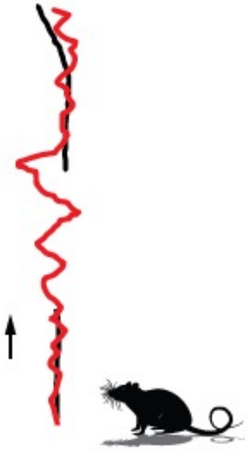
Learning to navigate turbulent environments

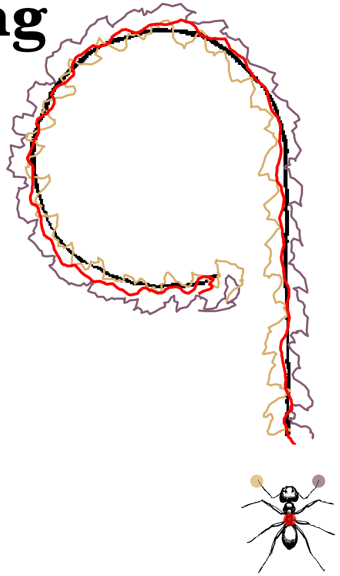
Massimo Vergassola

Long-distance olfactory searches

Soaring flight

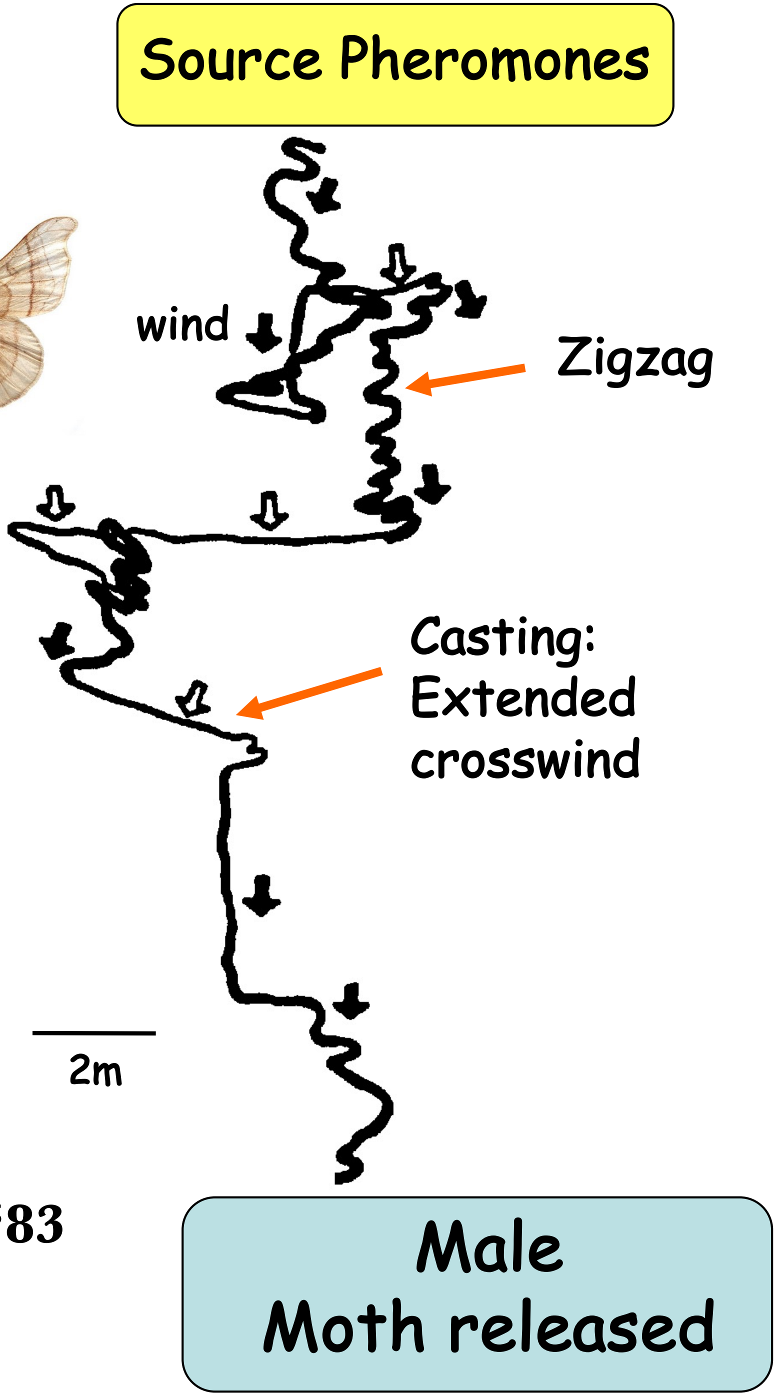
Olfactory trail tracking





Olfactory searches by insects

Rates for the emission of pheromones by female moths are on the order of a few picograms/s. Typical molecular weight of pheromone components is a few hundred Daltons.



