Attractor dynamics approach to behavior generation: vehicle motion

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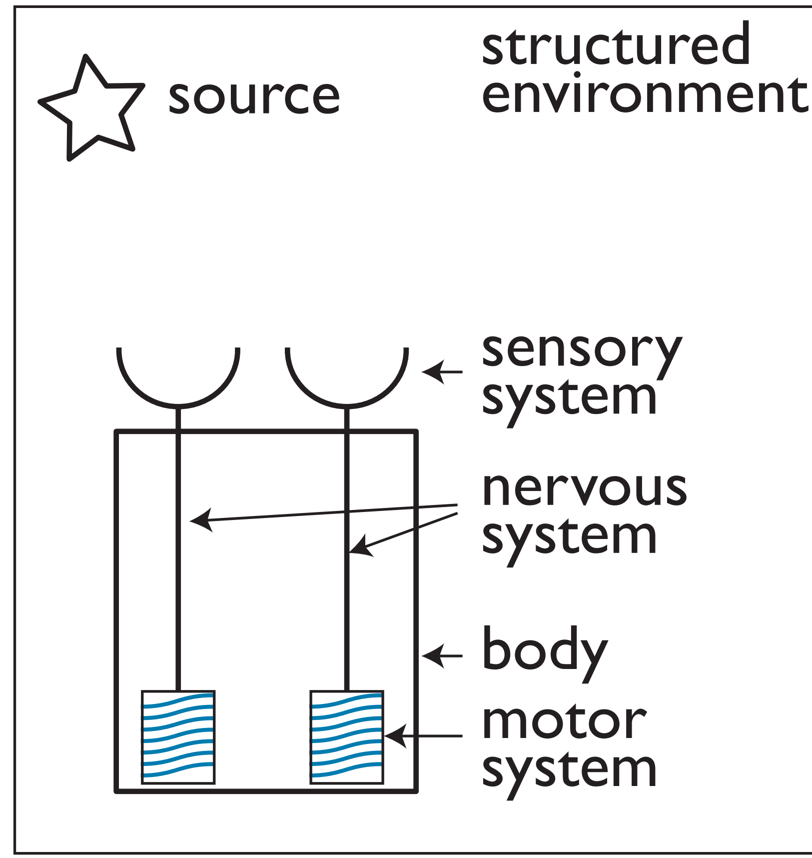
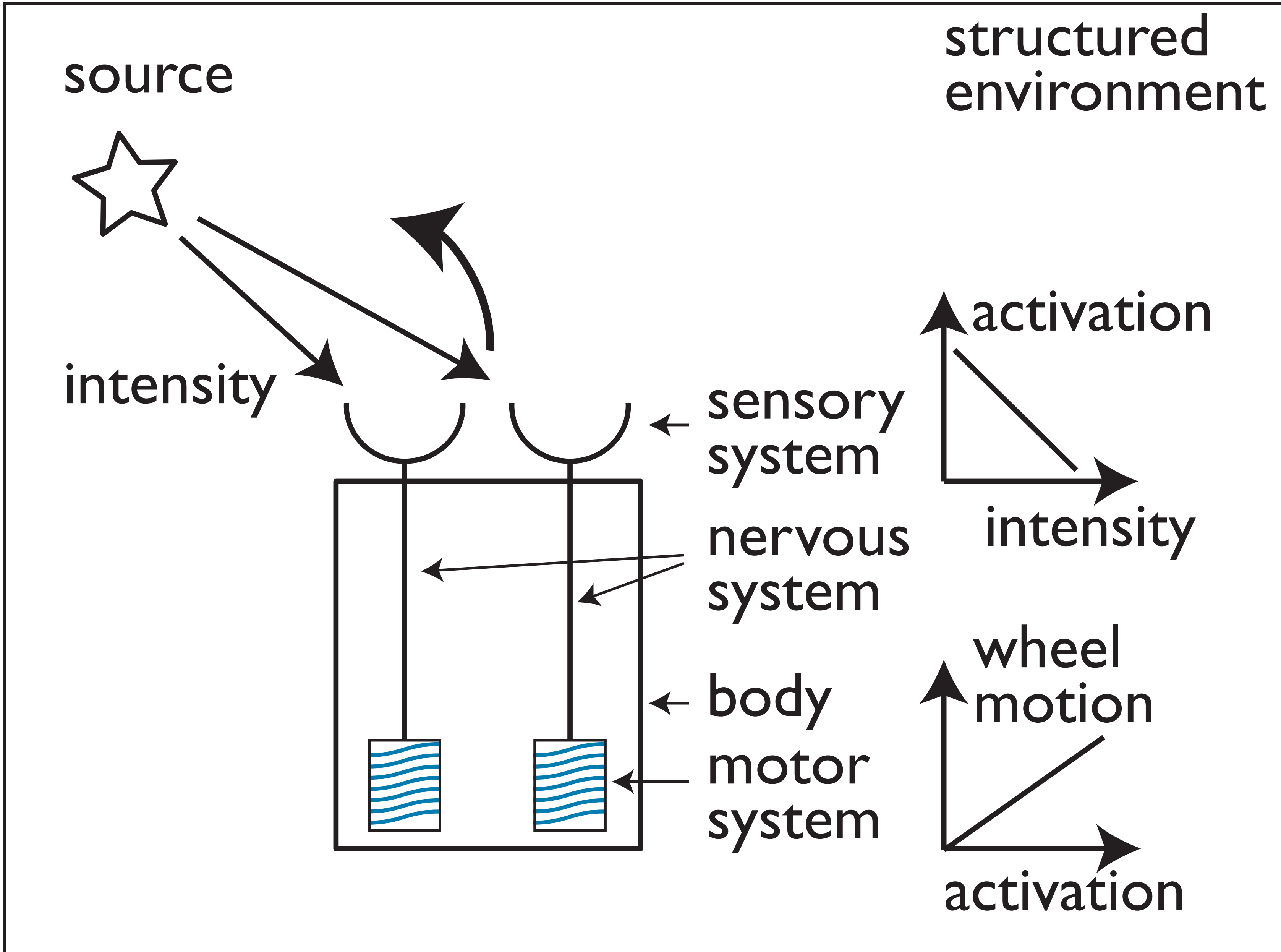
Embodied nervous system

- effectors
- sensors
- a nervous system
- a body
- situated in a structured environment
- => emergent behavior



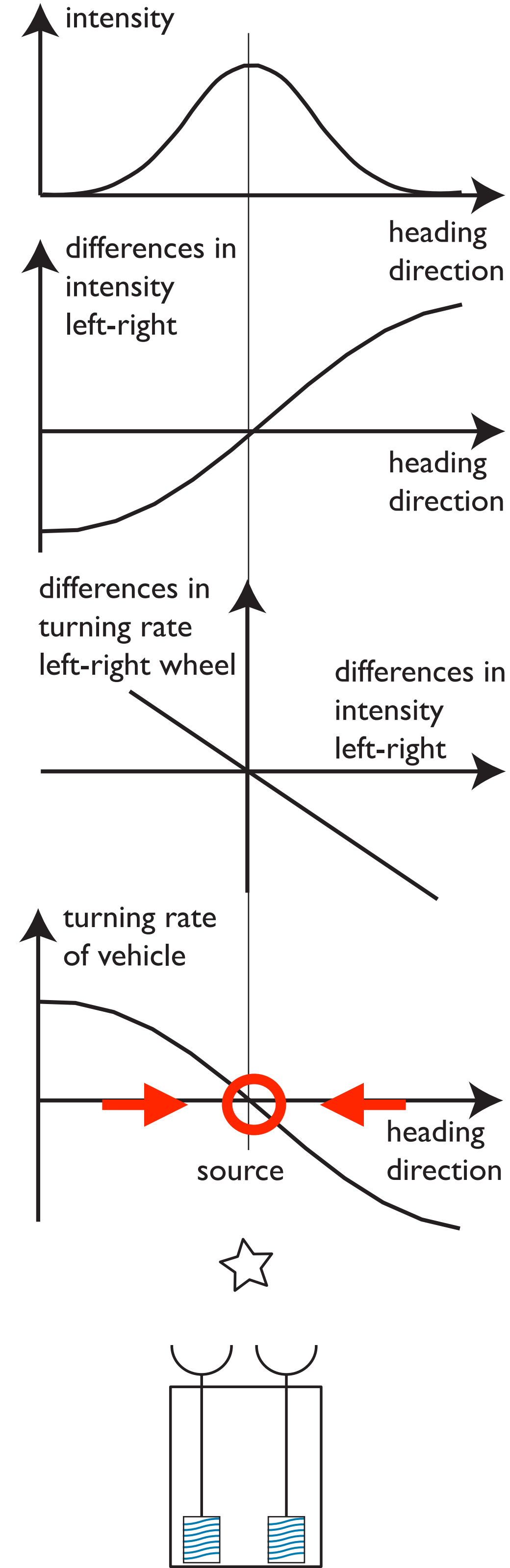
Braitenberg vehicle

Emergent behavior: taxis



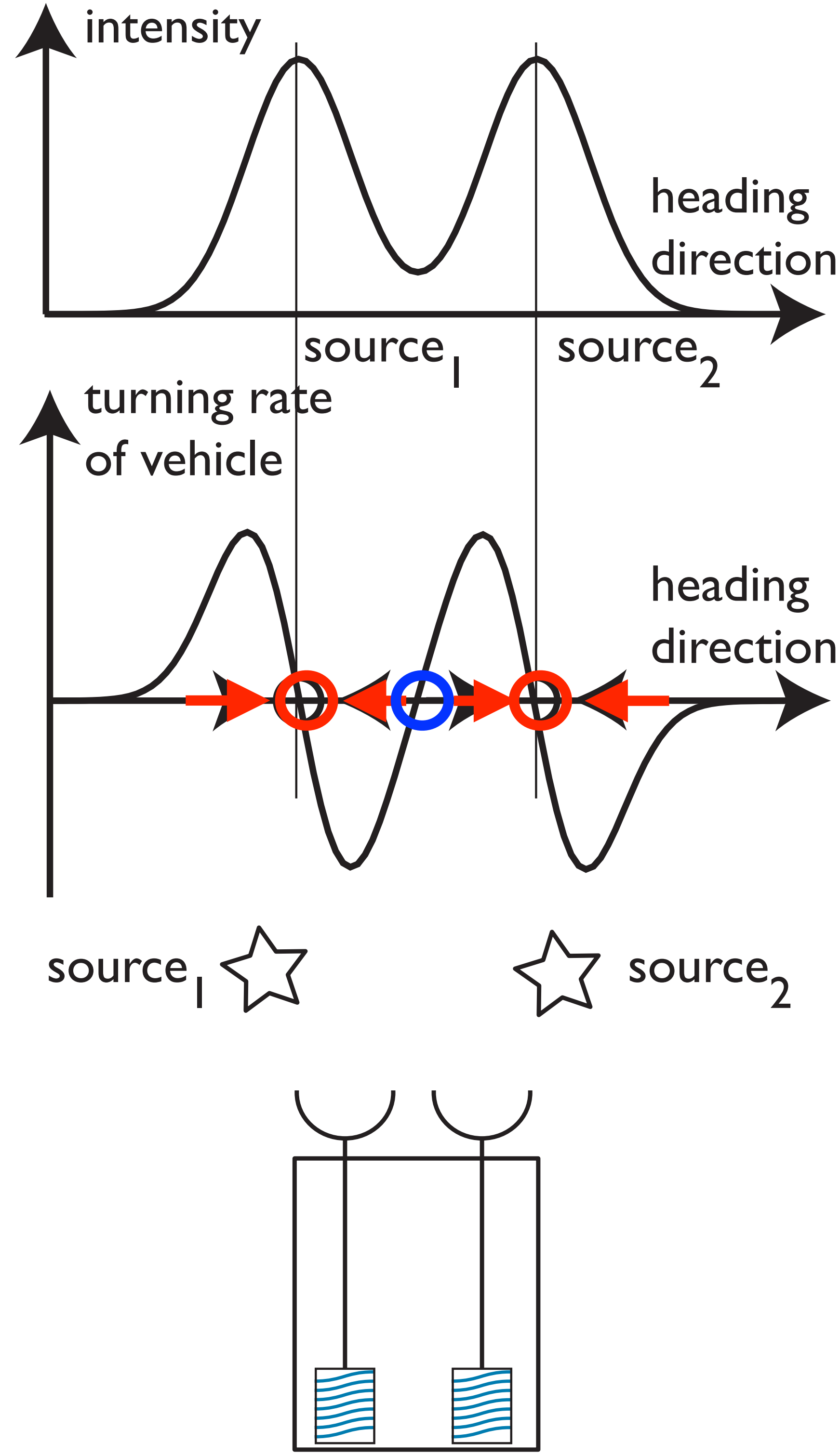
Emergent behavior: this is a dynamics

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



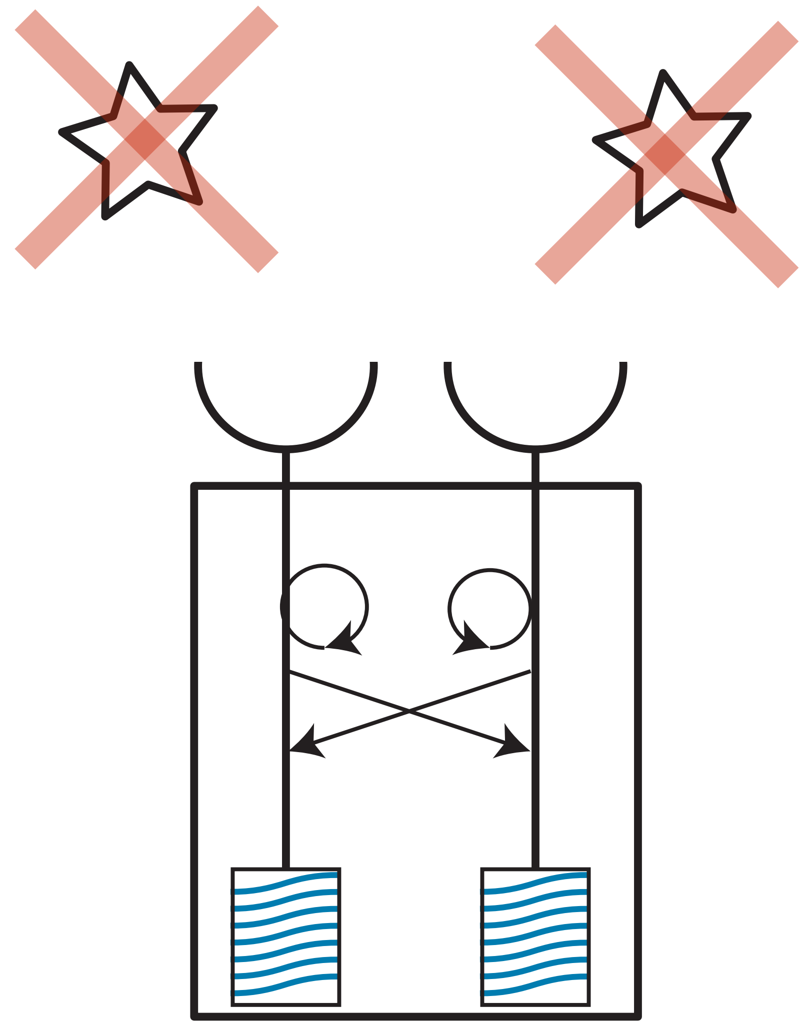
Complex environment => complex dynamics

- bistable dynamics for bimodal intensity distribution
- => nonlinear dynamics makes selection decision



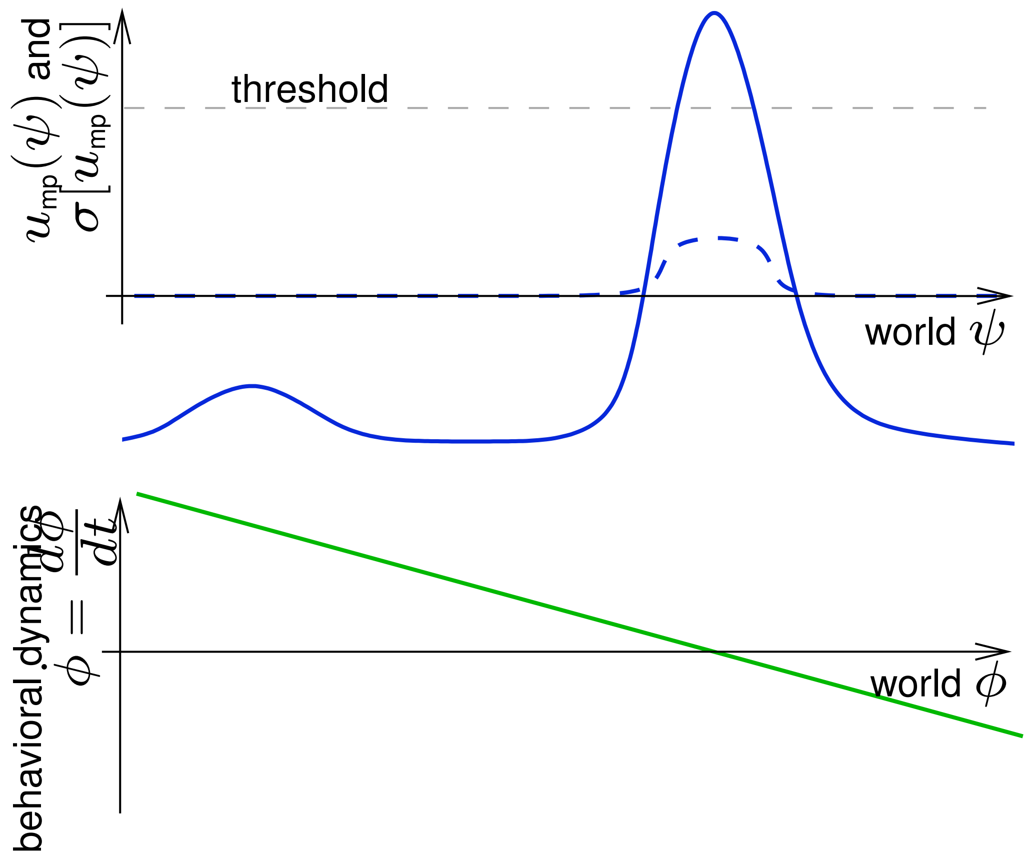
Neural dynamics

- "inner dynamic state" of the nervous system that is independent of body or sensors: activation dynamics=neural dynamics
- can create cognitive competences such as "mental selection" (e.g.,, selective attention), or working memory



Neural and behavioral dynamics

- couple peak in direction field into dynamics of heading direction as an attractor

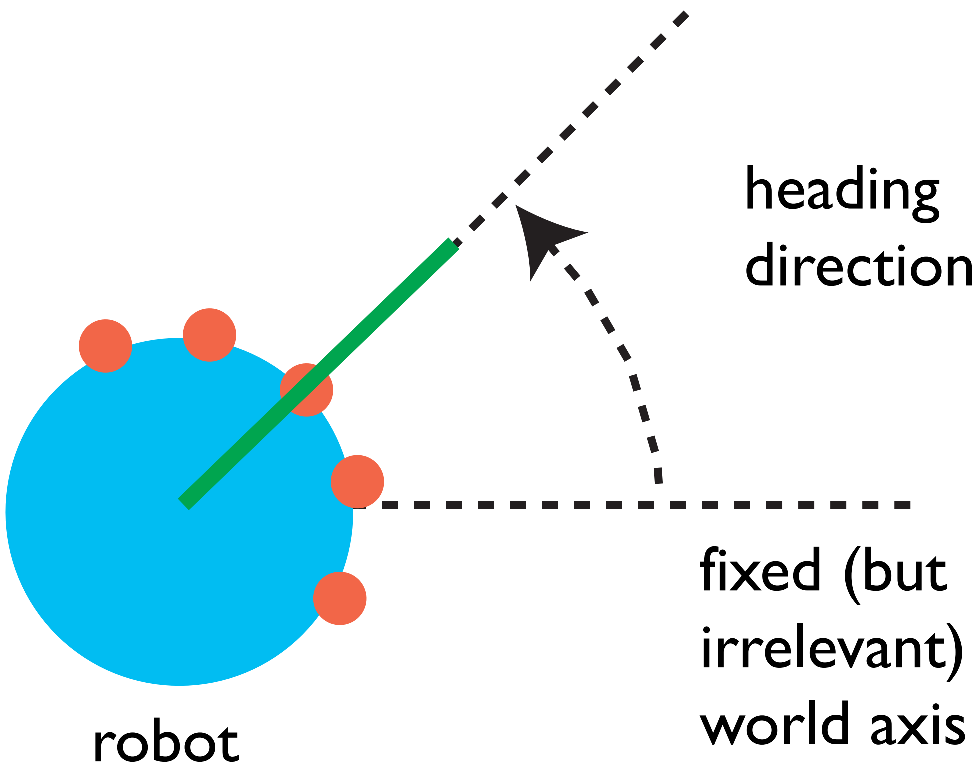


Basic ideas of attractor dynamics approach

- behavioral variables
- time courses from dynamical system: attractors
- tracking attractors
- bifurcations for flexibility

