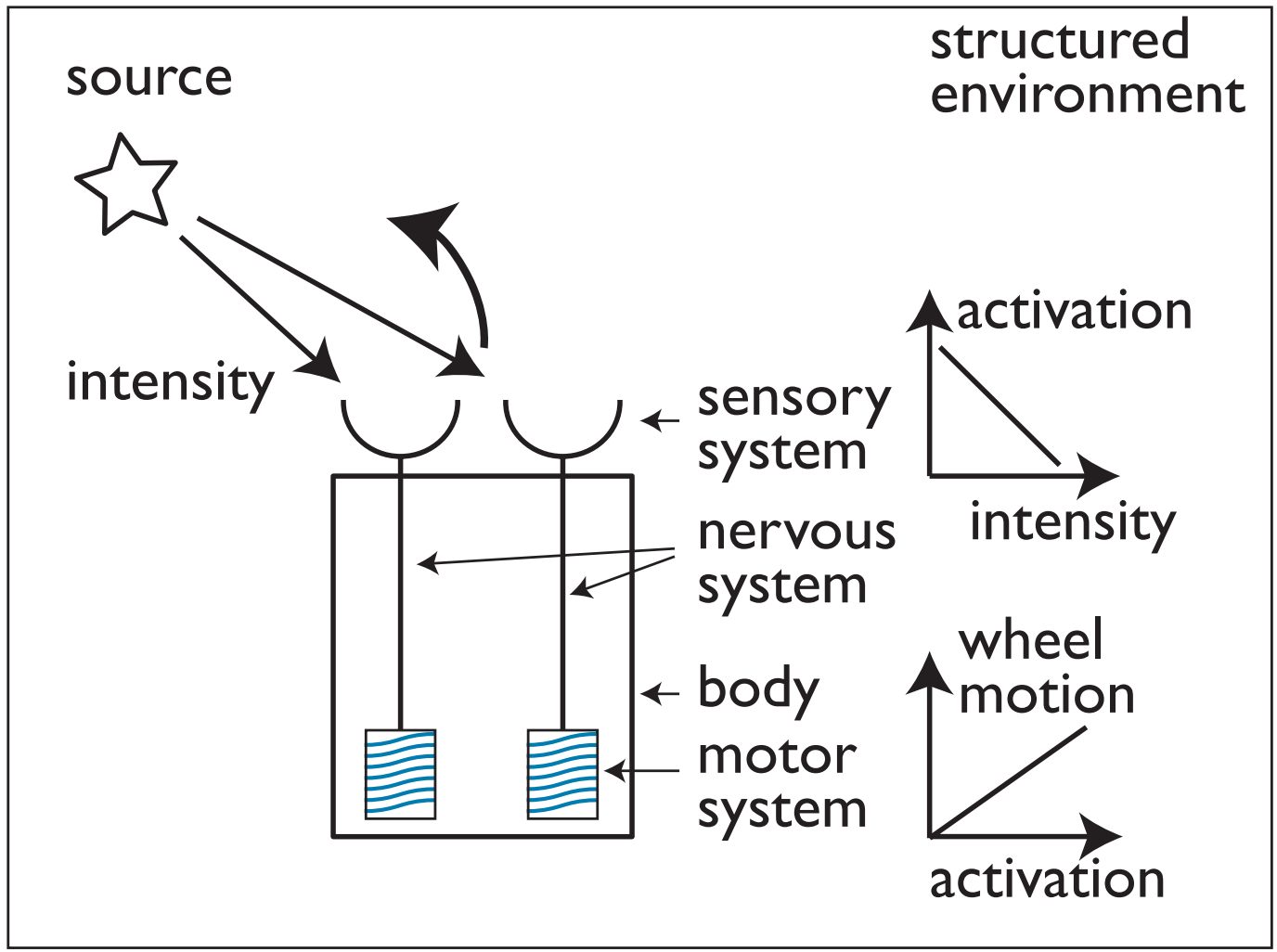
Braitenberg vehicles: embodied nervous systems

Gregor Schöner

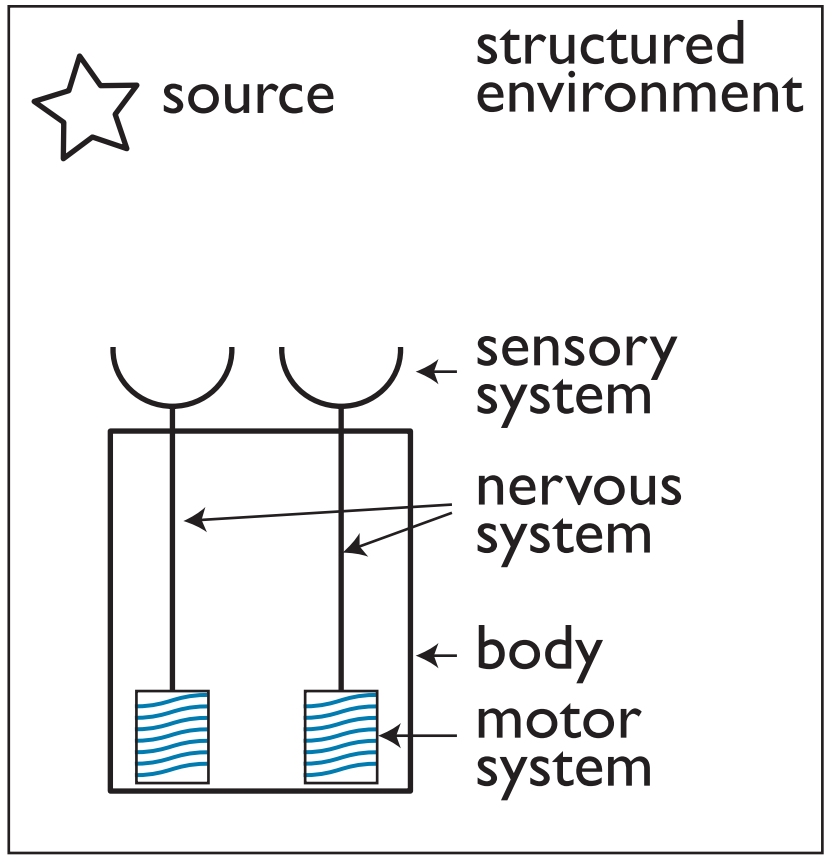
Braitenberg's vehicle metaphor

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



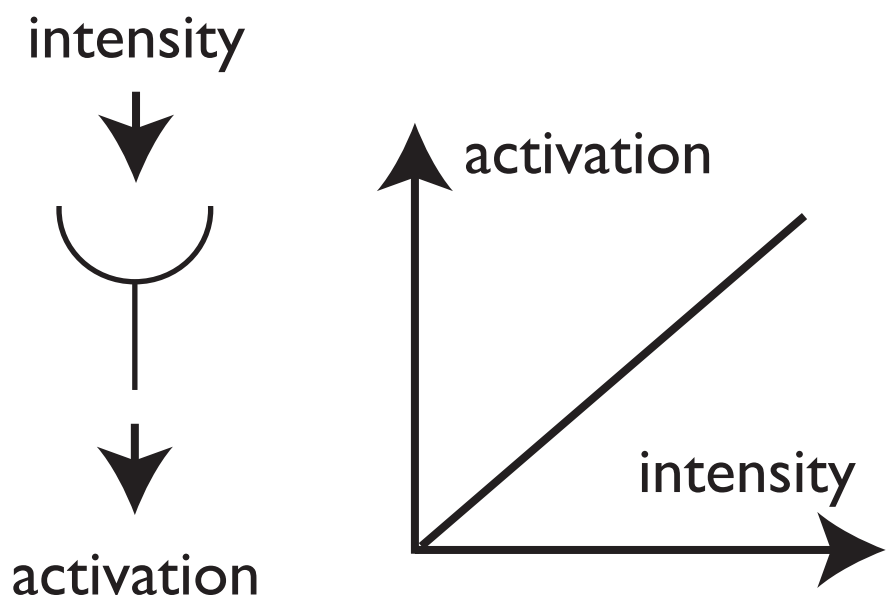
Braitenberg vehicles

- =embodied nervous systems with:
  - effectors
  - sensors
  - a nervous system
  - a body
- + situated in a structured environment
- = emergent function



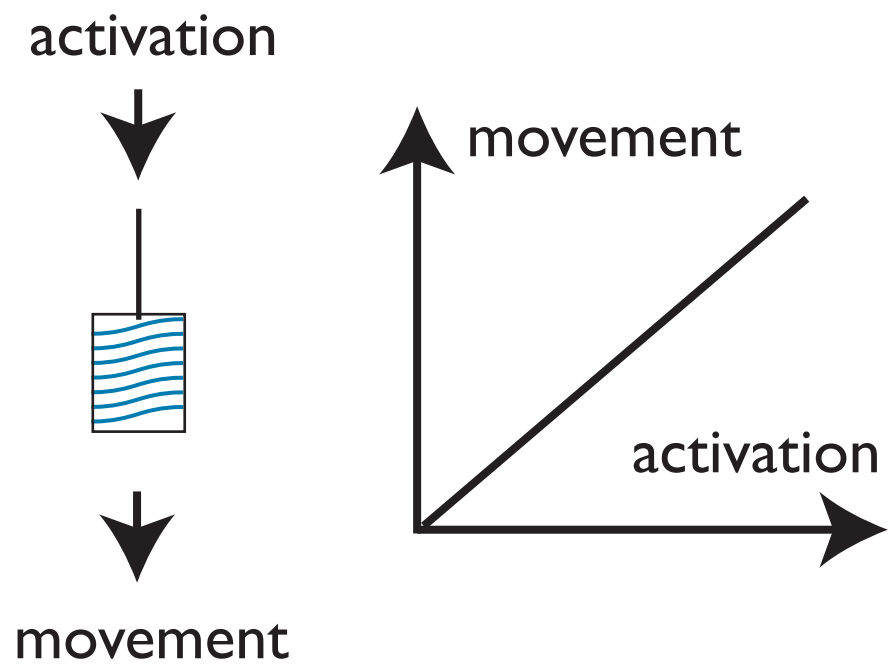
Sensors

- 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"