Source Pheromones

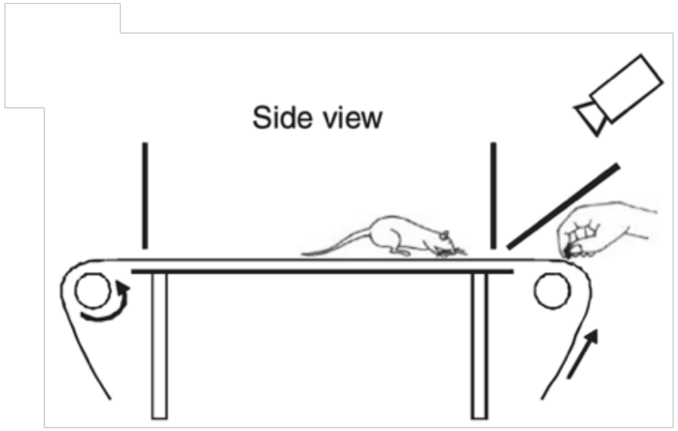
Male
Moth released

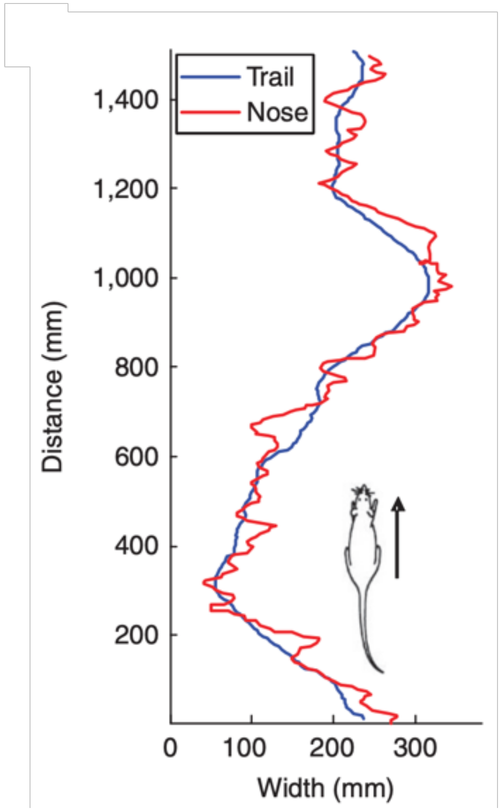
David *et al.*, Nature, ‘83

Olfactory trail tracking

Draft *et al.*, JEB, 2018

Khan et al. Nat. Comm.. 2012

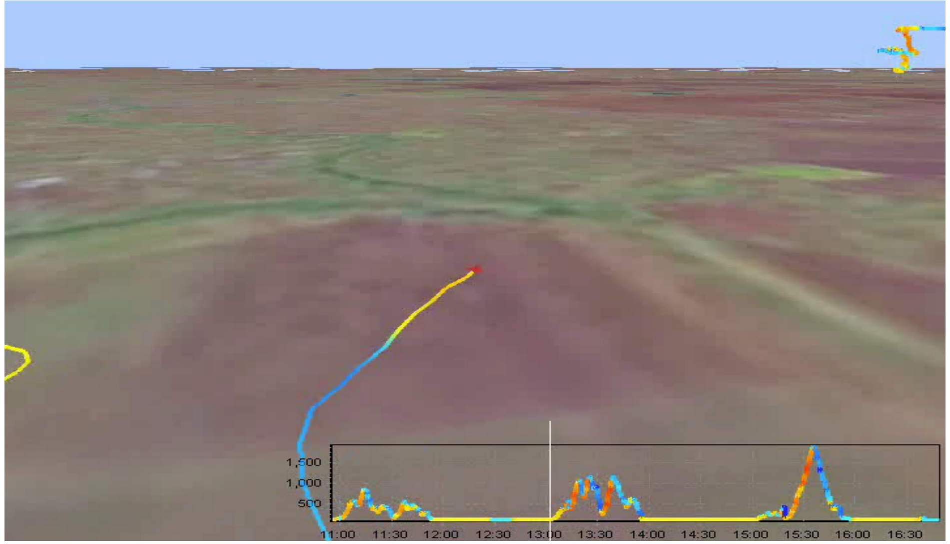




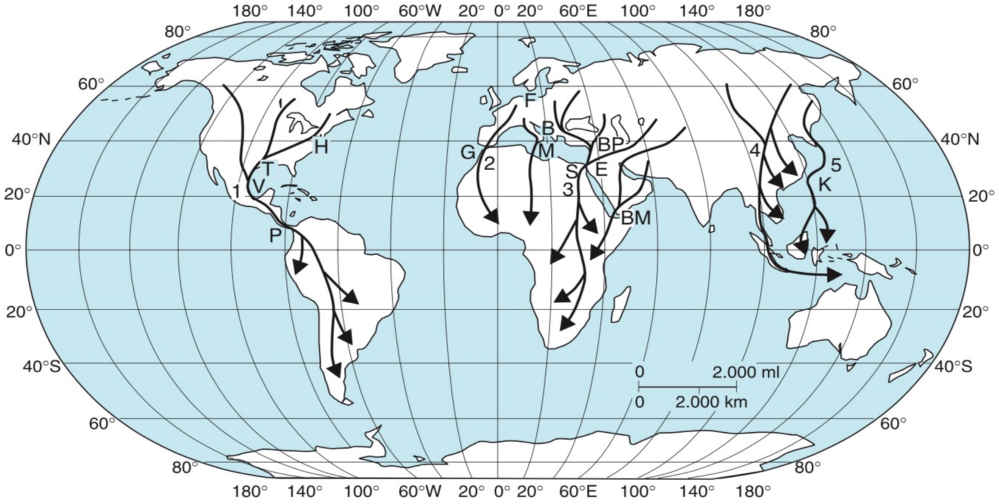
Porter et al, Nat. Neuro., 2007

Widening casts

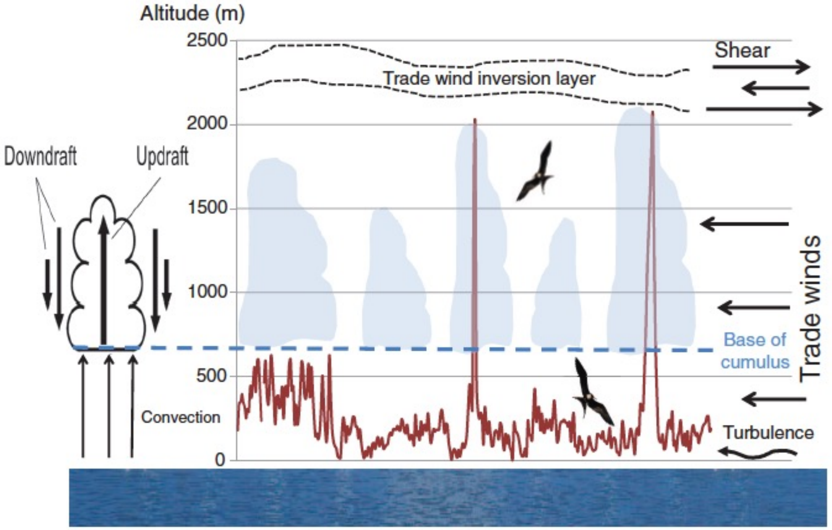
Thermal soaring by birds



Akos, Nagy, Vicsek, PNAS, ‘08



Migration Ecology of Birds, Ian Newton



Weimerskirch *et al.*, Science ‘16

A bit of history…

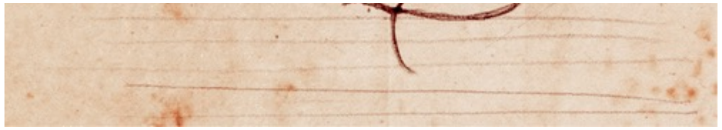
$$\dot{E} = -\mathrm{v}D + mg\mathbf{w}_z - m\mathbf{v}.\frac{d\mathbf{w}}{dt}$$

