Machine learning in biology: Teaching a glider to soar like a bird

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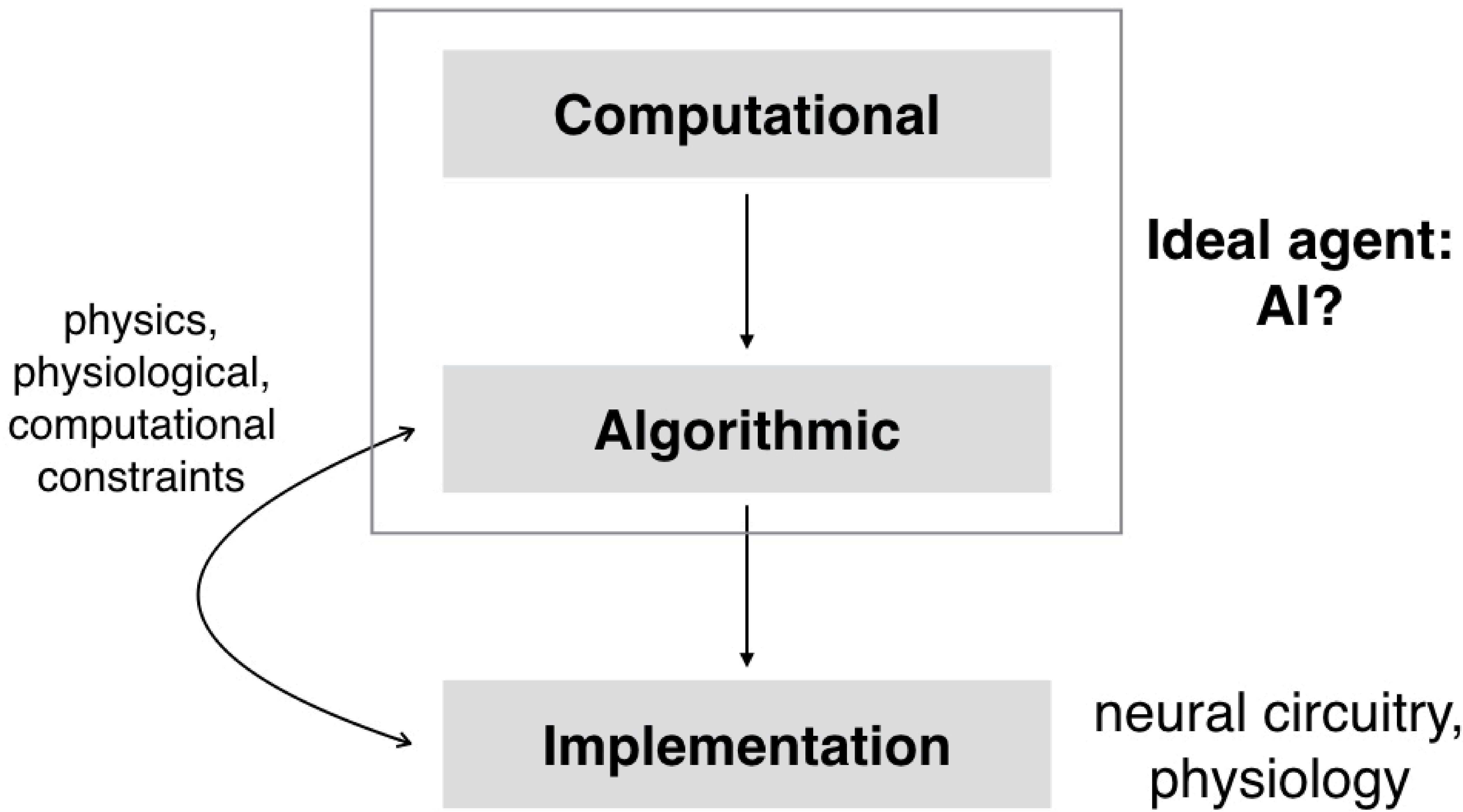
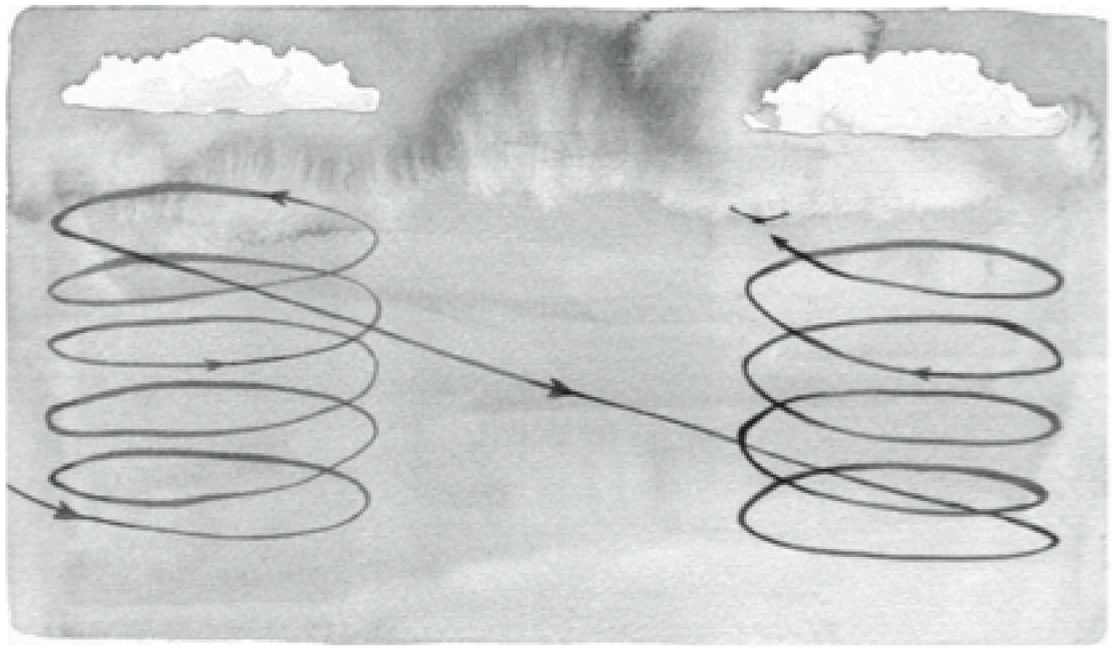
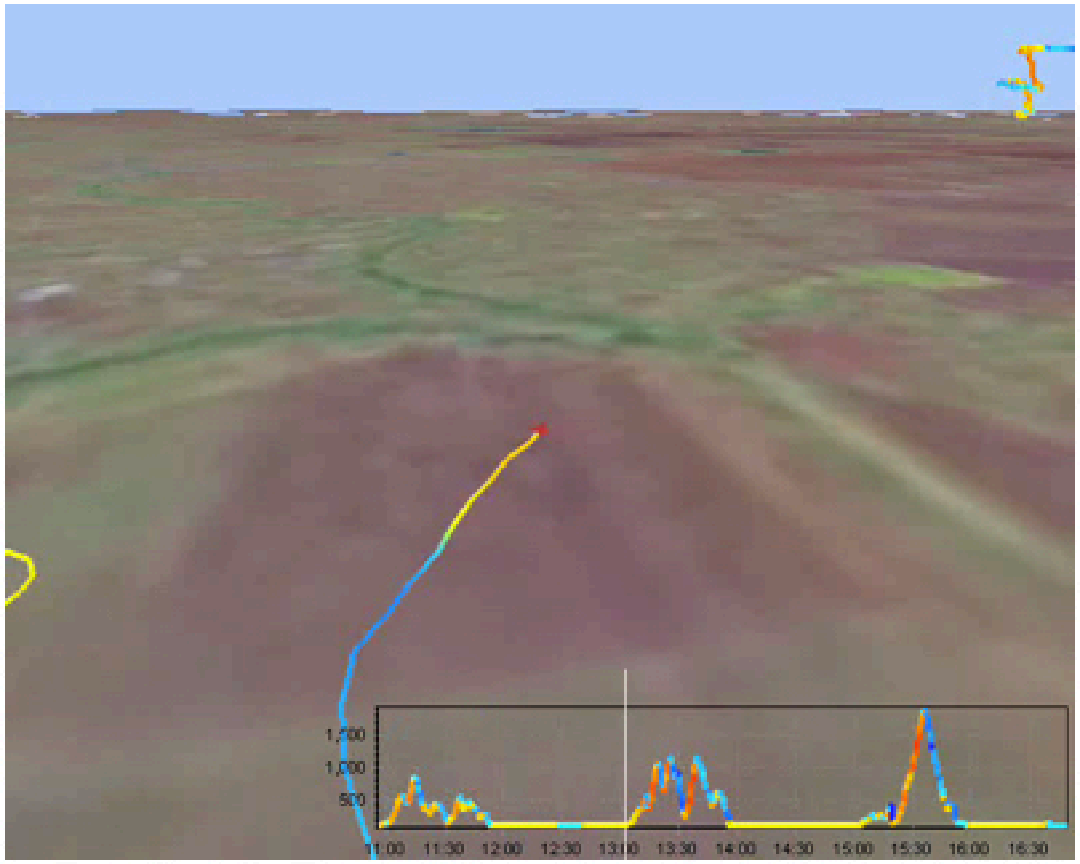
SIMONS FOUNDATION