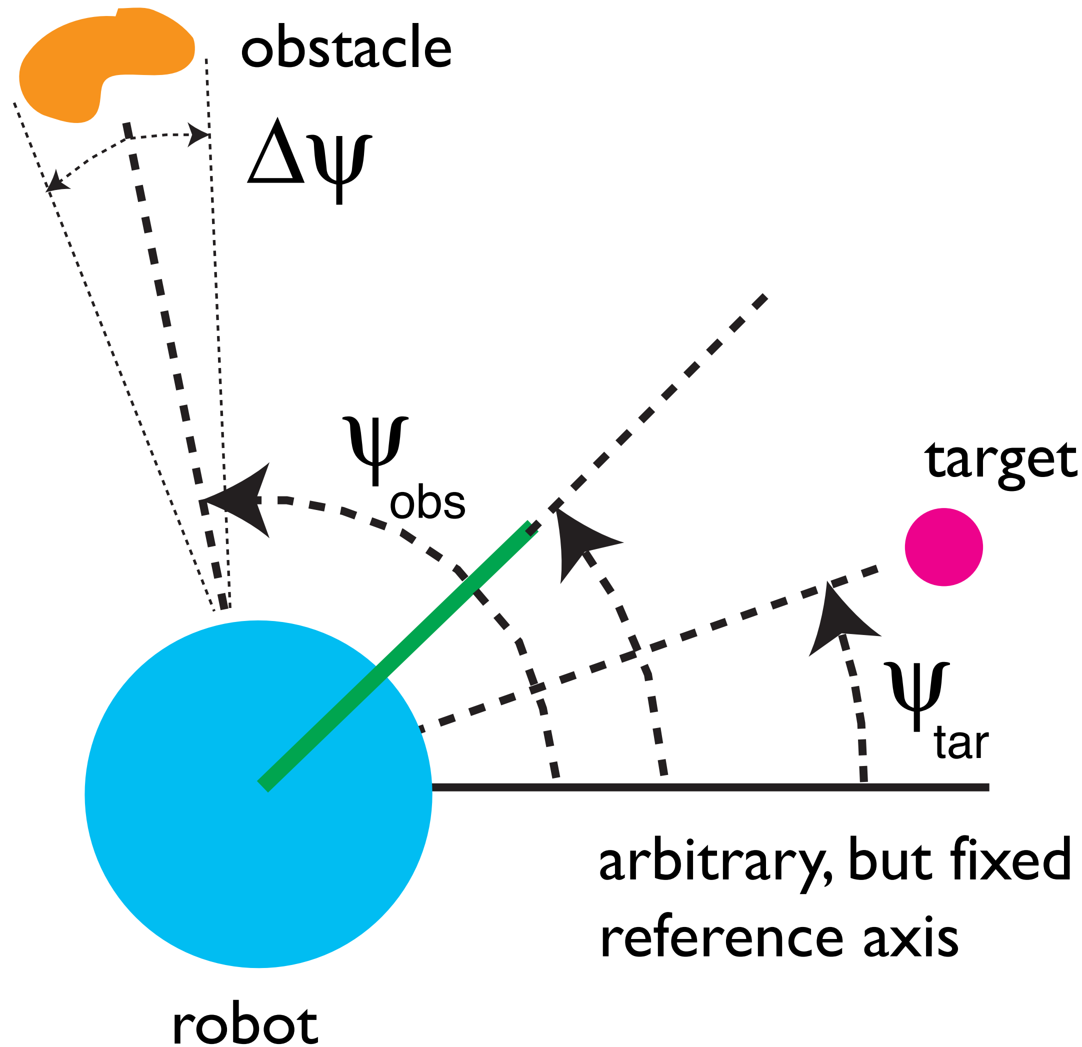
Behavioral variables: example

- vehicle moving in 2D: heading direction



Behavioral variables: example

- constraints: obstacle avoidance and target acquisition



Behavioral variables

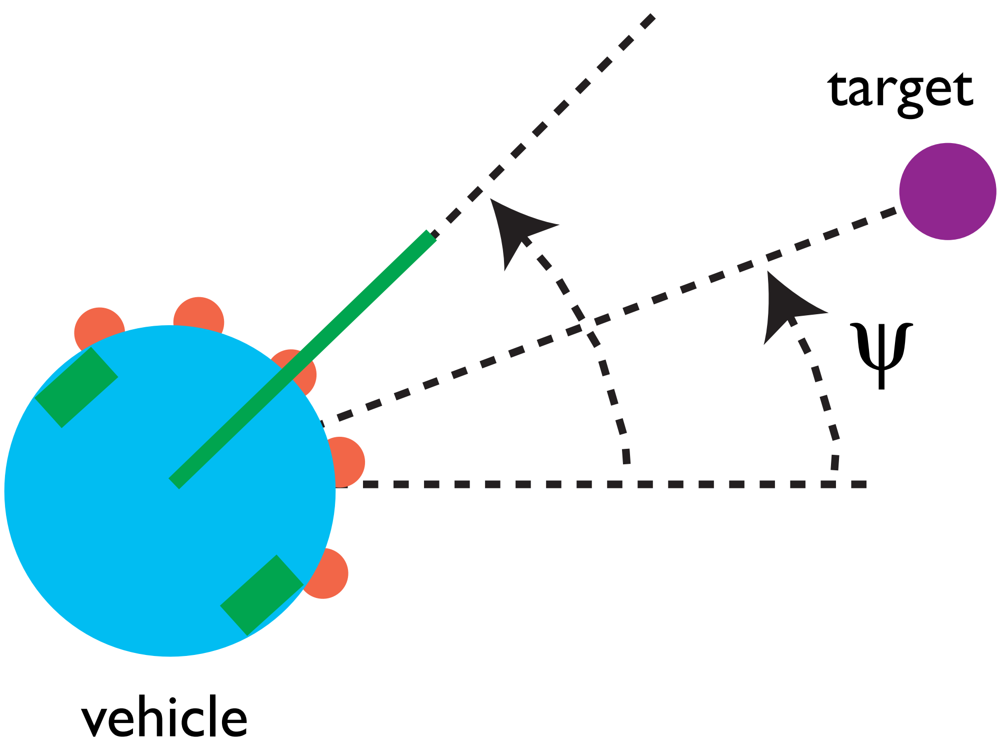
- describe desired motor behavior
- “enactable”
- express constraints as values/value ranges
- appropriate level of invariance

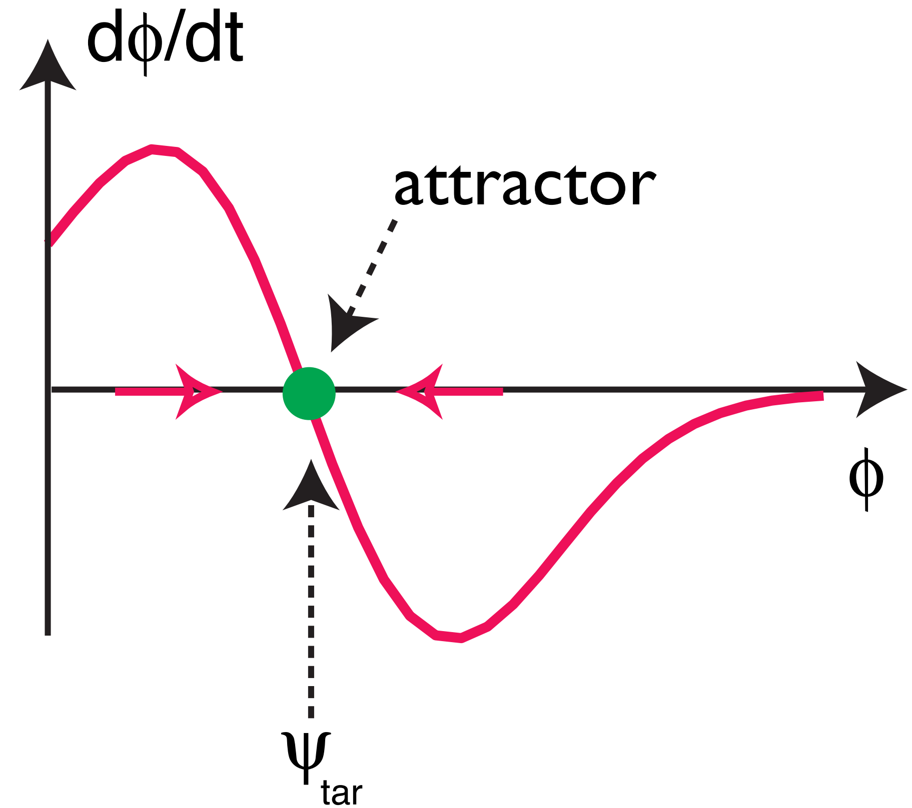
Behavioral dynamics

- generate behavior by generating time courses of behavioral variables
- generate time course of behavioral variables from attractor solutions of a (designed) dynamical system
- that dynamical system is constructed from contributions expressing behavioral constraints

Behavioral dynamics: example

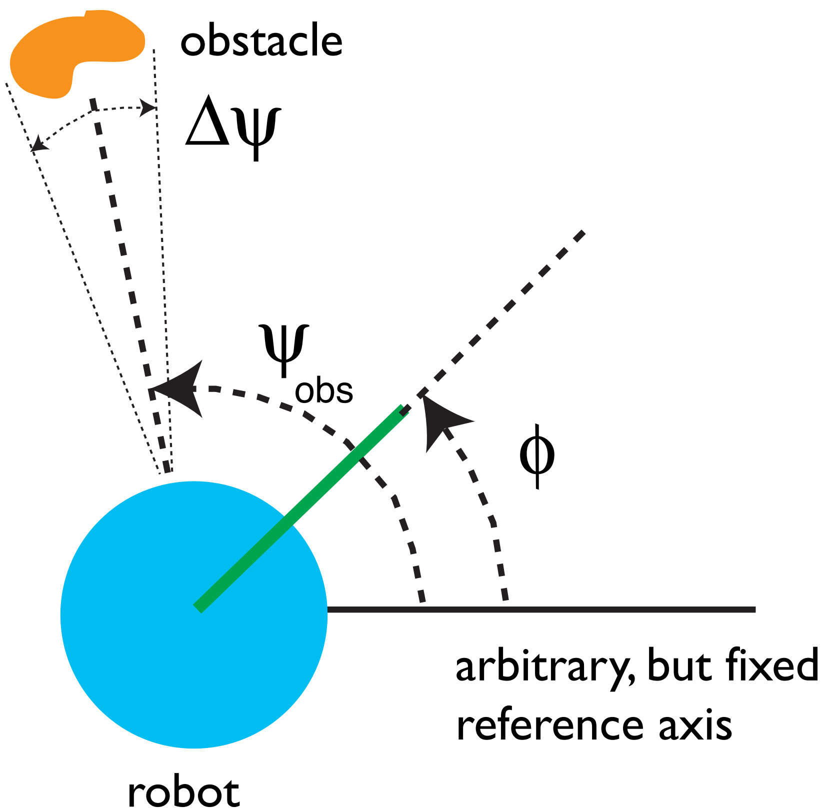
- behavioral constraint: target acquisition

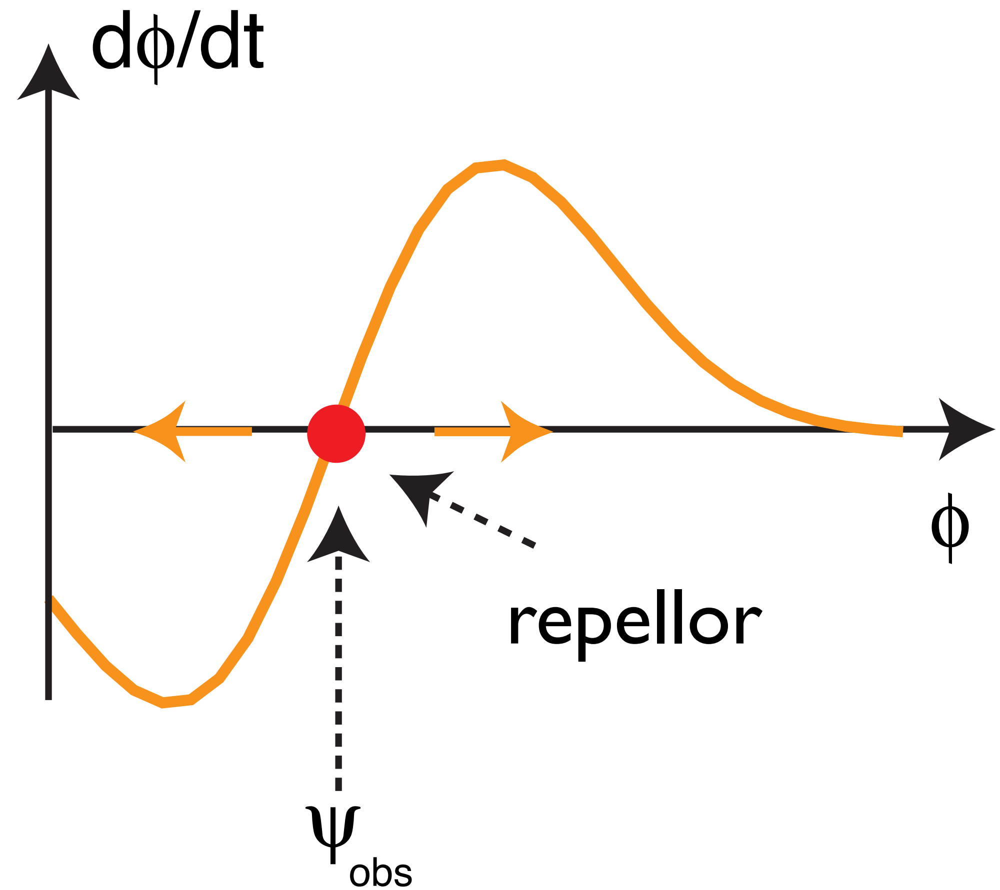




Behavioral dynamics: example

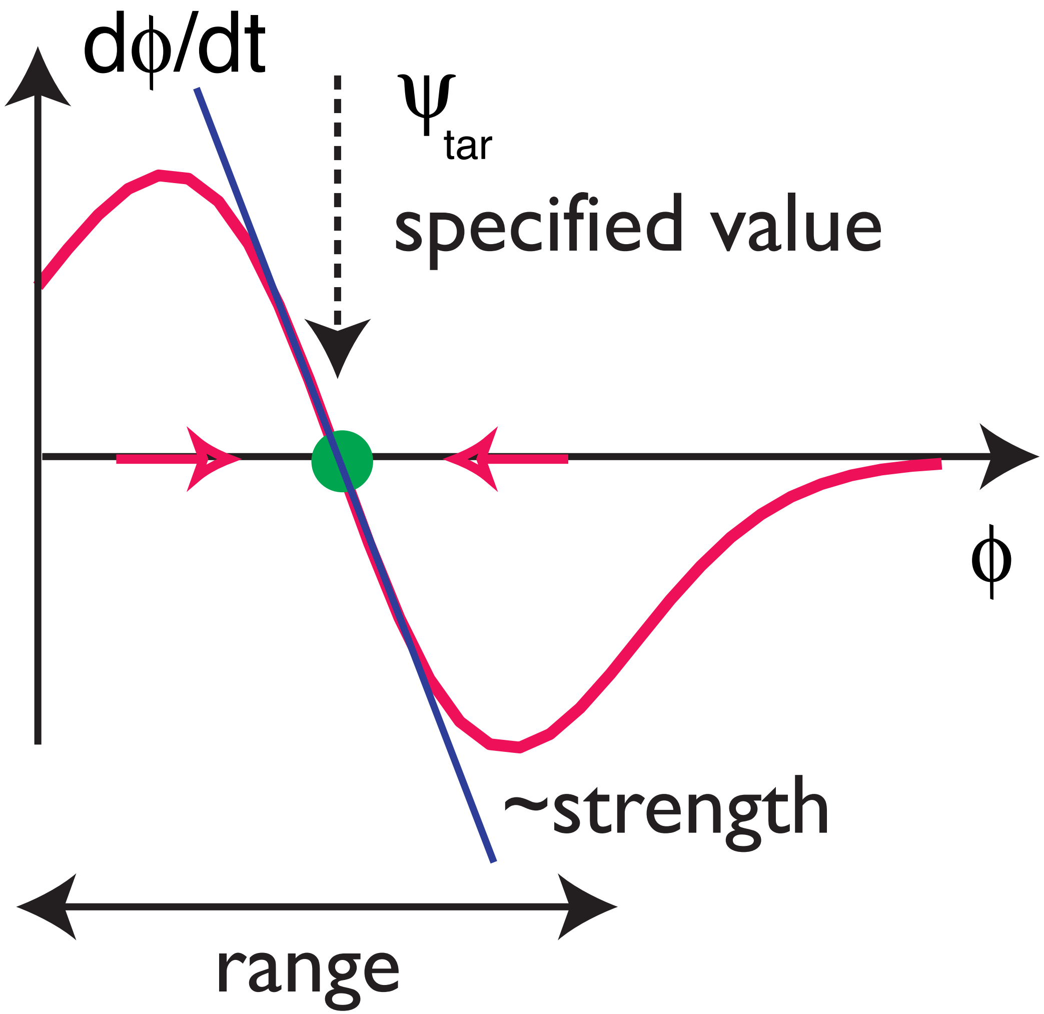
- behavioral constraint: obstacle avoidance





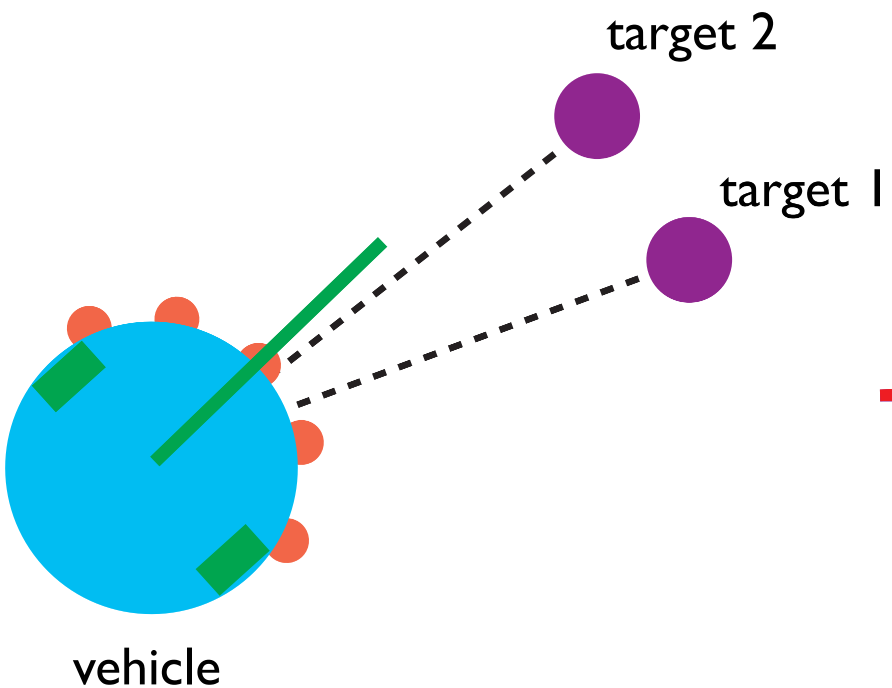
Behavioral dynamics

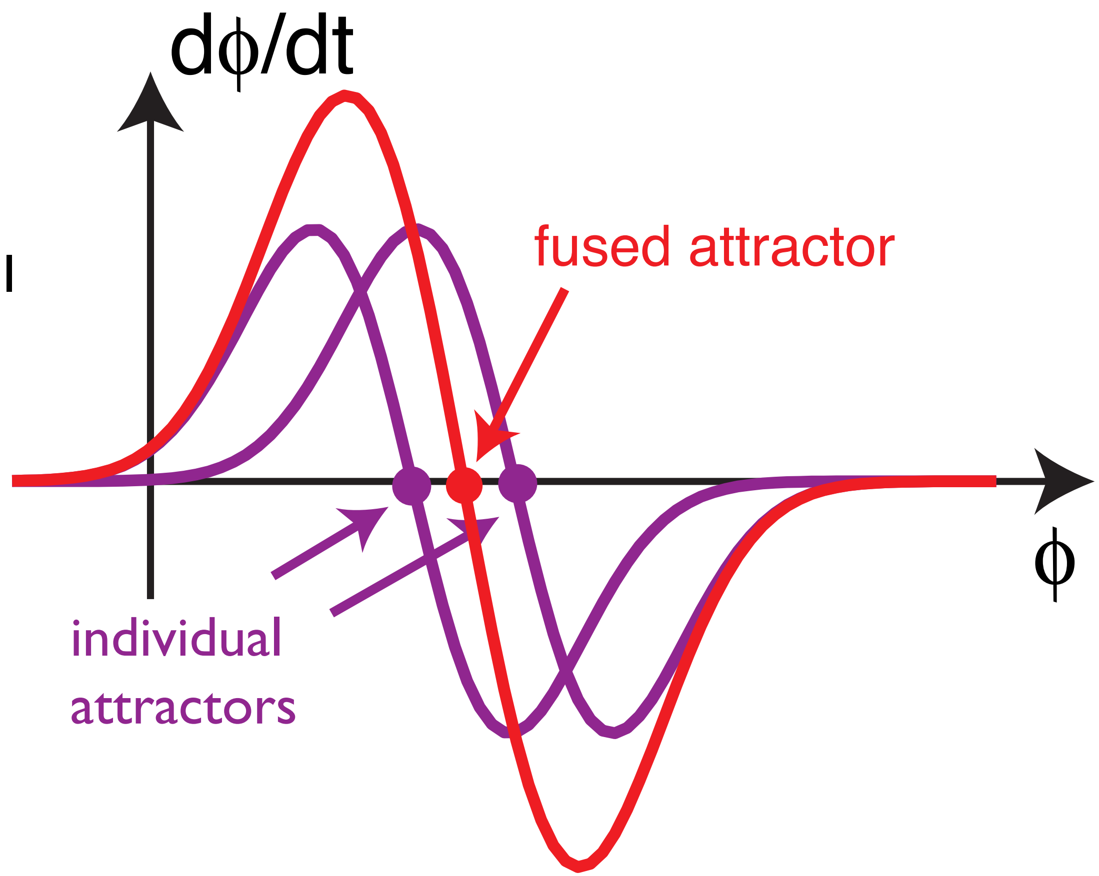
- each constribution is a “force-let” with
  - specified value
  - strength
  - range