$$(\partial\mathbf{w} \quad . \quad ds\,\partial\mathbf{w})$$

Lord Rayleigh, 1883: ”…Whenever therefore a bird pursues his course for some time without working his wings, we must conclude either

1. that the course is not horizontal,
2. that the wind is not horizontal, or
3. that the wind is not uniform.

It is probable that the truth is usually represented by (1) or (2); but the question I wish to raise is whether the cause suggested by (3) may not sometimes come into operation."

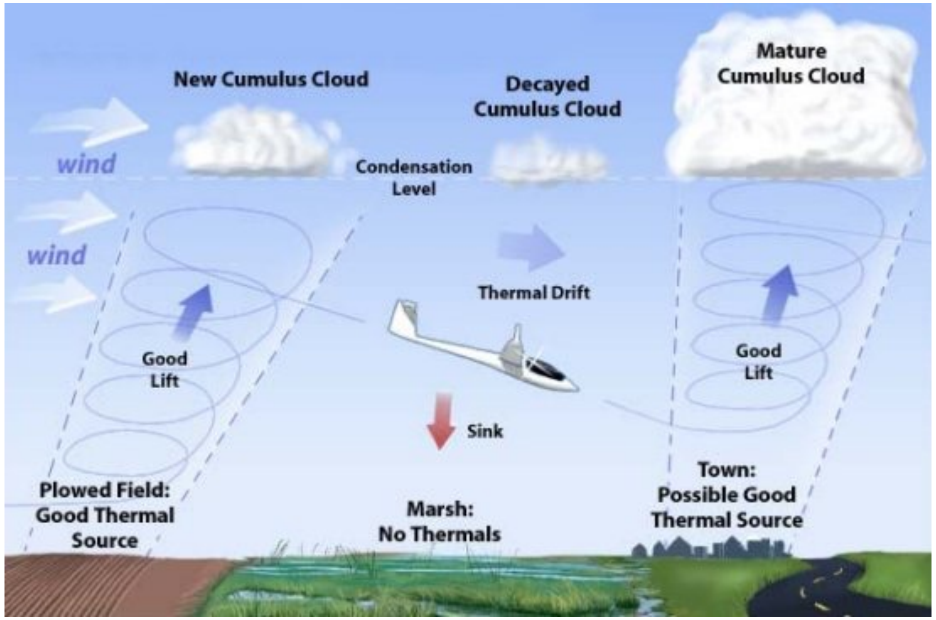


Dynamic
and gust soaring

Thermal and
ridge soaring

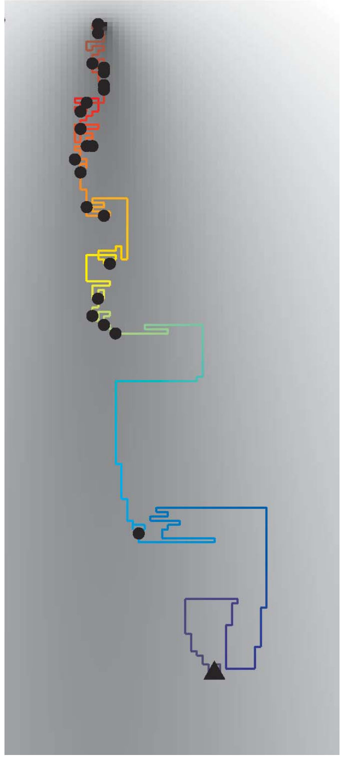
da Vinci, ca 1513-1515
P. Richardson, “da Vinci's discovery of the dynamic soaring by birds in wind shear", 2018