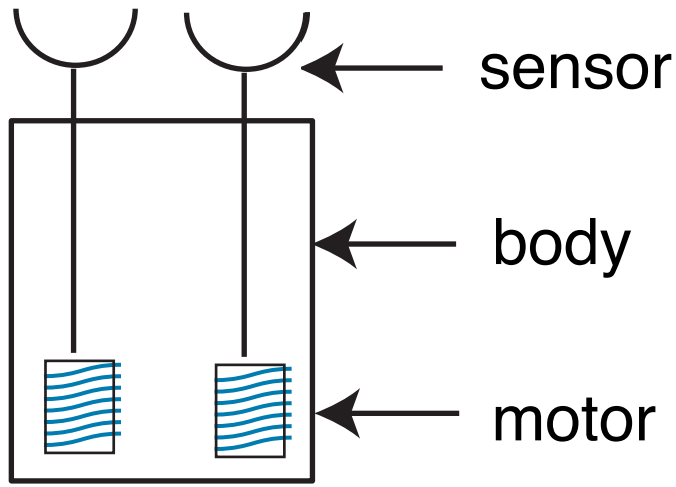
Effectors

- 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, …)



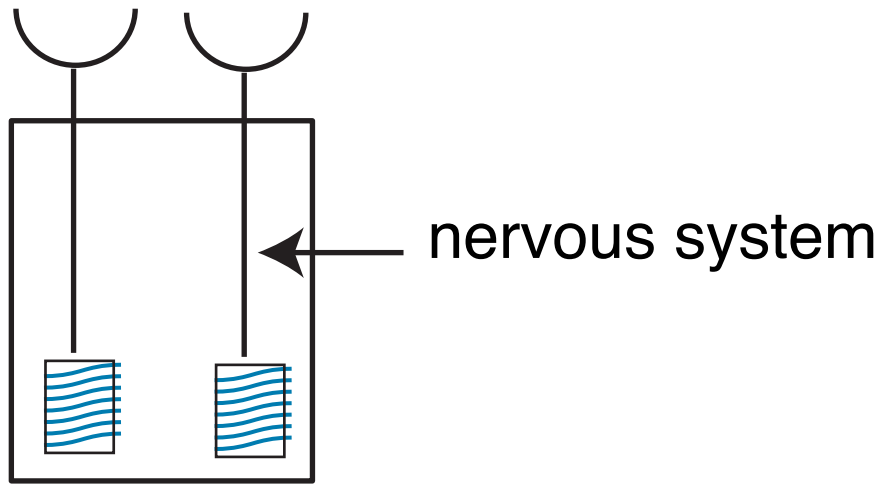
Body

- mechanically links the sensors to effectors



Nervous system

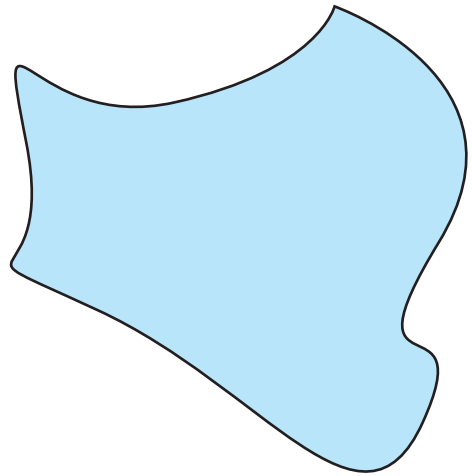
- links sensors to effectors through the inner activation state