Marr’s levels of analysis

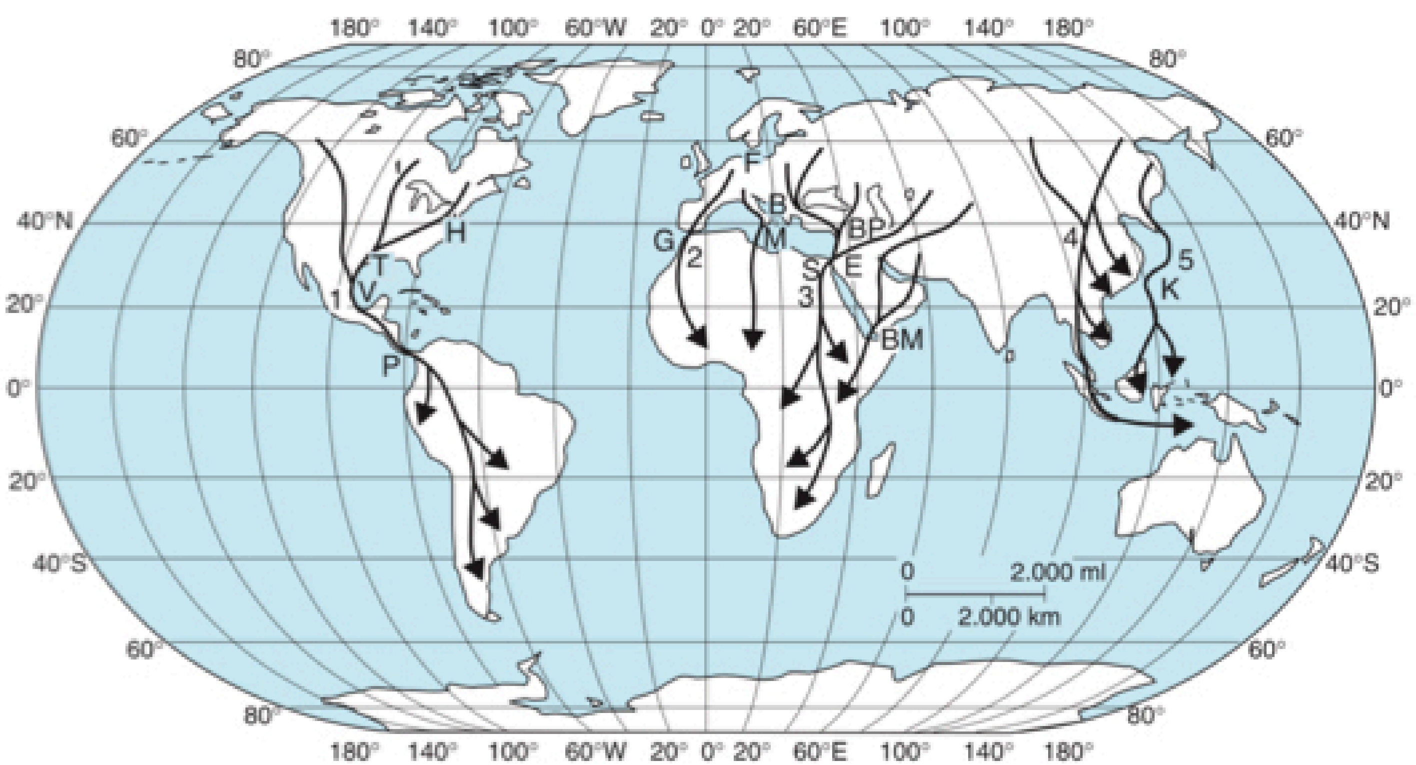


Thermal soaring





Akos, Nagy, Vicsek, PNAS, 2008



Migration Ecology of Birds, Ian Newton

We will focus on the problem of navigating a single thermal

How do birds find and navigate thermals?

What quantities should a bird sense? vertical velocities, temperature, gradients, etc?

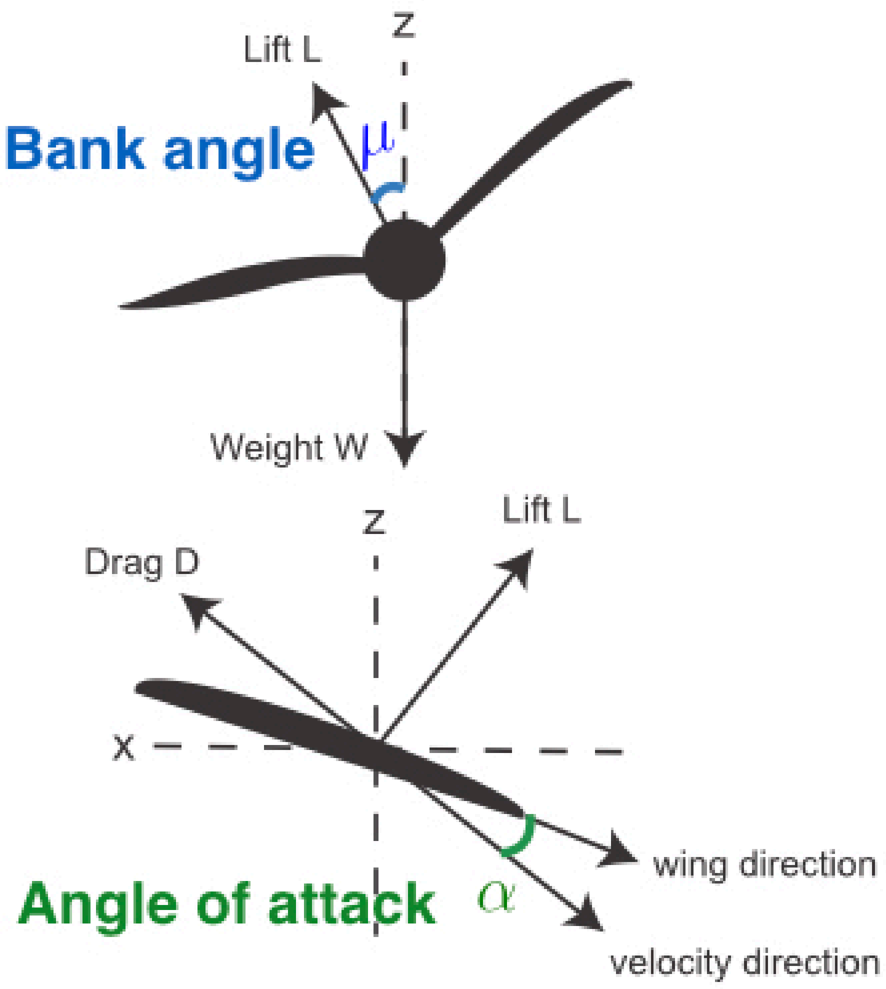
How should the bird respond to these cues?