Technological applications

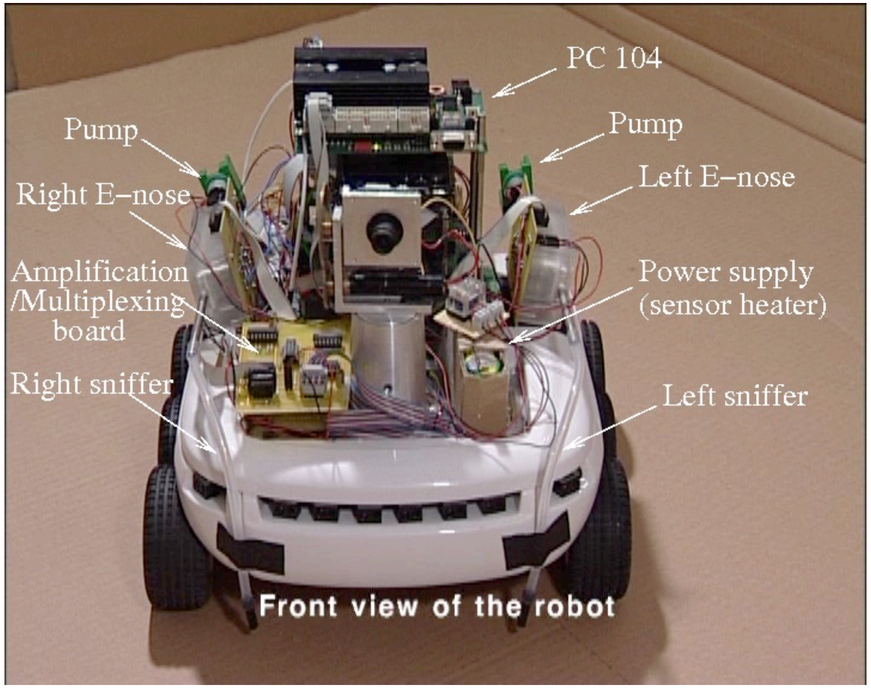


UAVs for surveillance, delivery, monitoring (and, of course, drones)

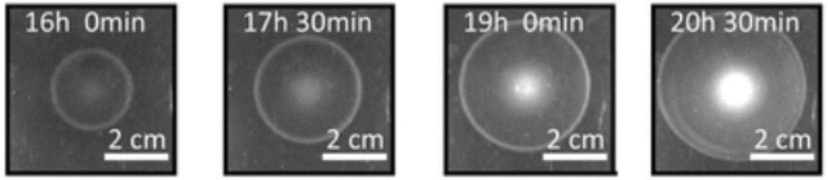
Infotaxis,
Nature ‘07

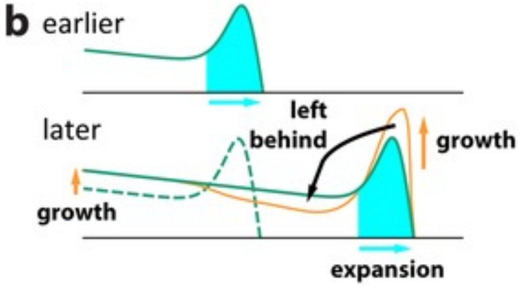


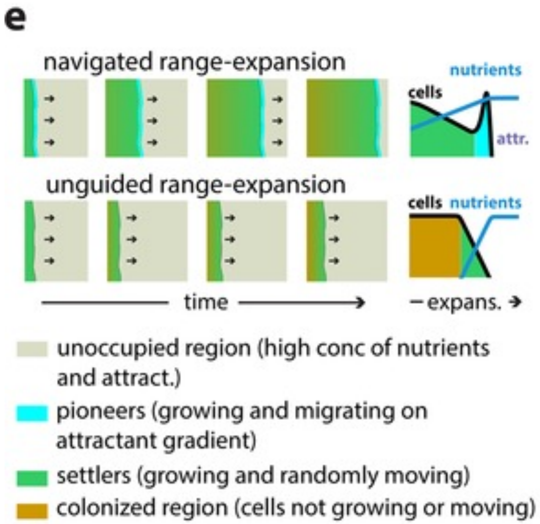
Olfactory robots: applications to detection of chemical leaks, drugs, bombs, land and/or sea mines, sources of toxic substances, etc.



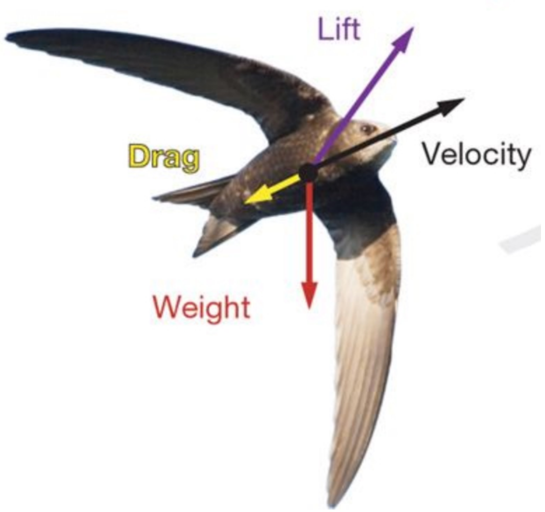
Why does physics matter?







Cremer et al.,
Nature, Chemotaxis
as a navigation
strategy to boost
range expansion,
2019

