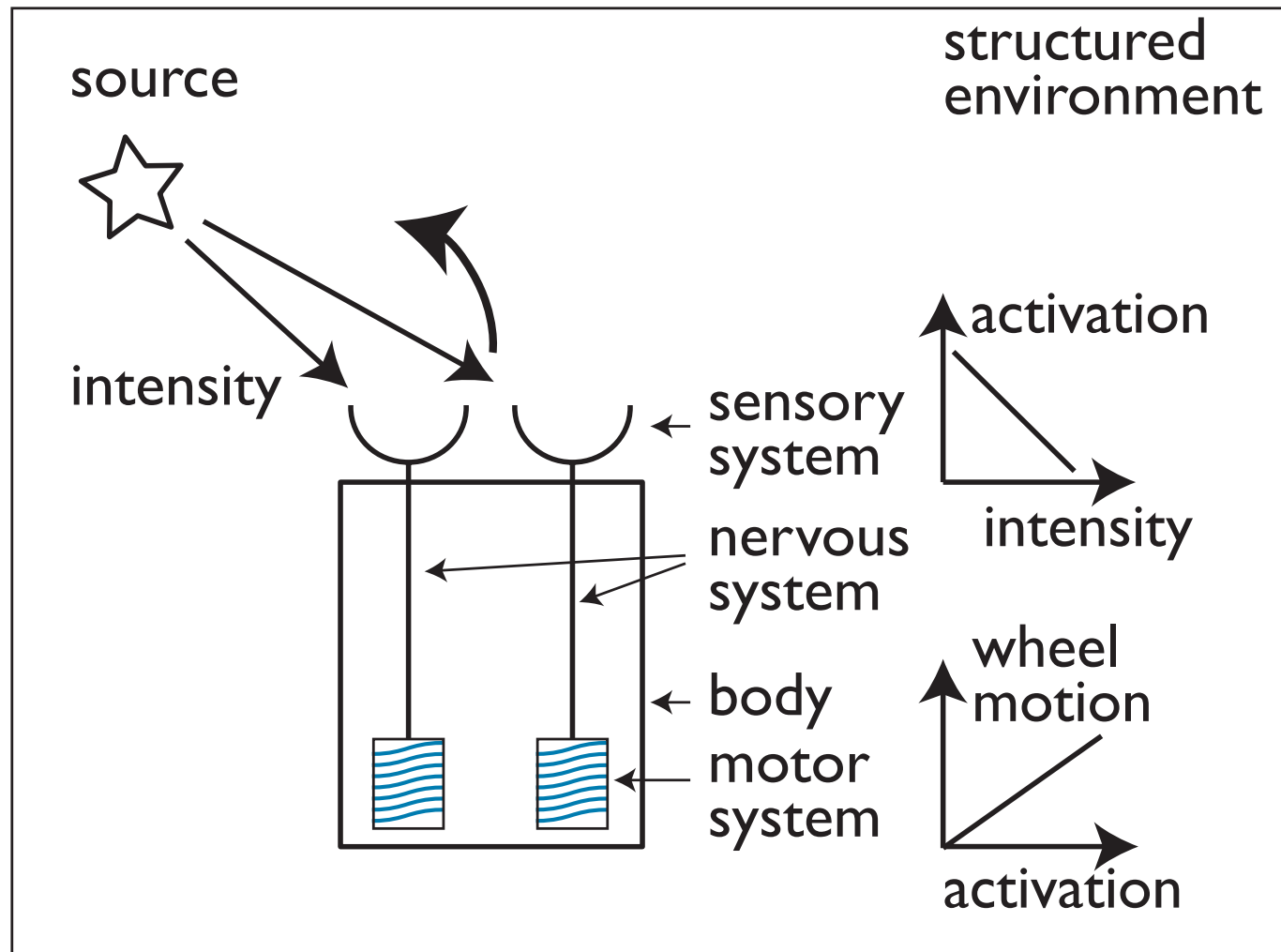


# Braitenberg vehicles: embodied nervous systems

Gregor Schöner

# Braitenberg's vehicle metaphor

- vehicle=organism whose body moves its sensors and motor systems through its environment



# Braitenberg vehicles

■ =embodied nervous systems  
with:

■ effectors

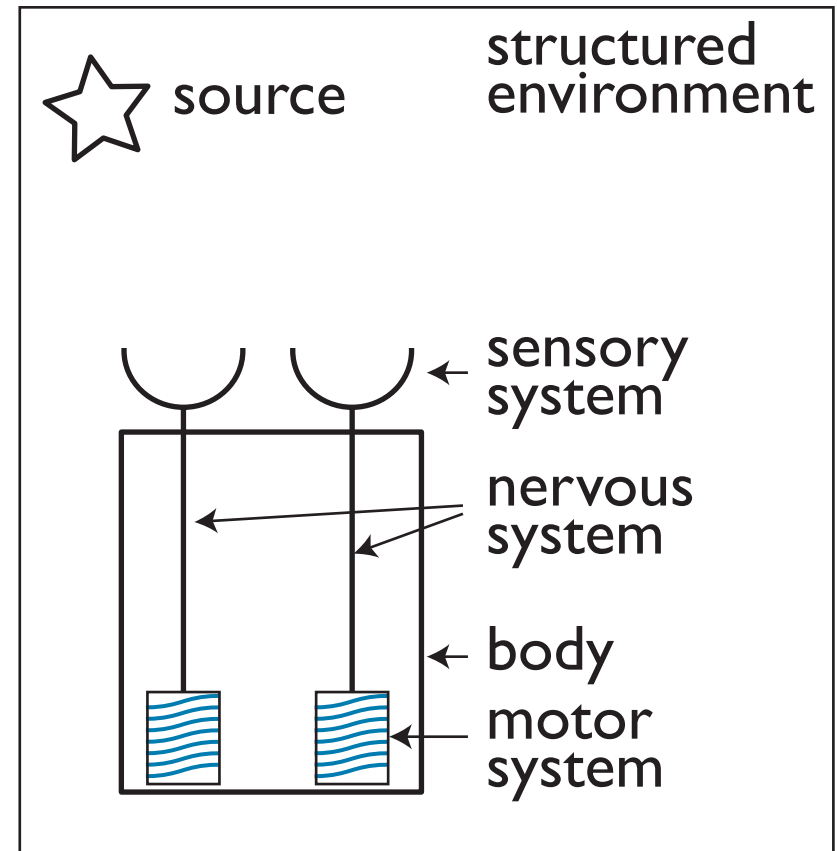
■ sensors

■ a nervous system

■ a body

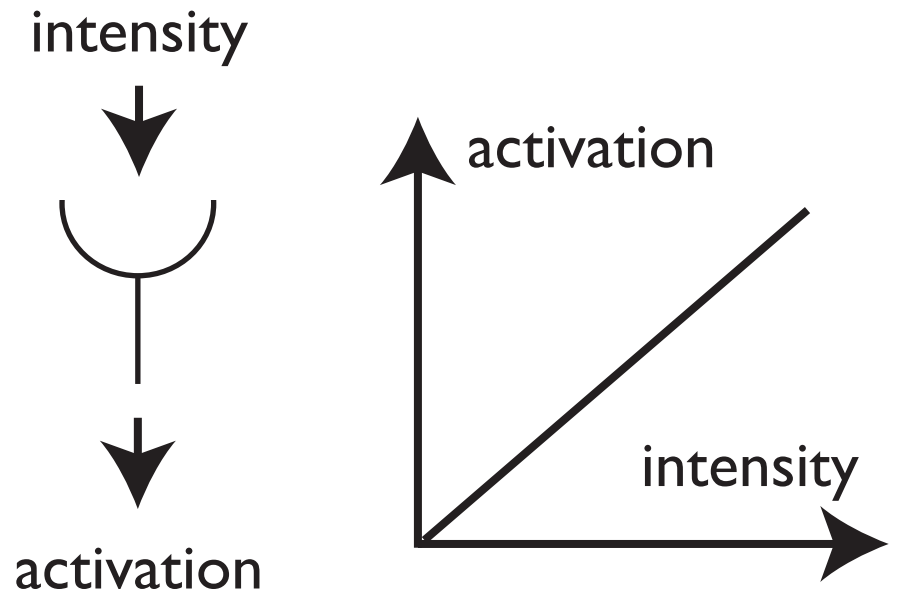
■ + situated in a structured environment

■ = emergent function



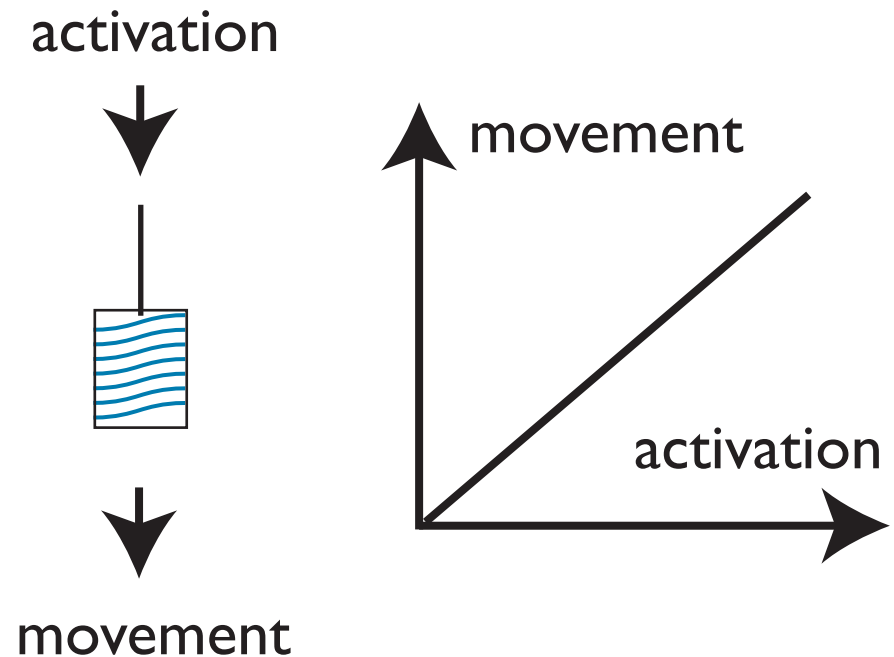
# Sensors

- are characterized by a sensor characteristic= relationship between the physical quantity (e.g. sound, luminance, chemical concentration, mechanical pressure....) and an inner state variable: “activation”