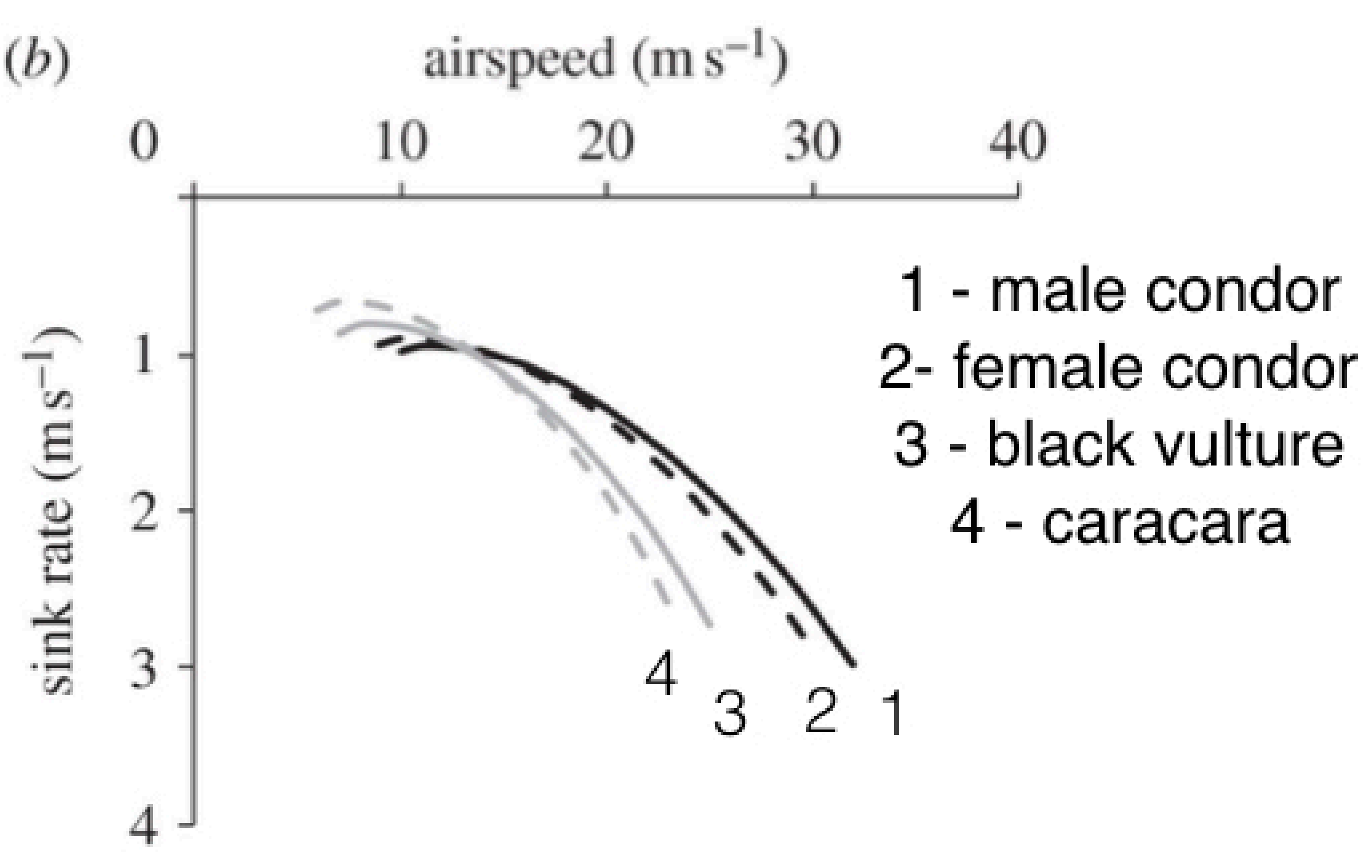
Experiments are hard to control and strategies are difficult to infer from limited data

We will instead ask: how does an optimal agent navigate thermals? and what sensory information does it use to find them?

Aerodynamics of a gliding bird

Shephard & Lambertucci, 2013





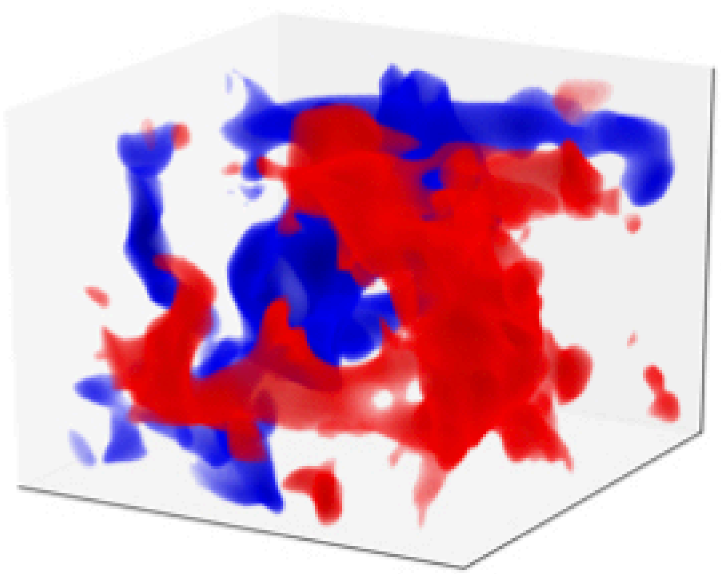
Control over bank angle and angle of attack

Convective environment in the atmosphere

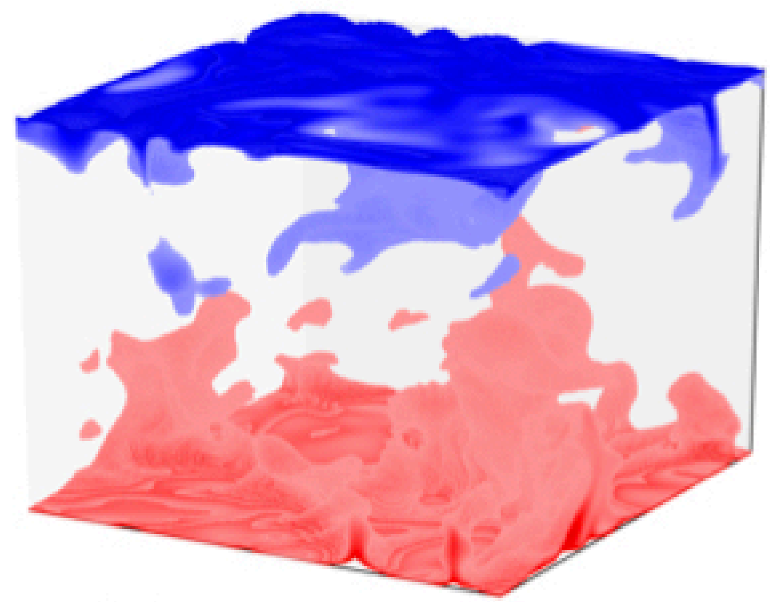
Rayleigh-Benard convection

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla P + \left(\frac{\mathrm{Pr}}{\mathrm{Ra}}\right)^{1/2} \nabla^2 \boldsymbol{u} + \boxed{\theta \hat{\boldsymbol{z}}}$$

$$\frac{\partial \theta}{\partial t} + \boldsymbol{u} \cdot \nabla \theta = \frac{1}{(\mathrm{Pr}\,\mathrm{Ra})^{1/2}} \nabla^2 \theta \,,$$



Vertical velocity



Temperature

An optimally behaving agent: the reinforcement learning framework

$$\cdots \longrightarrow s_t \xrightarrow[a_t]{r_t} s_{t+1} \xrightarrow[a_{t+1}]{r_{t+1}} s_{t+2} \xrightarrow[a_{t+2}]{r_{t+2}} \cdots$$

Action-value: $Q(s_t, a_t) = r_{t+1} + \gamma r_{t+2} + \gamma^2 r_{t+3} + \ldots, 0 \leq \gamma < 1$