Behavioral dynamics

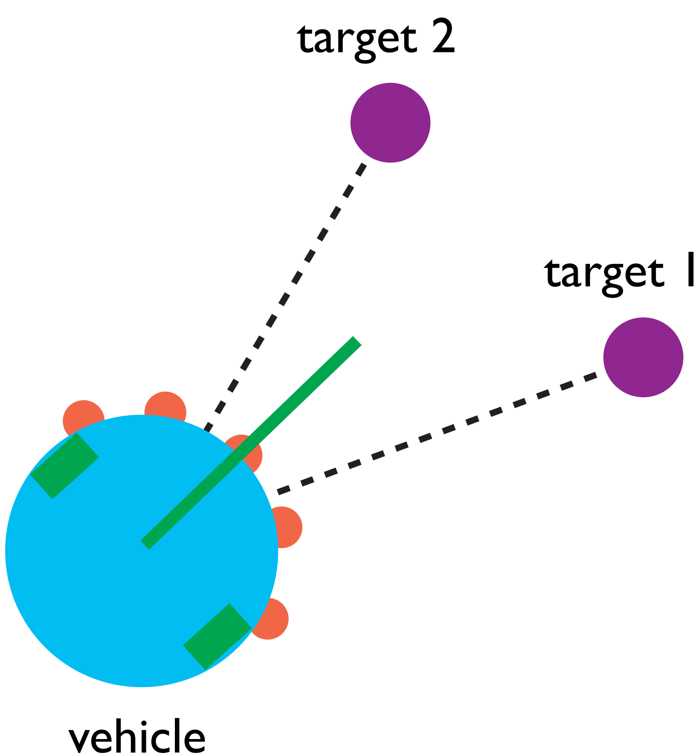
- multiple constraints: superpose “force-lets”
- fusion

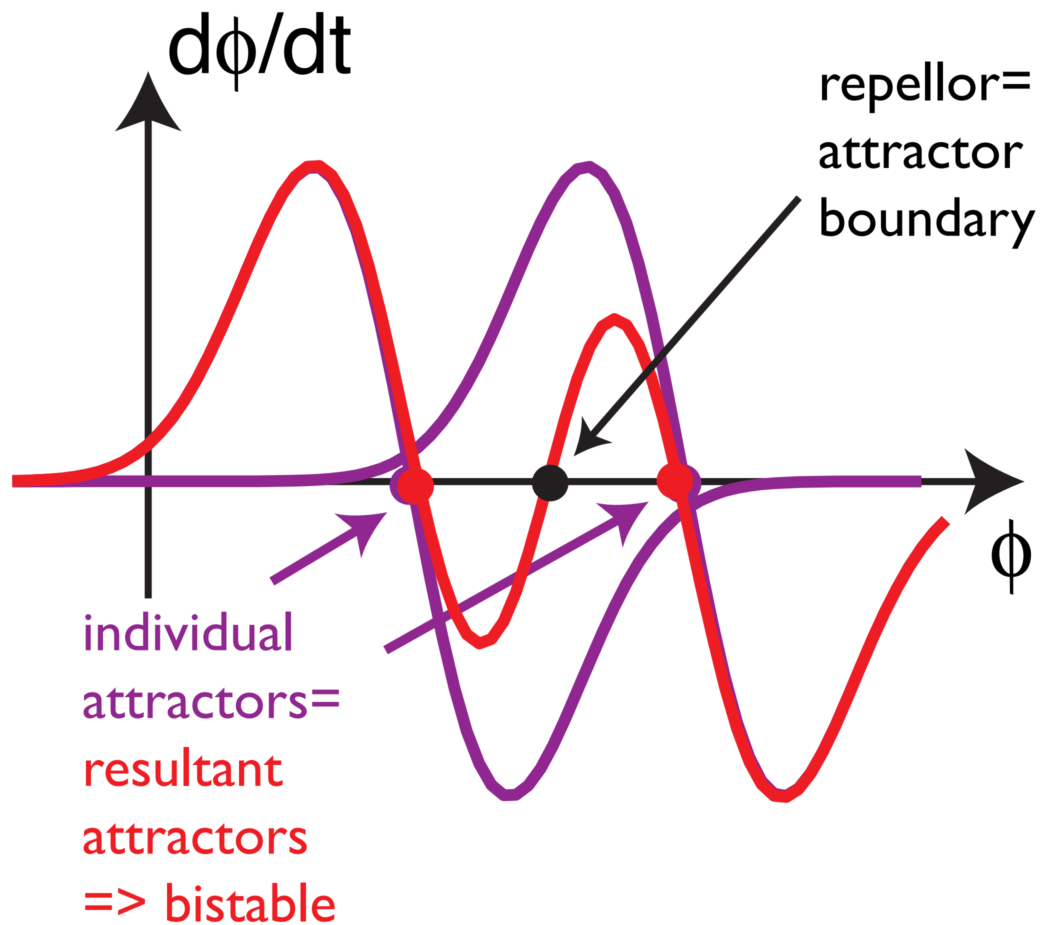




Behavioral dynamics

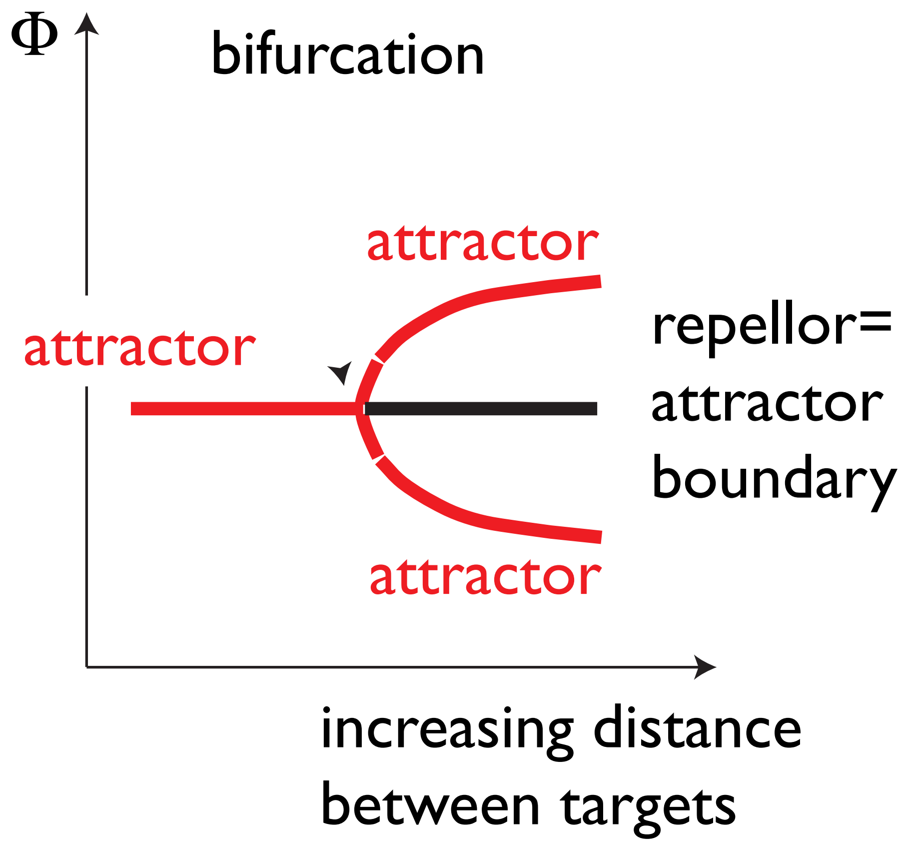
- decision making





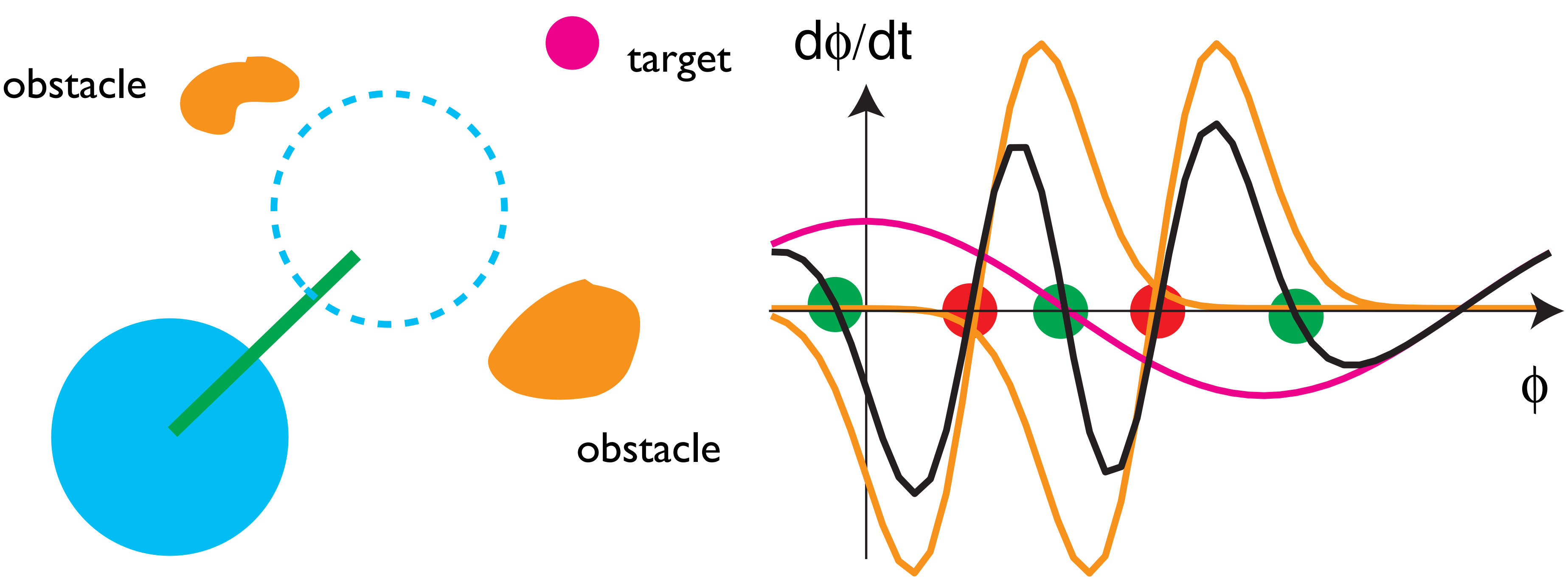
Behavioral dynamics

- Bifurcations switch between fusion and decision making



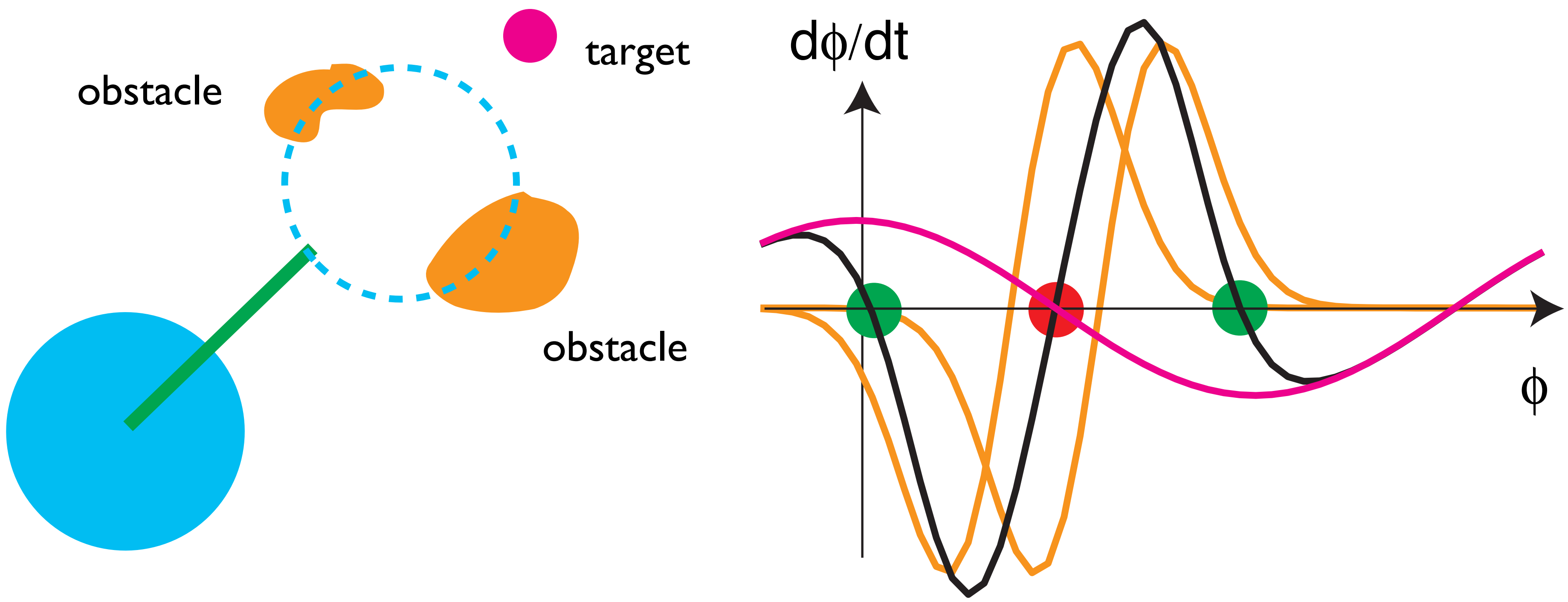
Behavioral dynamics

- an example closer to “real life”: bifurcations in obstacle avoidance and target acquisition
- constraints not in conflict



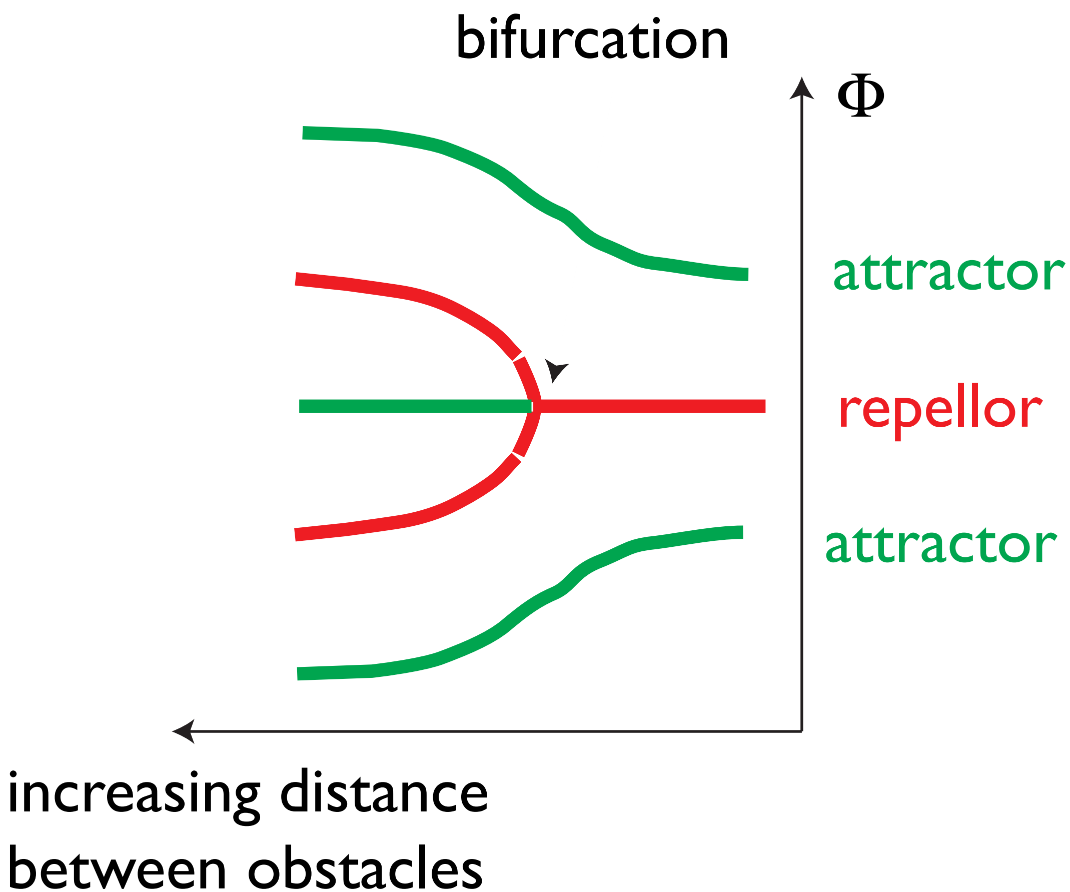
Behavioral dynamics

- constraints in conflict



Behavioral dynamics

- transition from "constraints not in conflict" to "constraints in conflict" is a bifurcation