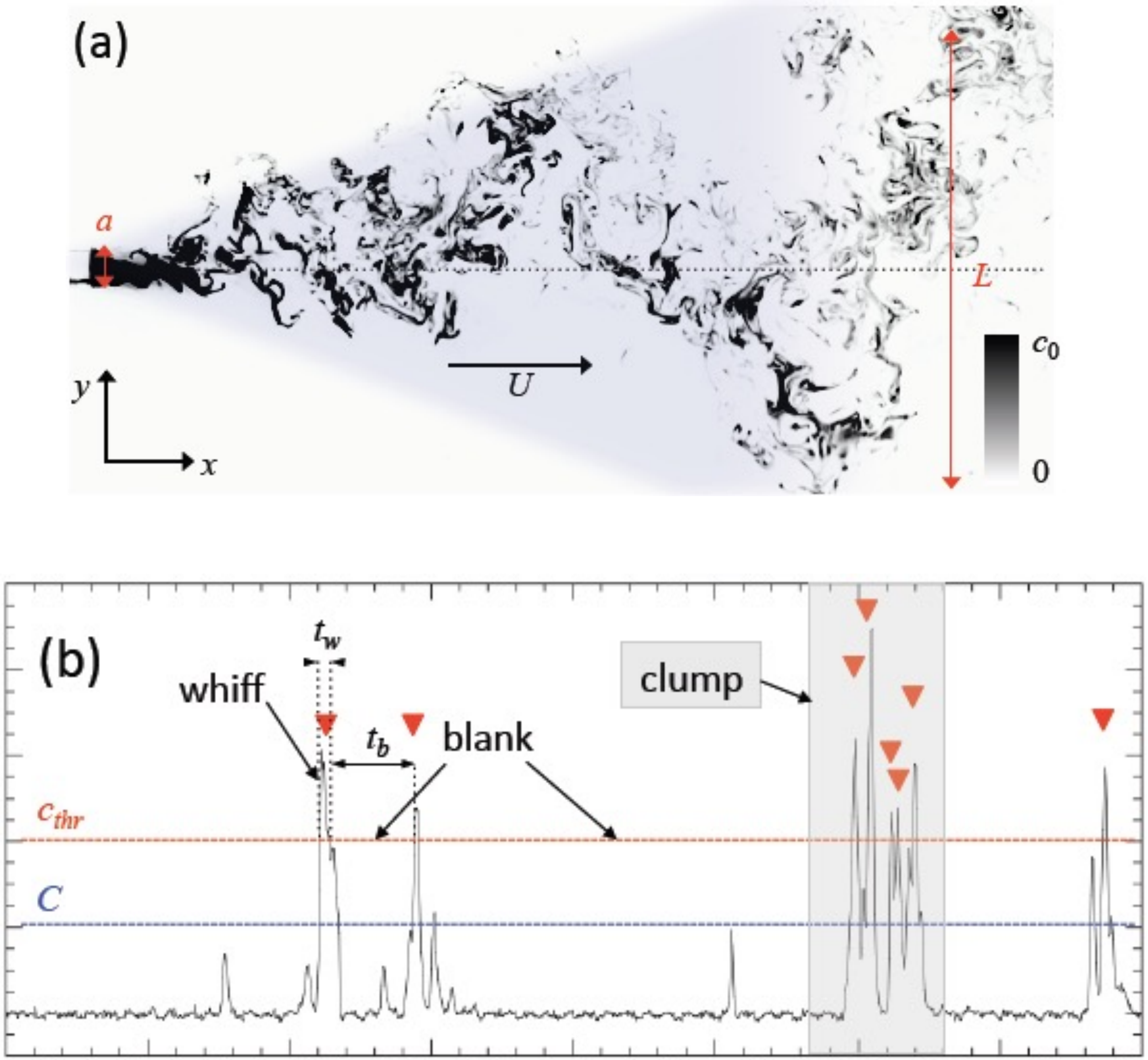


Statistics of odor detections

Concentration fields are very different than diffusive ones.