Policy: $\pi_s^a = \arg\max_{a'} Q(s, a')$

Learns empirical statistics and rewards solely through experience

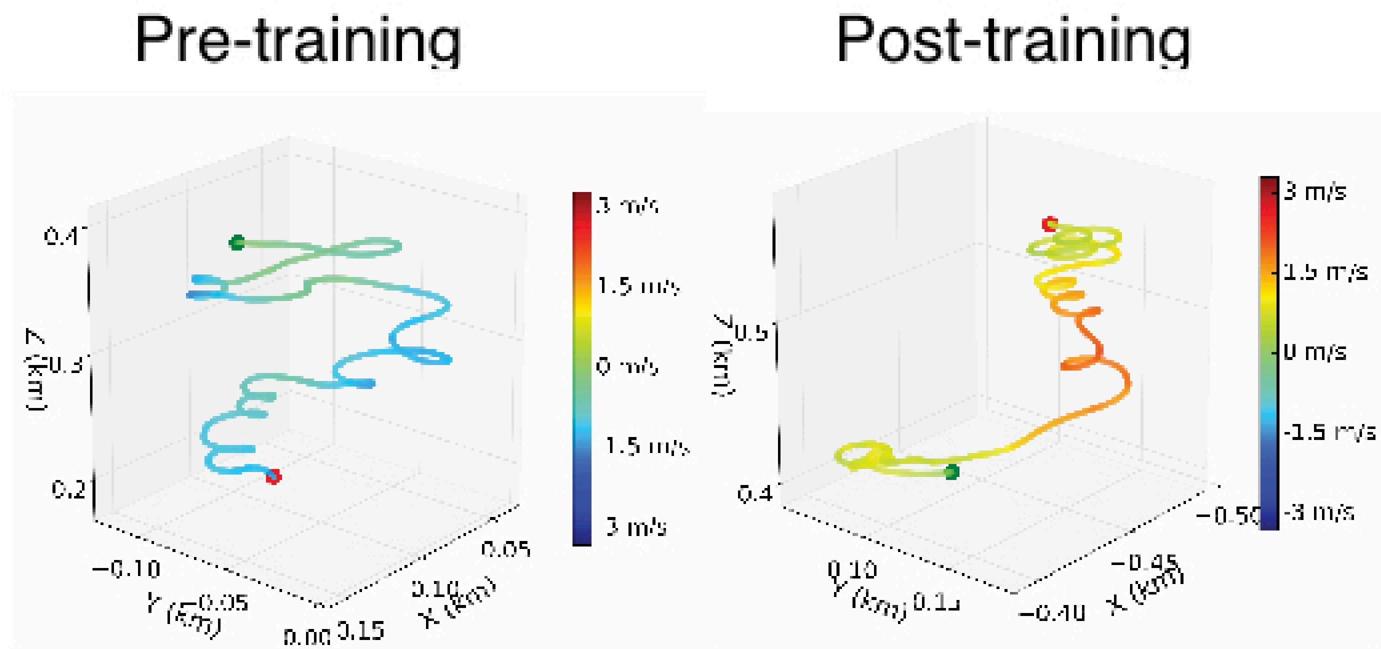
Model-free

States s — sensory cues + bank angle + angle of attack

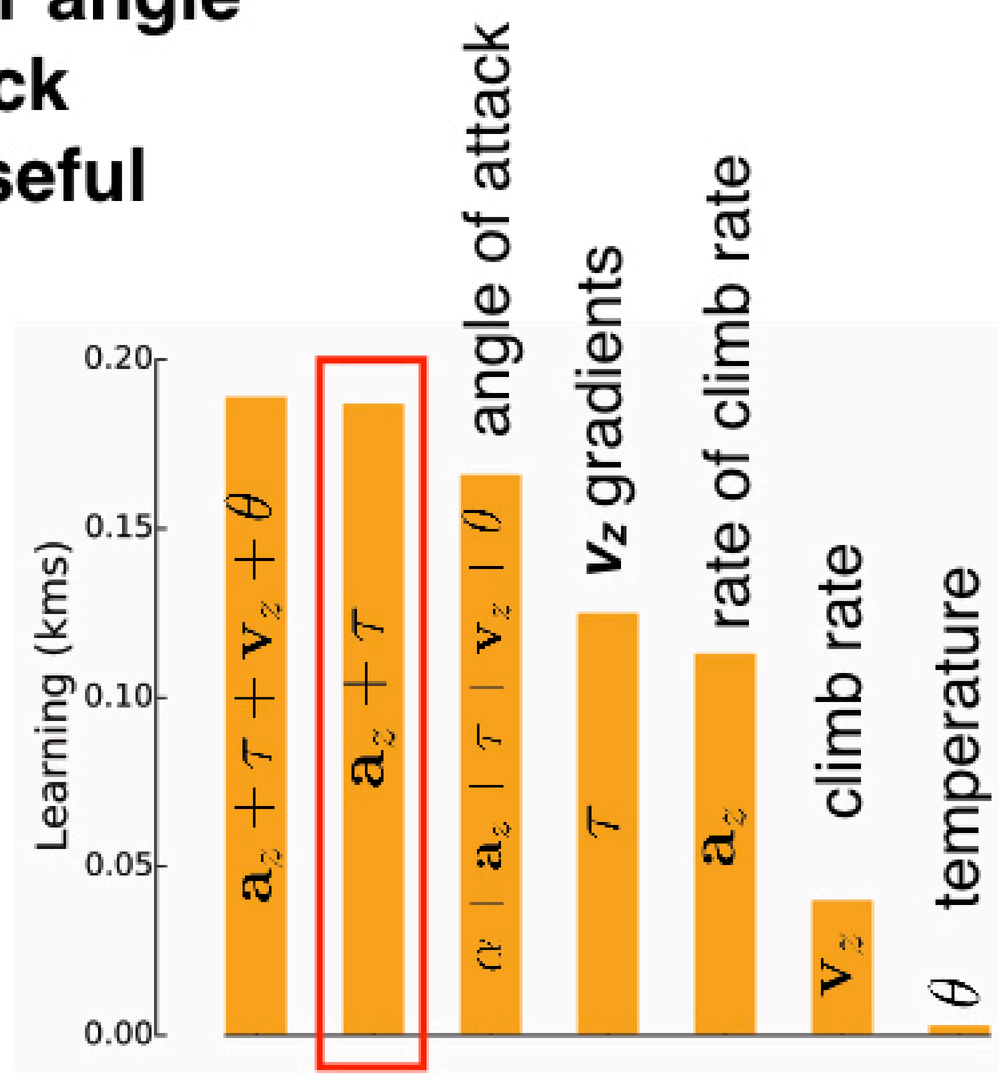
Actions a — modify angles

After training....