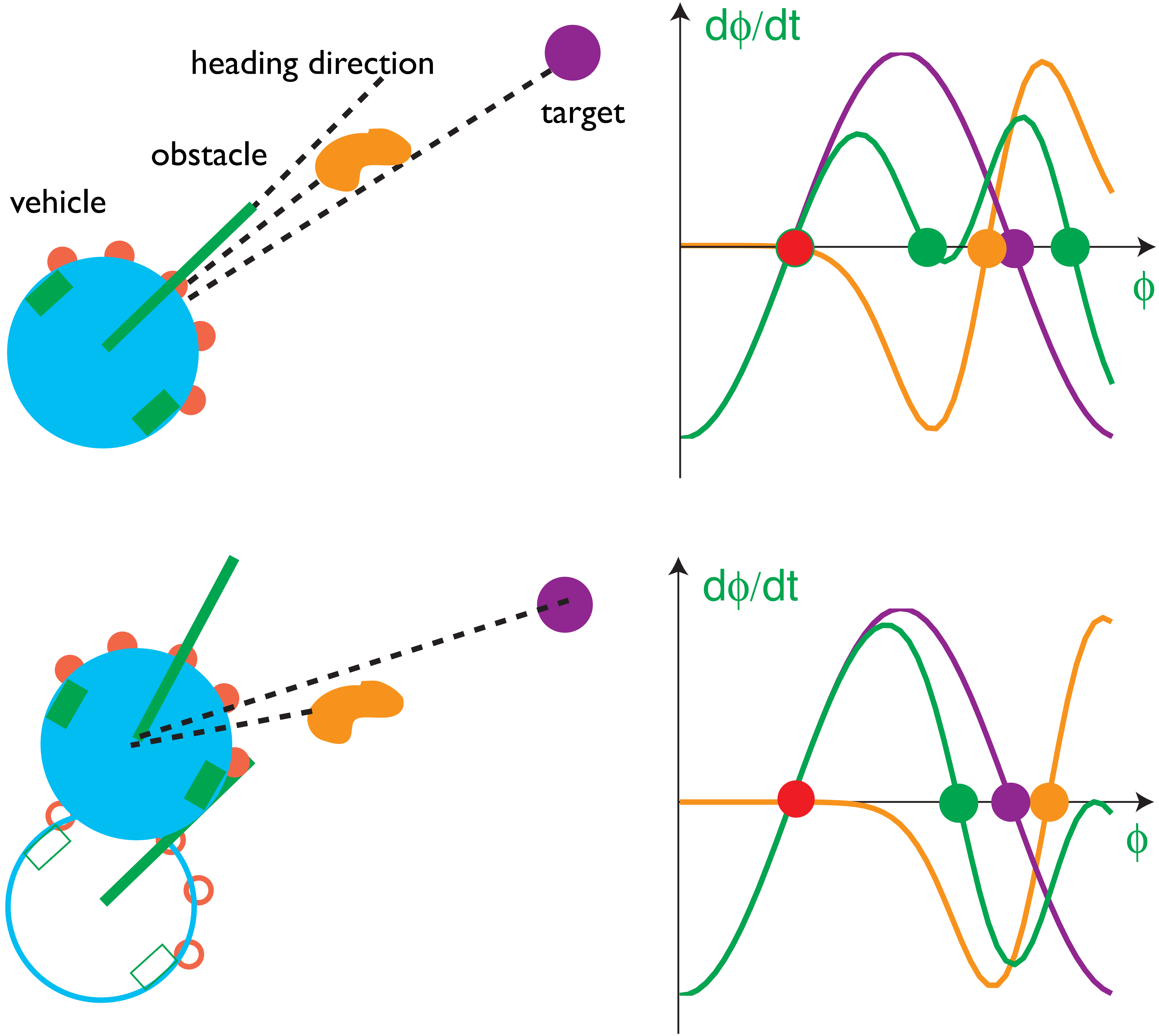


Behavioral dynamics

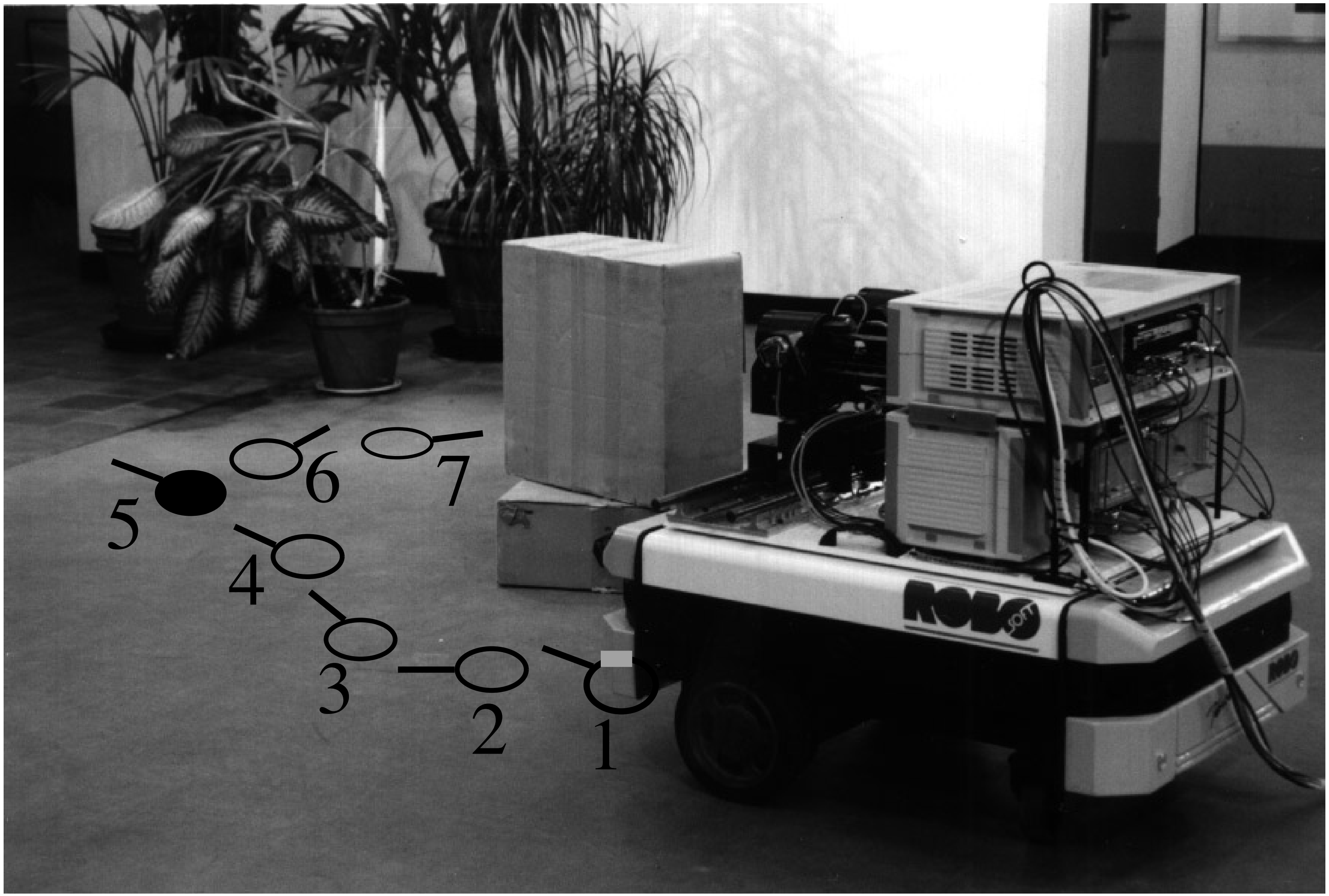
- Such design of decision making is only possible because system "sits" in attractor.
- This reduces the difficult design of the full flow (ensemble of all transient solutions) of non-linear dynamical systems to the easier design of attractors (bifurcation theory).

Behavioral dynamics

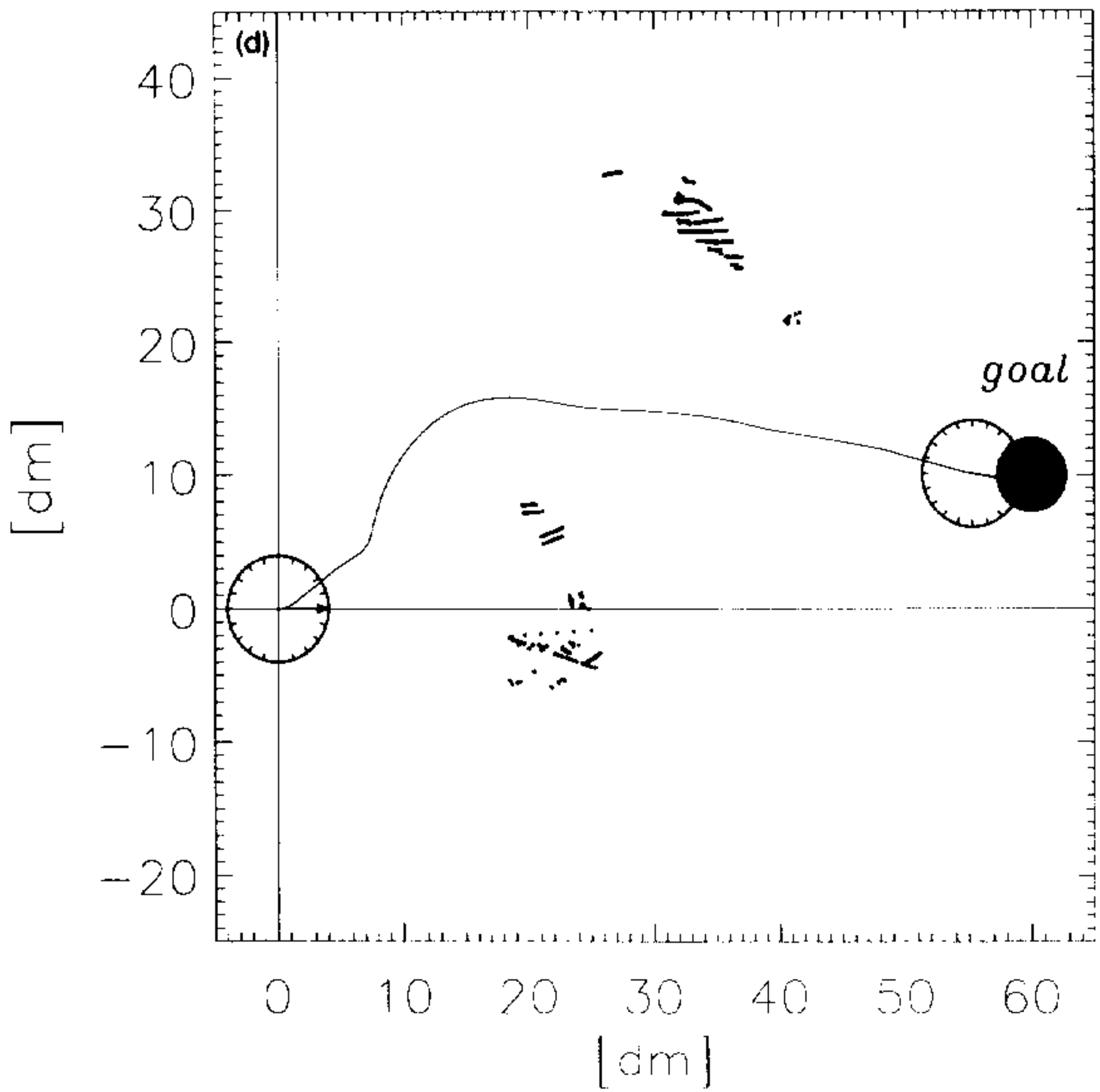
- But how may complex behavior be generated while “sitting” in an attractor?
- Answer: force-lets depend on sensory information and sensory information changes as the behavior unfolds



heading direction
target
obstacle
vehicle
dϕ/dt
ϕ
dϕ/dt
ϕ



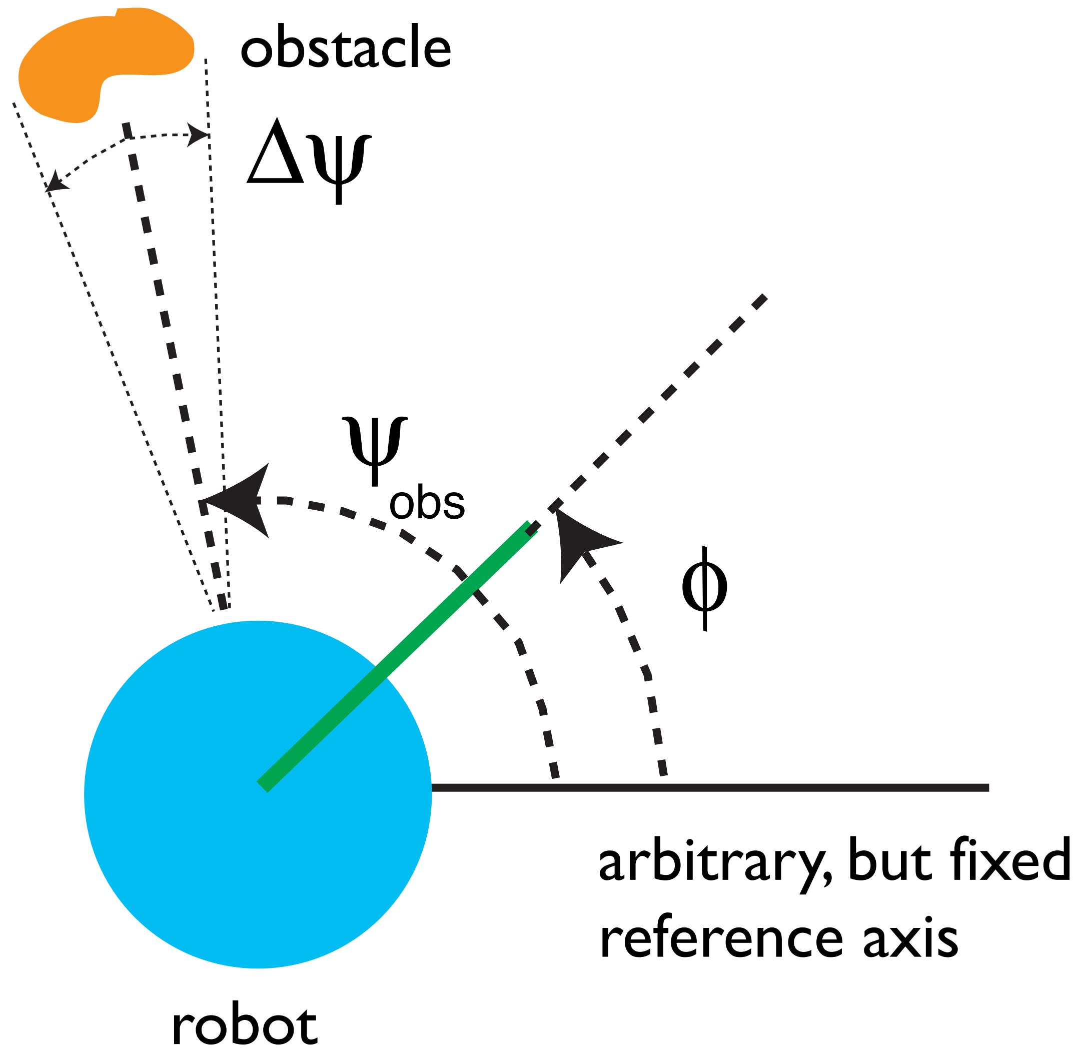
[Schöner, Dose, 1992]



[Schöner, Dose, Engels, 1995]

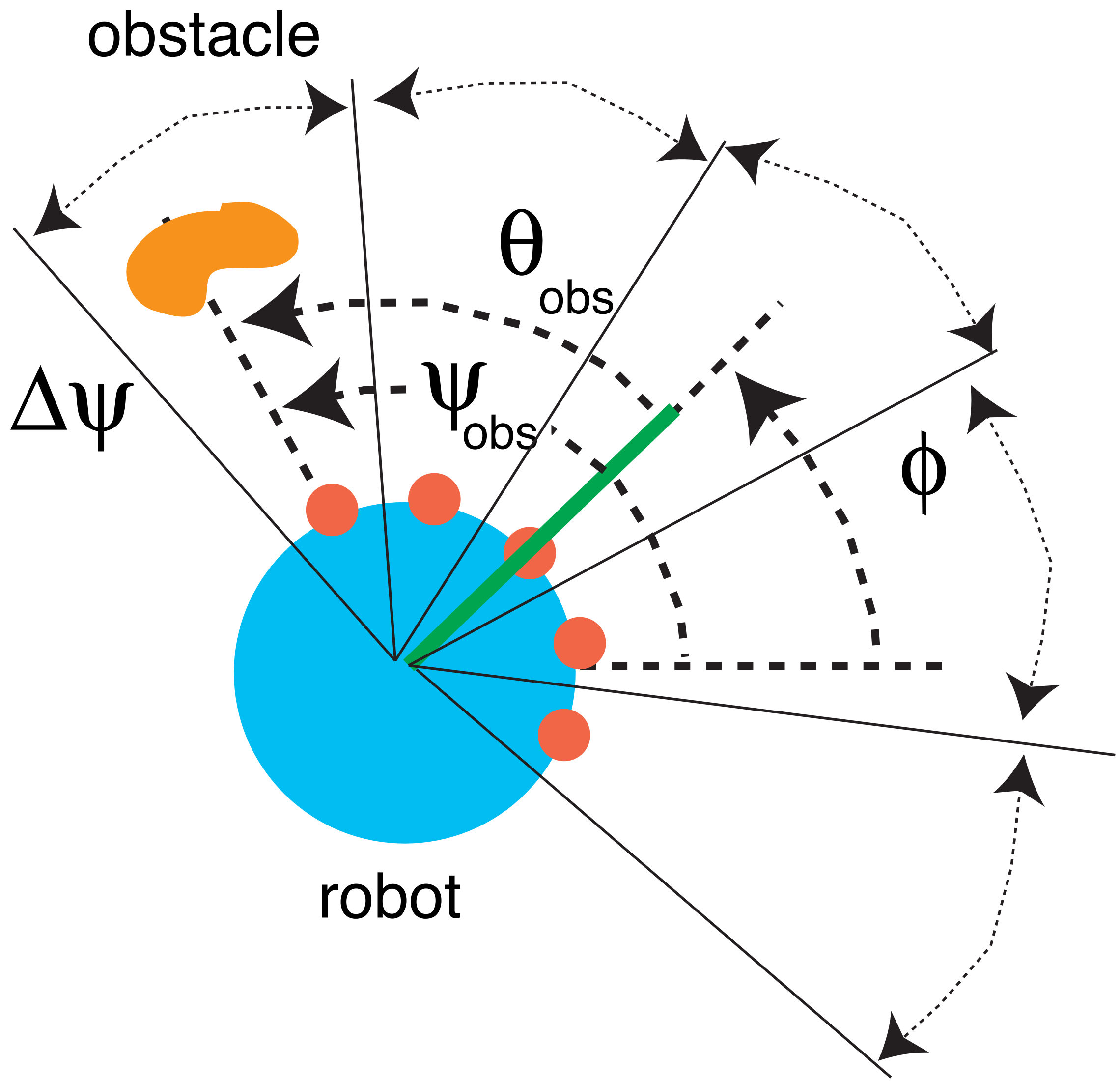
So far: "symbolic" approach

- high-level implementation: knowledge about objects in the world ("obstacles", "targets", etc)



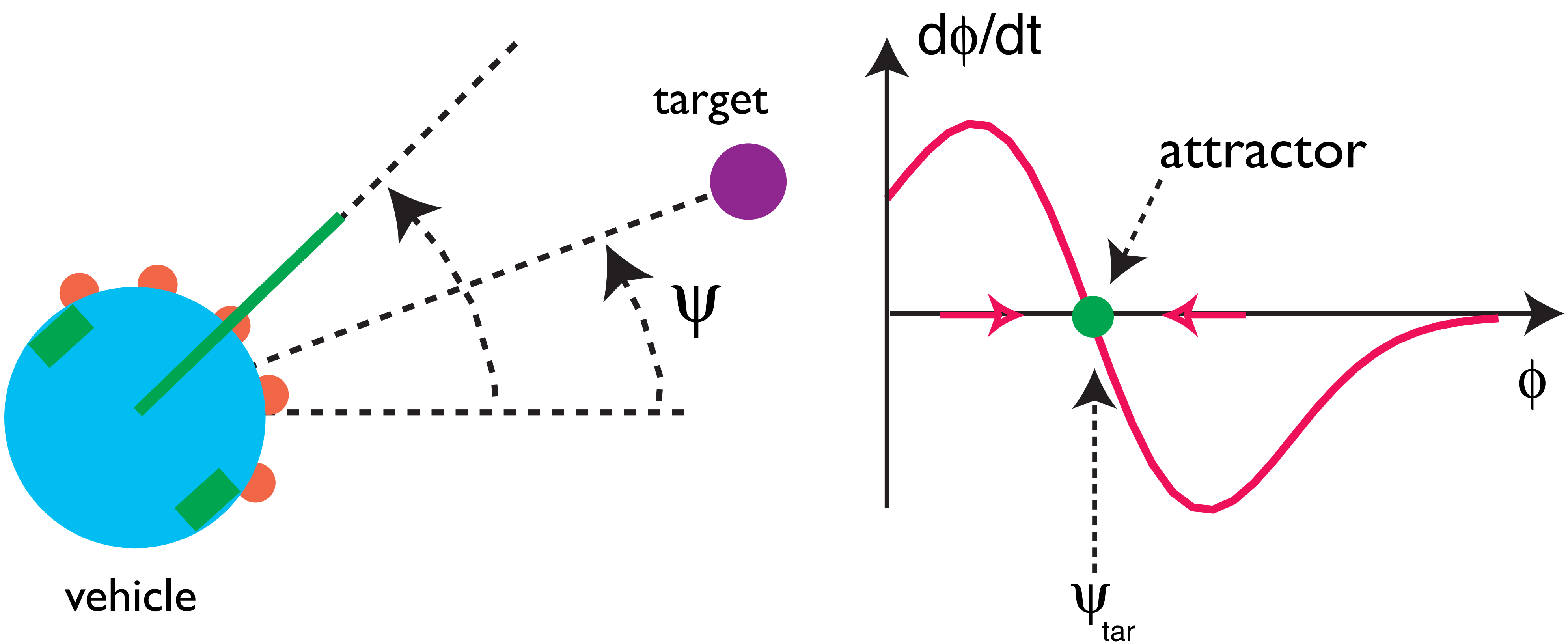
Now: "sub-symbolic" approach

- low-level implementation: use sensory information directly, not via objects



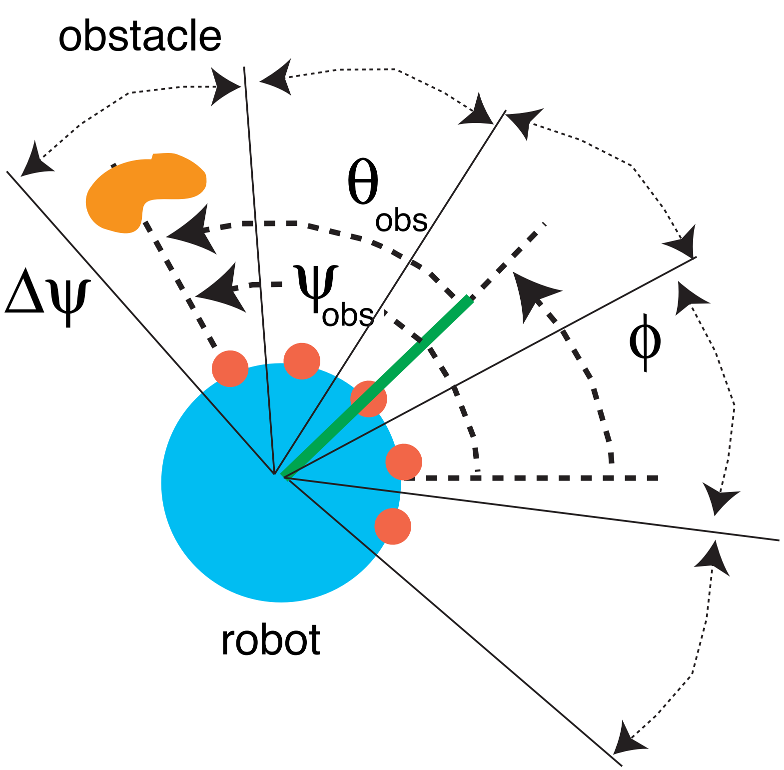
Target acquisition: still symbolic

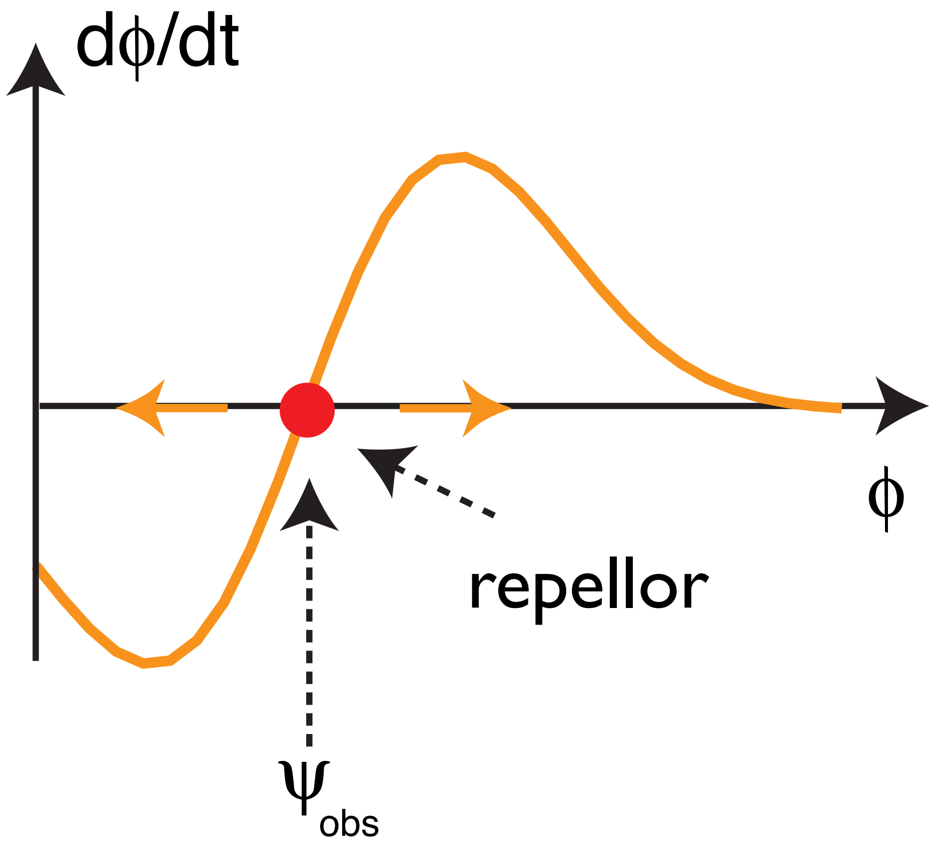
- targets are segmented… in the foreground
- => need neural fields to perform this segmentation from low-level sensory information: Dynamic Field Theory …