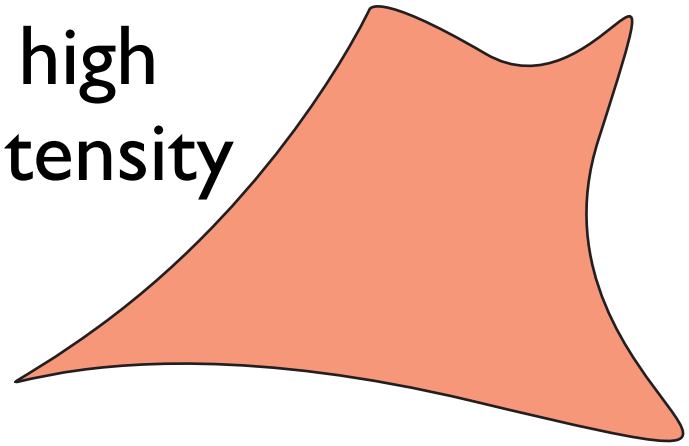
Environment

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

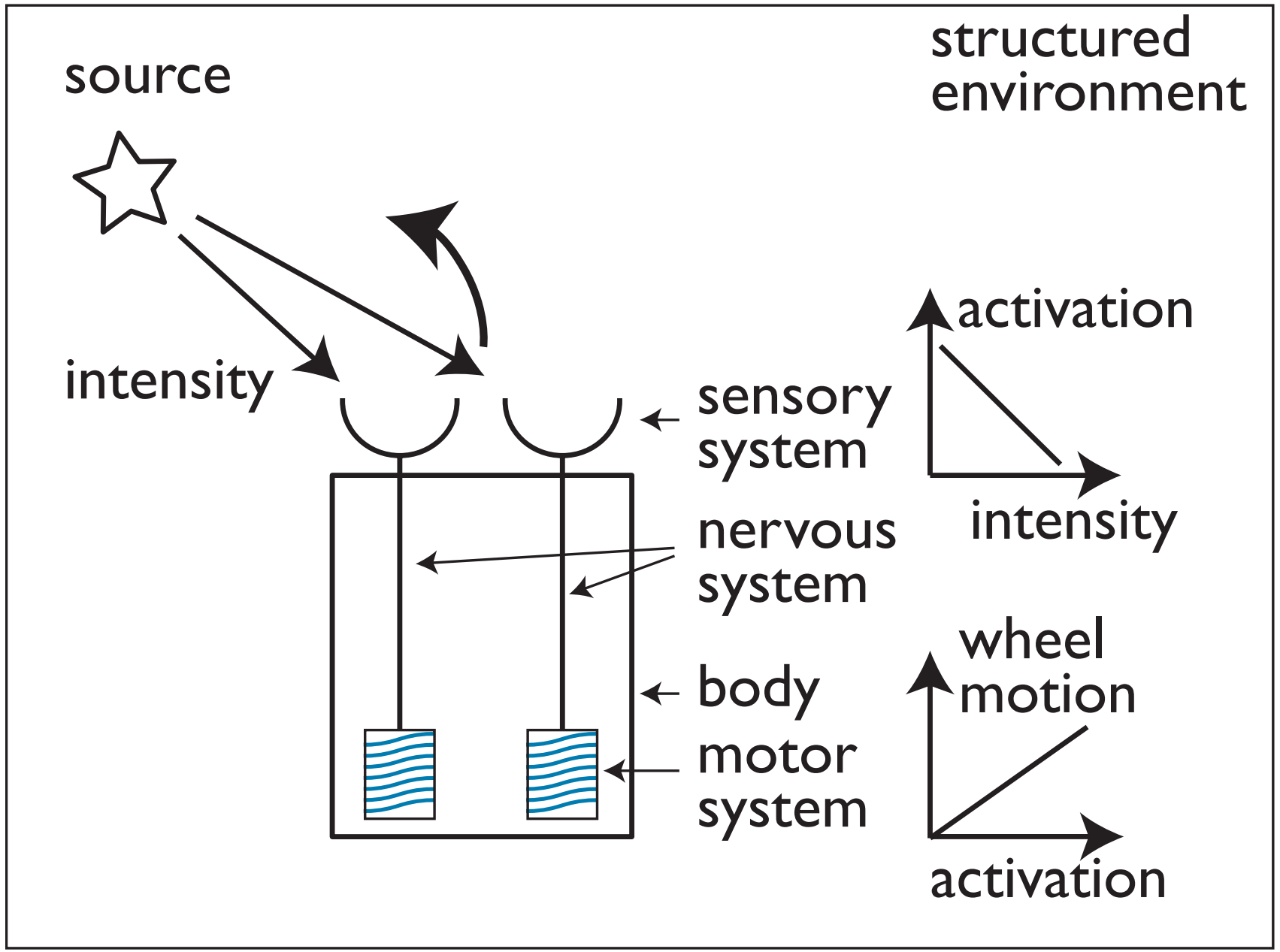
low intensity



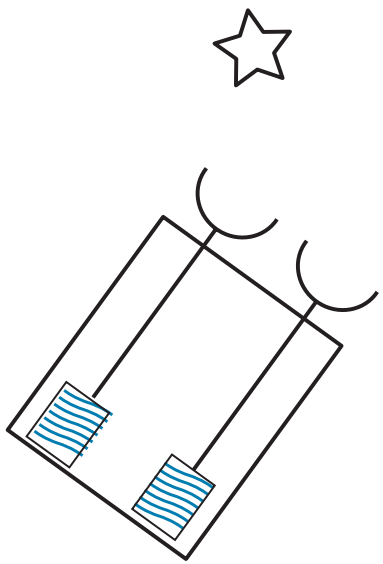
high intensity

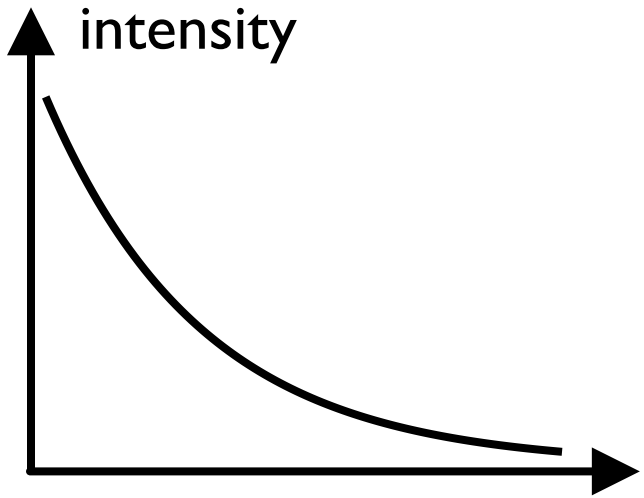


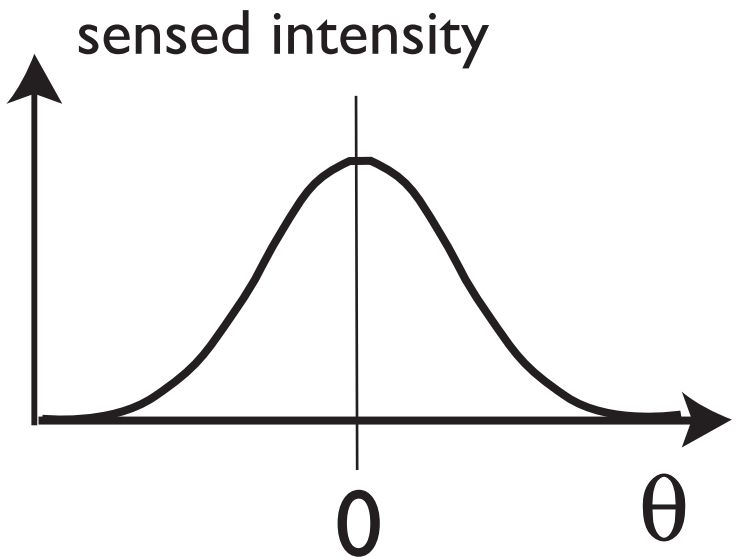
Emergent behavior: taxis



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

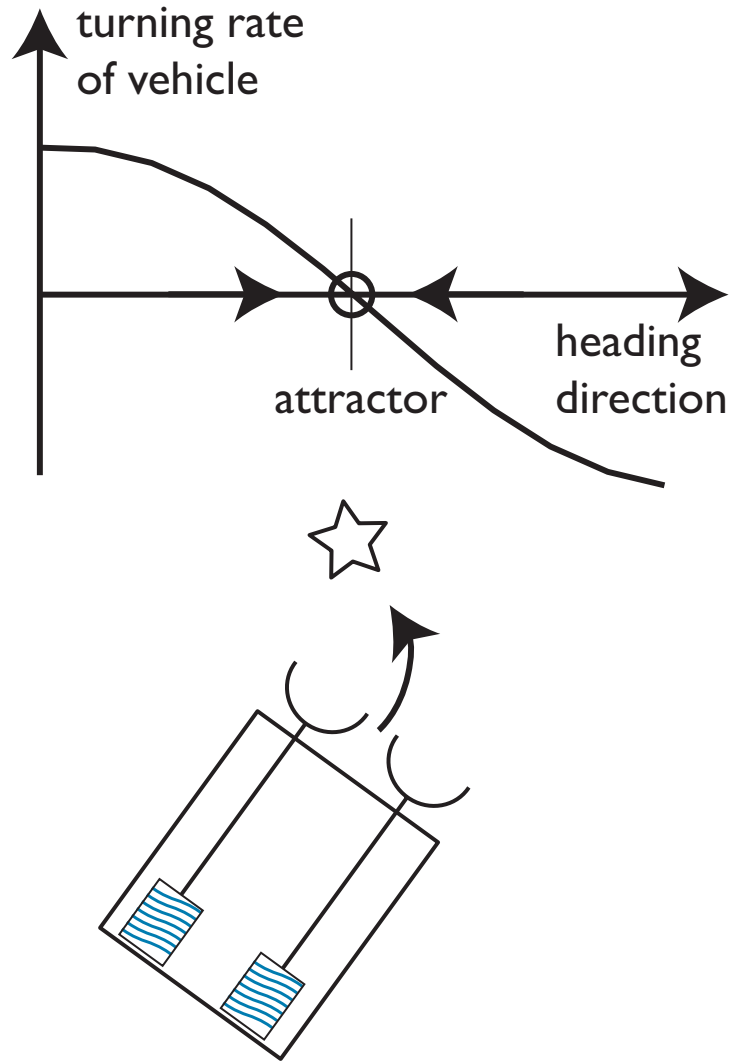






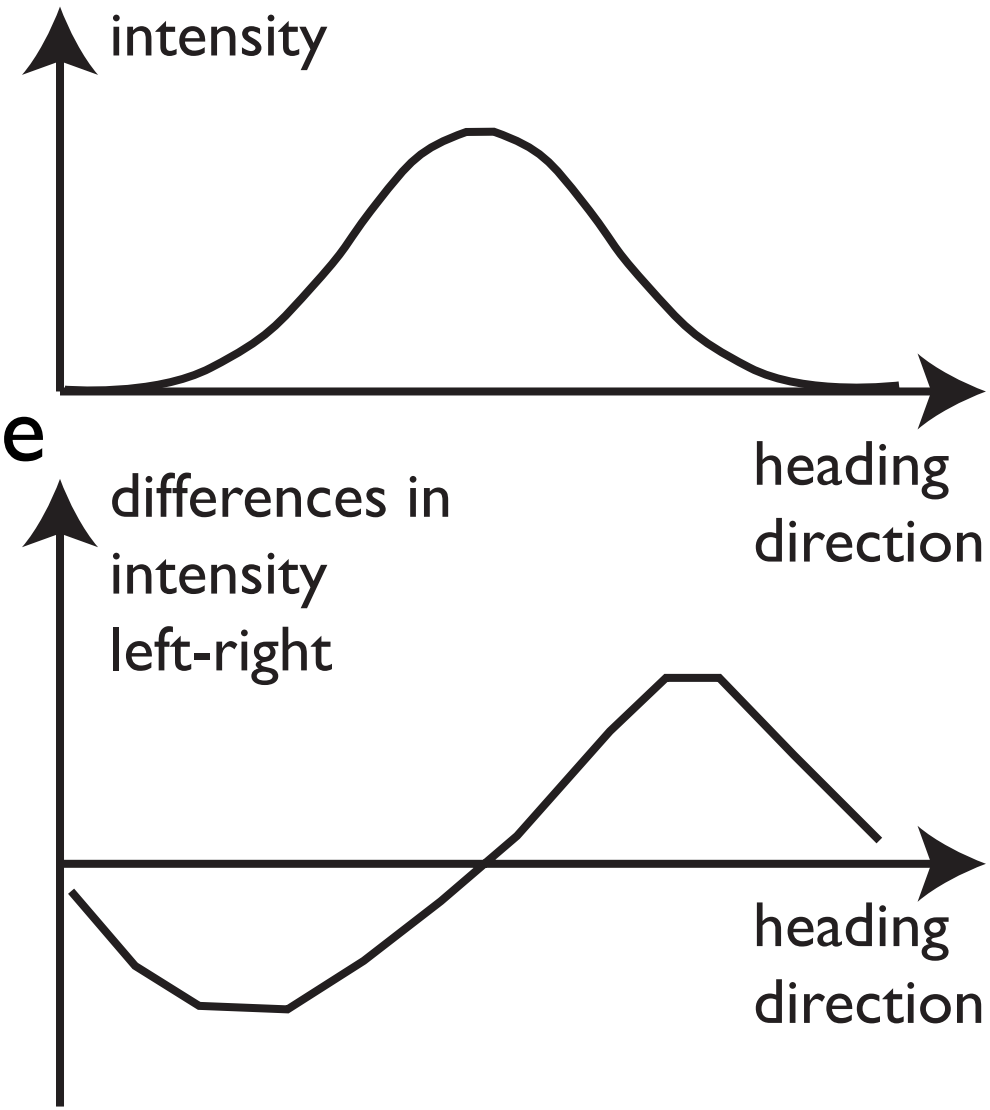
=> enables proving this theorem

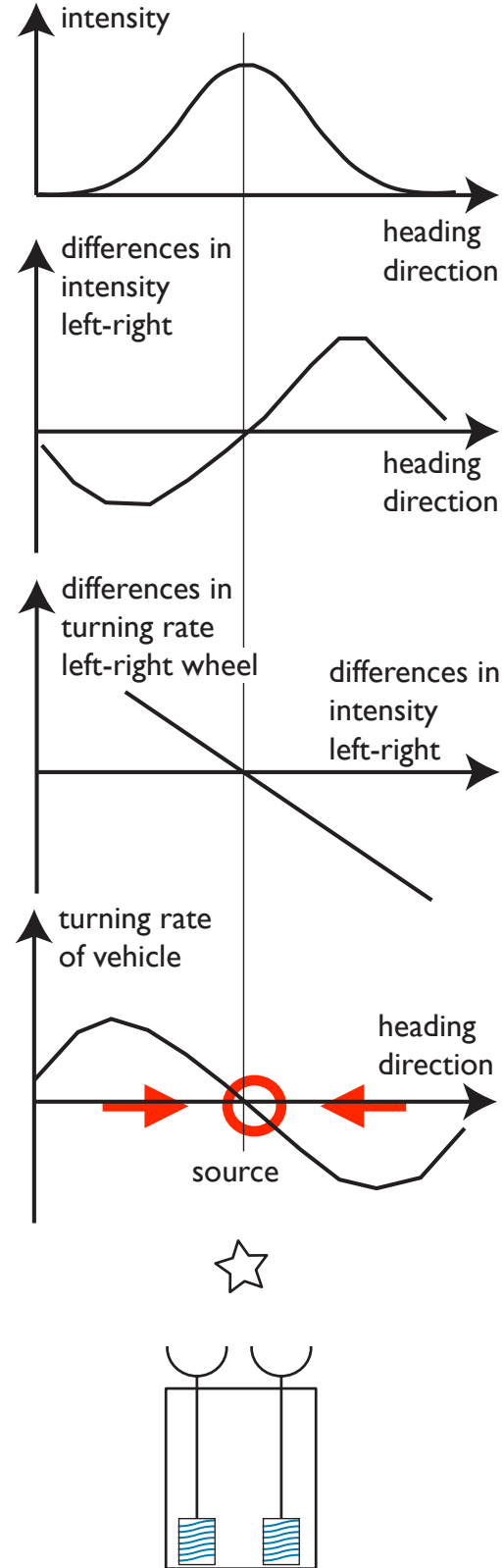
- the vehicles' behavior emerges from an attractor of a dynamical system