a_z and v_z gradients across wings are useful

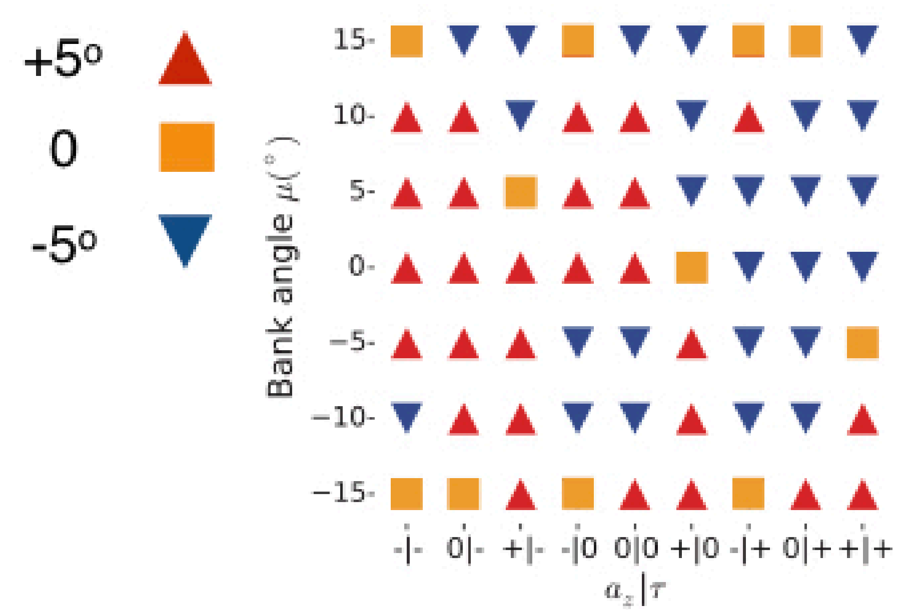


control over angle of attack is not useful

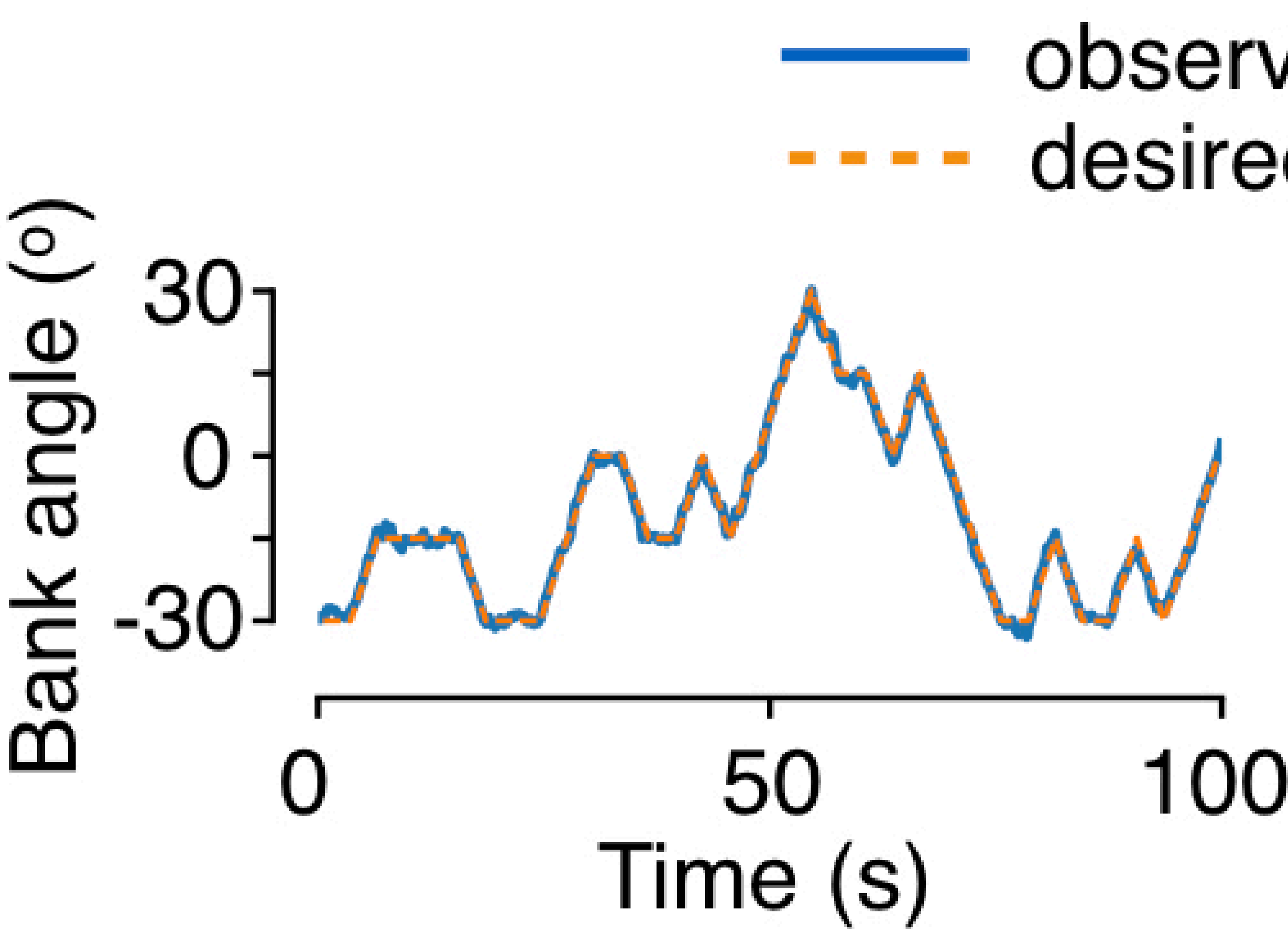


How do birds measure these quantities?

Still works in the field?



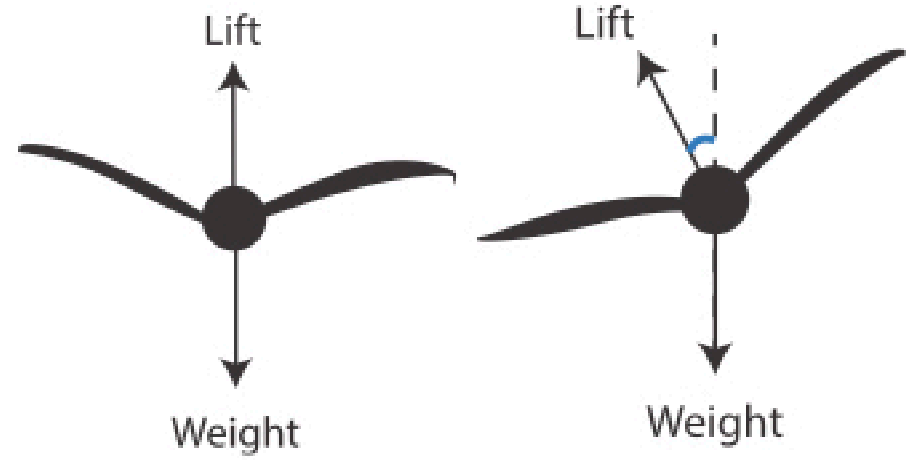
In the field


observed
desired
Bank angle (°)
30
0
-30
0
50
100
Time (s)


Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google Earth

Measuring the vertical wind acceleration

We need to estimate vertical wind velocity - how?



GPS/baro

$$u_z = v_z + w_z$$

modeling

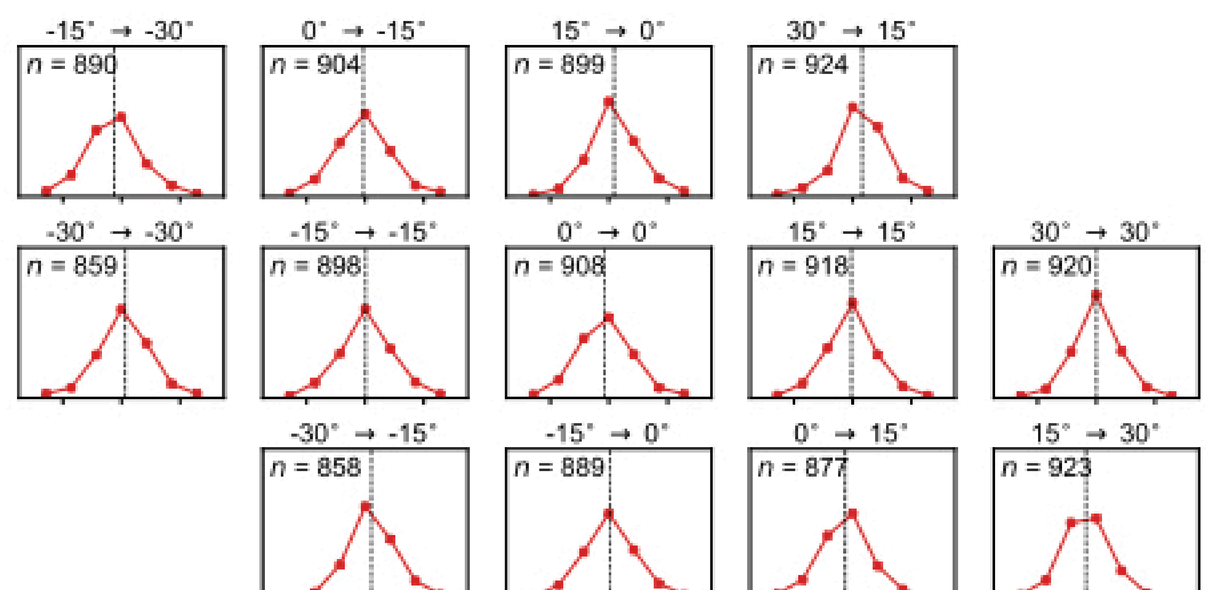
$$\omega \approx g/V \sim 1\mathrm{Hz}$$