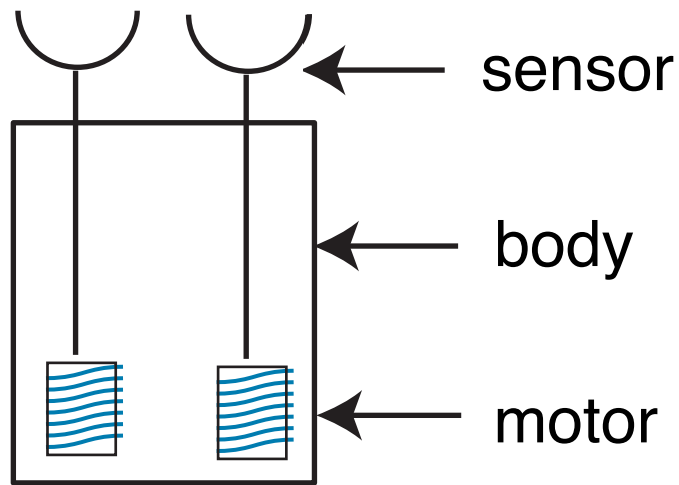
# Effectors

- are defined by a motor characteristic = a functional relationship between an inner activation state and a physical effect generated in the world (e.g., turning rate (rotations per minute rmp), force level, stiffness, ...)



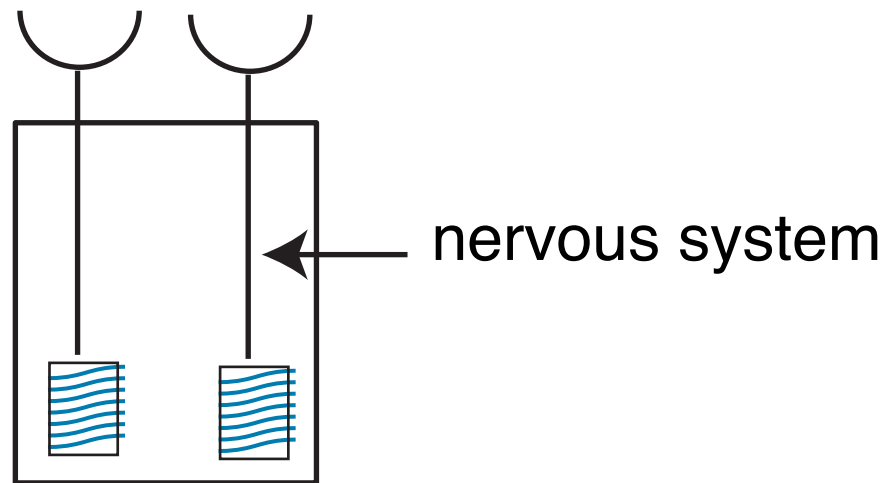
# Body

- mechanically links the sensors to effectors



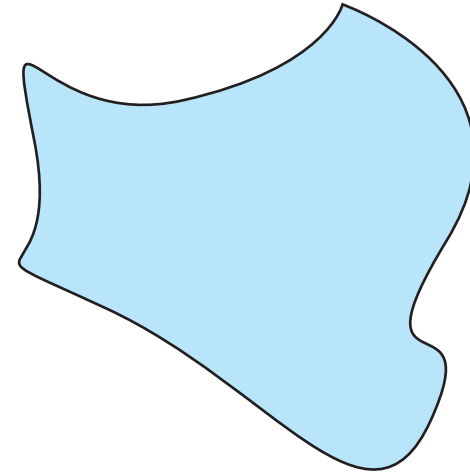
# Nervous system

- links sensors to effectors through the inner activation state



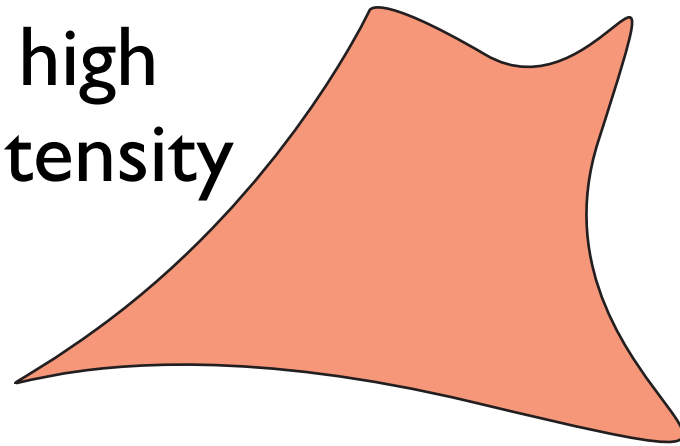
# Environment

low  
intensity



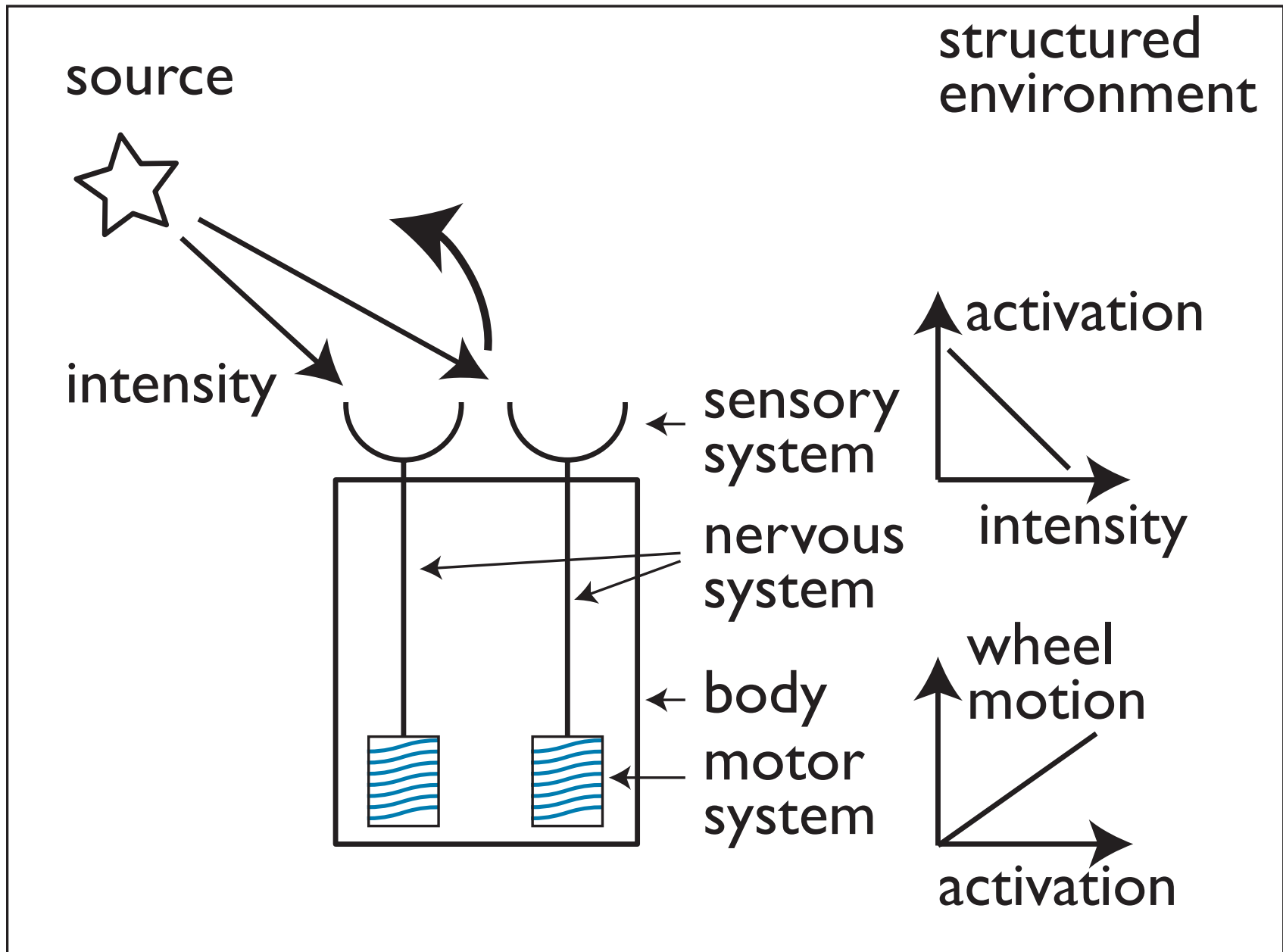
- is structured at a relevant scale in terms of the physical variables to which organism is sensitive

