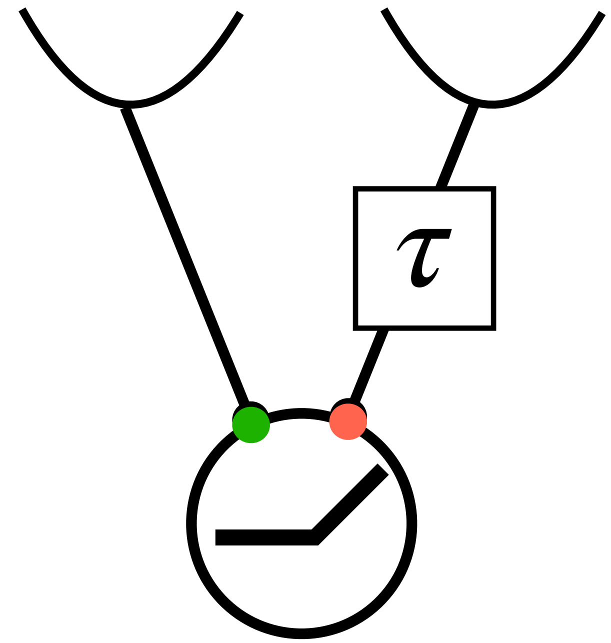
Borst & Groschner, Annual Review Neuroscience 2023



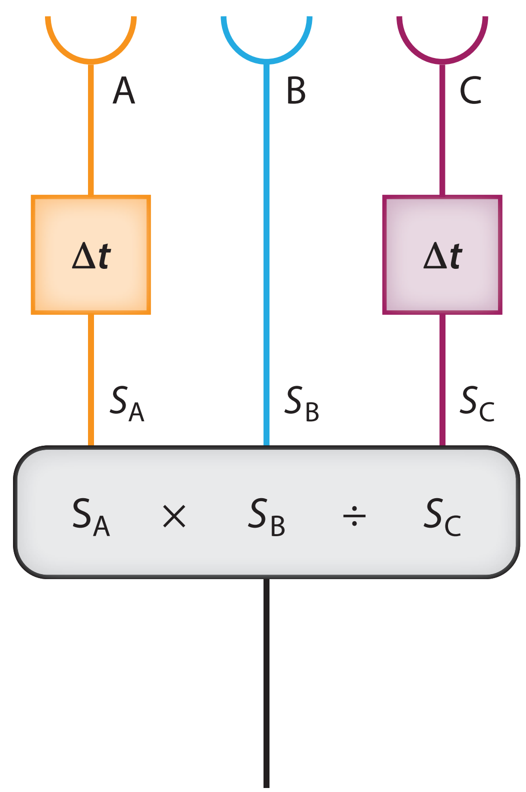
Gonzalez-Suarez AD et. al., Current Biology 2022



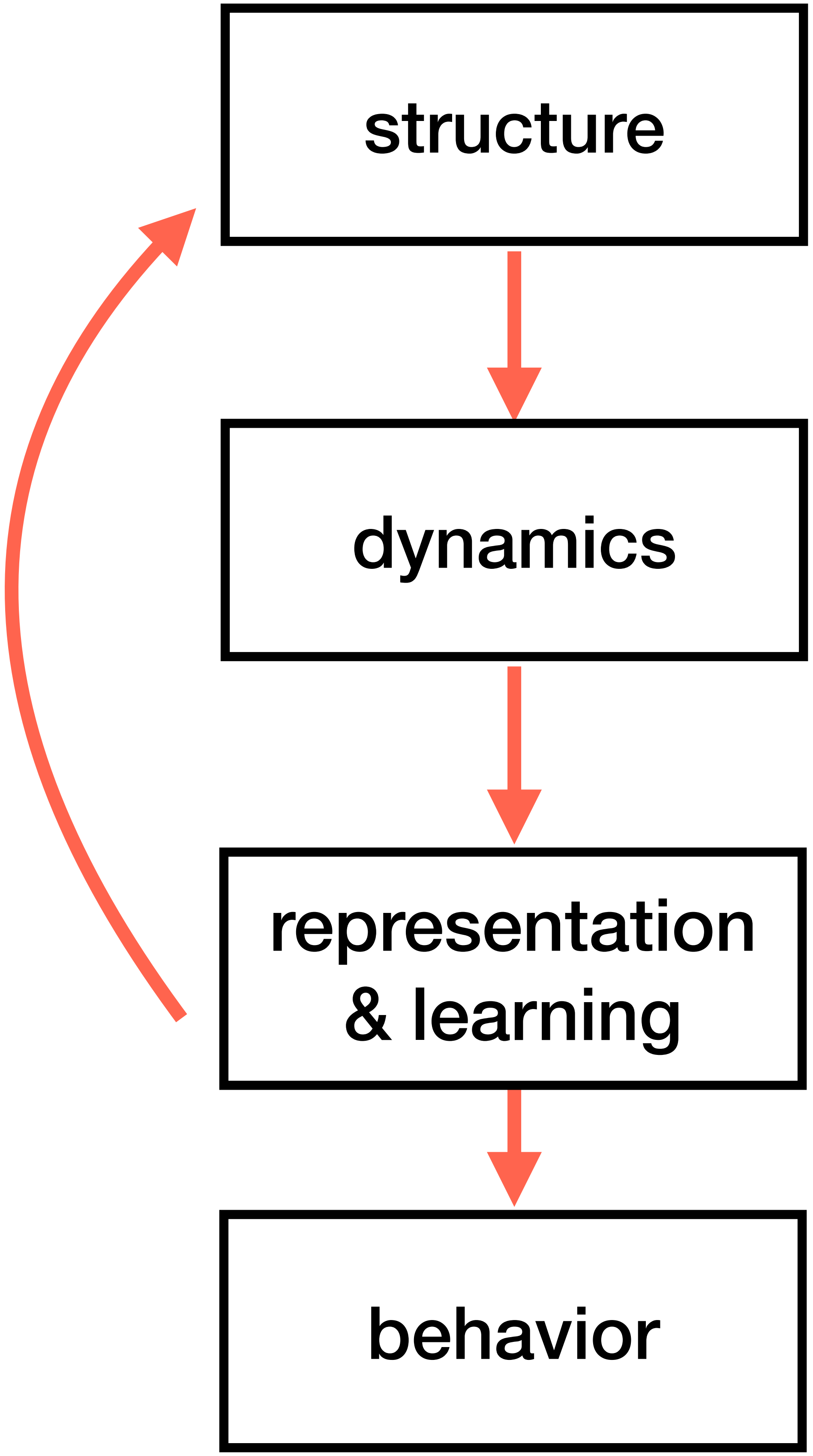
Reichardt



barlow-levick



Borst & Groschner, Annual Review Neuroscience 2023


structure
dynamics
representation
& learning
behavior

Course Curriculum

- **Introduction to Computational Neuroscience**
- **Single Neuron Computation**
- **Connect Neurons to Perform Computation**
- **Recurrent network and Attractor Dynamics**
- **E/I balance and Chaotic Dynamics**
- **Efficient coding principle**
- **Stimulus discrimination, Fisher information and Information-limited correlation**
- **Normative approach to neural computation and the emergence of sensory representation**
- **Dimensionality reduction and motor representation**
- **How does an animal move, an integrated approach, and insights from *C. elegans***
- **Reward and Reinforcement Learning**