$$u_z = -V\left(\alpha + \phi\right) + w_z$$

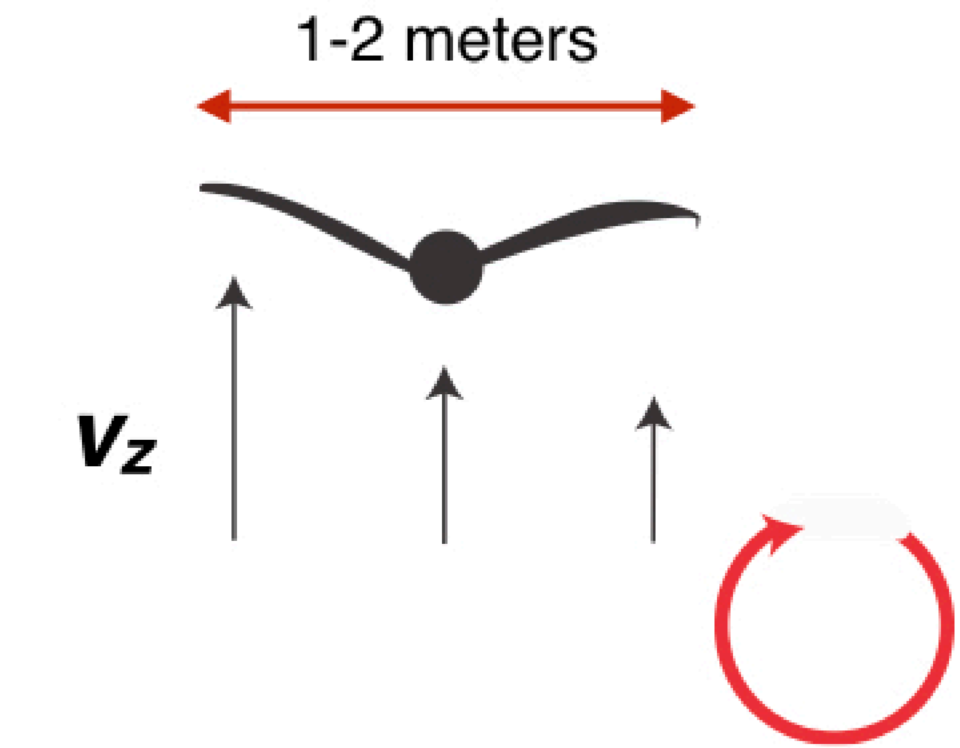
Airspeed

Angle of attack

Pitch

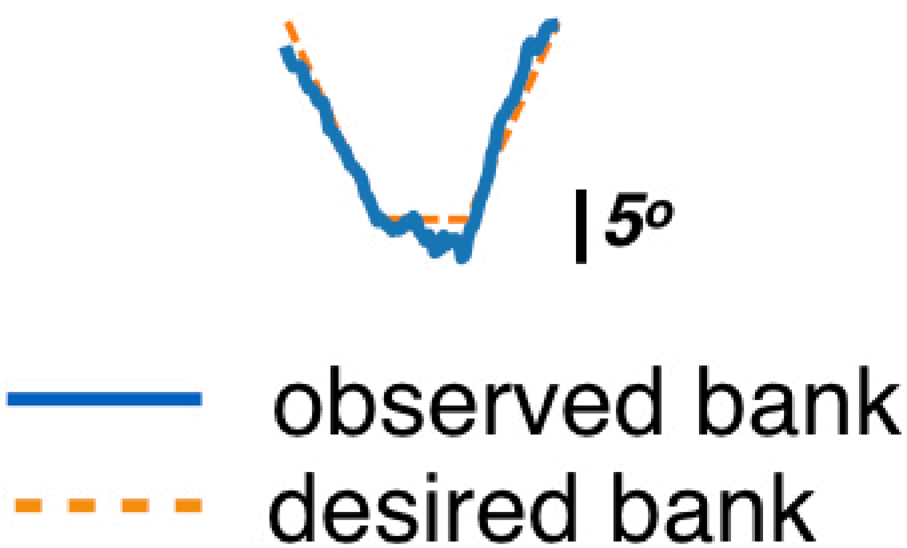


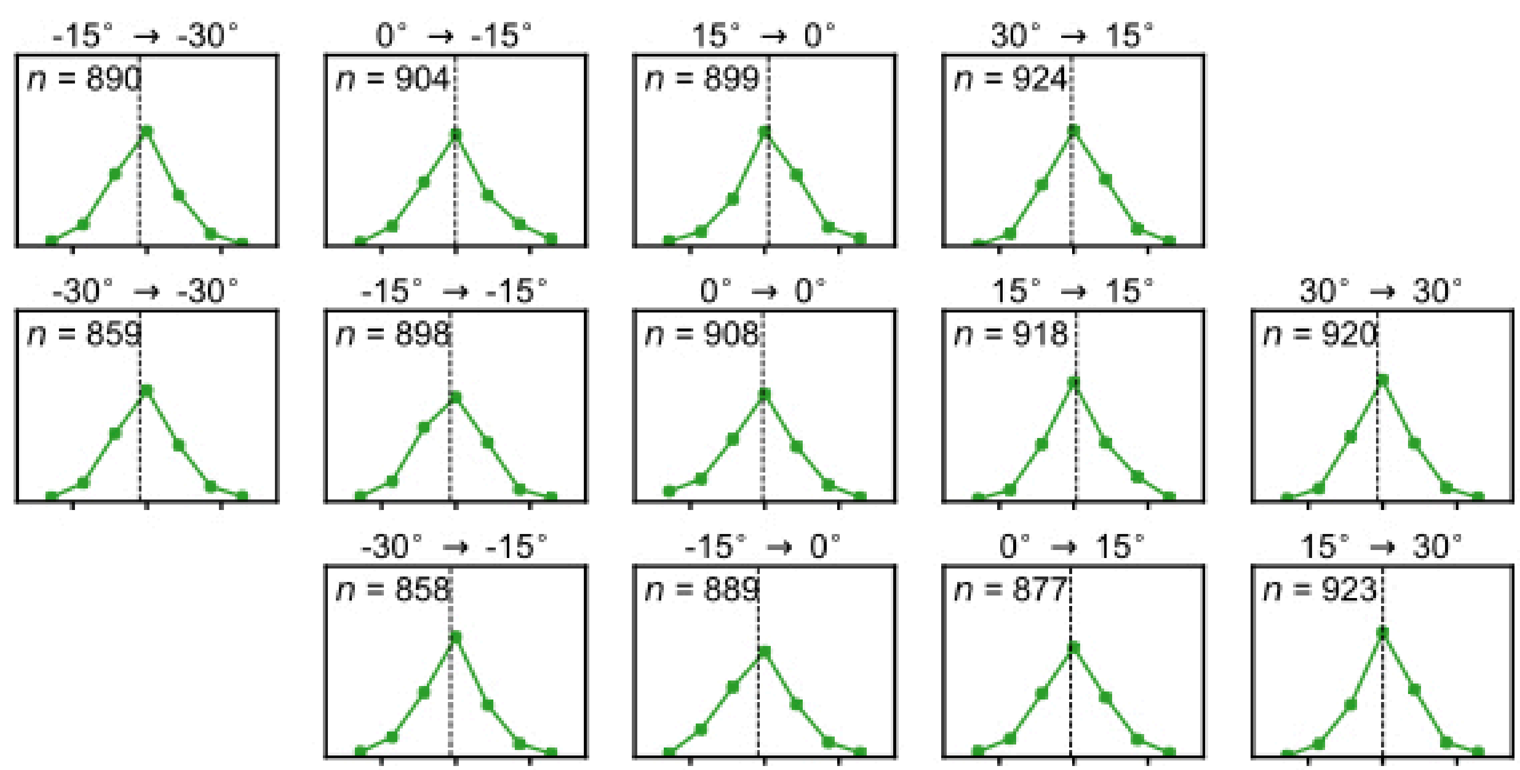
Measuring the vertical wind velocity gradients