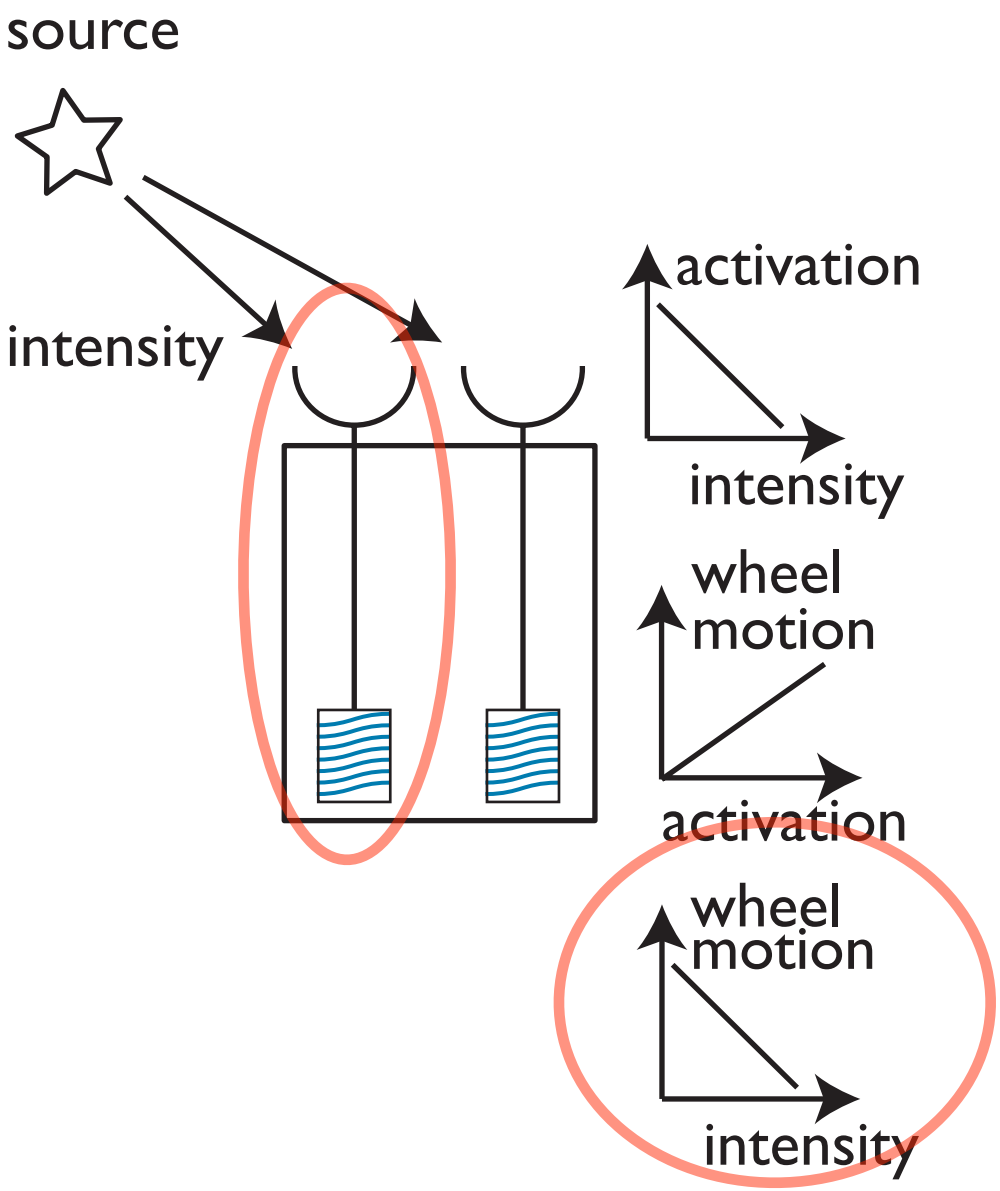
model of the environment

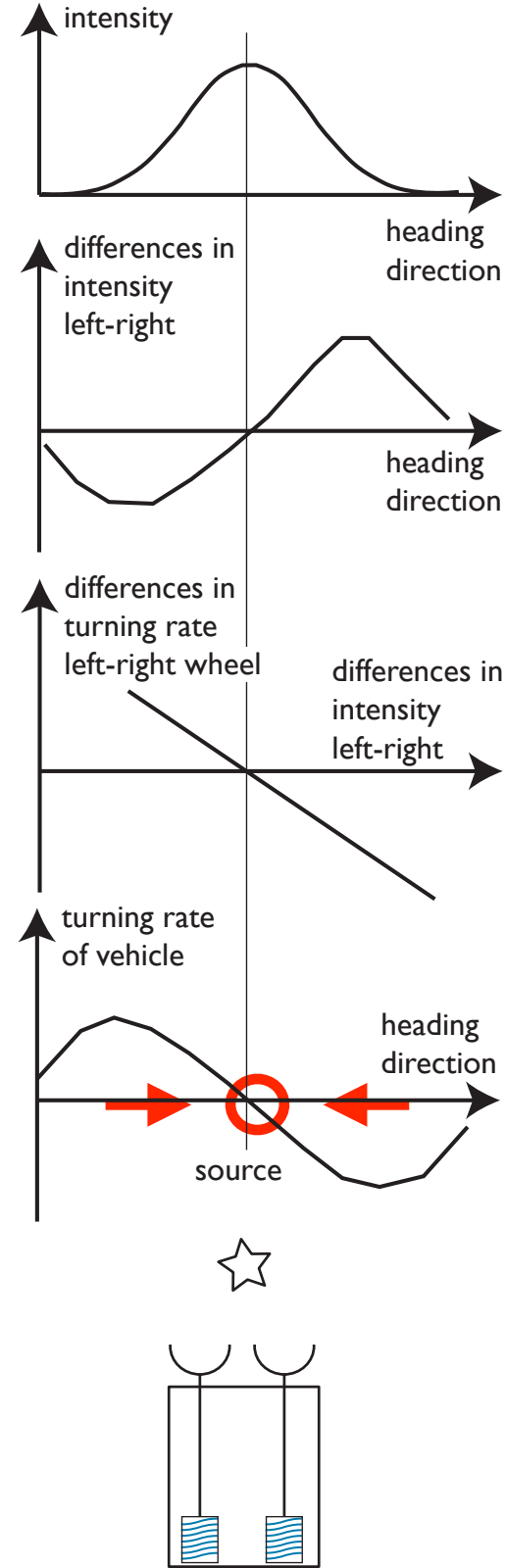
model of the sensors



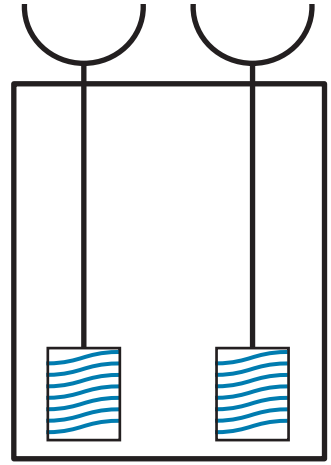


individual forward neural networks





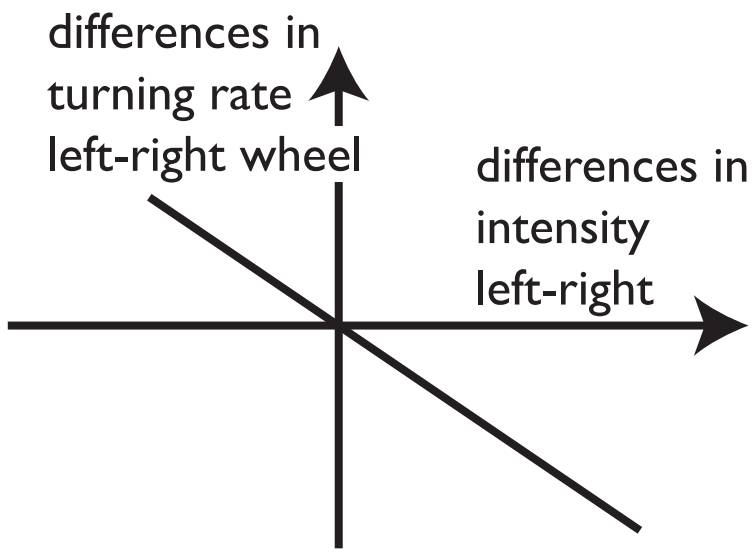
combining the two forward neural networks: sensori-motor model