high  
intensity

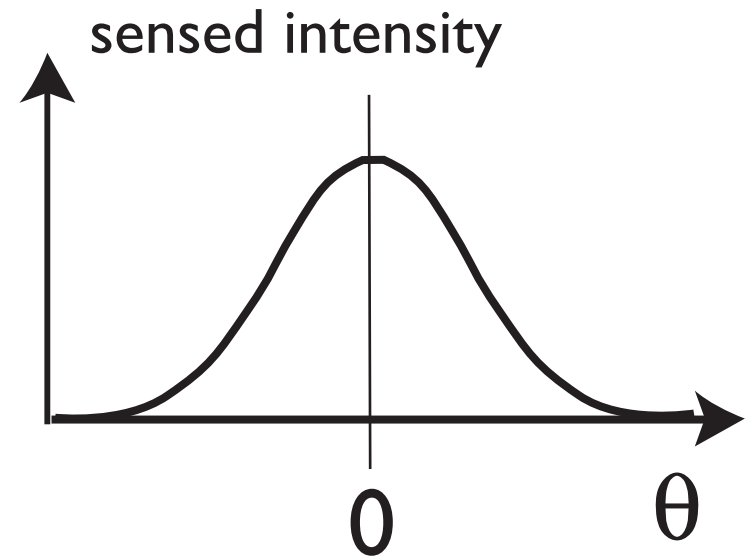
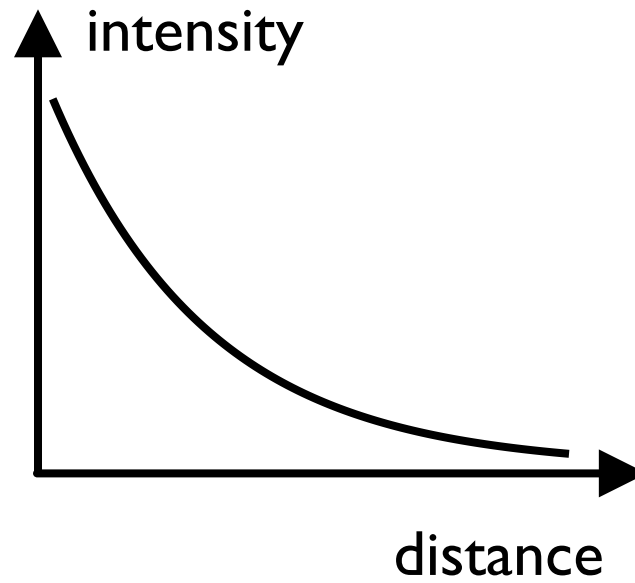
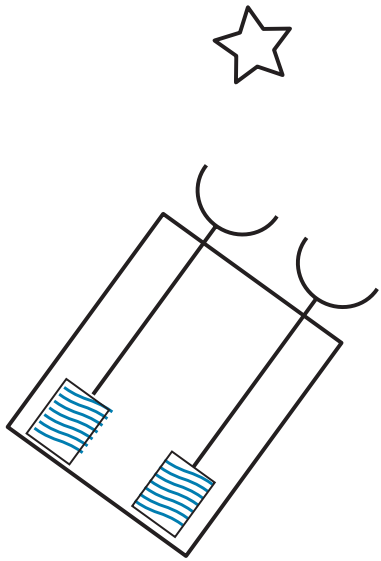




# Emergent behavior: taxis

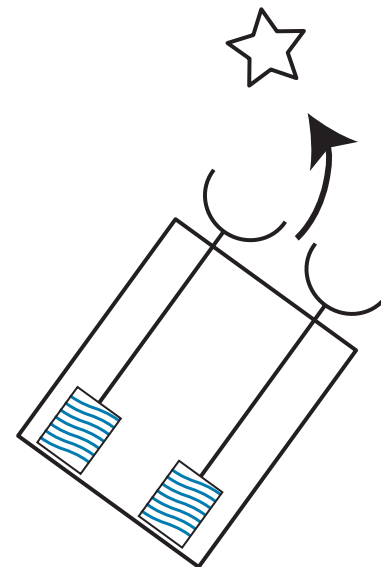
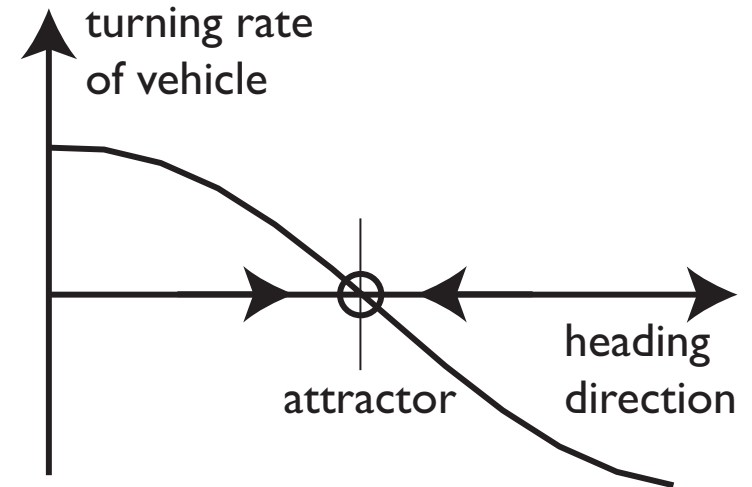


To make this more formal,  
need an environmental and a  
sensor model



=> enables proving this theorem

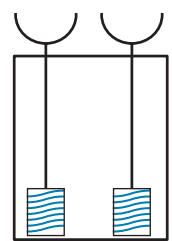
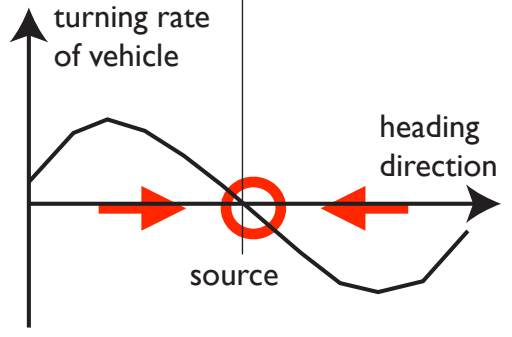
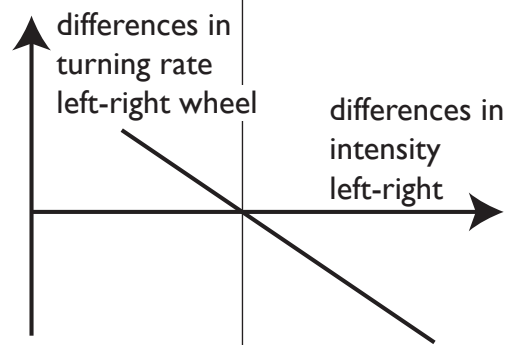
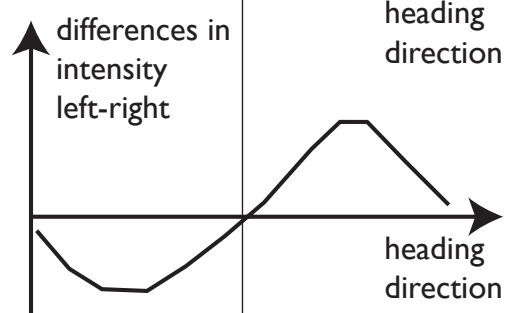
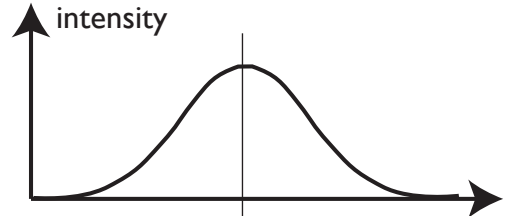
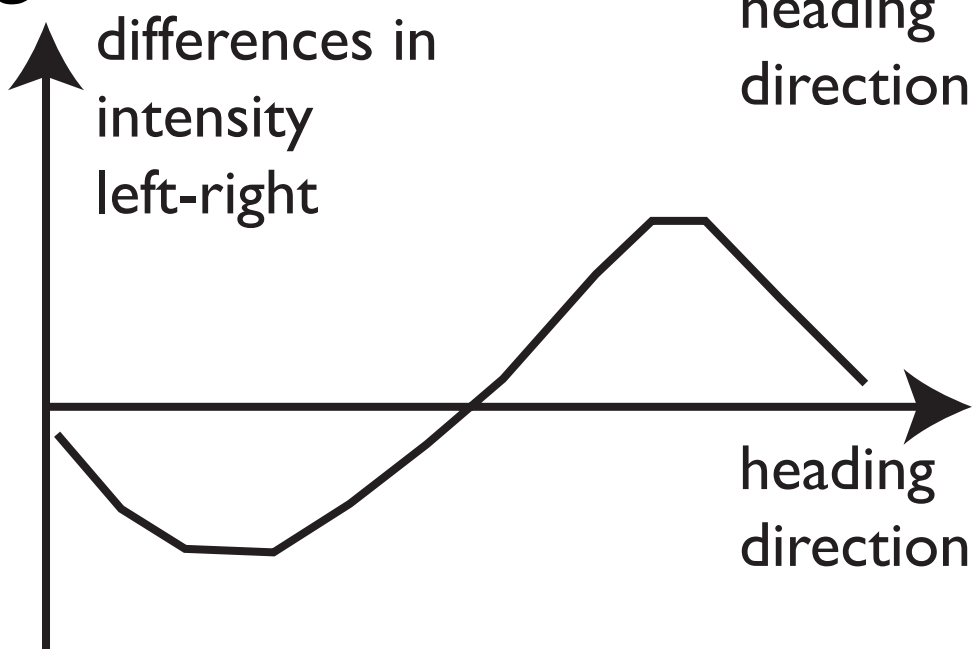
- the vehicles' behavior emerges from an attractor of a dynamical system