Obstacle avoidance: sub-symbolic

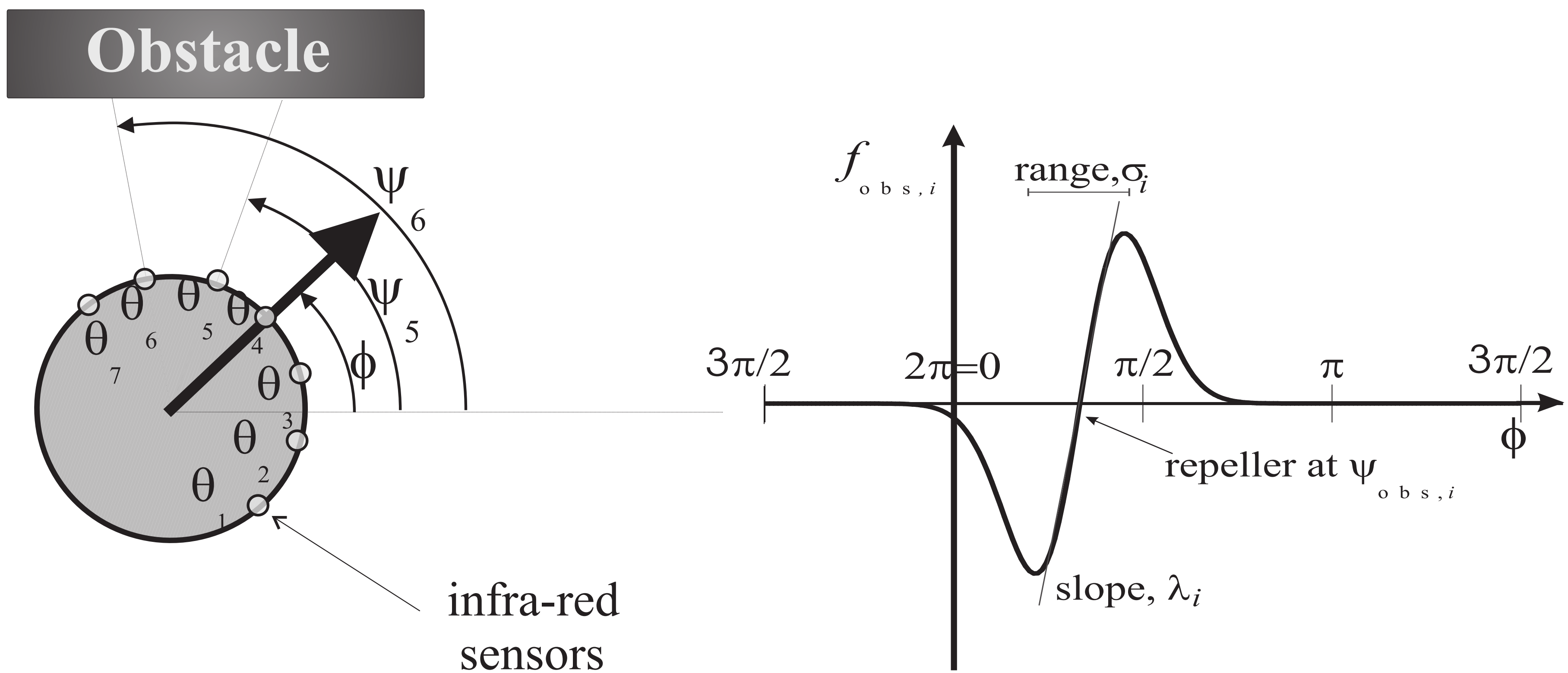
- obstacles need not be segmented
- do not care if obstacles are one or multiple: avoid them anyway…





Obstacle avoidance: sub-symbolic

- each sensor mounted at fixed angle θ
- that points in direction ψ=Φ+θ in the world
- erect a repellor at that angle

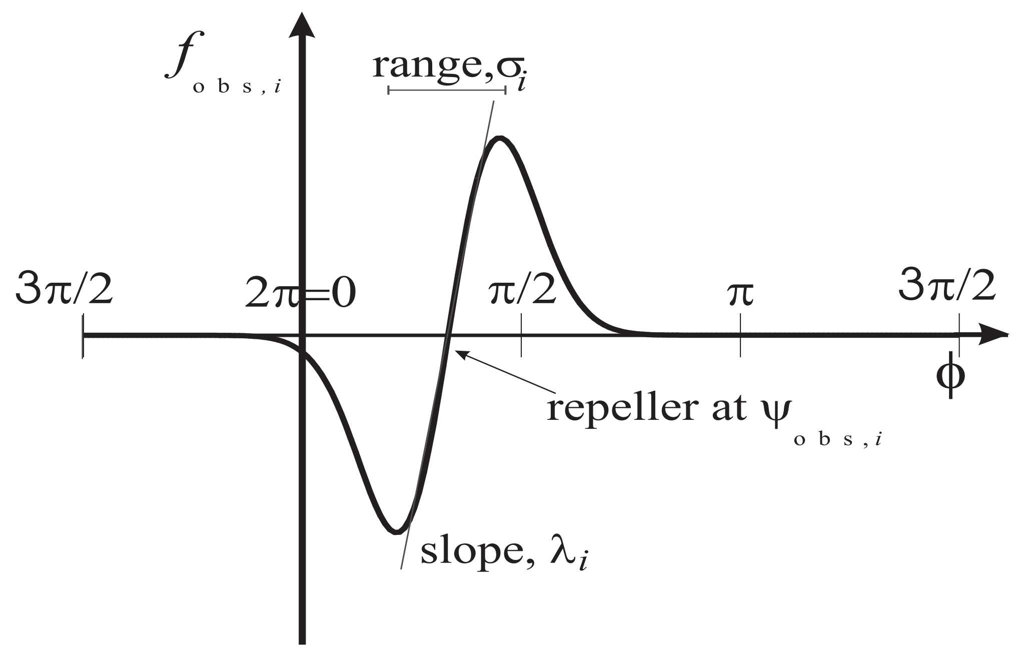


[from: Bicho, Jokeit, Schöner]

Obstacle avoidance: sub-symbolic

$$f_{\text{obs},i}(\phi) = \lambda_i(\phi - \psi_i)\exp\left[-\frac{(\phi-\psi_i)^2}{2\sigma_i^2}\right] \qquad i = 1, 2, \ldots, 7$$

- Note: only Φ-ψ=-θ shows up, which is constant!
- => force-let does not depend on Φ !



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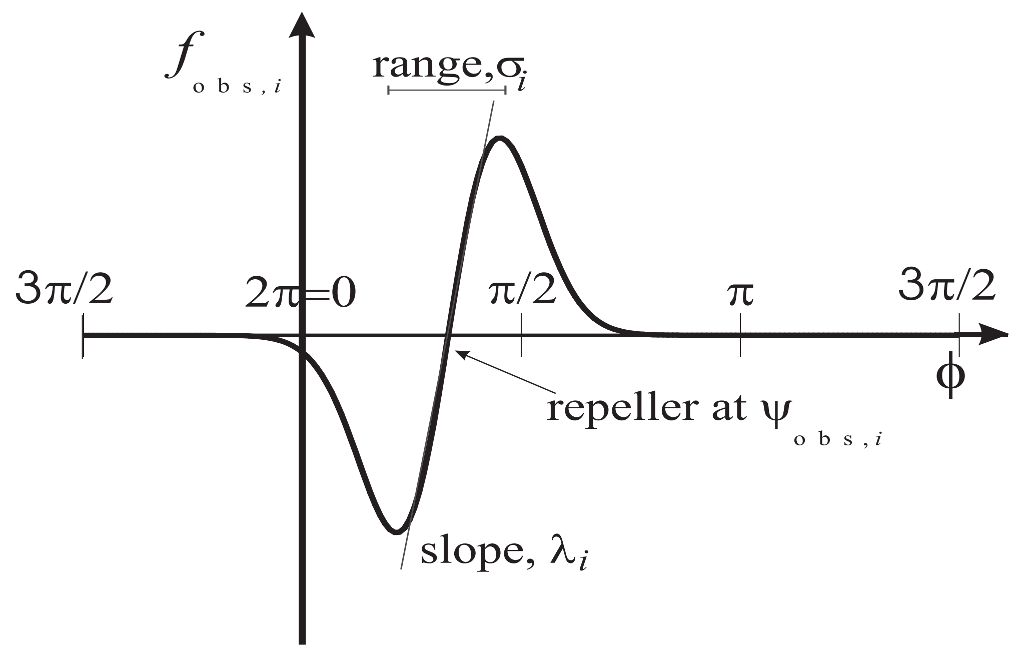
$$\lambda_i = \beta_1 \cdot \exp\left[-\frac{d_i}{\beta_2}\right]$$

- Repulsion strength decreases with distance, d_i
- => only close obstacles matter



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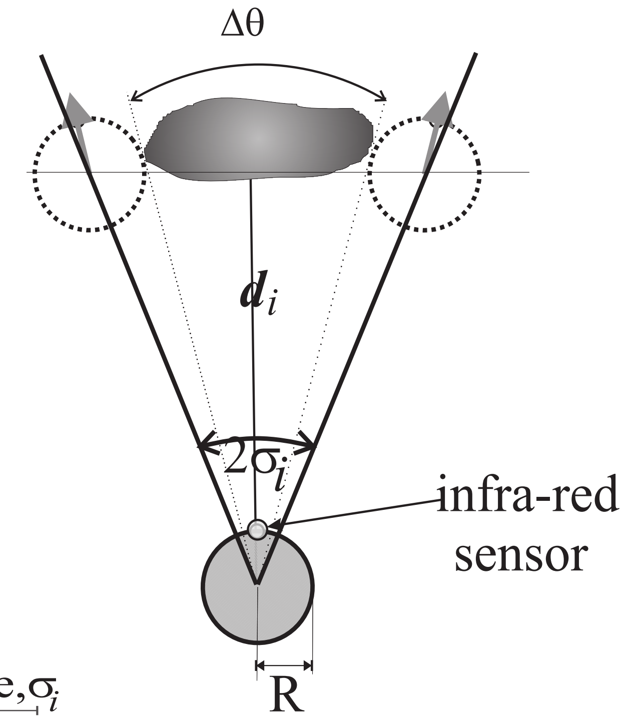
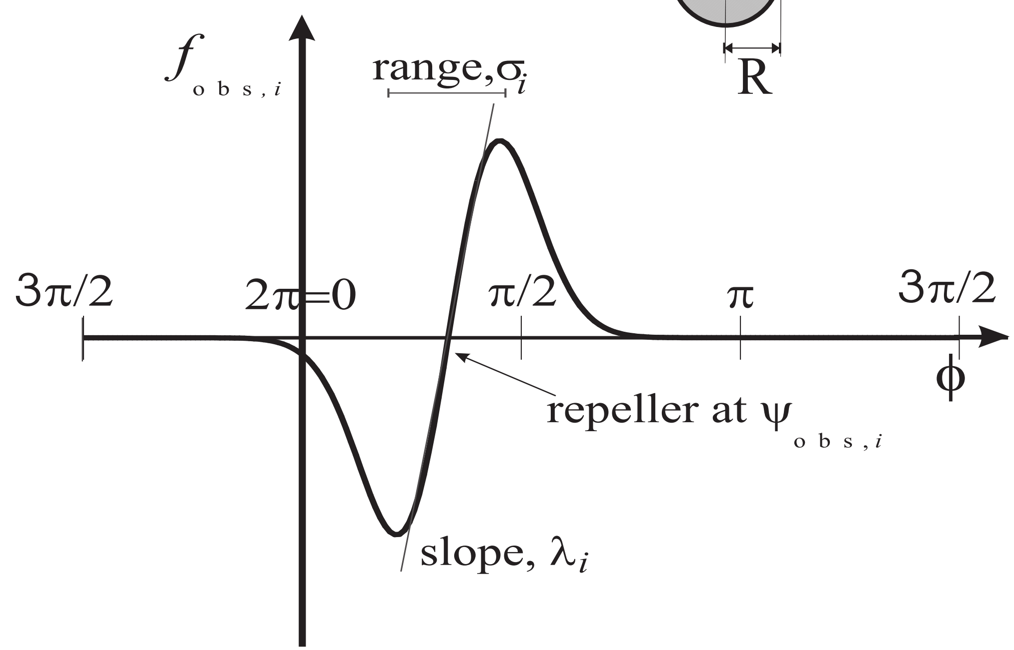
$$\sigma_i = \arctan\left[\tan\left(\frac{\Delta\theta}{2}\right) + \frac{R_{\text{robot}}}{R_{\text{robot}} + d_i}\right].$$



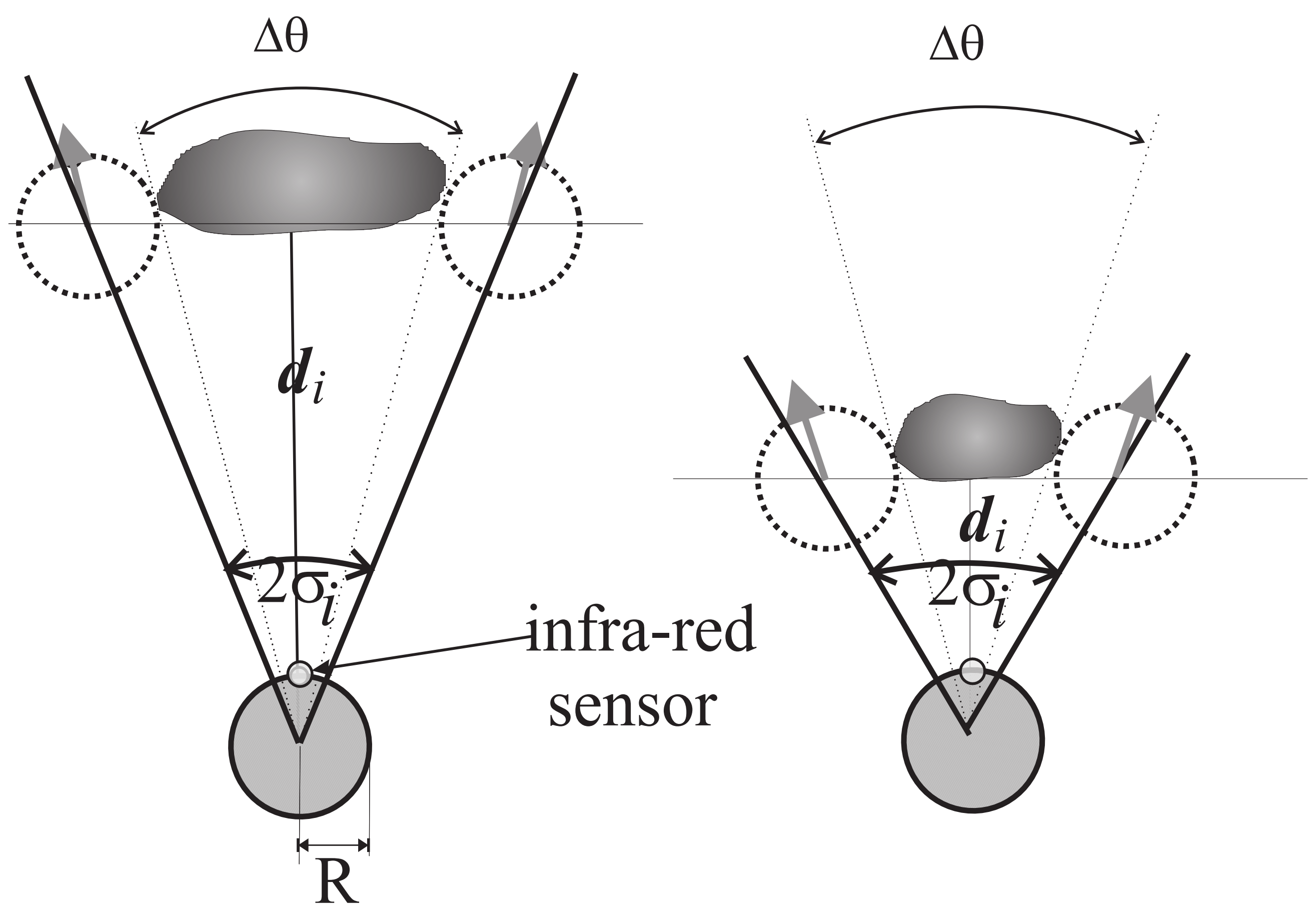
- angular range depends on sensor cone Δθ and size over distance



[from: Bicho, Jokeit, Schöner]

Obstacle avoidance: sub-symbolic

- => as a result, range becomes wider as obstacle moves closer

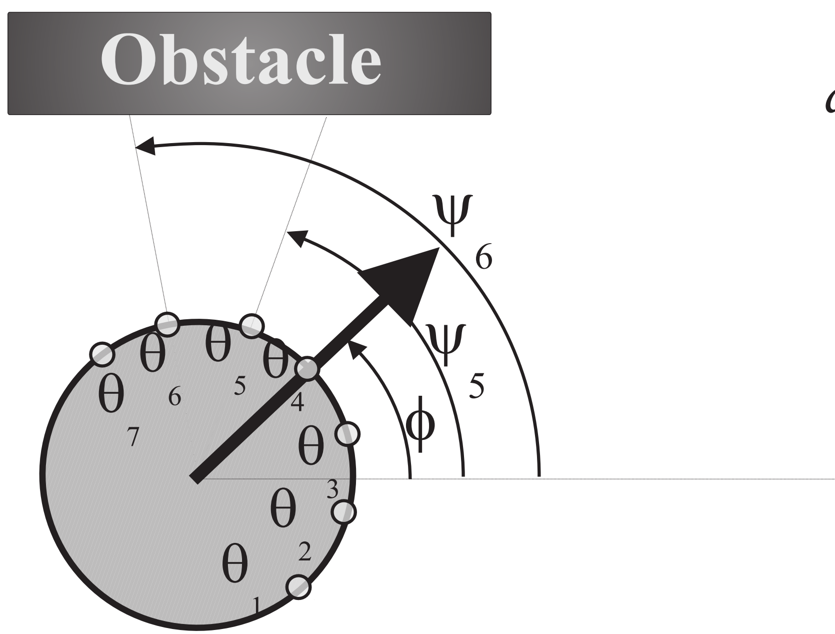


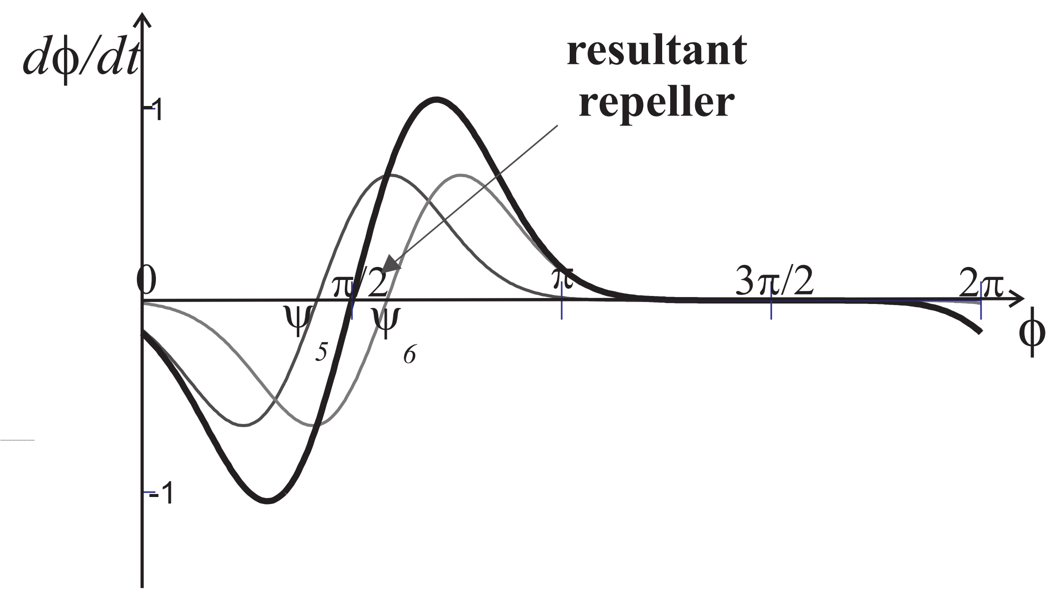
[from: Bicho, Jokeit, Schöner]