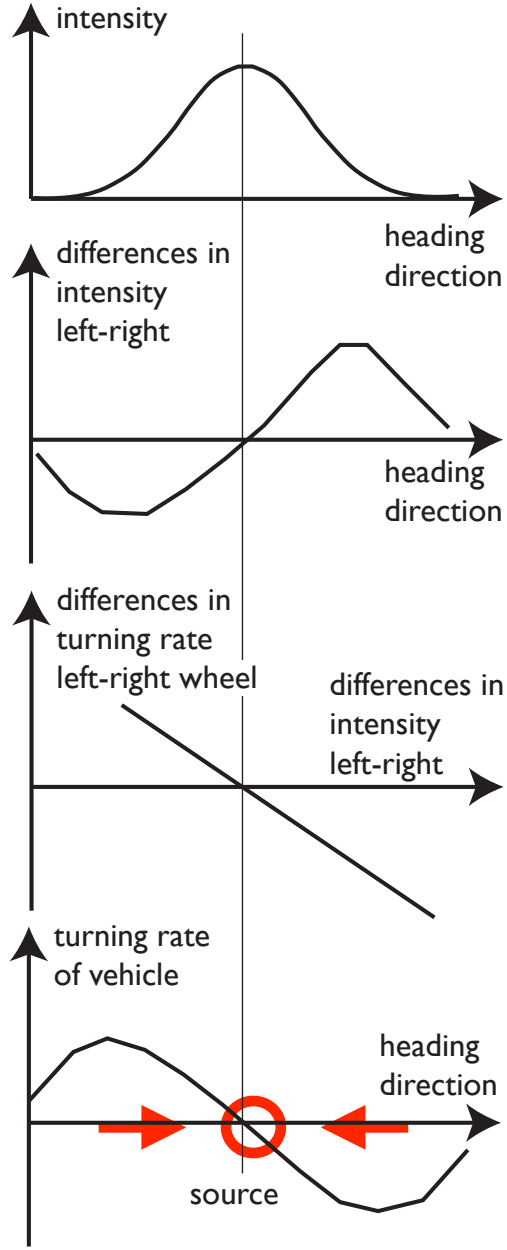


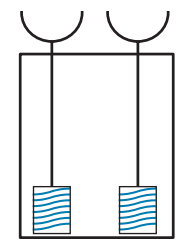
$$\omega_l = \omega_0 - cI_l$$

$$\omega_r = \omega_0 - cI_r$$

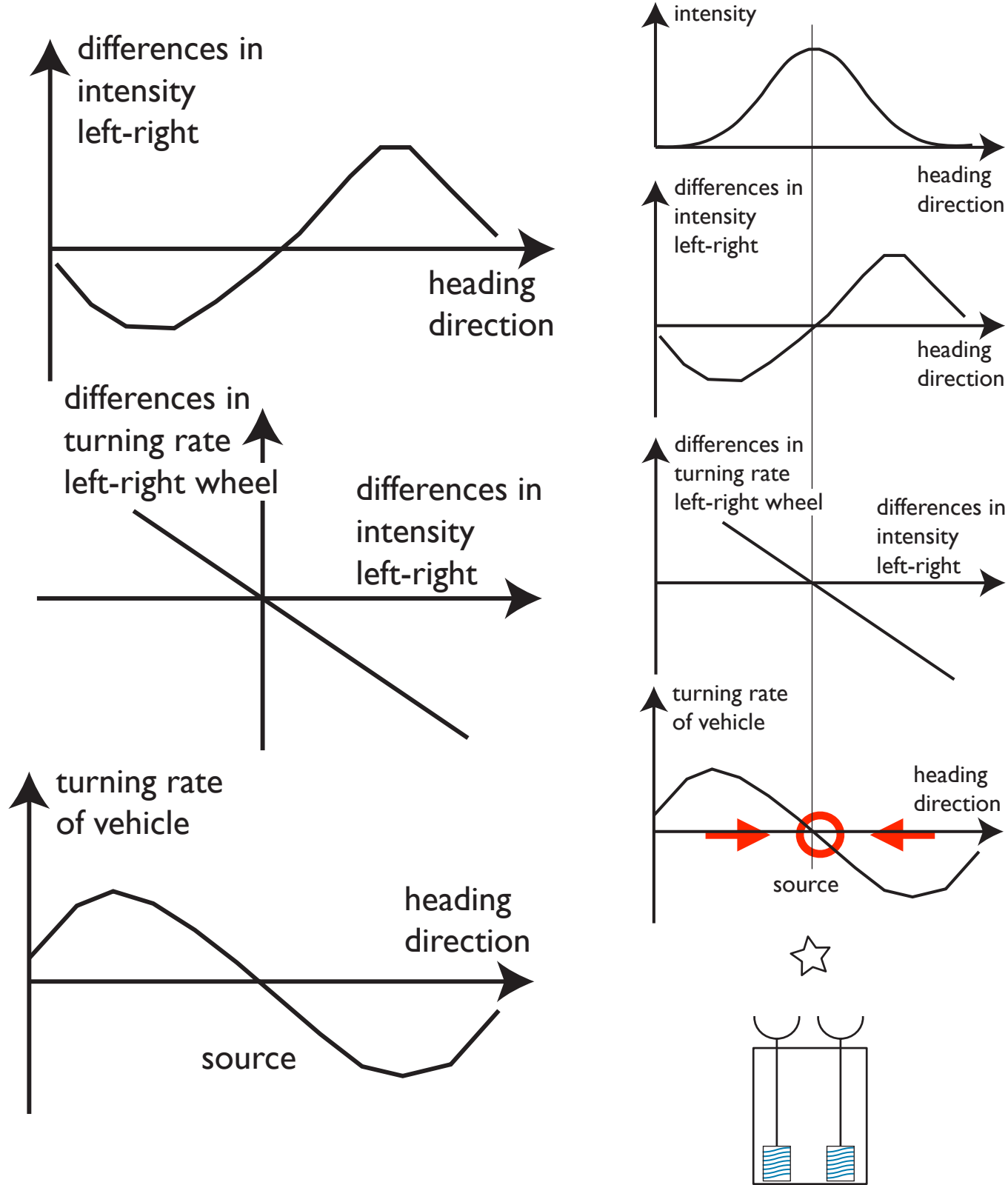
$$\Delta\omega = -c\Delta I$$





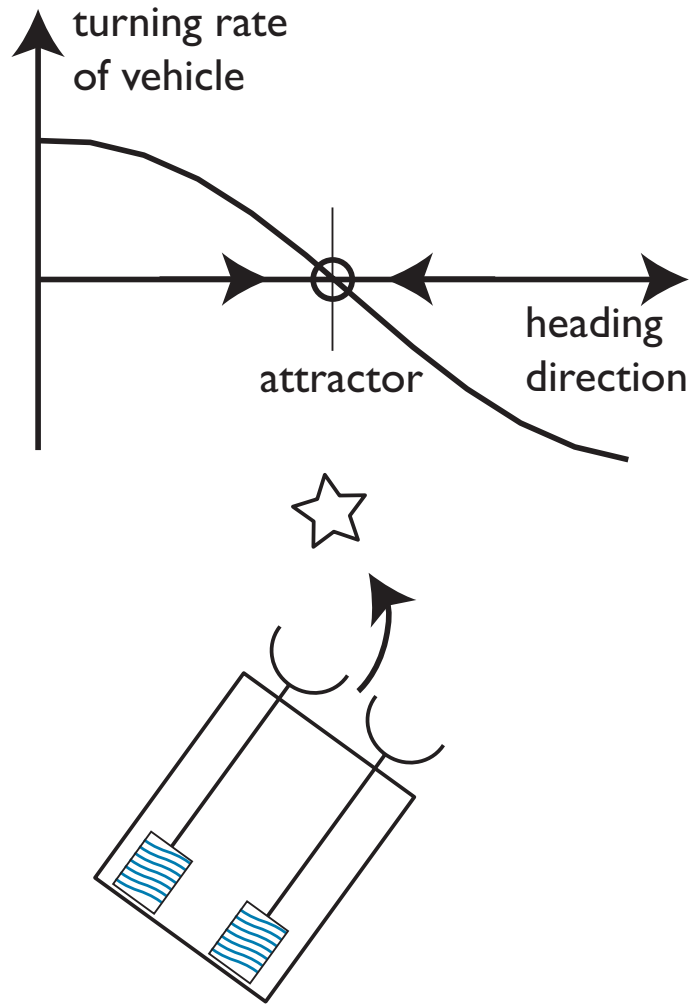


combining environmental, sensor, and sensori-motor model



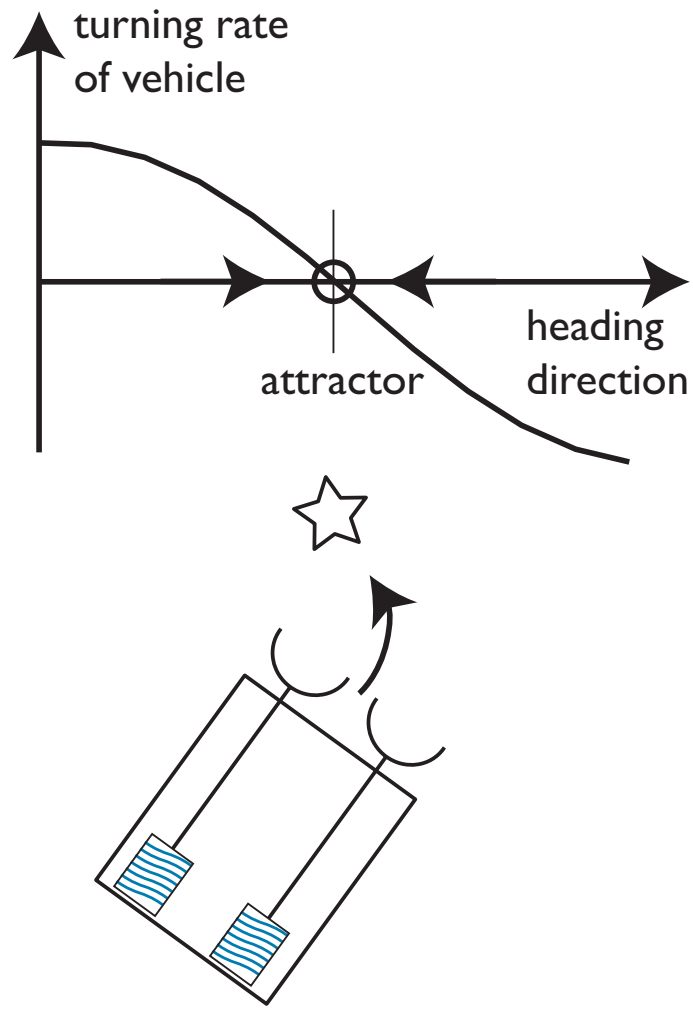
Behavior emerges from a dynamical system