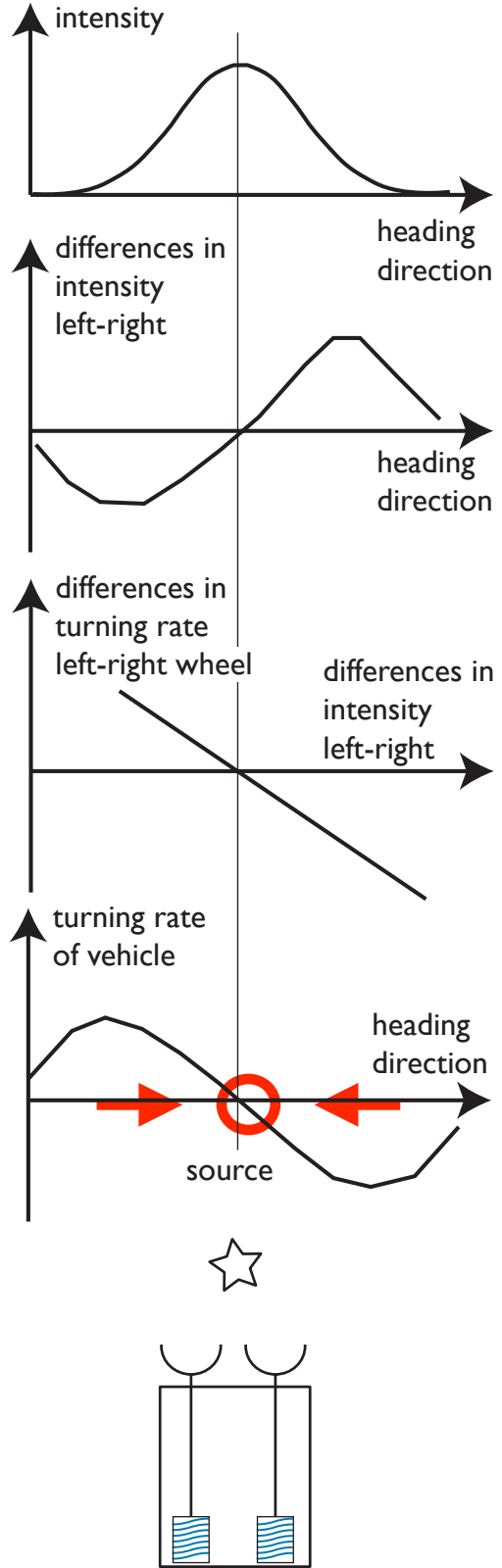
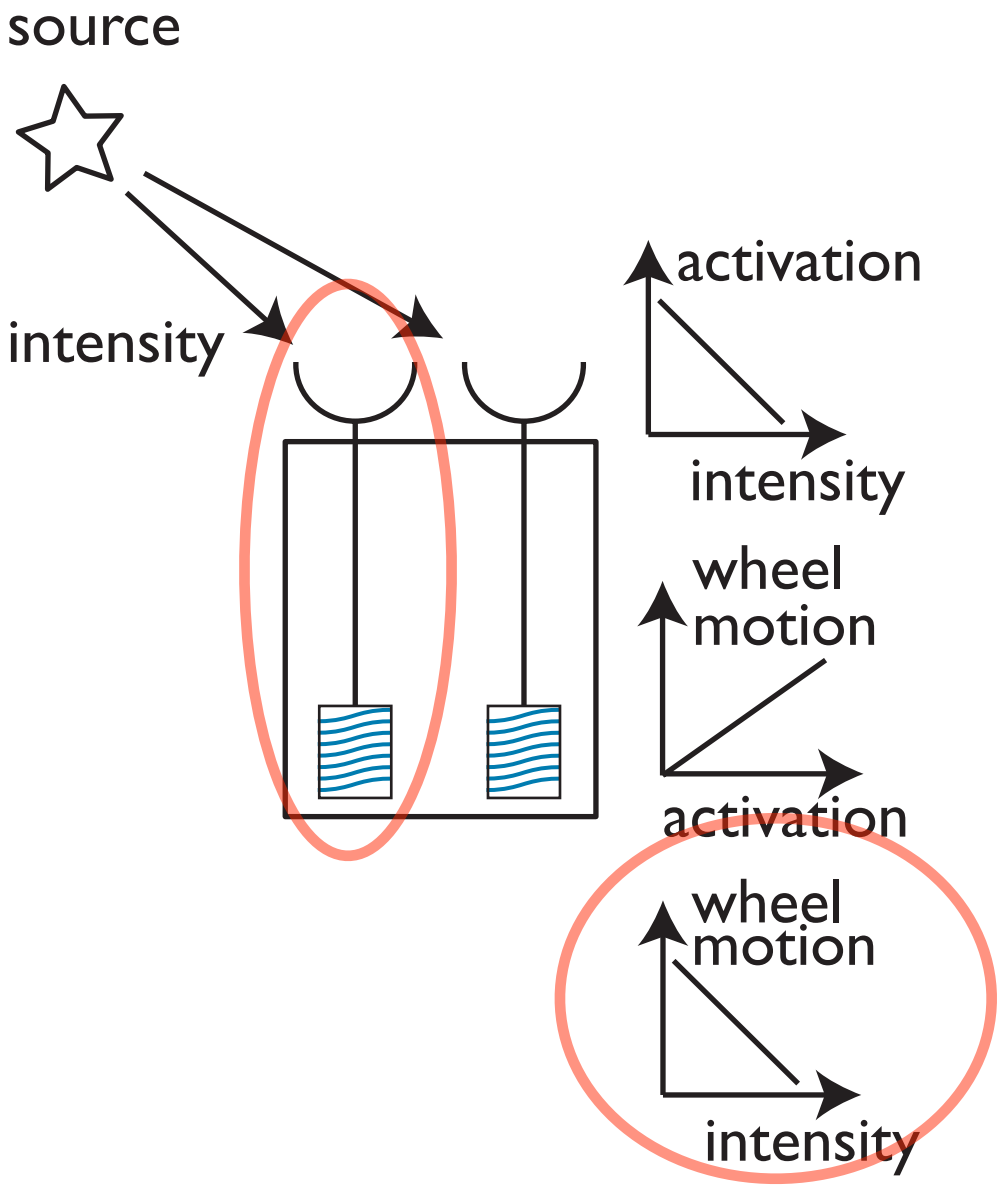
# model of the environment



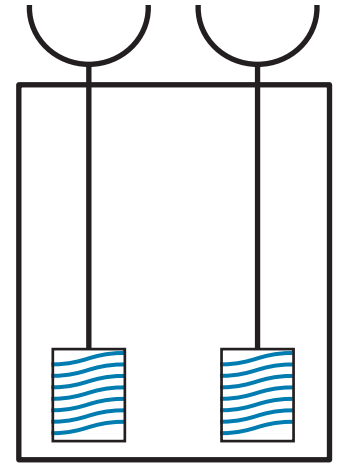
# model of the sensors



# individual forward neural networks



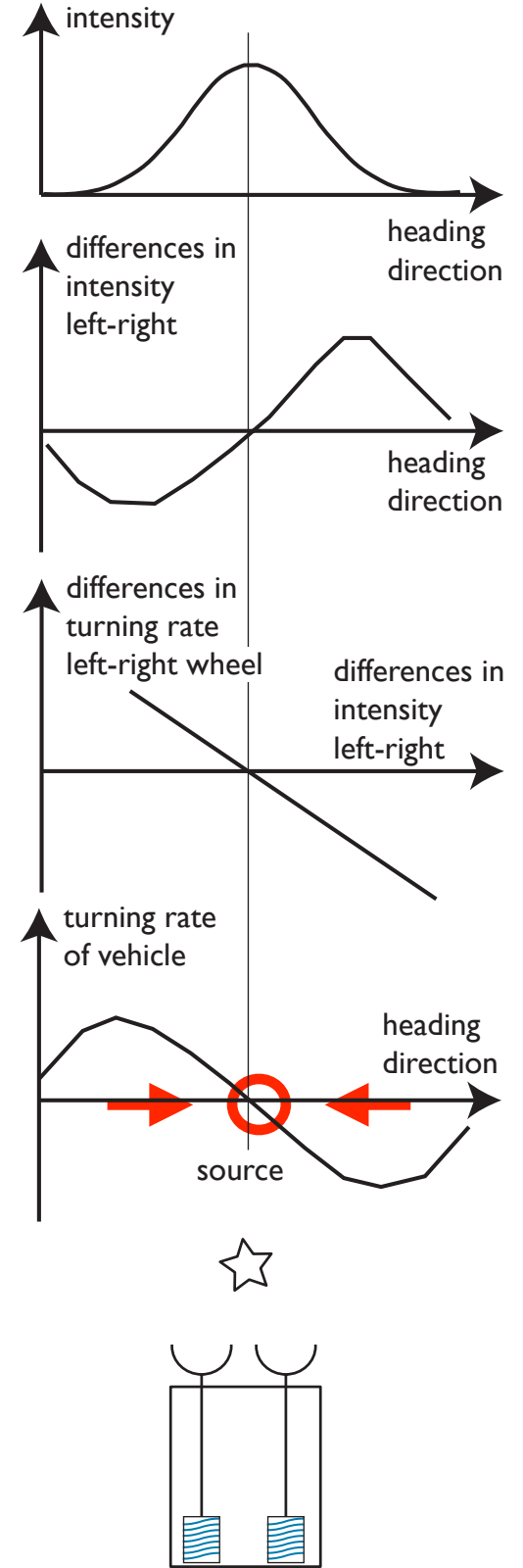
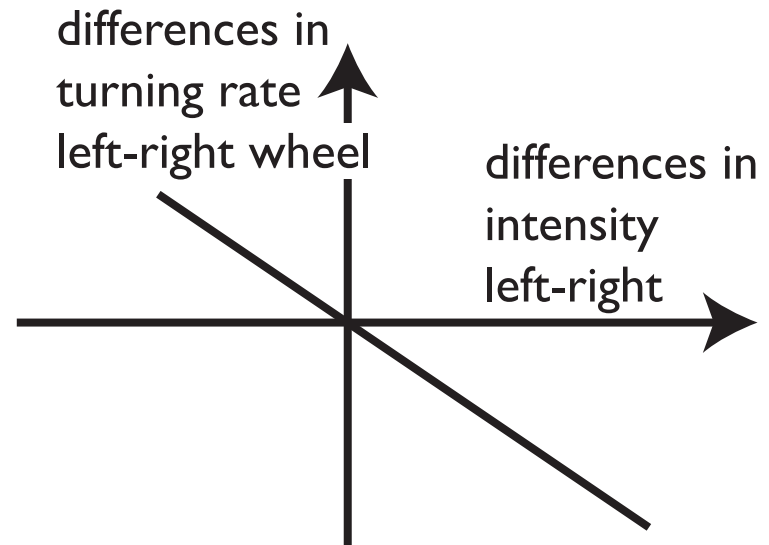
# combining the two forward neural networks: sensori-motor model