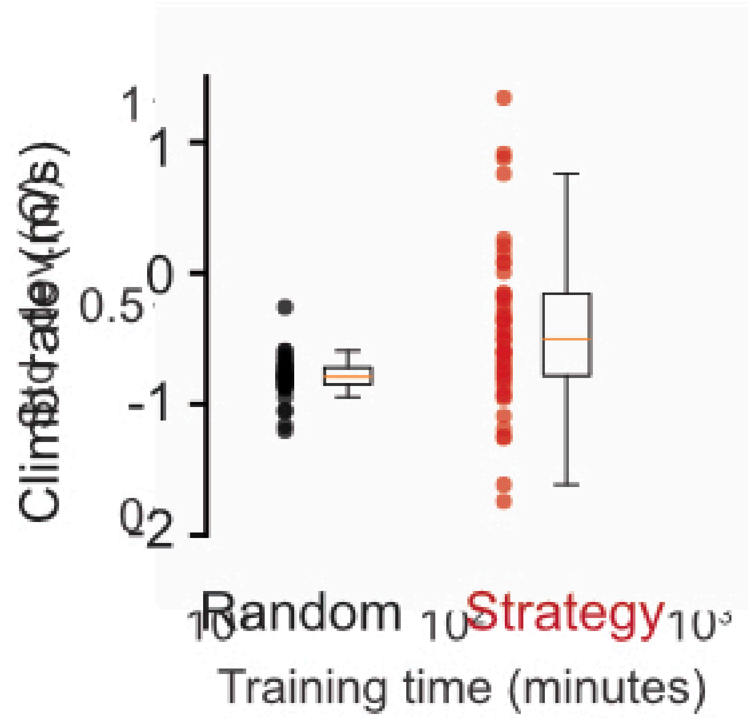
change in bank = feedback control + aerodynamics + wind gradients

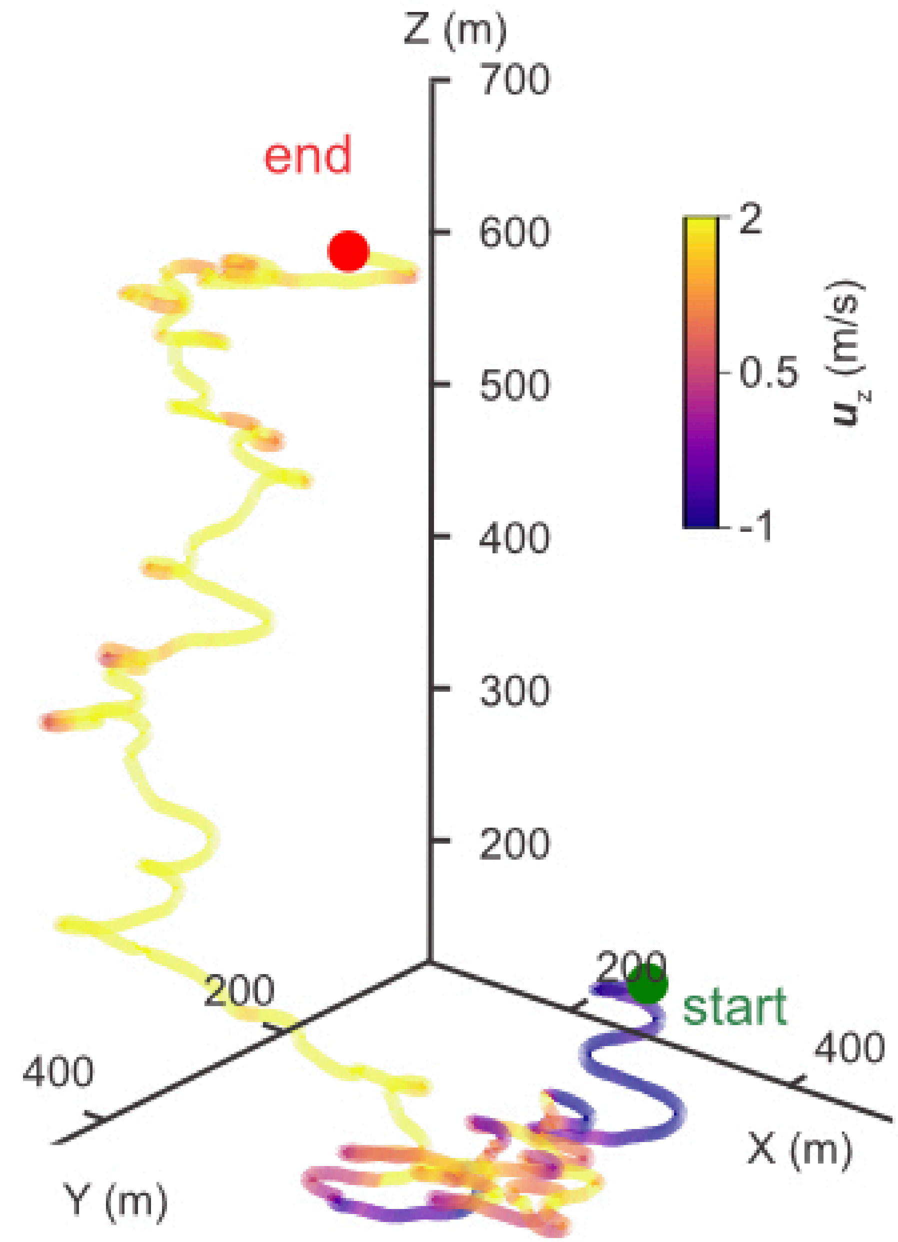
$$\frac{d\mu}{dt} = \omega_{\mathrm{ctrl}} + \omega_{\mathrm{aero}} + \omega_{\mathrm{wind}}$$