- 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



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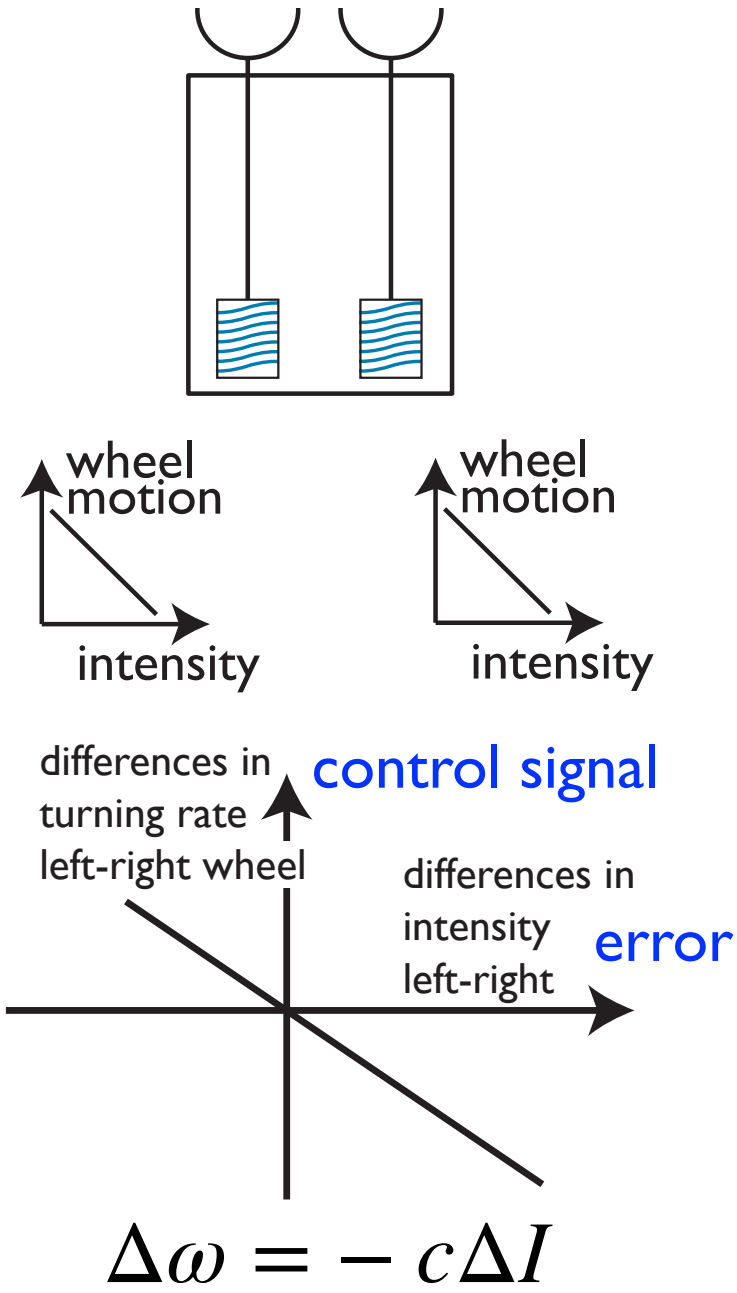
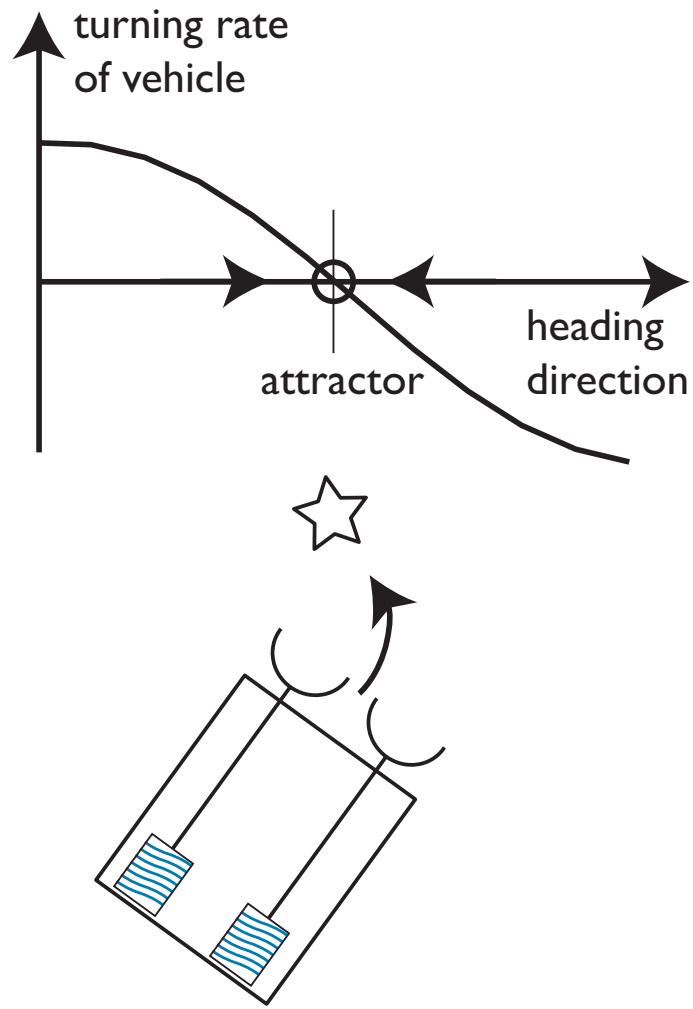


Cybernetic reading of dynamics

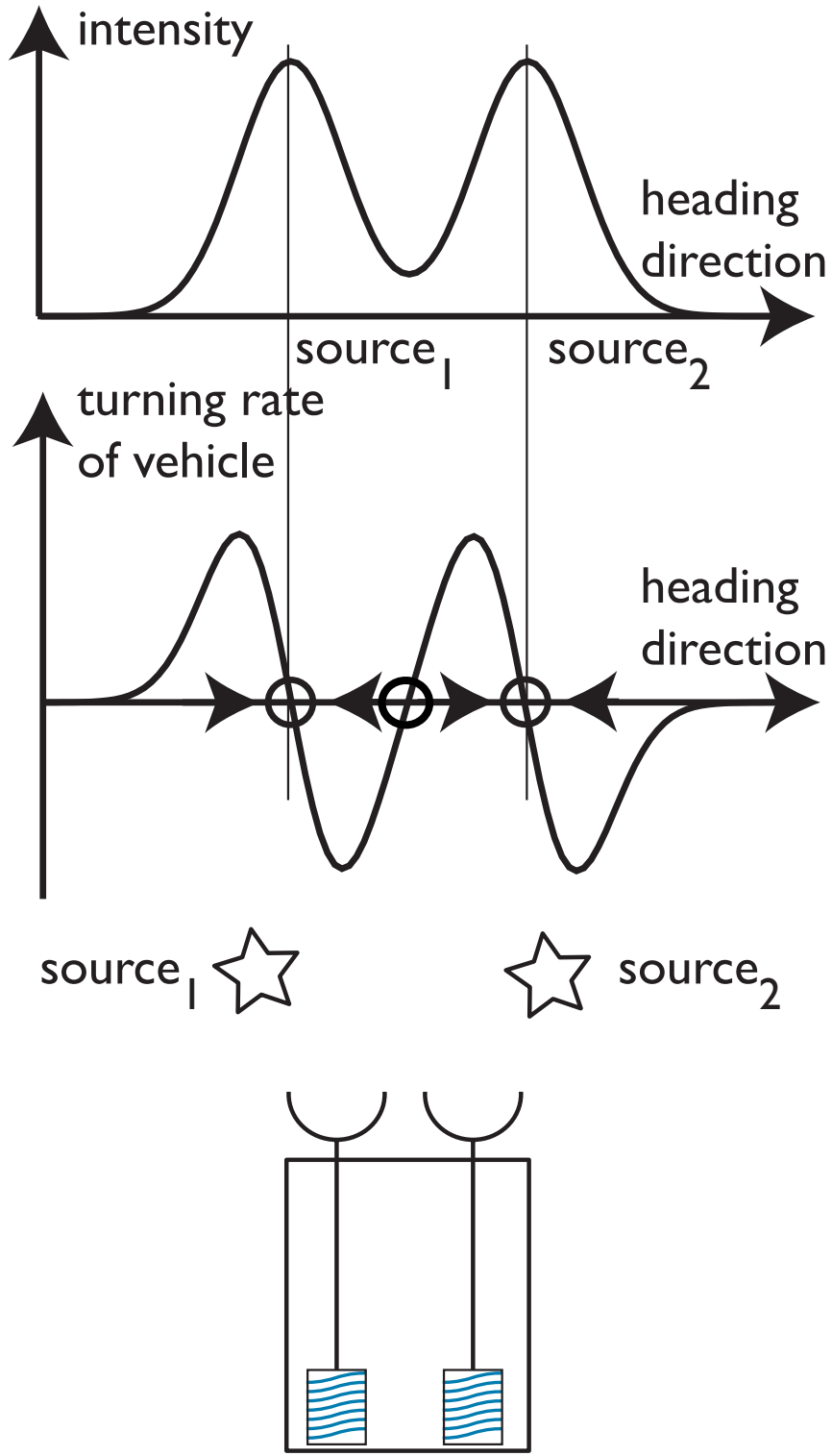
- … depends critically on the *closed loop*: the body's movement changes the sensory information..
- this is a loop through the environment
- the state of the dynamics is the body's physical state in the environment



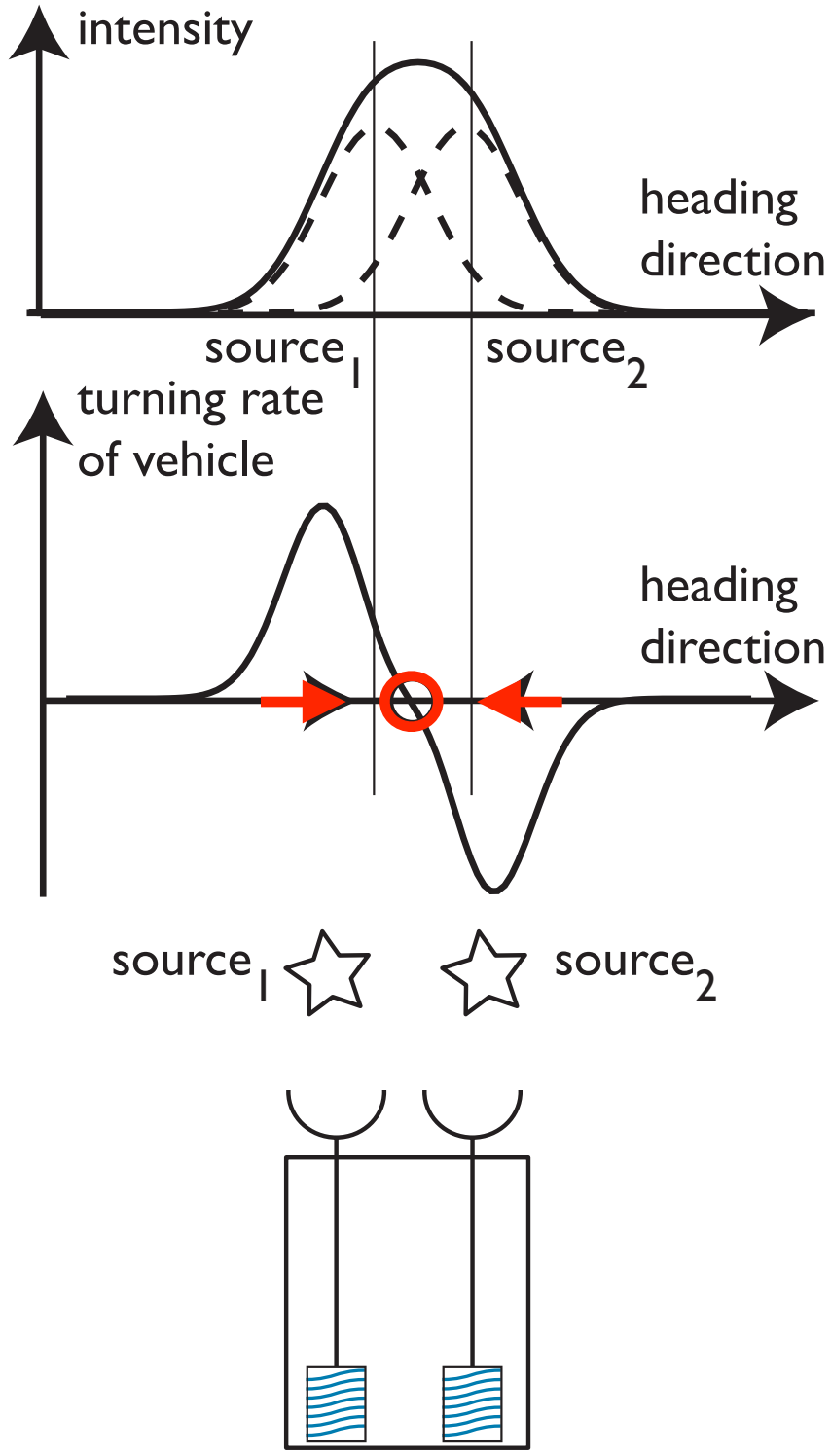
Limits of the cybernetic view of dynamics