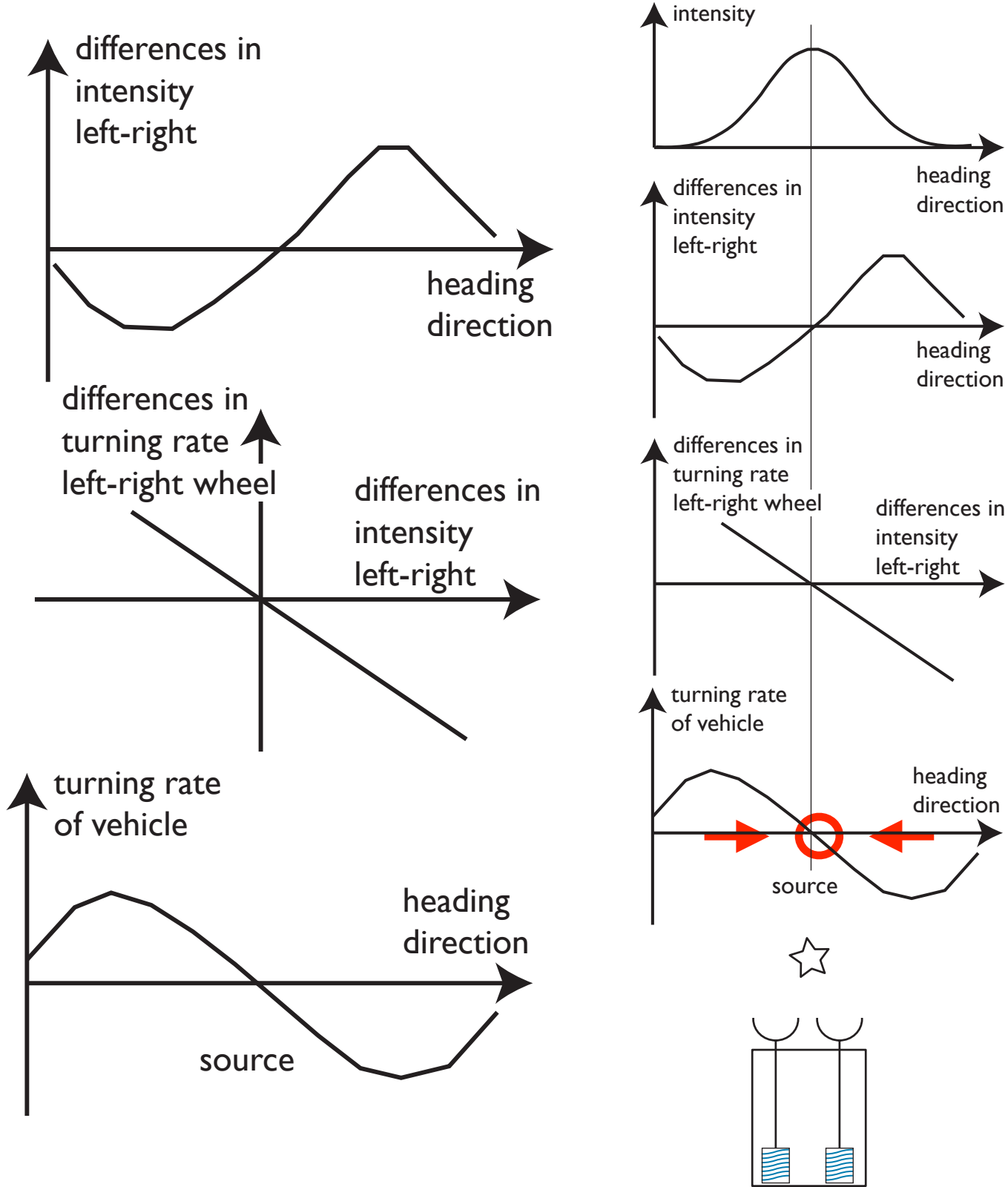
$$\omega_l = \omega_0 - cI_l$$

$$\omega_r = \omega_0 - cI_r$$

$$\Delta\omega = -c\Delta I$$

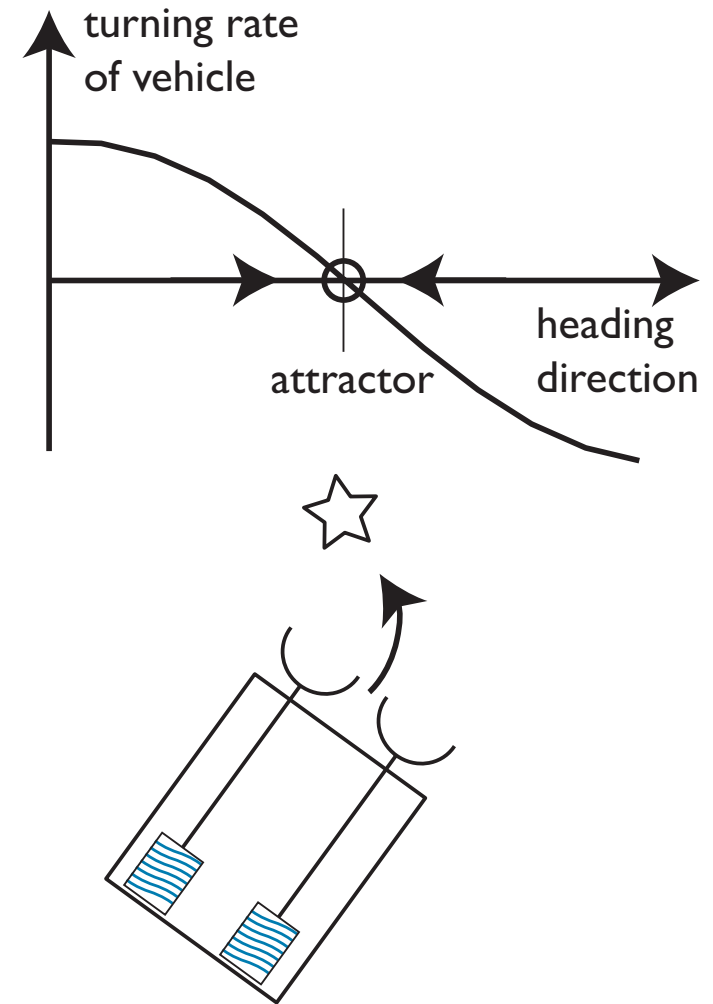


# combining environmental, sensor, and sensori-motor model



# Behavior emerges from a dynamical system

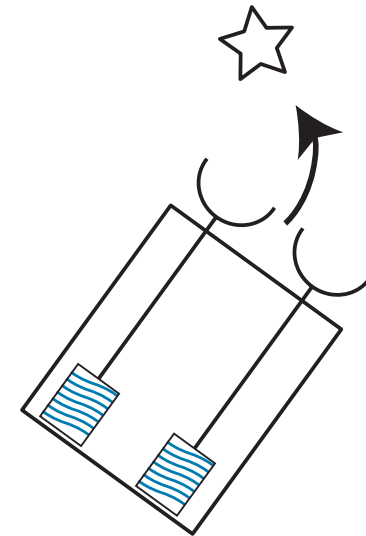
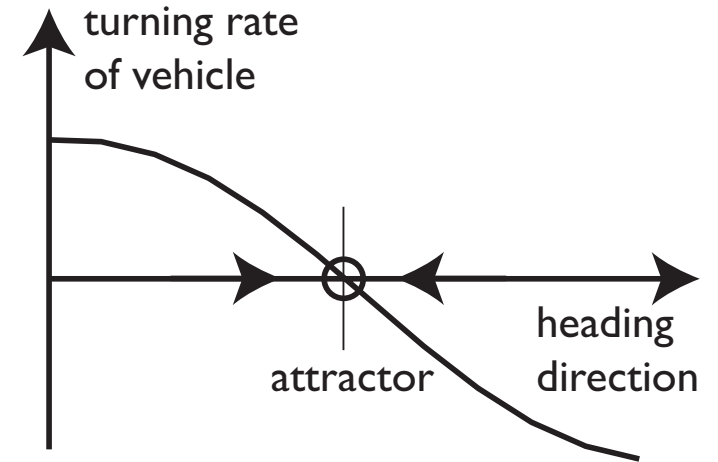
- feedforward nervous system
- + closed loop through environment
- => (behavioral) dynamics





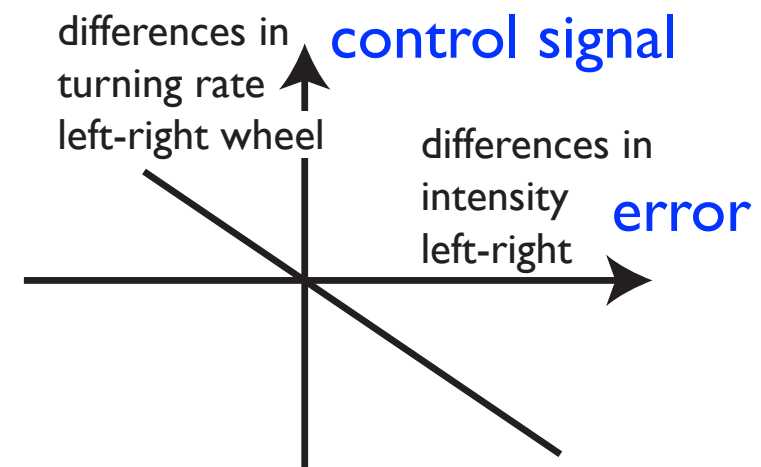
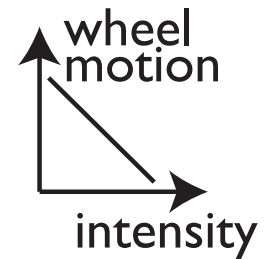
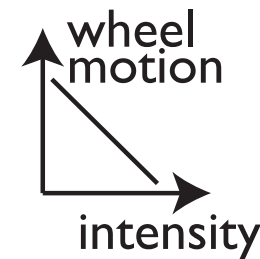
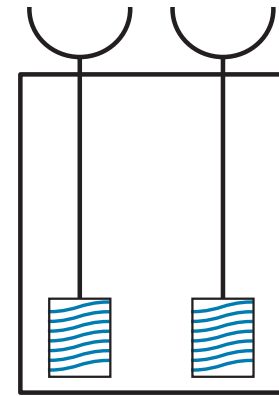
# Cybernetic reading of dynamics

- the CNS reduces the deviation from the desired behavioral state to zero
- by its sensors measuring the “error”
- and the CNS sending a feedback control signal to its actuators to reduce the error