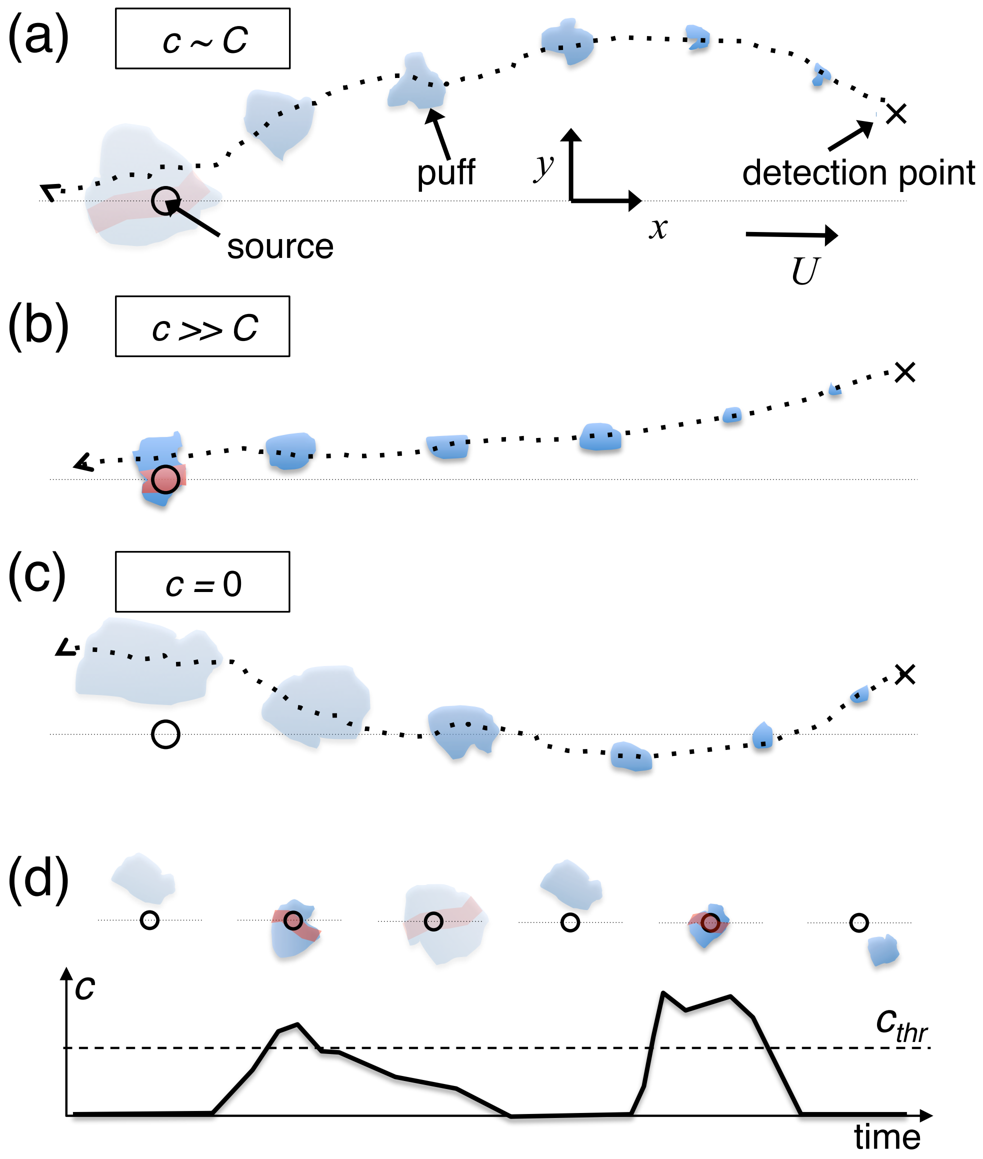
Falkovich et al., Rev. Mod. Phys., 2001

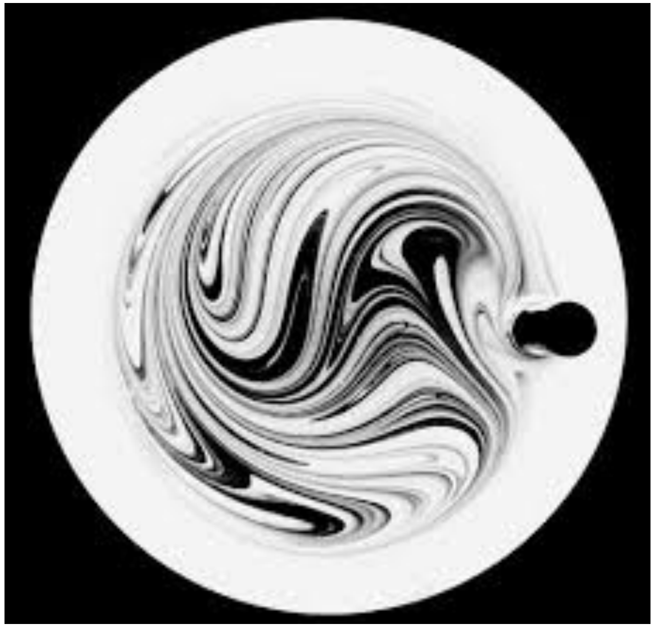
Reddy et al., Ann. Rev. Cond. Matter Phys., 2022



Why could we make progress?

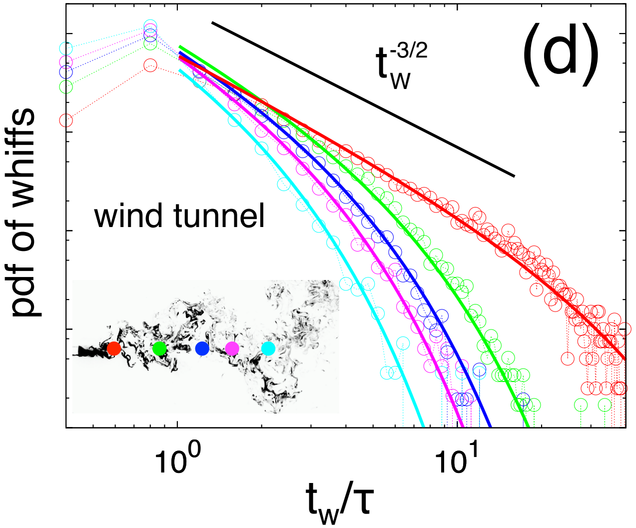
(Celani et al., Phys. Rev. X, ‘14; APS Physics Synopsis)



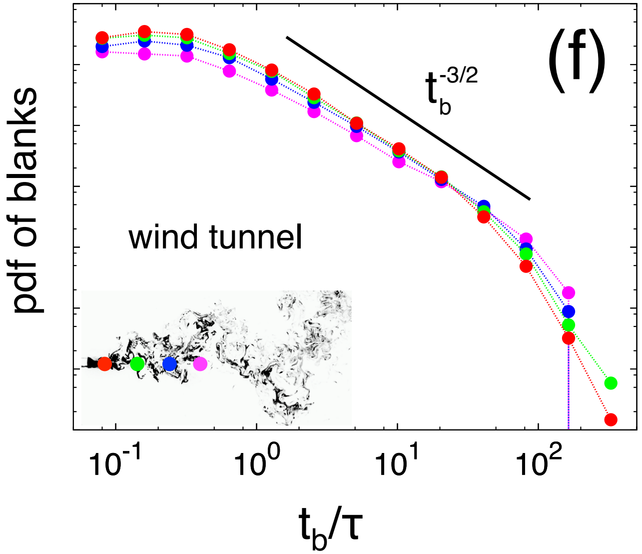


We are interested in the integral over time and the source is larger than the folds. We can try integrating over the internal structure, i.e. track only the size and the position of the puff