- presumes there is a single "goal" or set-point

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



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



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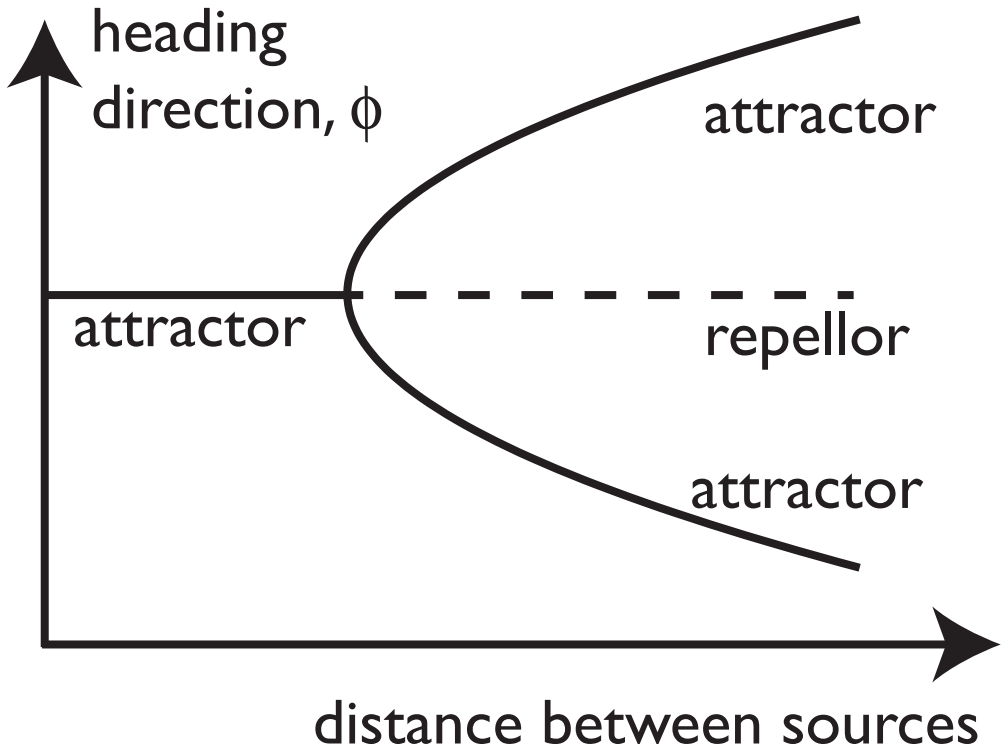
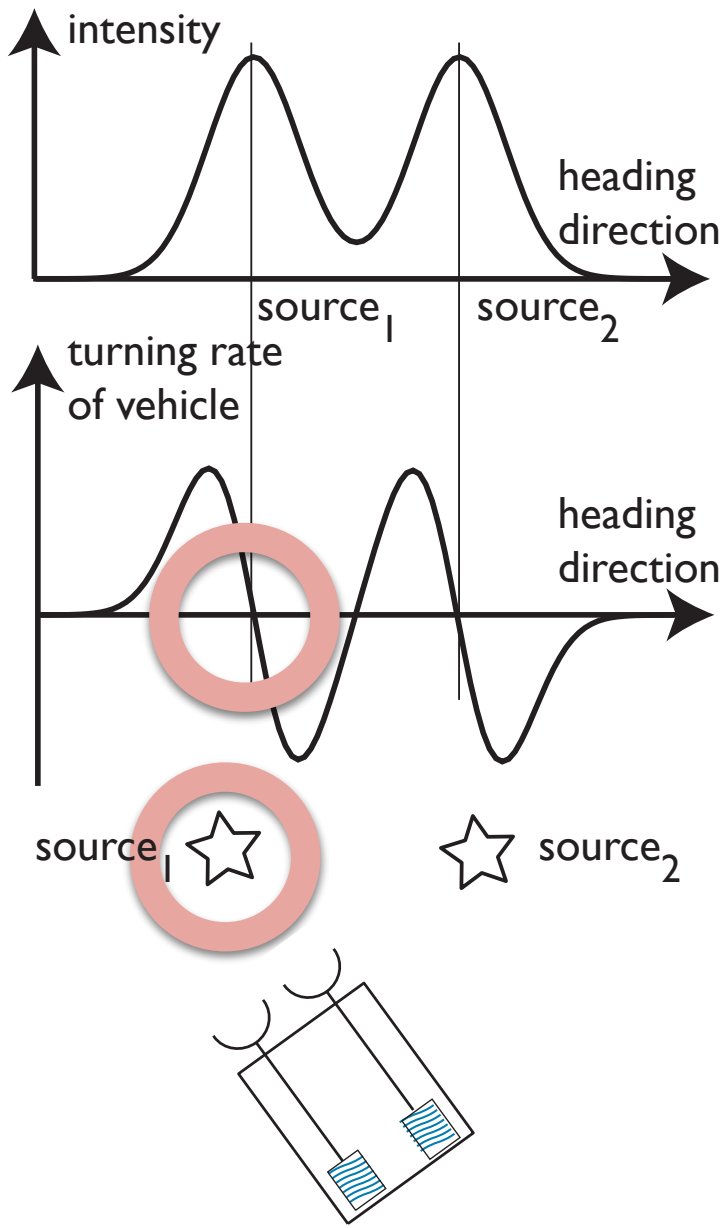


Limits of the cybernetic view of dynamics

- 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 ≠ cybernetics/control theory

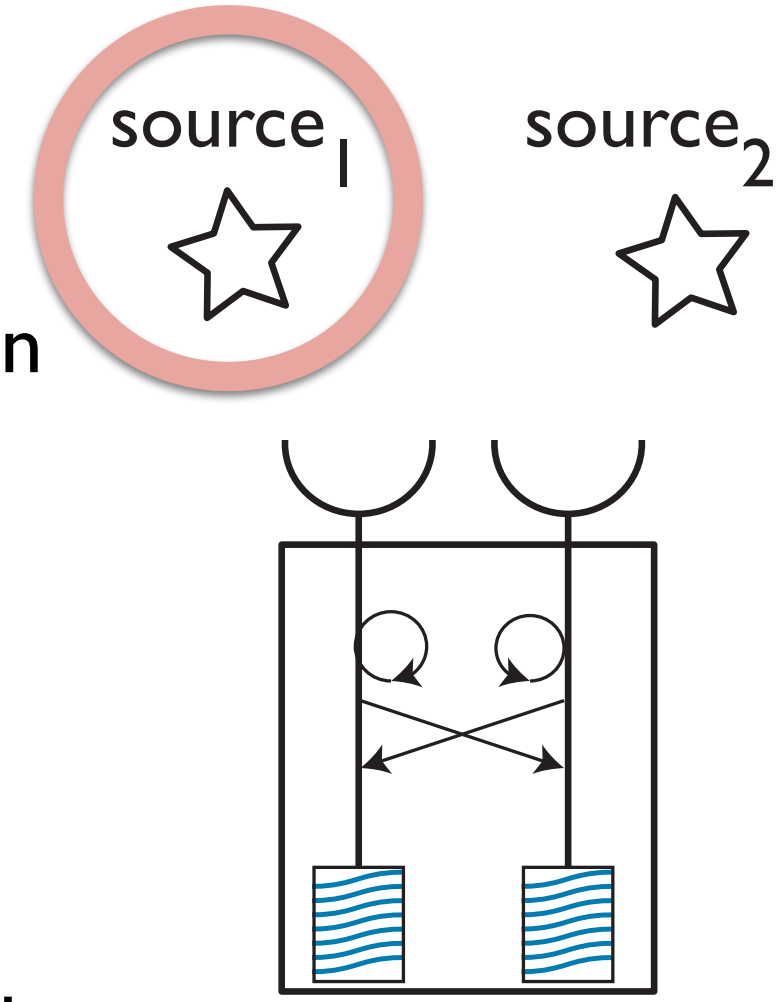
Beyond behavioral dynamics …

- so far: behavioral decision is ``overt''
- => the vehicle's physical state "stores" the state of that decision