# Cybernetic reading of dynamics

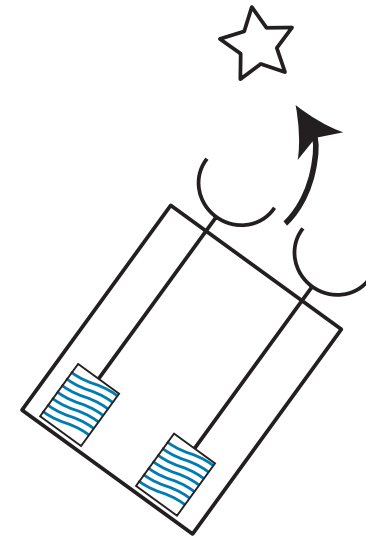
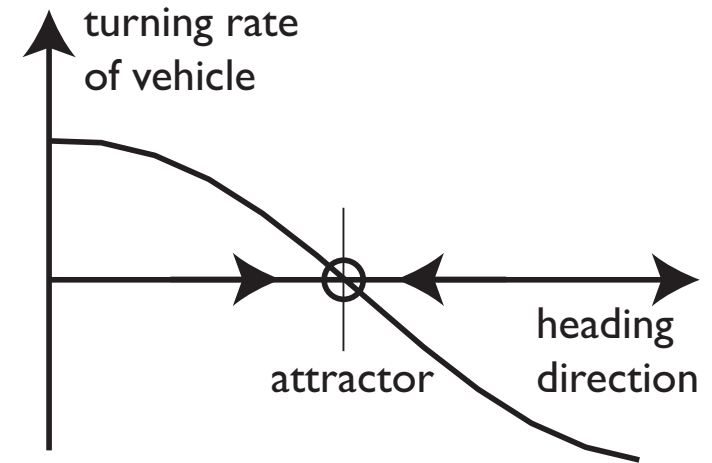
- the CNS reduces the deviation from the desired behavioral state to zero
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- and the CNS sending a feedback control signal to its actuators to reduce the error



$$\Delta\omega = -c\Delta I$$

# Cybernetic reading of dynamics

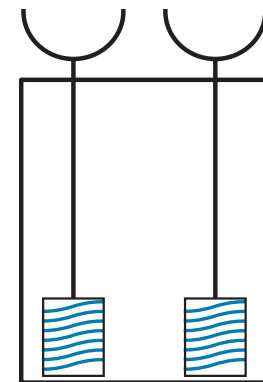
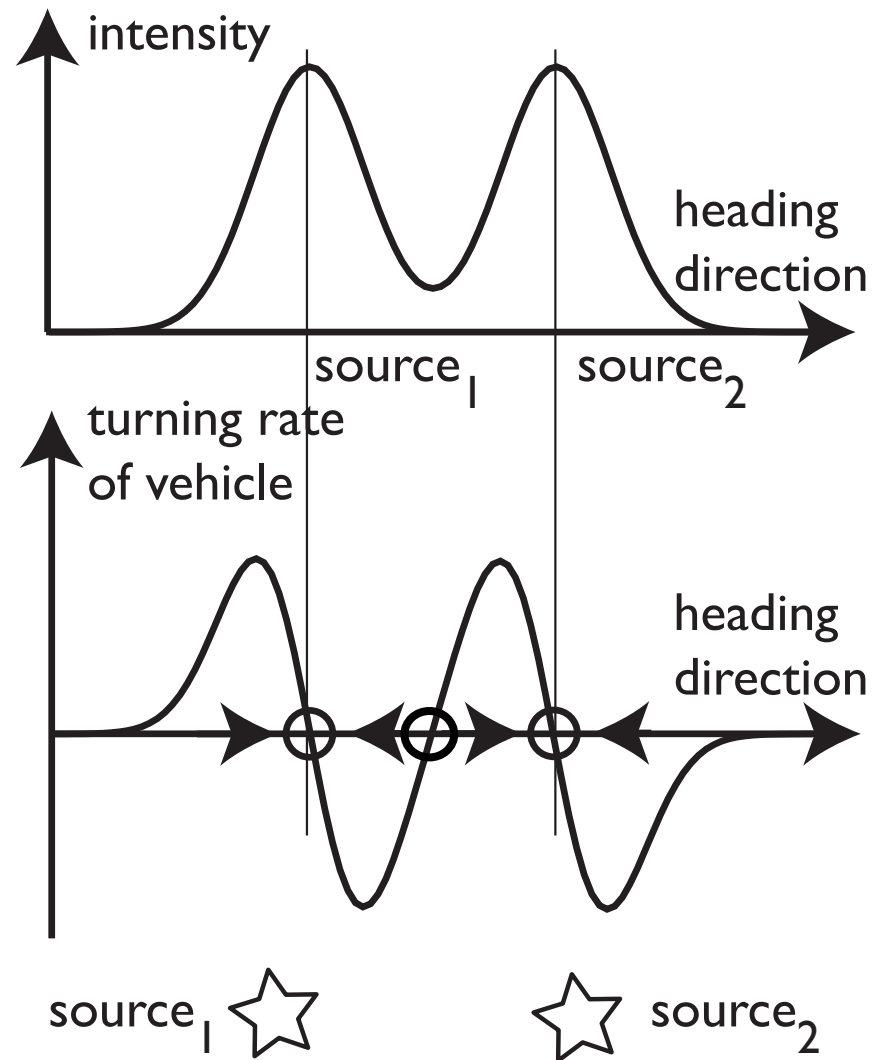
- ... depends critically on the *closed loop*: the body's movement changes the sensory information..
- this is a loop through the environment
- the state of the dynamics is the body's physical state in the environment



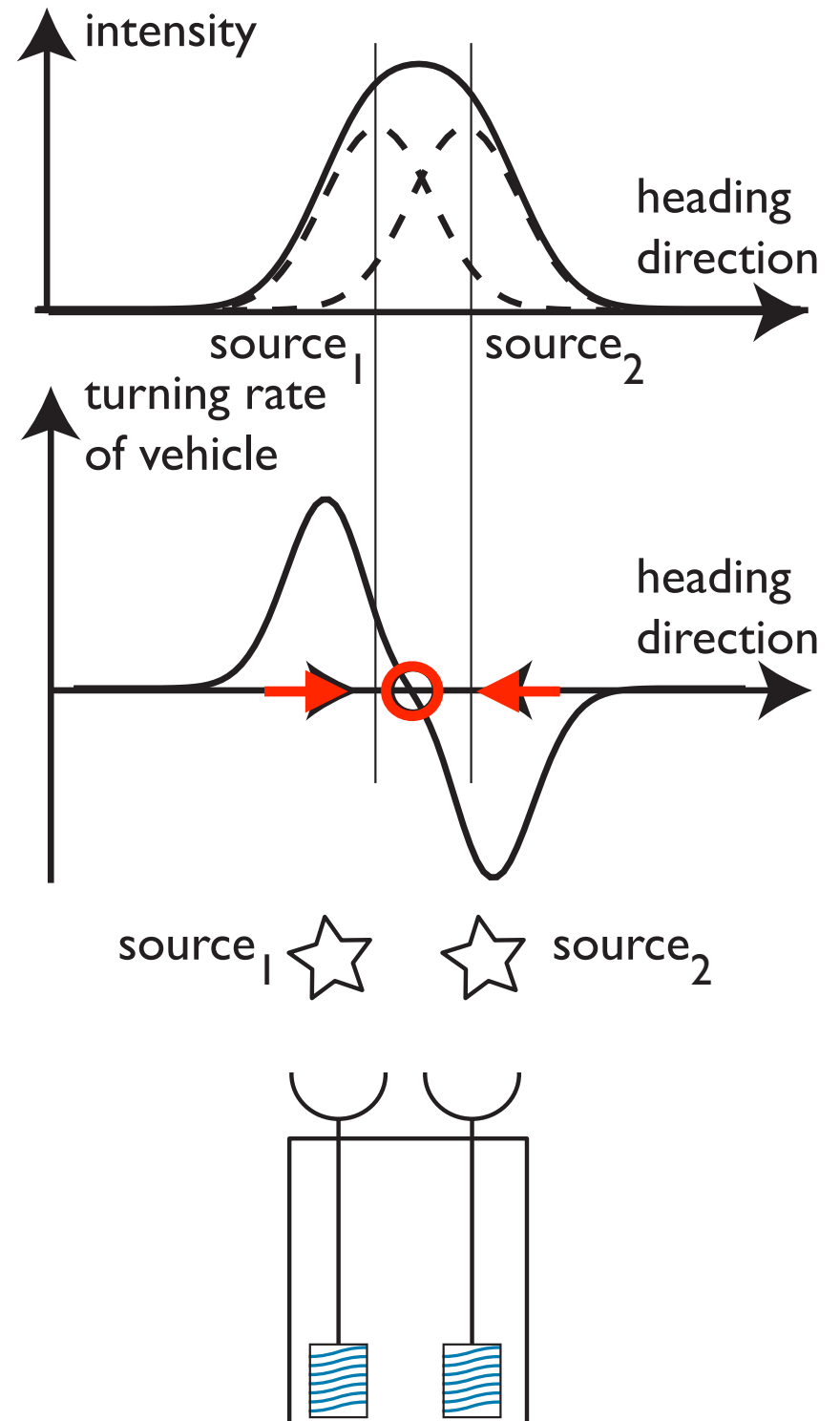
# Limits of the cybernetic view of dynamics

- presumes there is a single “goal” or set-point

- two sources
- bimodal distribution
- => bistable (non-linear) dynamics
- => selection decision