Whiff and blank duration

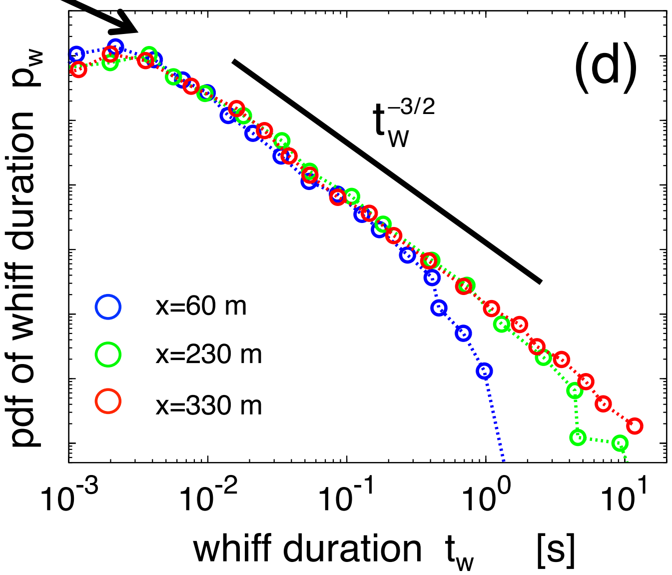


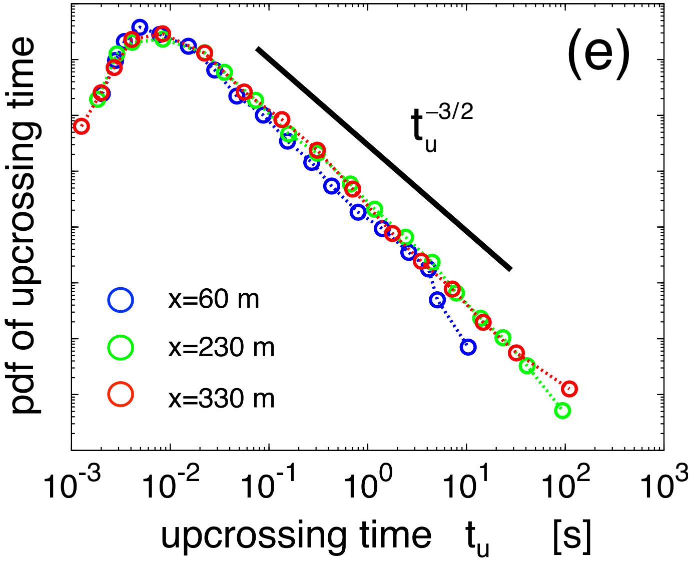
Jet flow



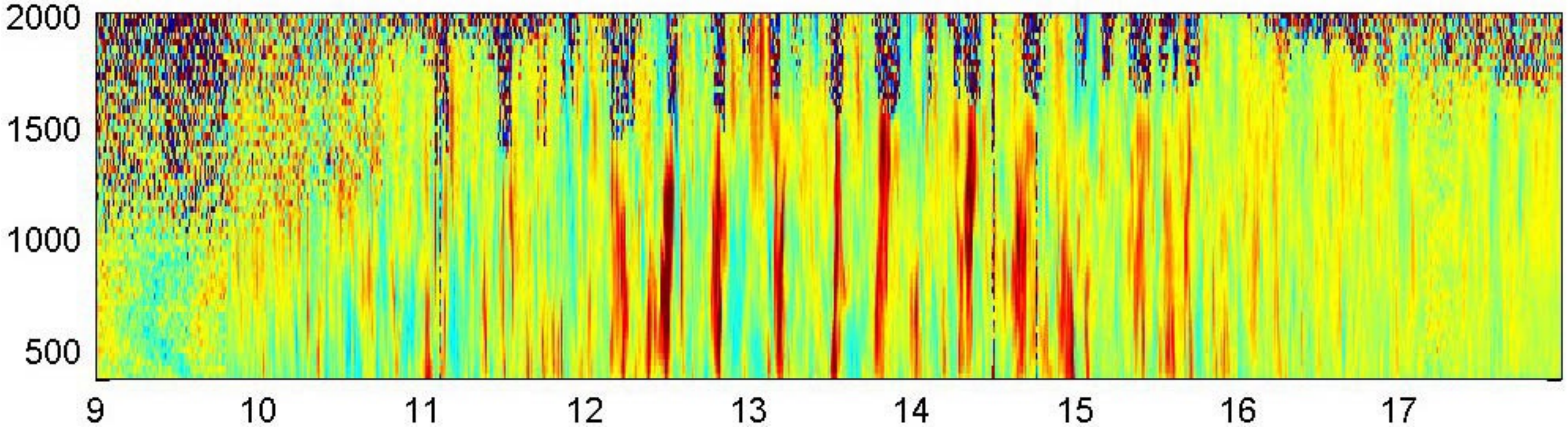
$\tau \sim a^2 U/(v^2 x)$

Atmospheric surface layer

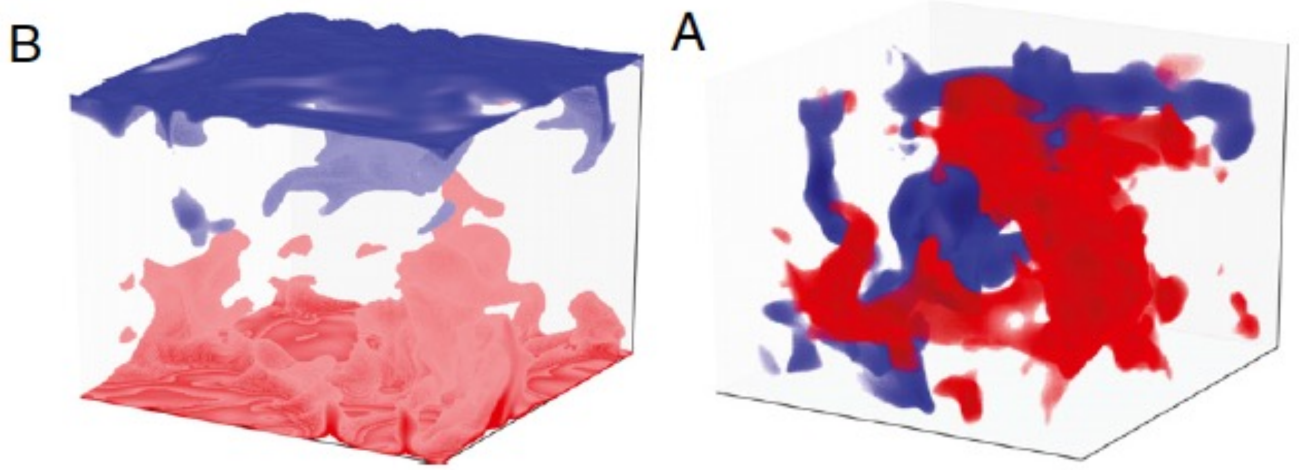




Model turbulent flow (Reddy *et al.*, PNAS, 2016)