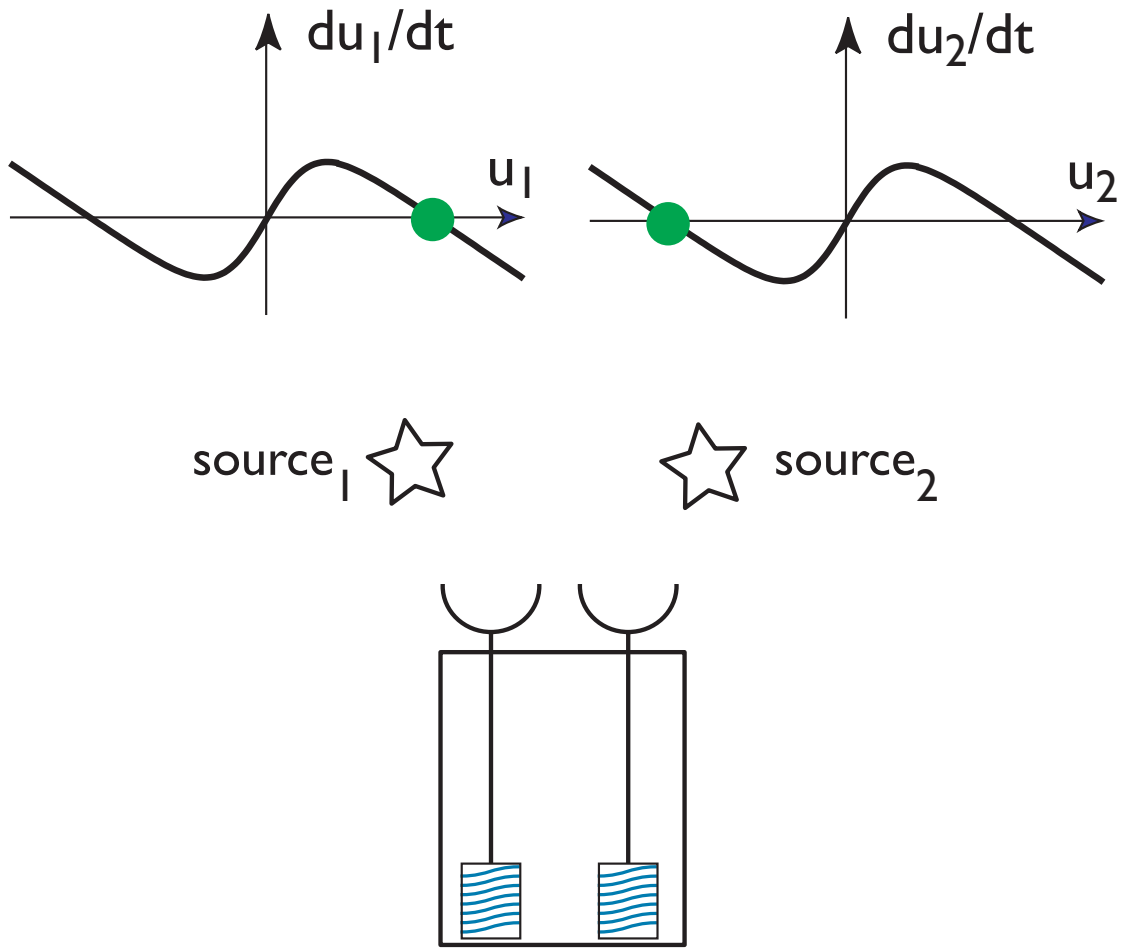
Beyond behavioral dynamics …

- 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



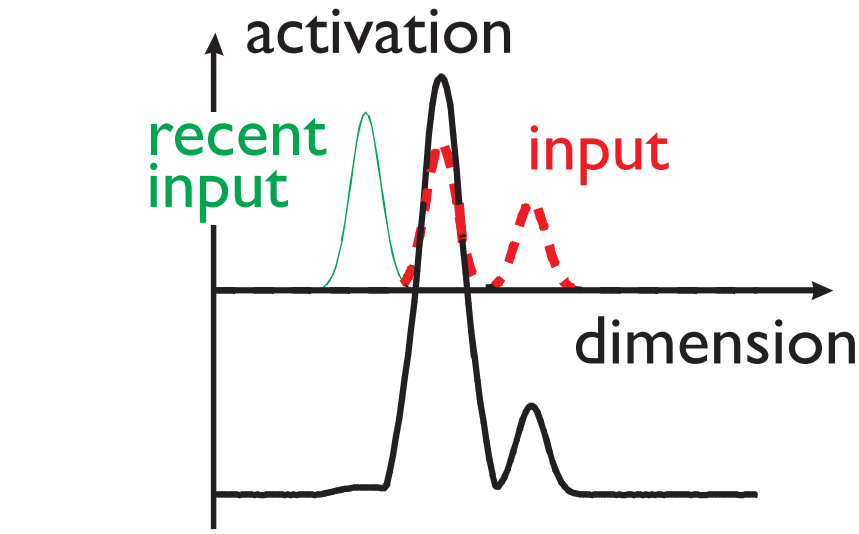
Beyond behavioral dynamics …

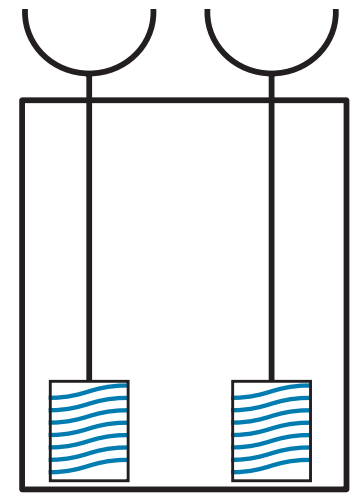
- neural state in the neural network: activation concept
- activation dynamics
- competitive/selective



Beyond behavioral dynamics …

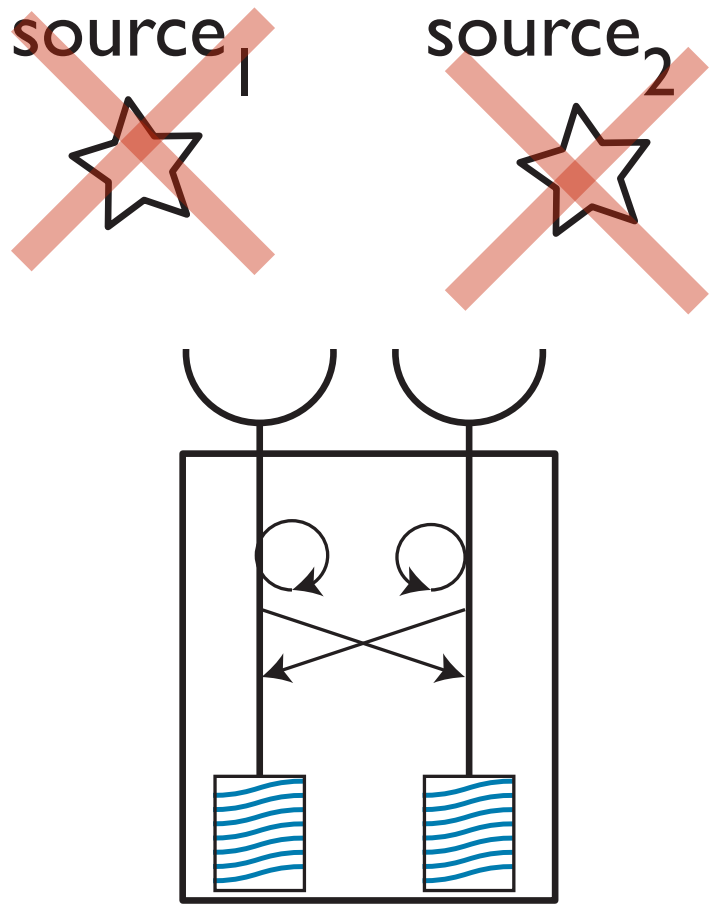
- neural activation field to represent continuous of possible target orientations





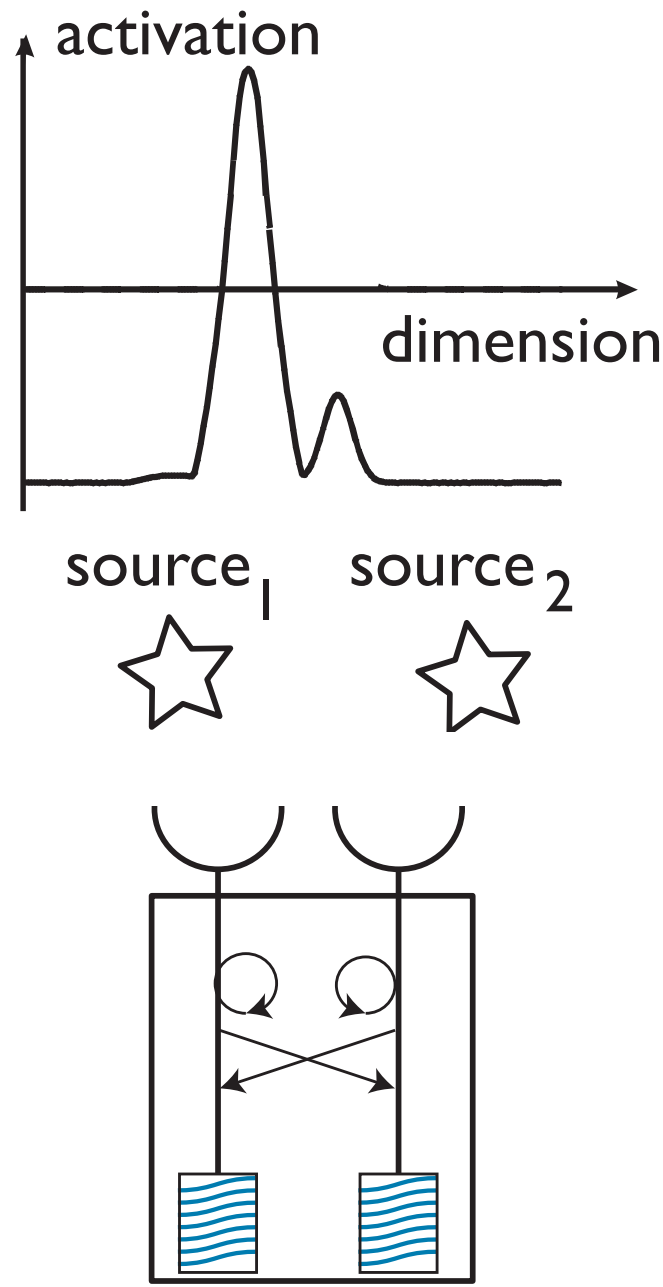
Beyond behavioral dynamics …

- 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



Conclusion

- 5 components required to understand behavior and cognition
  - sensors (sensory surfaces)
  - effectors (motor surfaces)
  - body
  - nervous system
  - environment, context, history
- closed loop => behavioral dynamics
- Behavioral vs neural dynamics