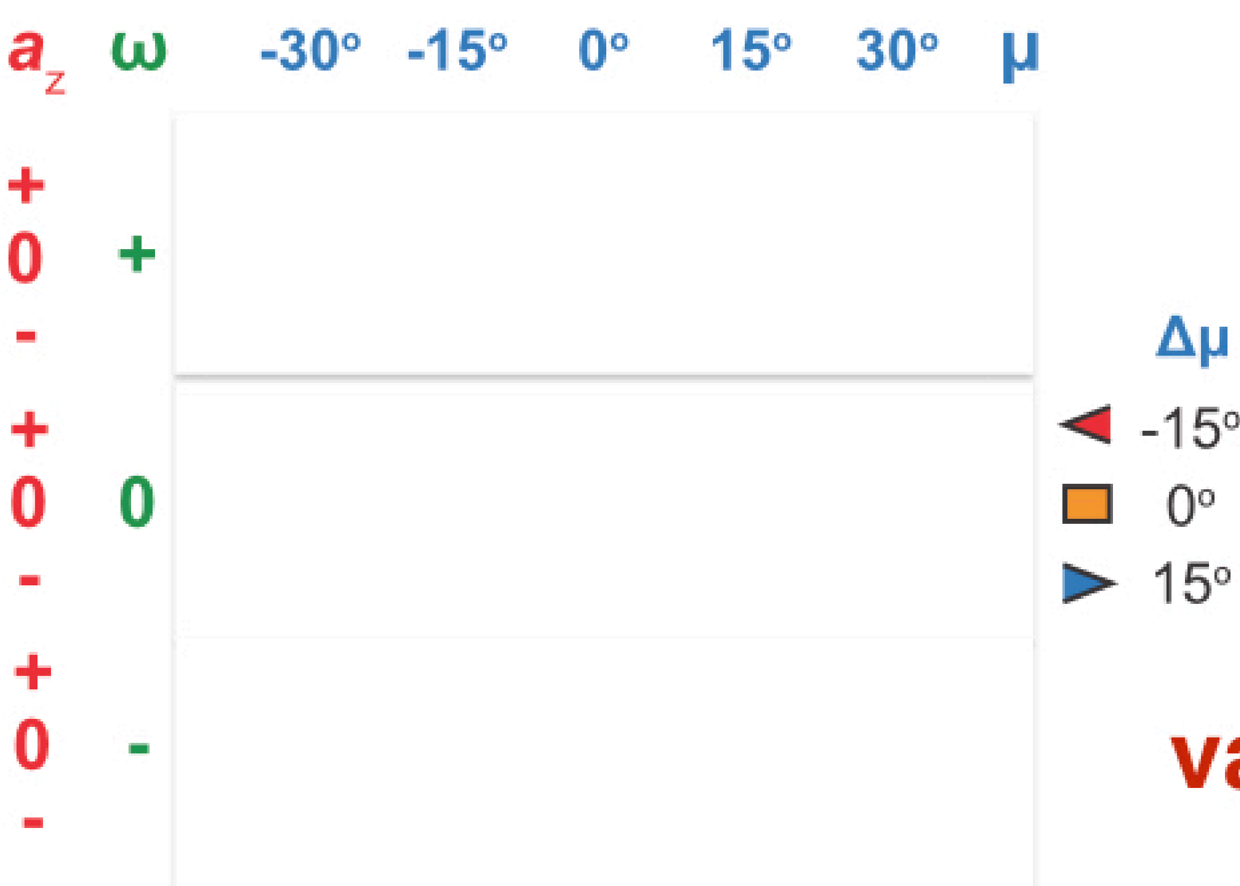




Training the glider in the field

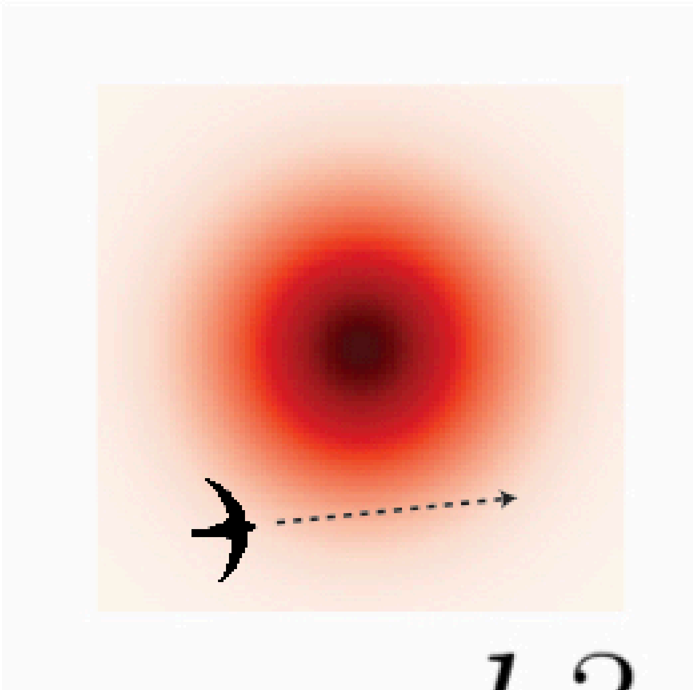






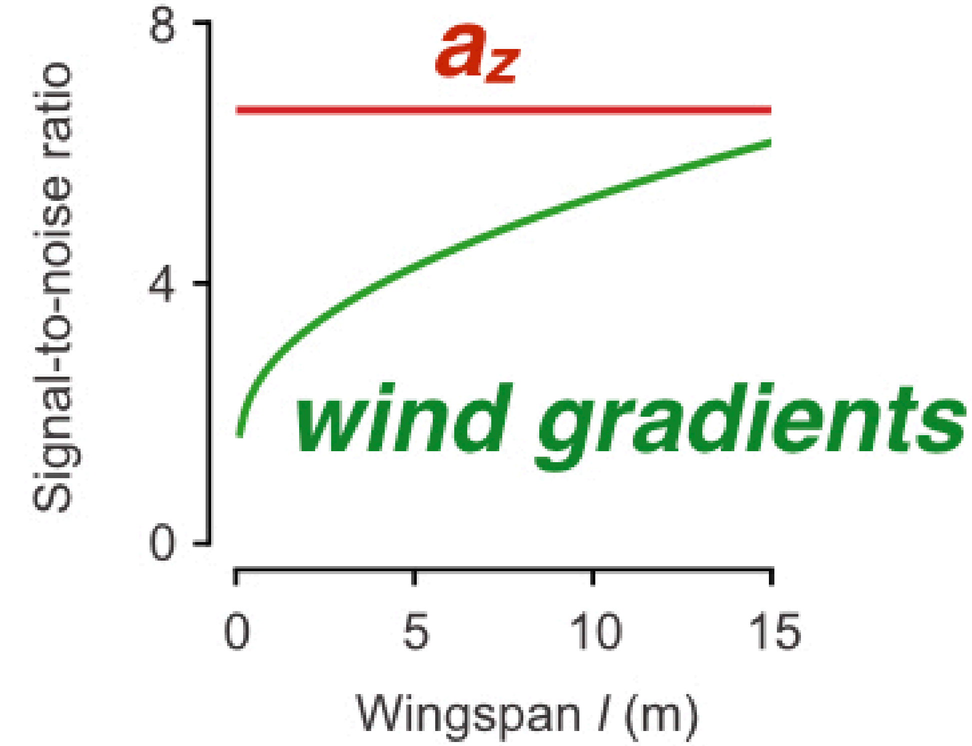
validates wind gradient estimation

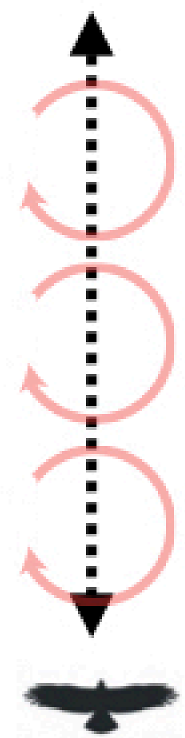
Can a bird sense vertical wind gradients?



$$\omega \sim l\,?$$

turbulence!





$$\frac{\omega}{\delta v} \sim l^{1/6}(VT)^{1/2}$$

$$\frac{a_z}{\delta a_z} \sim (VT)^{2/3}$$

$$\delta v \sim l^{1/3} \qquad n \sim VT/l$$

Future work

Requires development of new theoretical tools to infer behavior when the true environmental state is unknown - **inverse reinforcement learning**

Theory in reinforcement learning

Conclusion

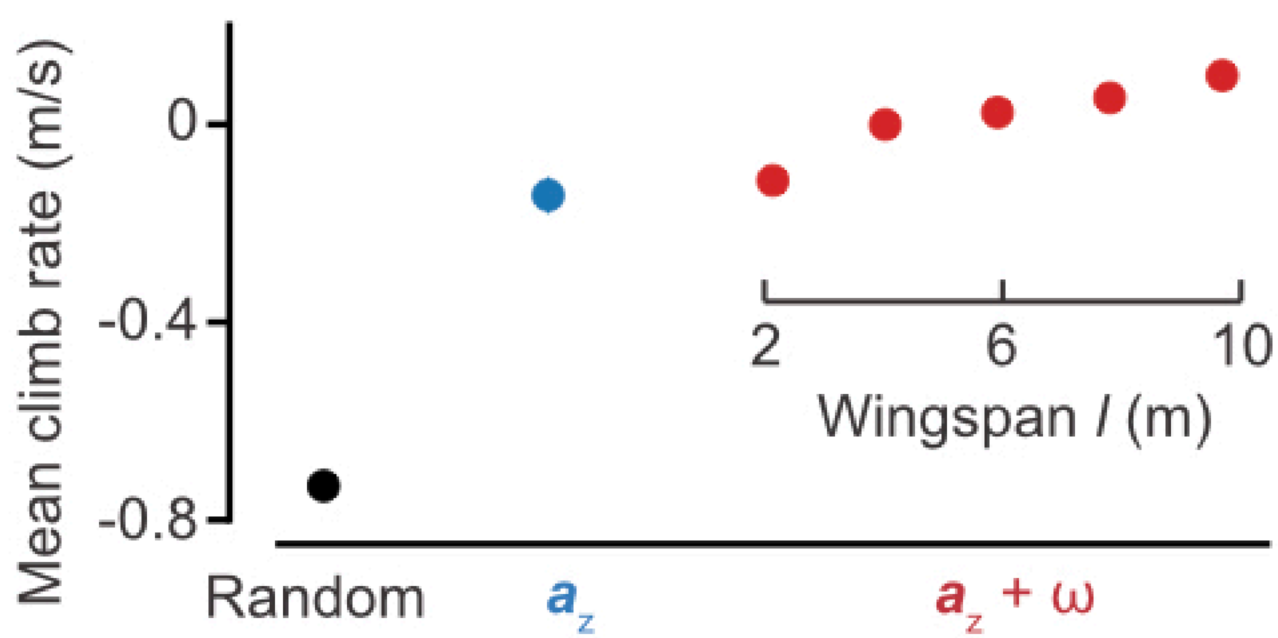
Birds likely use a more complex approach based on other cues and recent experience

BUT accelerations and torques will be useful for any other strategy

Future

Inferring thermalling strategies of birds from soaring data

Requires development of new theoretical tools to infer behavior when the true environmental state is unknown



Mean climb rate (m/s)
0
-0.4
-0.8
2
6
10
Wingspan l (m)
Random
a_z
a_z + ω