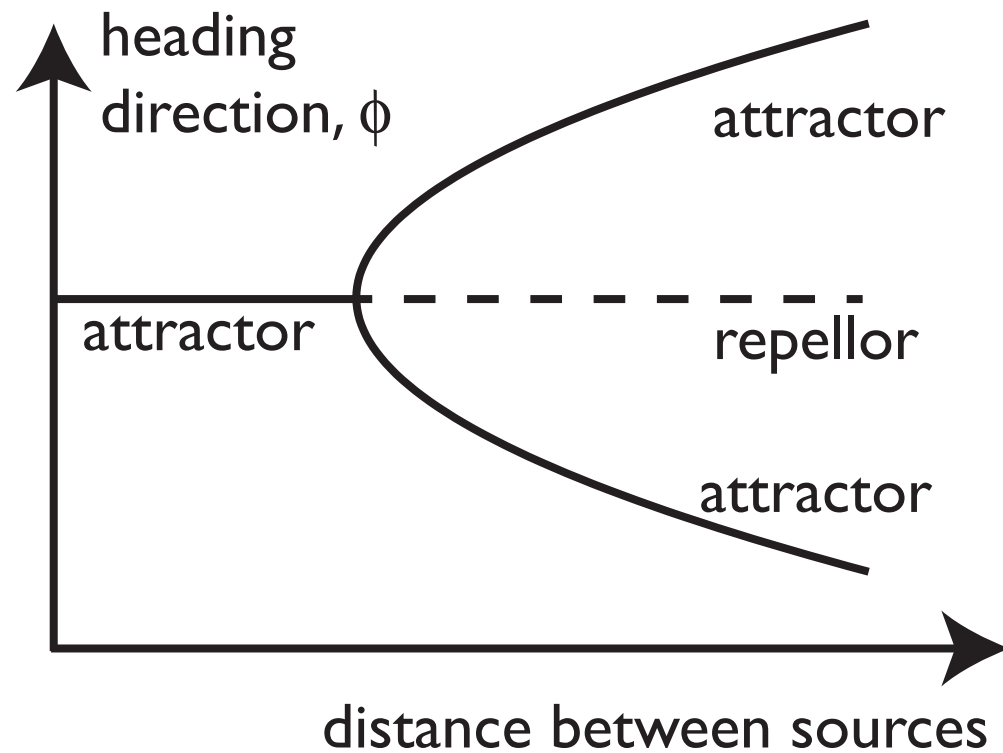


- transition to monostable for mono-modal distribution
- => instabilities lead to qualitative change of behavior



■ transition to monostable for mono-modal distribution

■ => instabilities lead to qualitative change of behavior



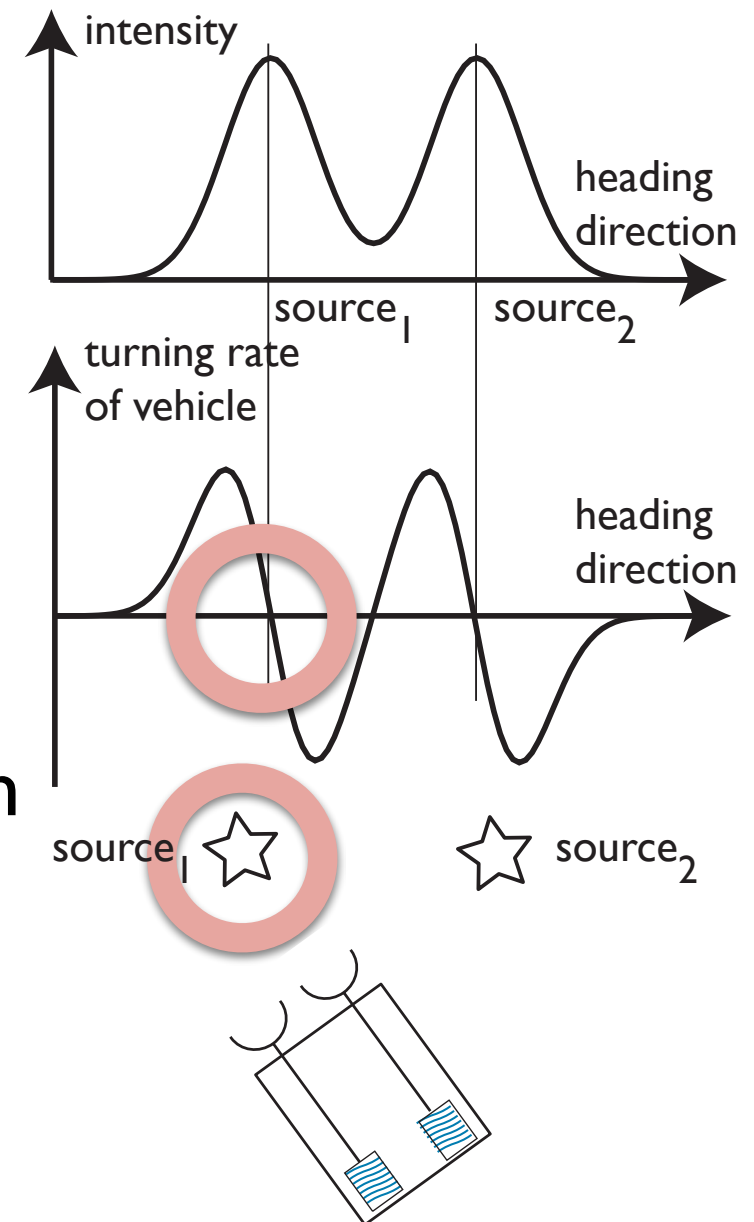
# Limits of the cybernetic view of dynamics

- far reaching implications ...
- for the nature of the perceptual variables (not “error-signals”)
- for the nature of the state variables (not “error-correcting-control-signals”)
- => dynamics  $\neq$  cybernetics/control theory



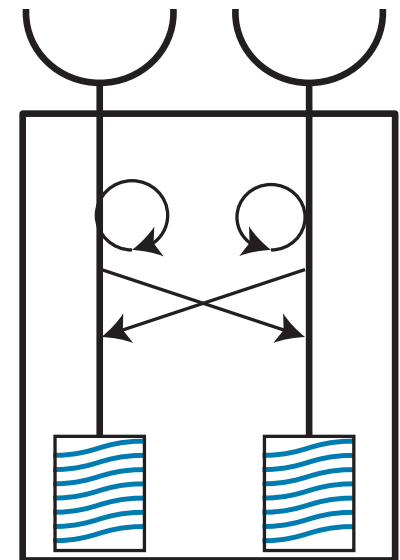
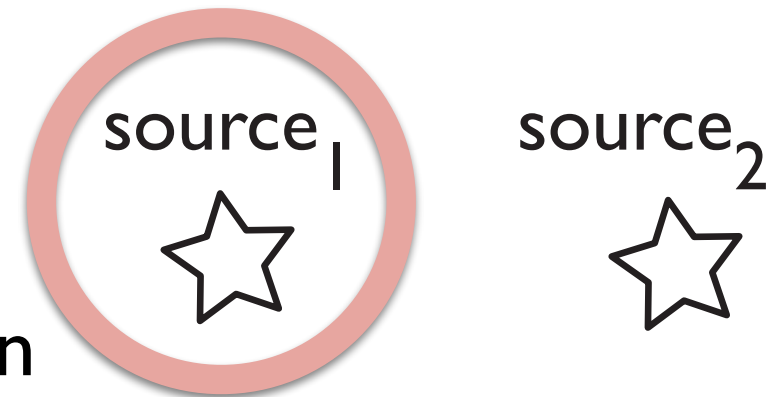
# Beyond behavioral dynamics ...

- so far: behavioral decision is “overt”
- => the vehicle’s physical state “stores” the state of that decision



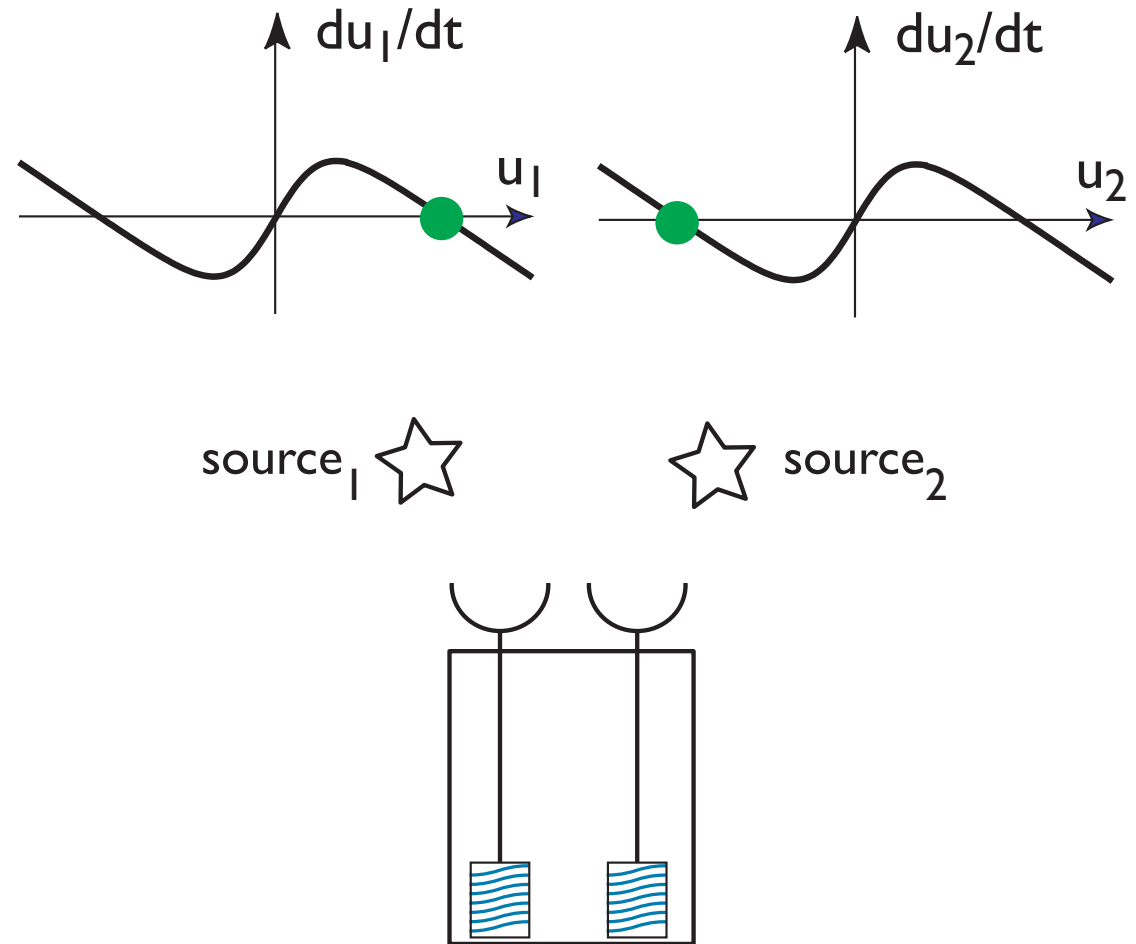
# Beyond behavioral dynamics ...