Obstacle avoidance: sub-symbolic

- summing contributions from all sensors

$$\frac{d\phi}{dt} = f_{\text{obs}}(\phi) = \sum_{i=1}^{7} f_{\text{obs},i}(\phi)$$

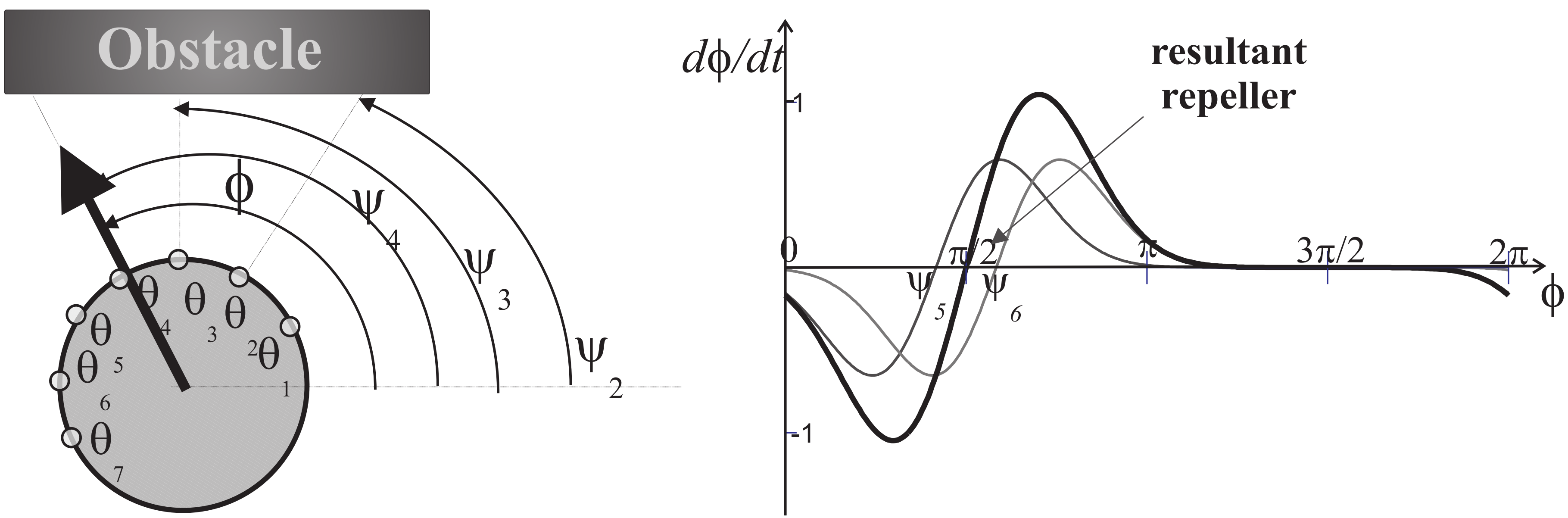




[from: Bicho, Jokeit, Schöner]

Obstacle avoidance: sub-symbolic

- but why does it work?
- shouldn't there be a problem when heading changes (e.g. from the dynamics itself)?



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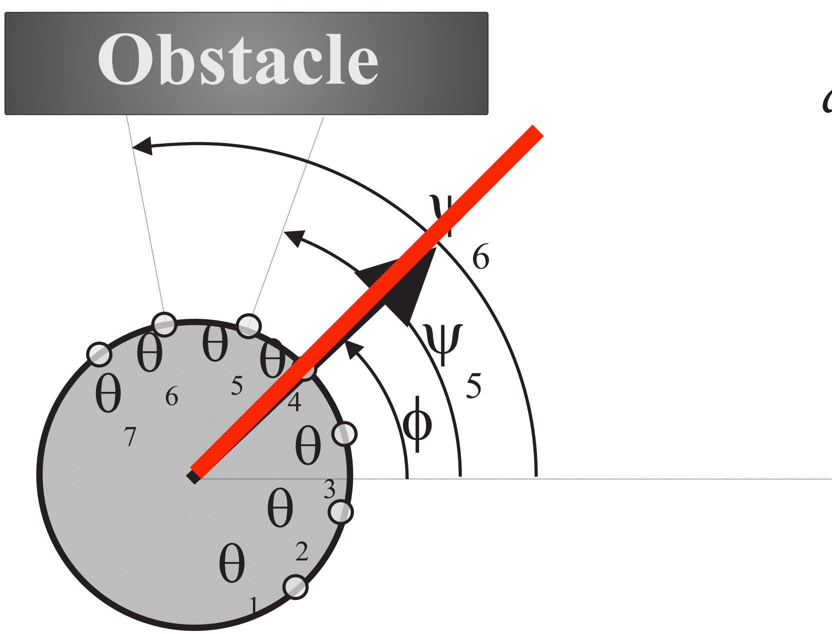

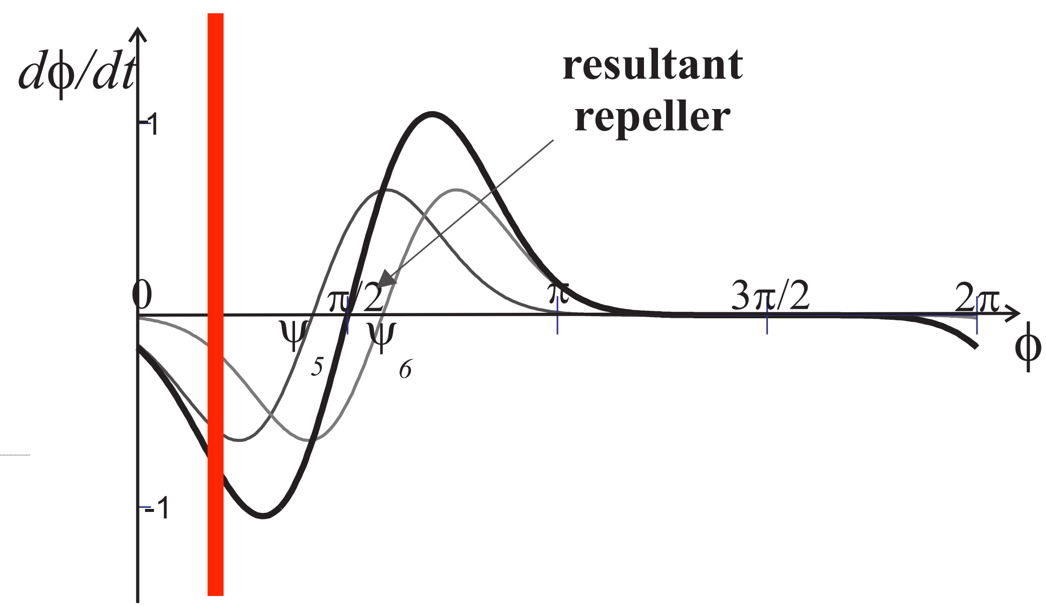

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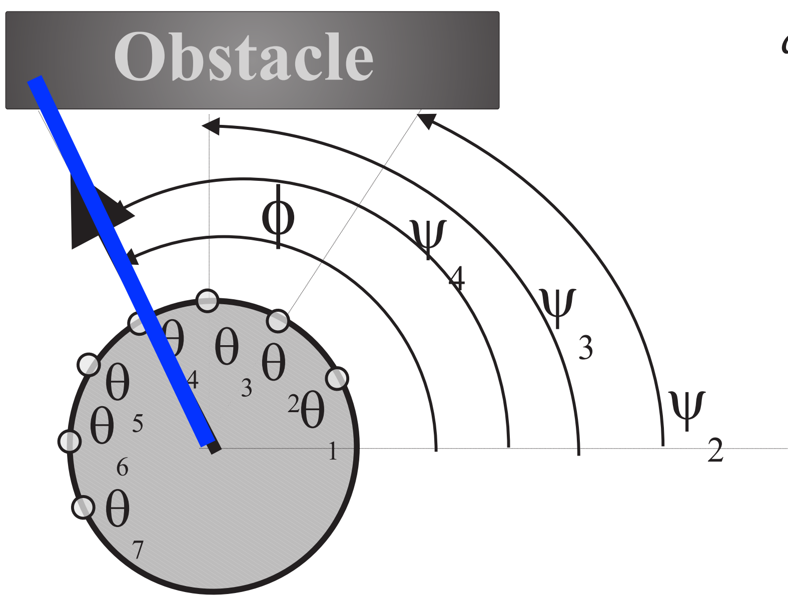

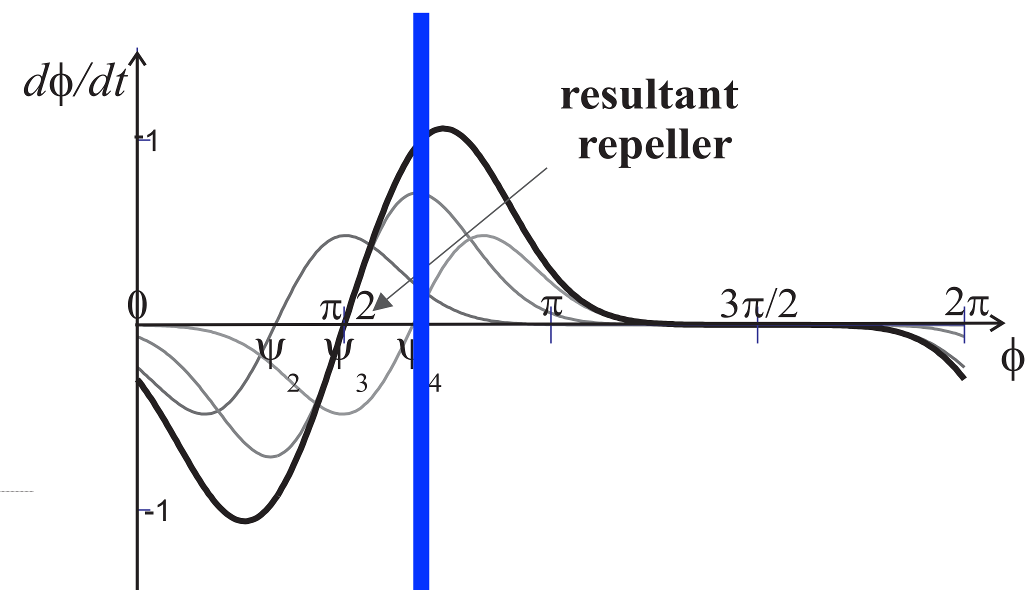

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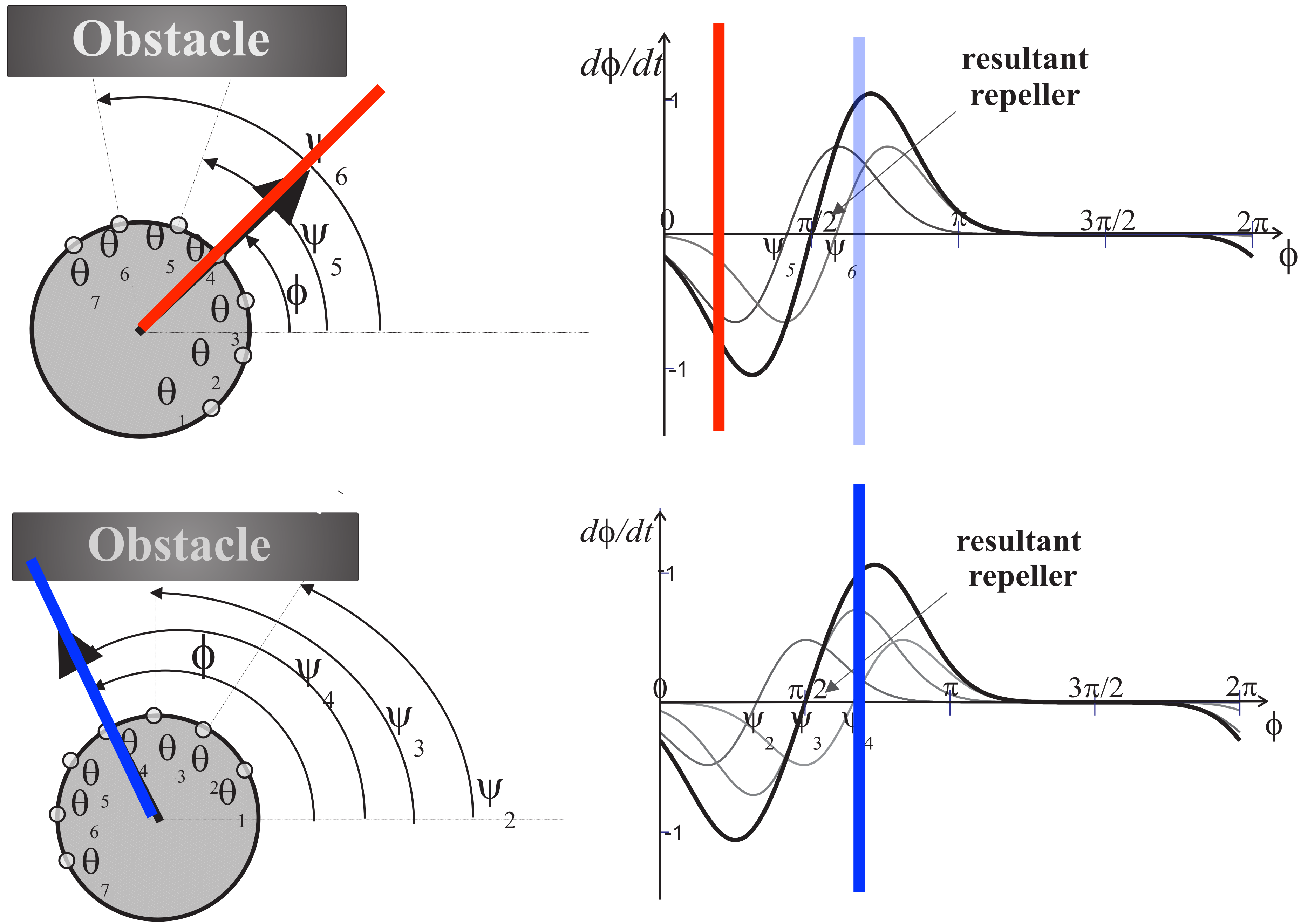


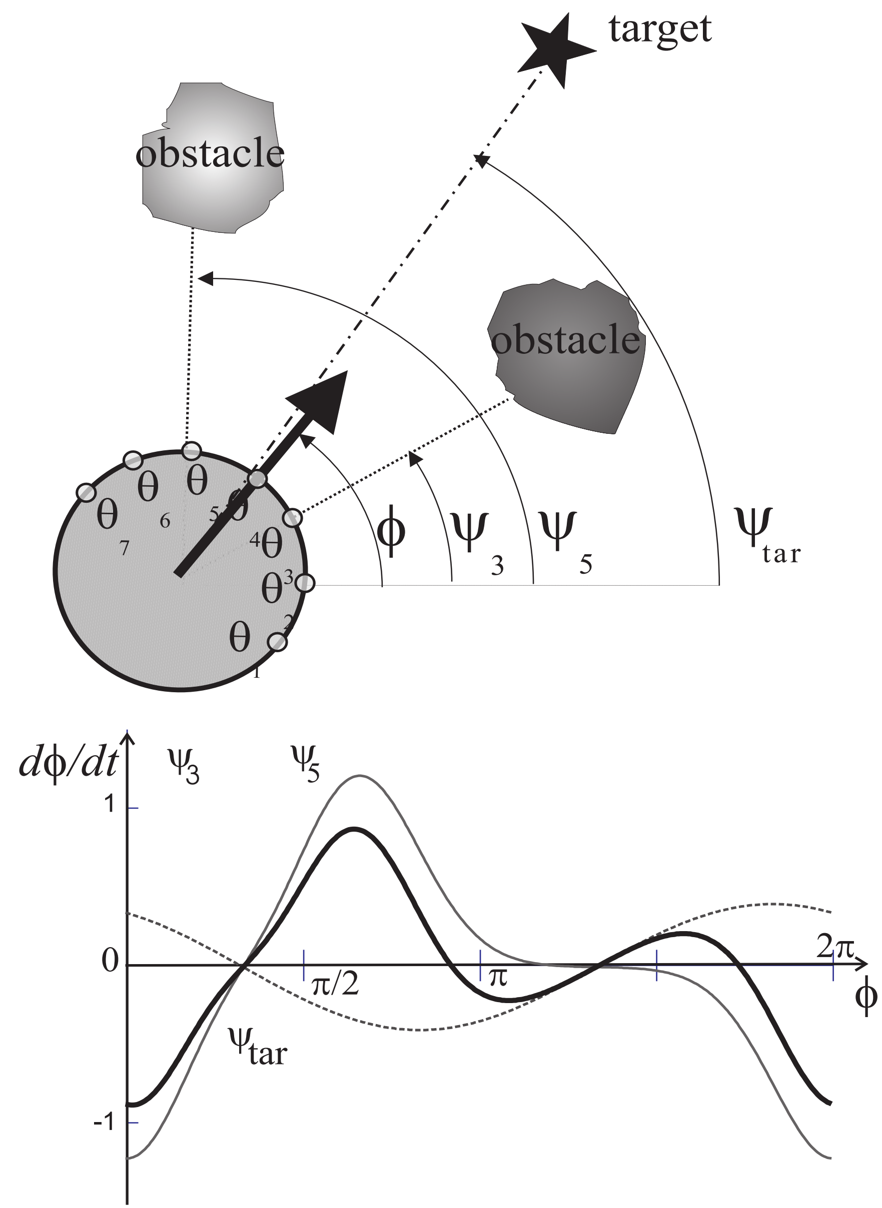
=> dynamics invariant!

[from: Bicho, Jokeit, Schöner]

Behavioral Dynamics

- integrating the two behaviors

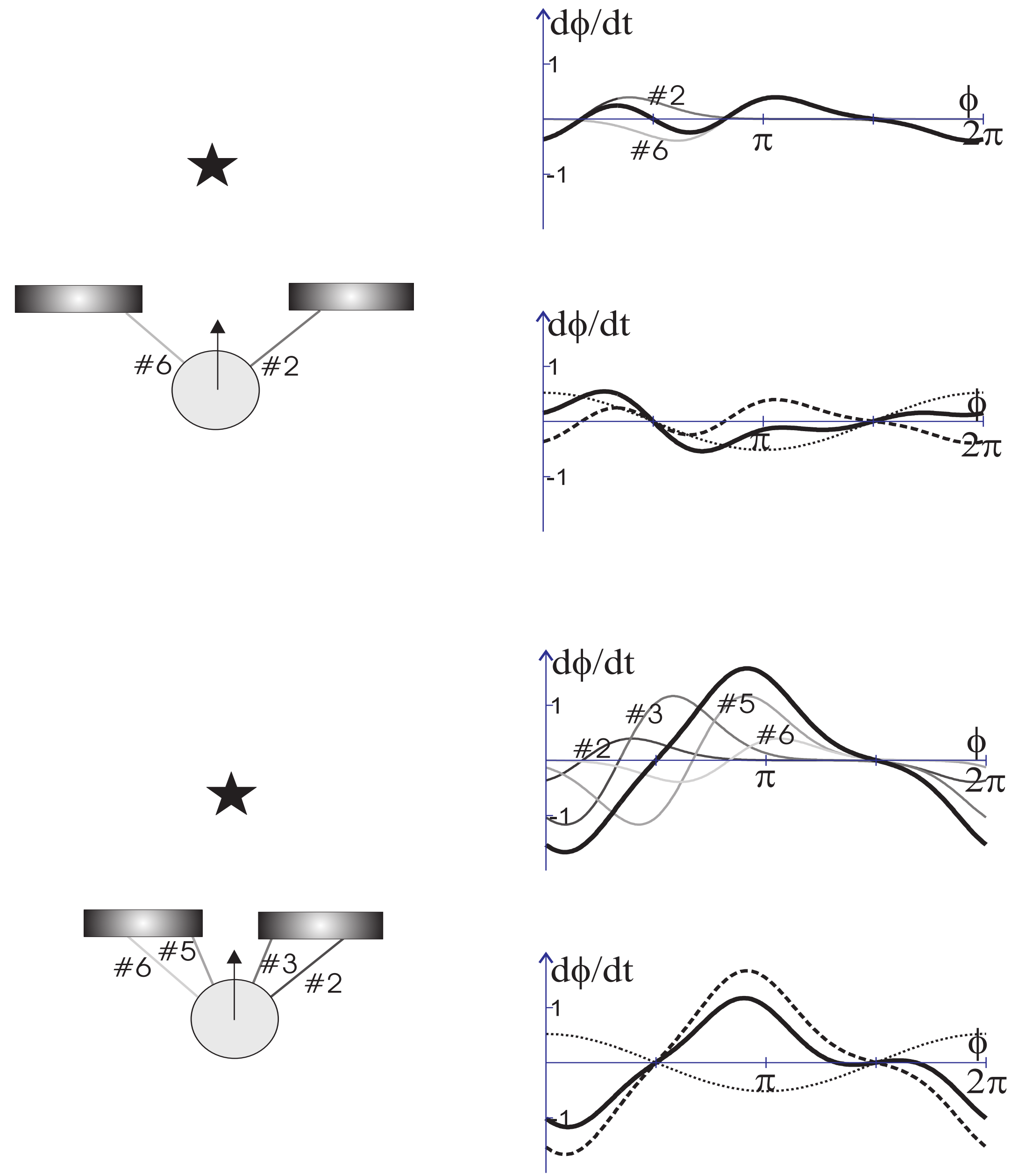
$$\frac{d\phi}{dt} = f_{\text{obs}}(\phi) + f_{\text{tar}}(\phi)$$



