Braitenberg vehicles: embodied nervous systems

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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
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”
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

![Diagram showing the body with sensors and motors](image-url)
Nervous system

- links sensors to effectors through the inner activation state
is structured at a relevant scale in terms of the physical variables to which organism is sensitive.
Emergent behavior: taxis

- Source
- Intensity
- Sensory system
- Nervous system
- Body
- Motor system
- Structured environment
- Activation
- Intensity
- Wheel motion
- Activation
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

intensity

differences in intensity left-right

heading direction

differences in heading direction

turnings rate of vehicle

differences in turning rate left-right

heading direction

source

intensity
individual forward neural networks

source

intensity

activation

wheel motion

intensity

activation

wheel motion

intensity

intensity

differences in intensity left-right

differences in heading direction

differences in turning rate left-right wheel

differences in intensity left-right

turning rate of vehicle

heading direction

source

wheel motion

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

\[
\begin{align*}
\omega_l &= \omega_0 - c I_l \\
\omega_r &= \omega_0 - c I_r \\
\Delta \omega &= -c \Delta I
\end{align*}
\]
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
- by its sensors measuring the “error”
- 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.

![Diagram](image)

- Turning rate of vehicle
- Heading direction
- Attractor
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

- $\Rightarrow$ 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**

\[
\frac{du_1}{dt} \\
\frac{du_2}{dt}
\]

\( source_1 \quad \star \)  \( source_2 \quad \star \)
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
store the state of the representation in a neural field as a pattern of sustained activation
Next…

neural dynamics