- what if we want the vehicle to make a decision for one target, without actually moving so that later, the outcome of that decision can be acted out..
- => “covert” orientation
- need to “store” the state of that decision somewhere other than the physical state of the vehicle: neural state in the neural network



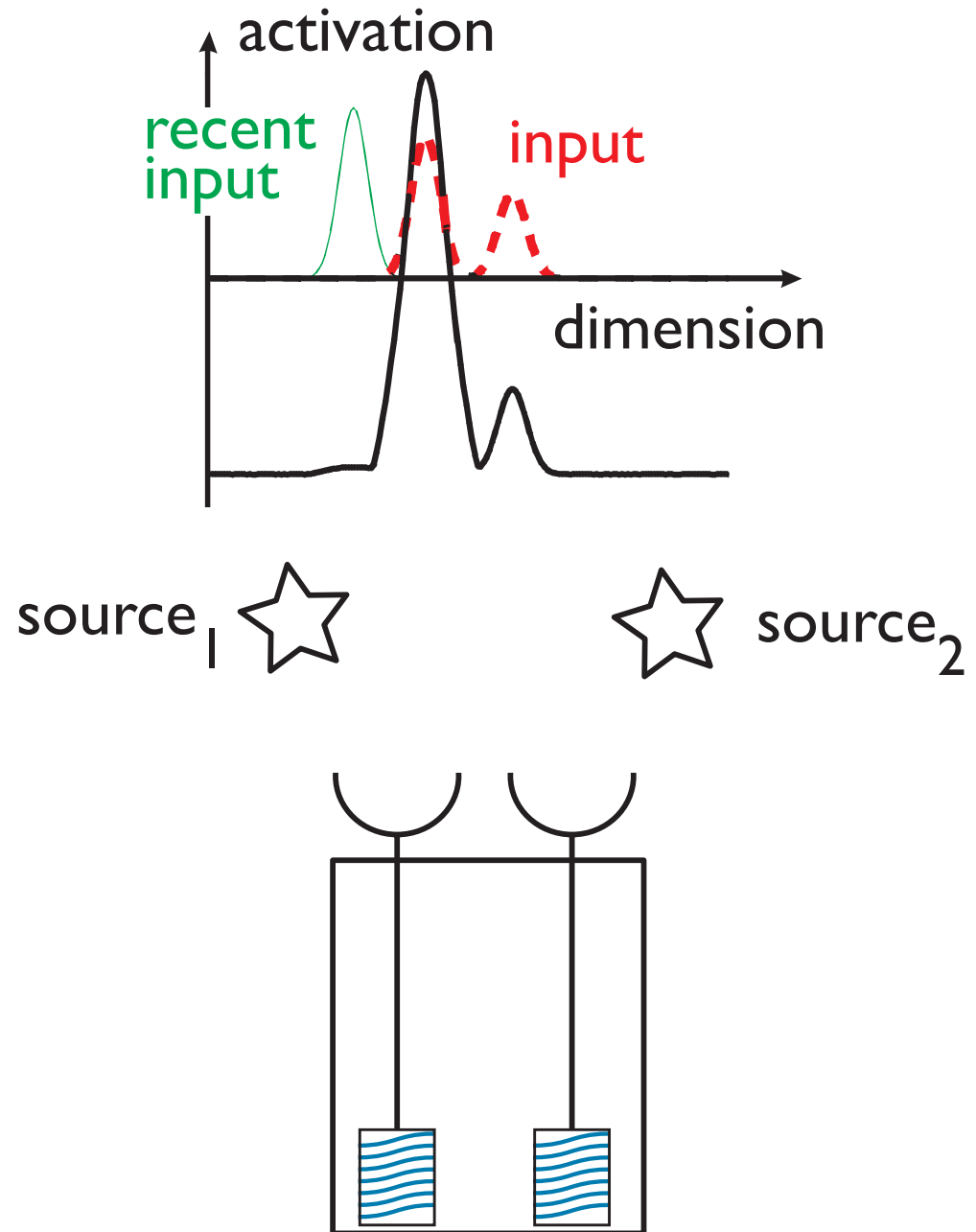
# Beyond behavioral dynamics ...

- neural state in the neural network: activation concept
- activation dynamics
- competitive/selective



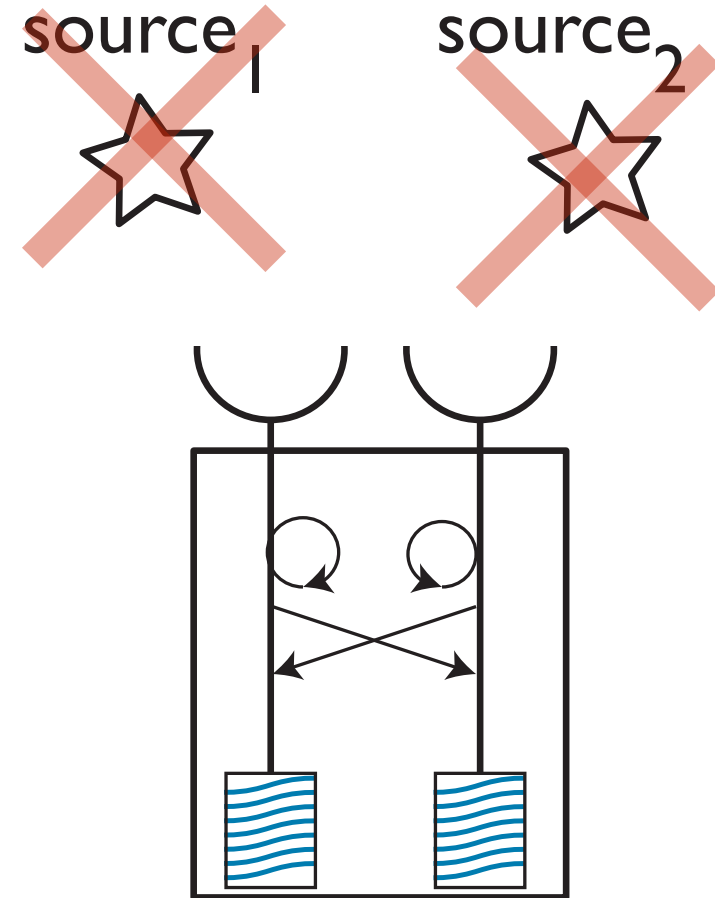
# Beyond behavioral dynamics ...

- neural activation field to represent continuous of possible target orientations



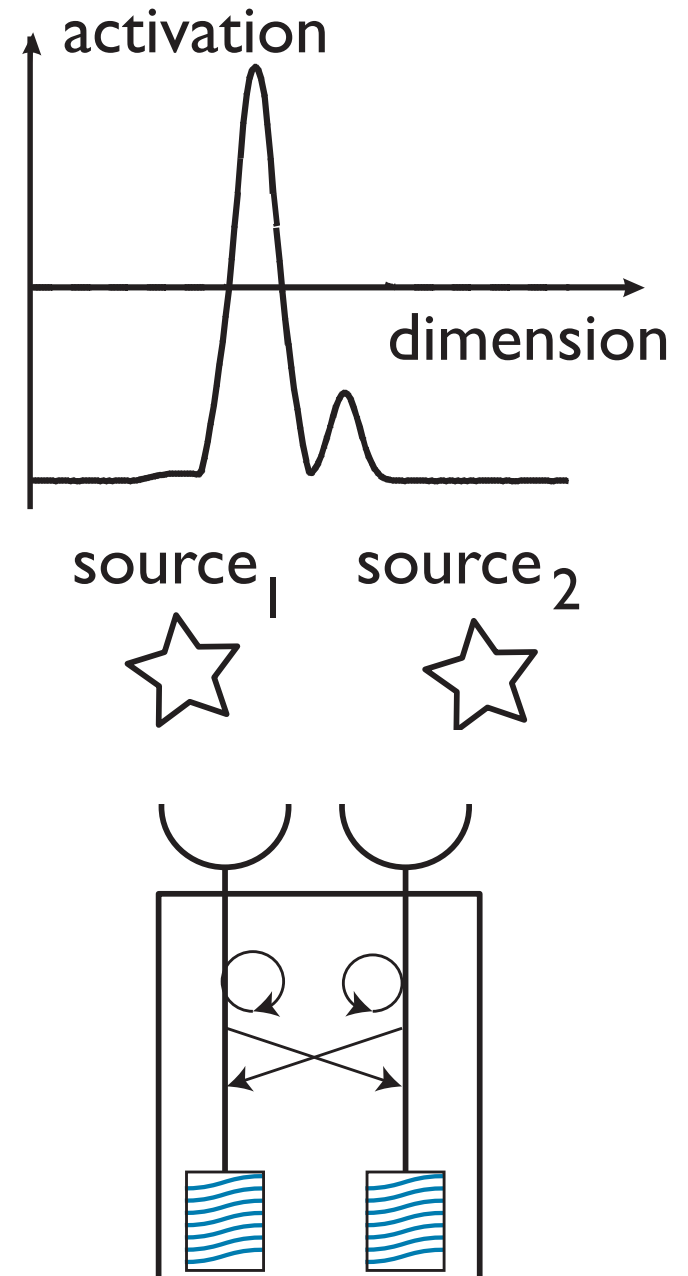
# Beyond behavioral dynamics ...

- or we want the system to be able to act on the sources after the external sources of stimulation are removed...
- => working memory
- need to store the state of that sensory representation in the neural network



# Beyond behavioral dynamics ...

- store the state of the representation in a neural field as a pattern of sustained activation



# Next...

 neural dynamics