[from: Bicho, Jokeit, Schöner]

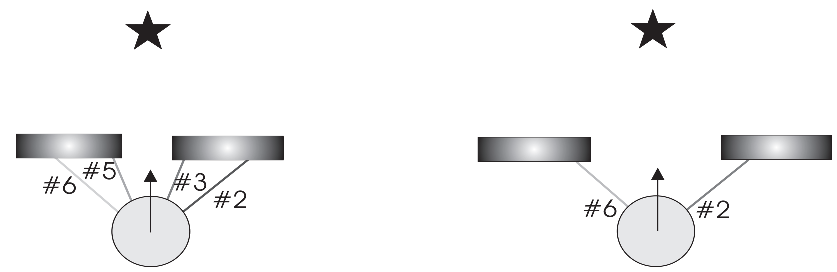
Bifurcations

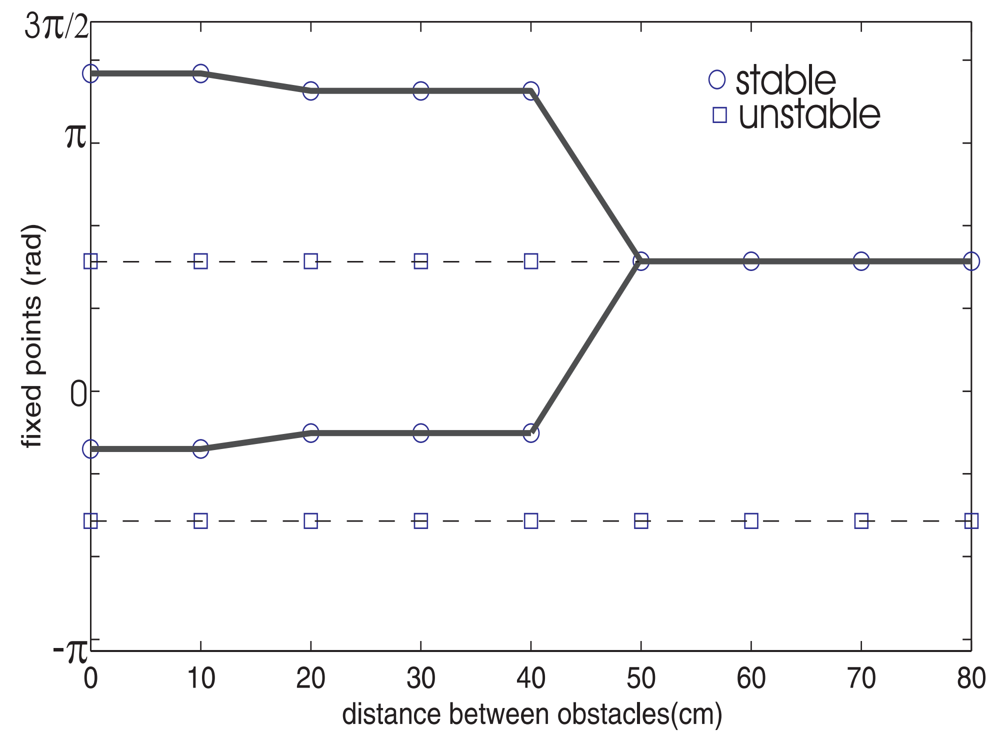
- bifurcation as a function of the size of the opening between obstacles



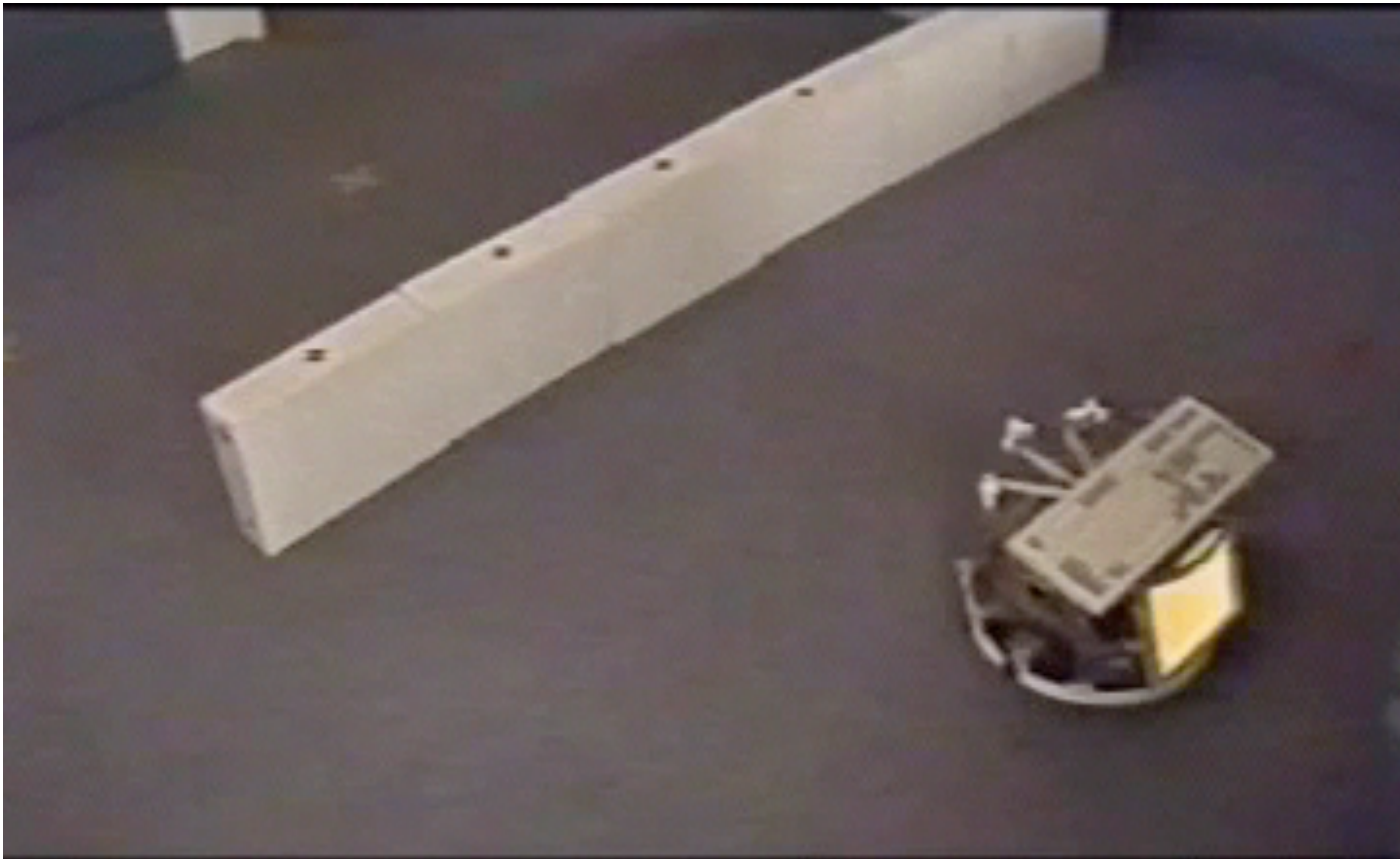
Bifurcations

- bifurcation as a function of the size of the opening between obstacles
- =>tune distance dependence of repulsion so that bifurcation occurs at the right opening



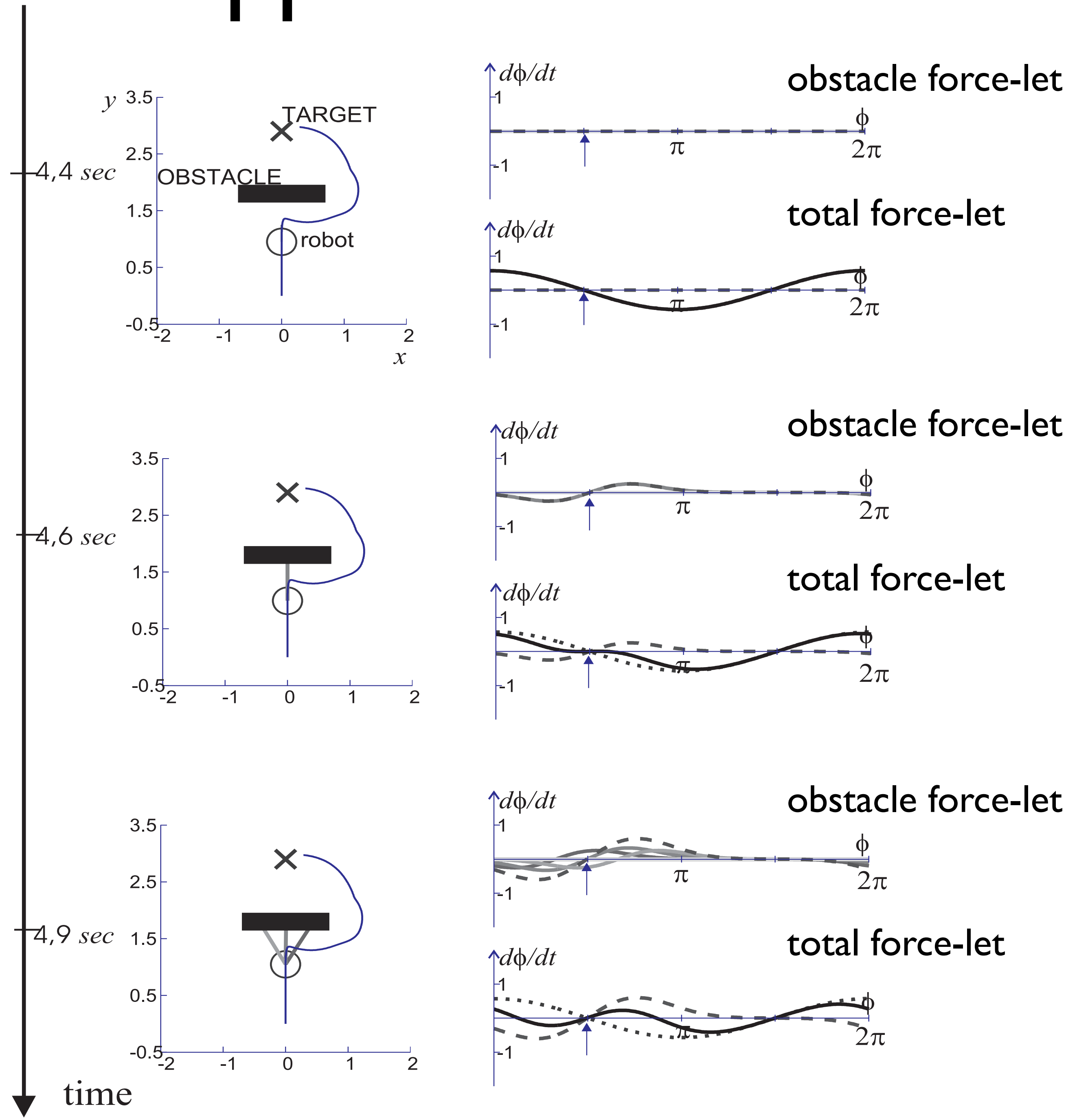


Bifurcations



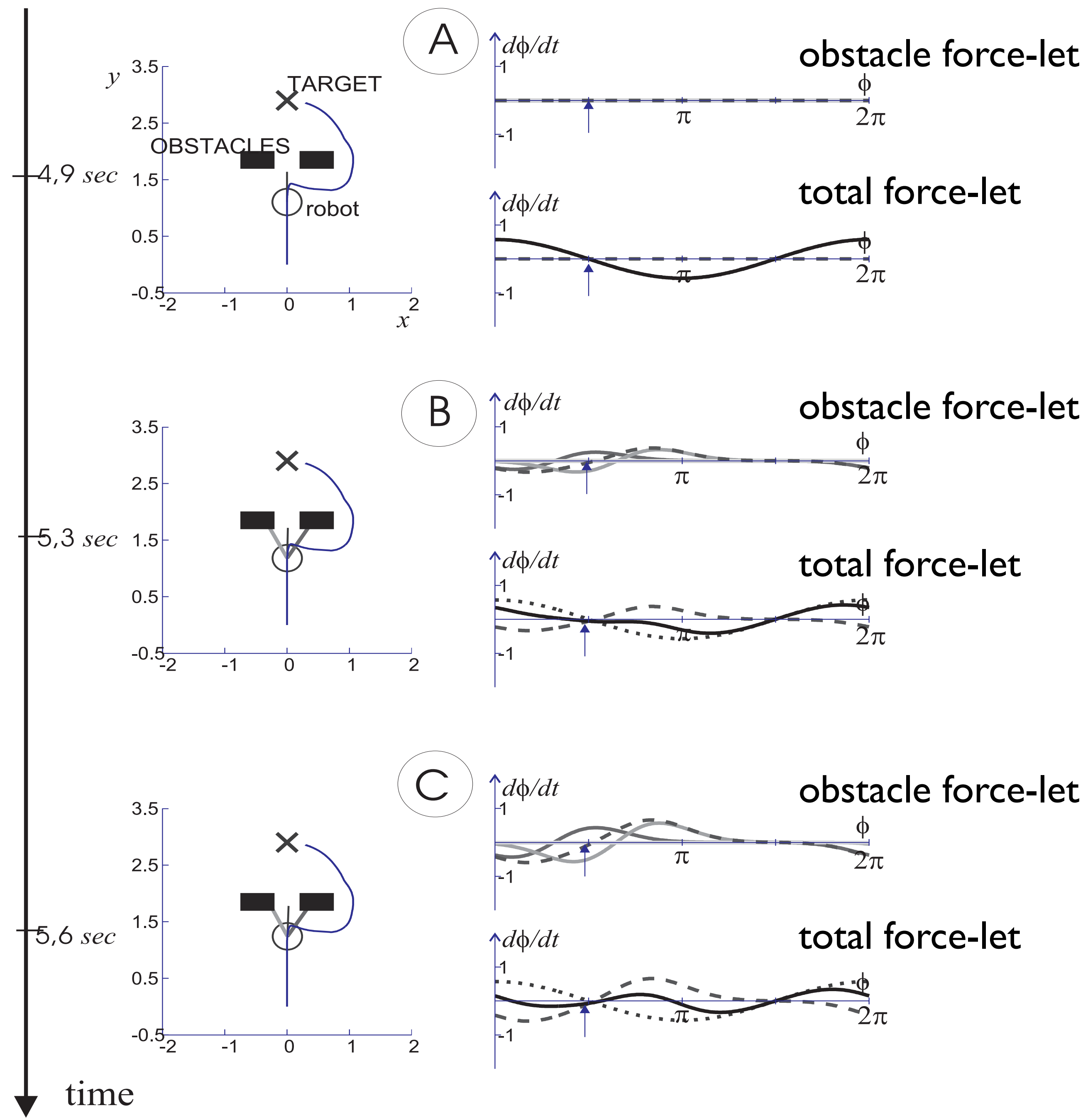
Bifurcation on approach to wall

- initially attractor dominates: weak repulsion
- bifurcation
- then obstacles dominate: strong repulsion and total repulsion



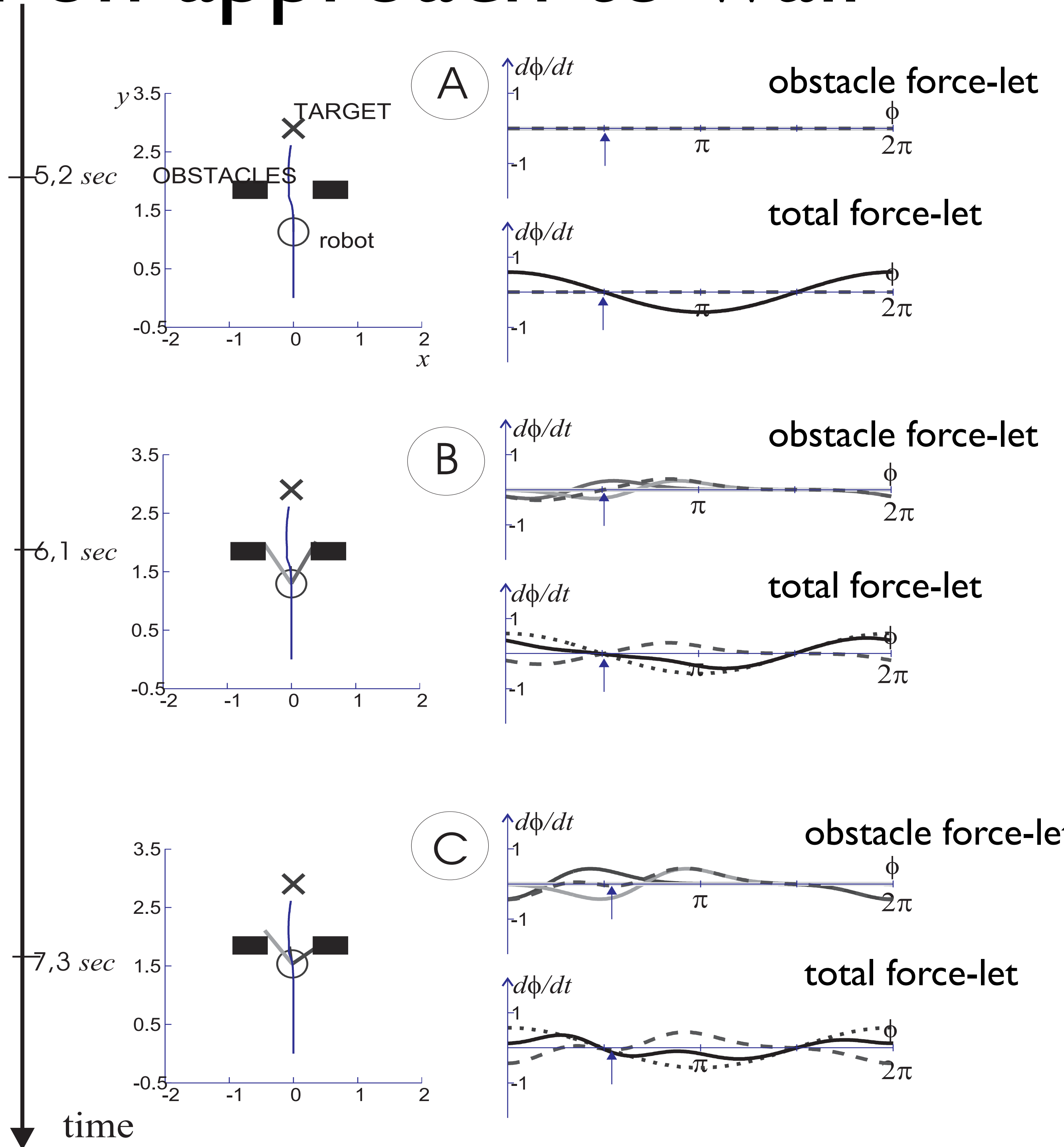
Bifurcation on approach to wall

- same with small opening



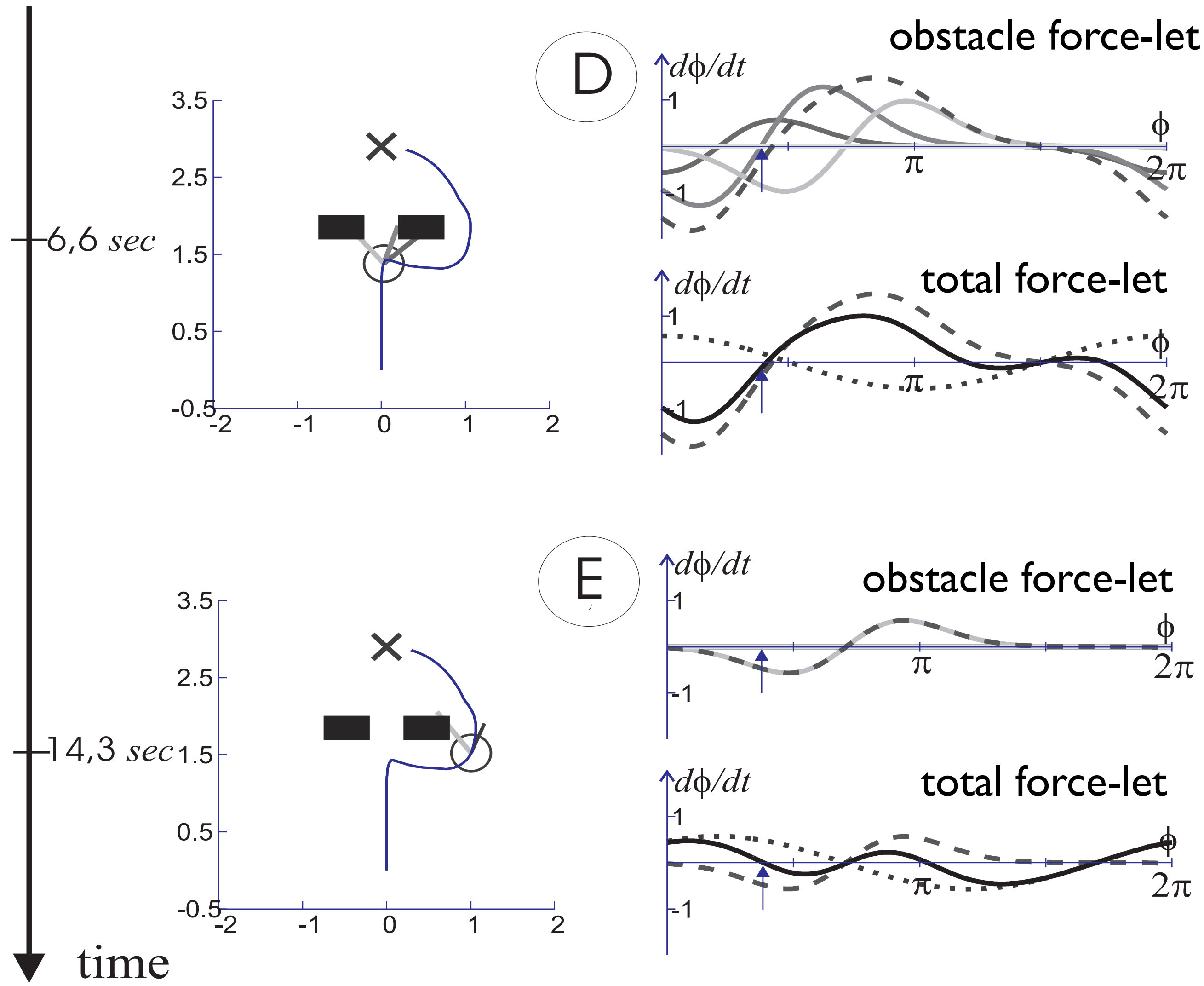
Bifurcation on approach to wall

- at larger opening: repulsion weak all the way through: attractor remains stable



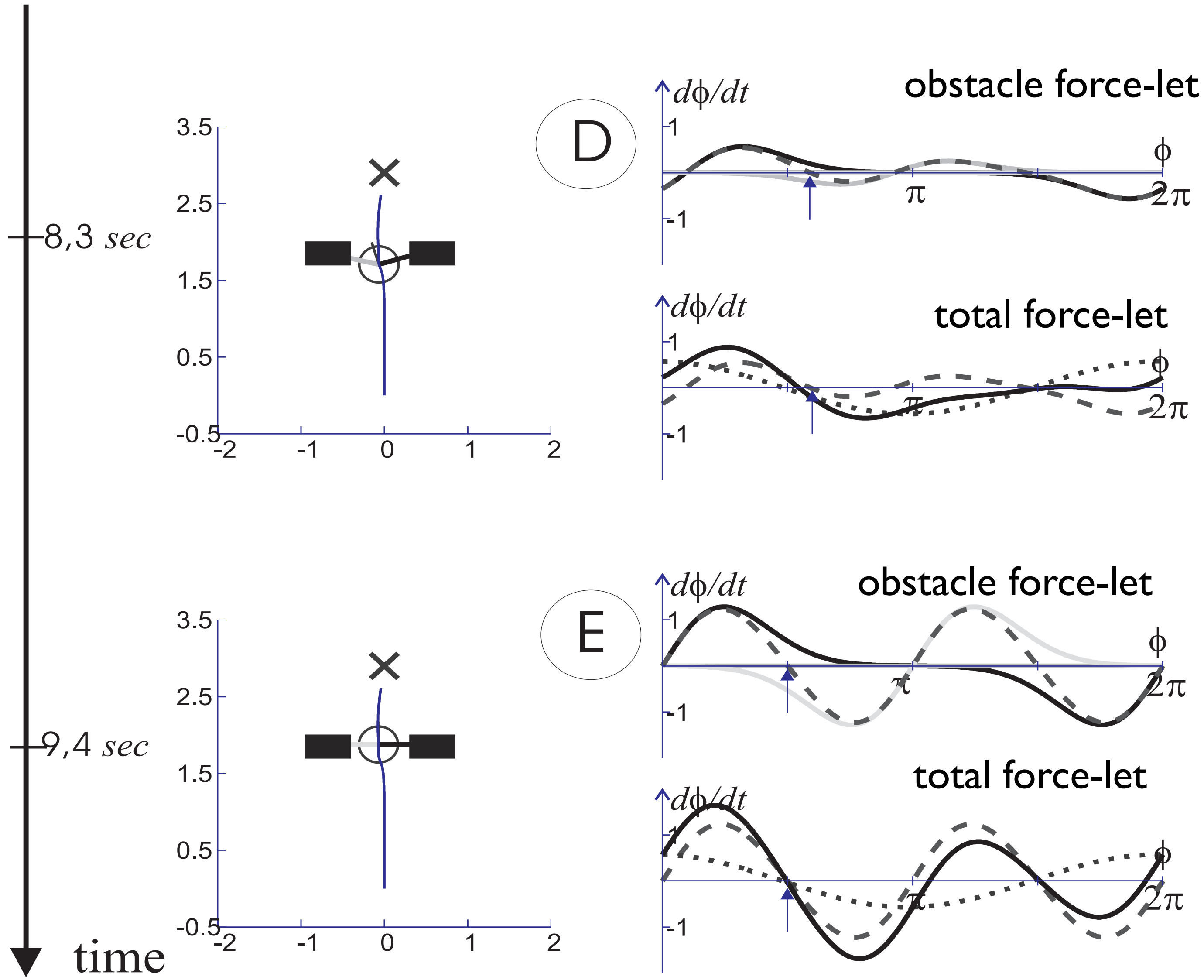
Tracking attractor

- as robot moves around obstacles, tracks the moving attractor

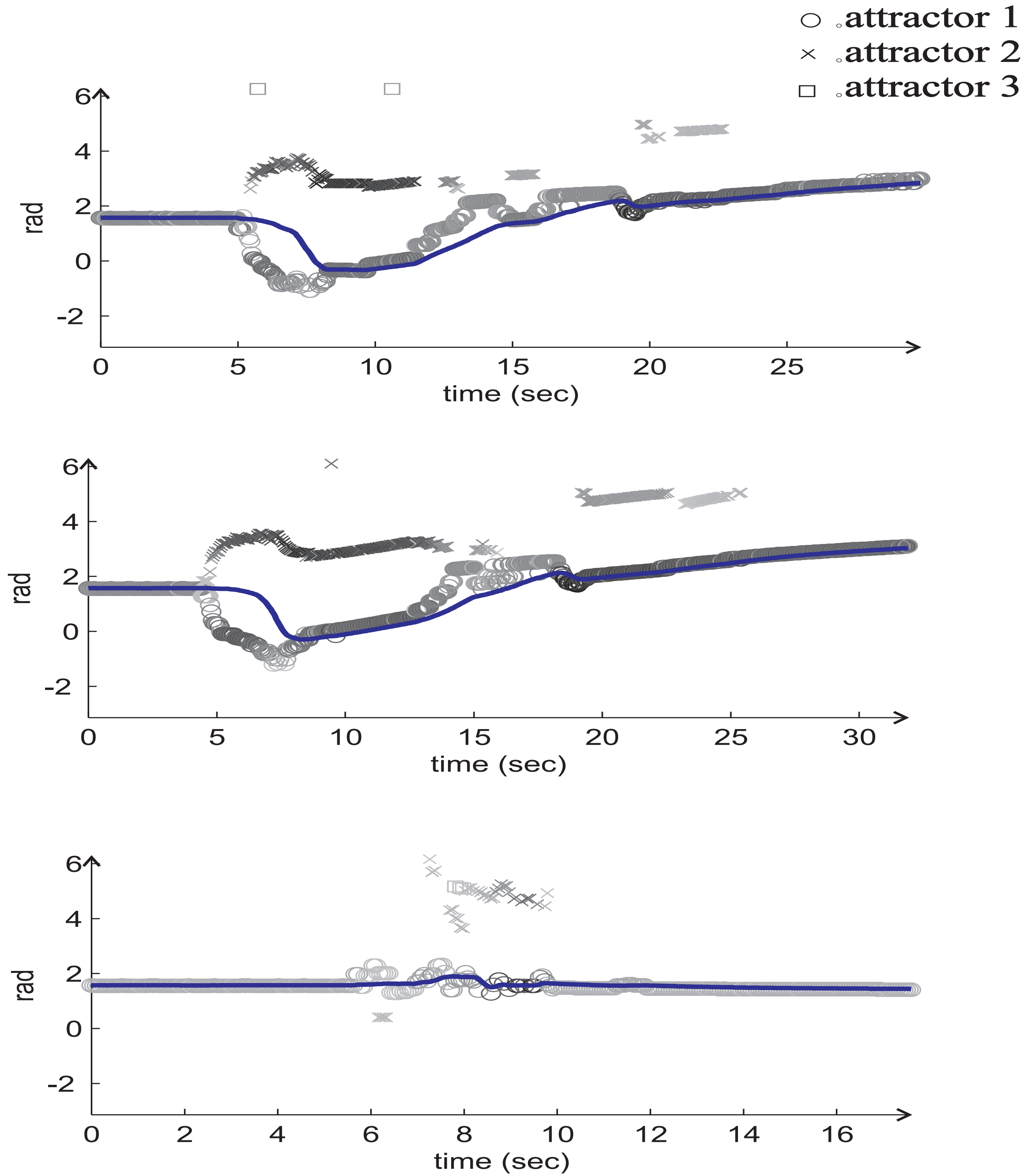


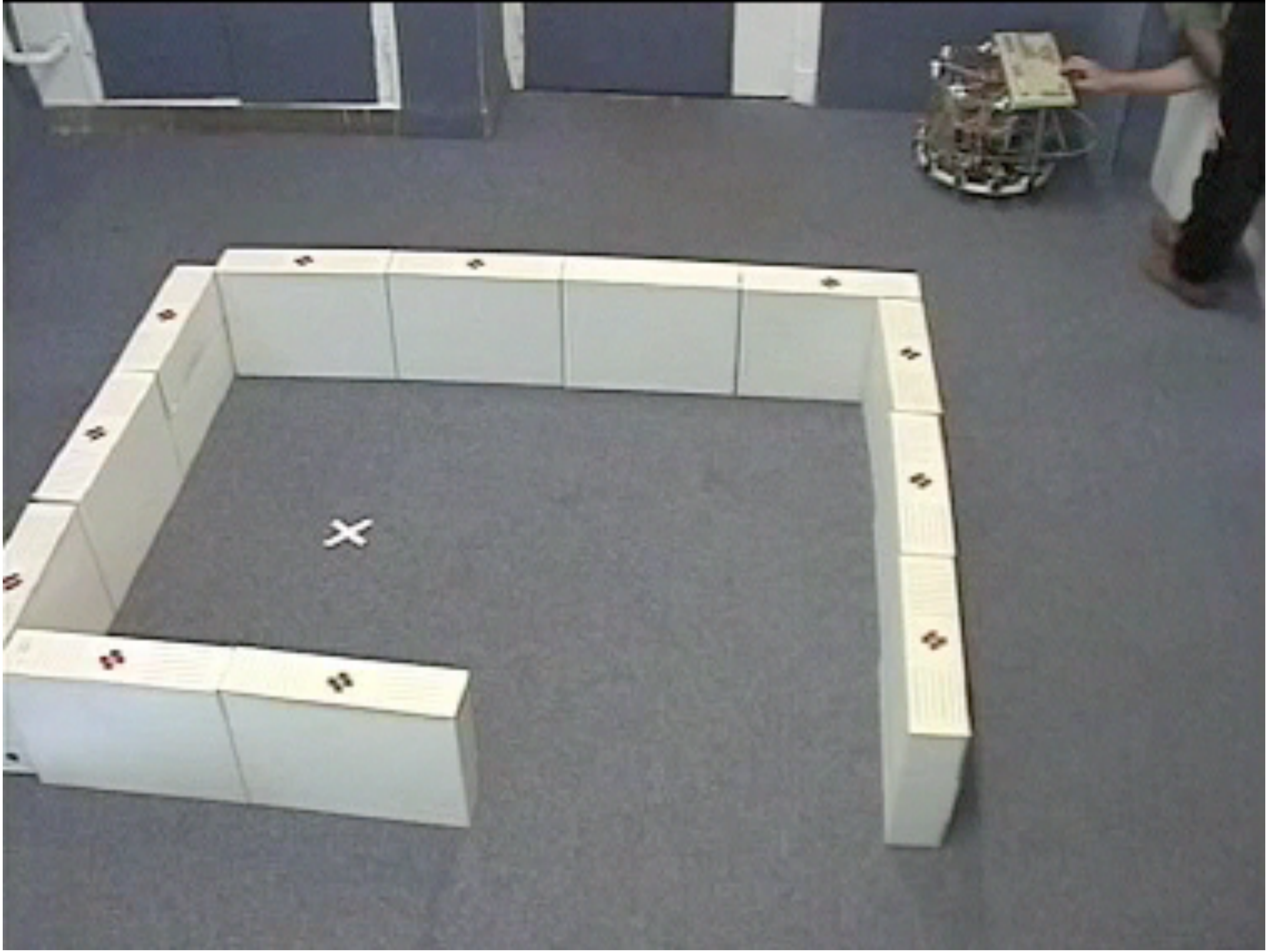
Tracking attractor

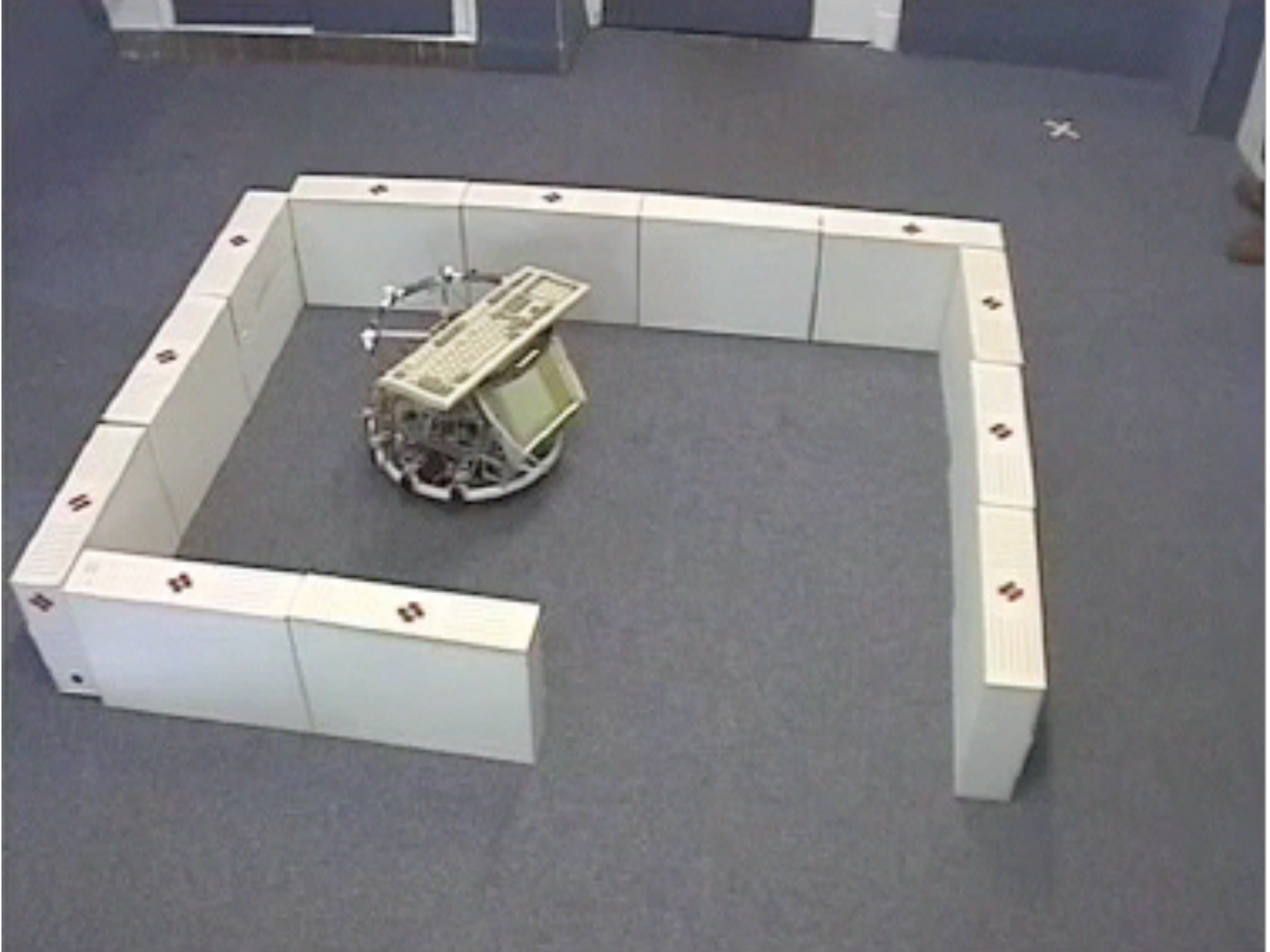
- as robot moves in between obstacles, the dynamics changes but not the attractor

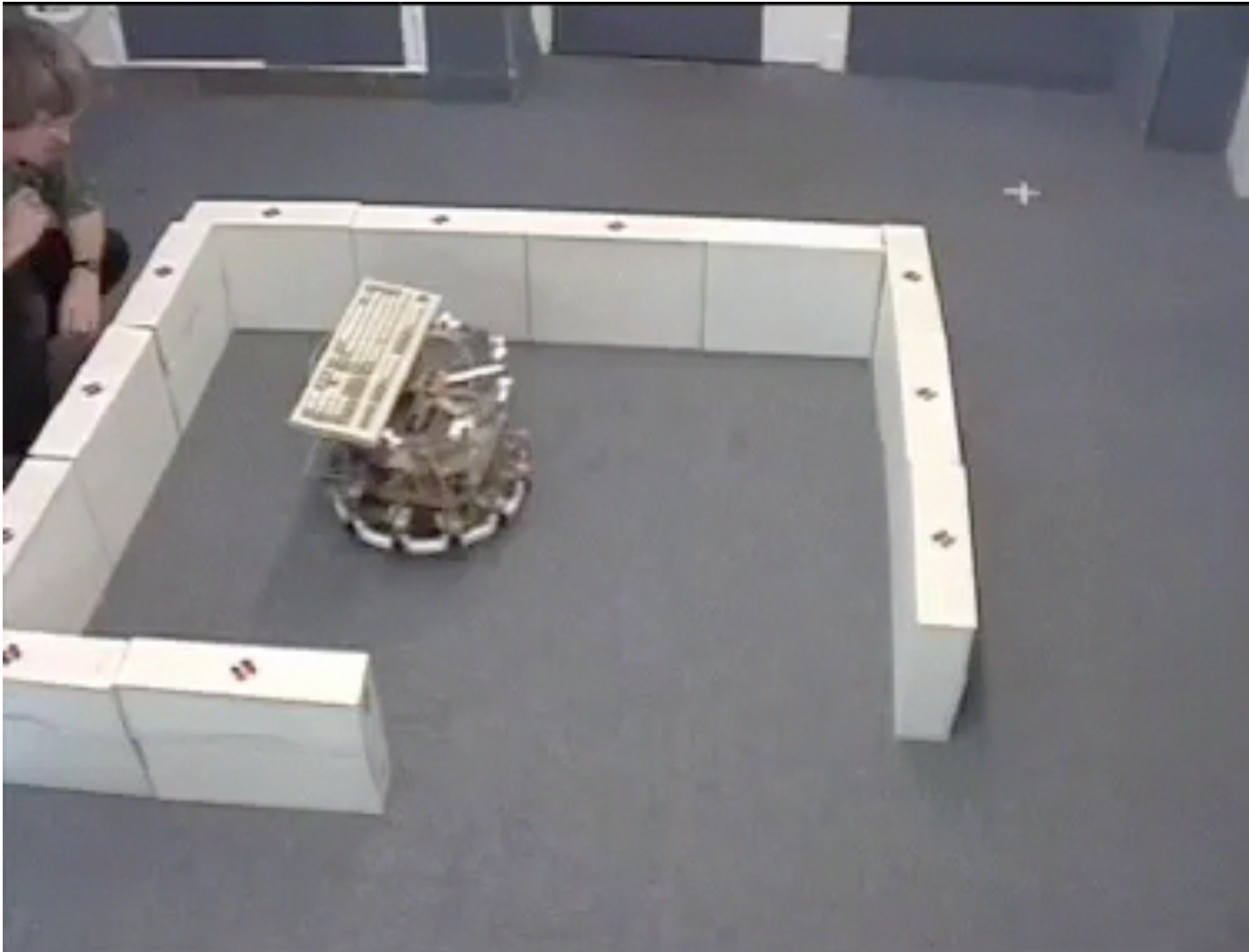


Tracking attractors









Observation:

- even though the approach is purely local, it does achieve global tasks
- based on the structure of the environment!

Conclusion

- attractor dynamics works on the basis low-level sensors information
- as long at the force-lets model the sensor-characteristics well enough to create approximate invariance of the dynamics under transformations of the coordinate frames

Summary

- behavioral variables
- attractor states for behavior
- attractive force-let: target acquisition
- repulsive force-let: obstacle avoidance
- bistability/bifurcations: decisions
- can be implemented with minimal requirements for perception