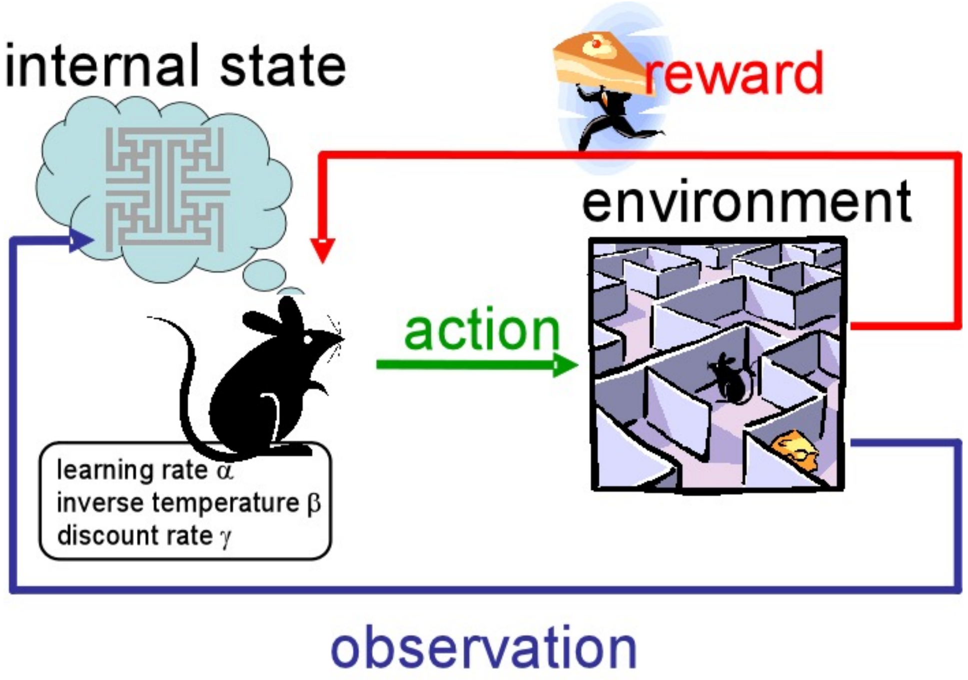
The profile of vertical velocity *vs* hour of the day

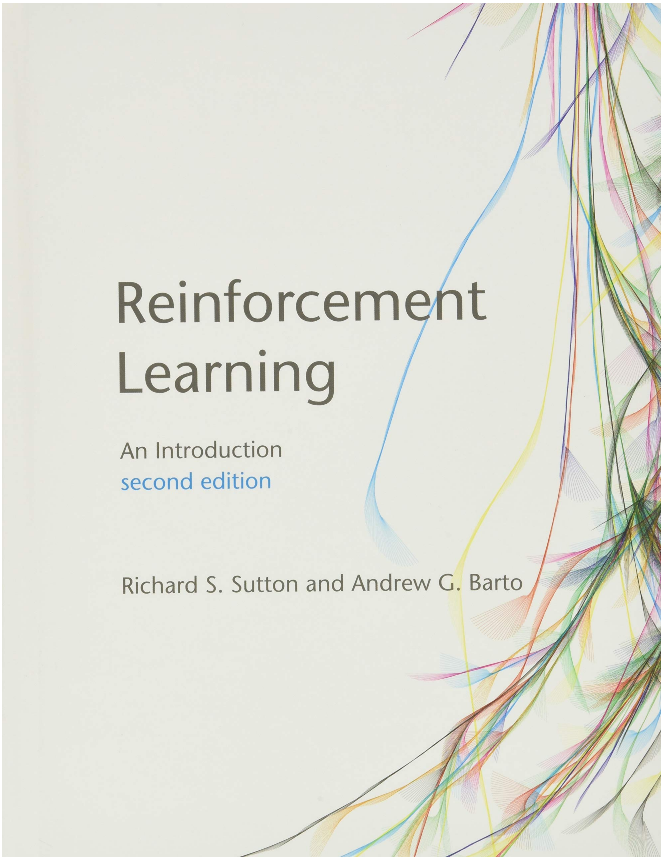


$$\frac{\partial u}{\partial t}+u\cdot\nabla u=-\nabla P+\left(\frac{\mathrm{Pr}}{\mathrm{Ra}}\right)^{1/2}\nabla^2 u+\theta\hat{z},$$

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

Why does Machine Learning, namely Reinforcement Learning, matter?




Reinforcement Learning

An Introduction
second edition

Richard S. Sutton and Andrew G. Barto

An "optimally" behaving agent: the reinforcement learning framework

$$\cdots\cdots \longrightarrow s_t \xrightarrow[a_t]{r_{t+1}} s_{t+1} \xrightarrow[a_{t+1}]{r_{t+2}} s_{t+2} \xrightarrow[a_{t+2}]{r_{t+3}} \cdots\cdots$$

Action-Value : $Q(s_t, a_t) = \underbrace{r_{t+1}}_{\text{reward}} + \underbrace{\beta Q(s_{t+1}, a_{t+1})}_{\text{sum of future rewards}} \,, \quad 0 \leq \beta < 1$

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

Learns empirical statistics and rewards solely through experience

Model-free

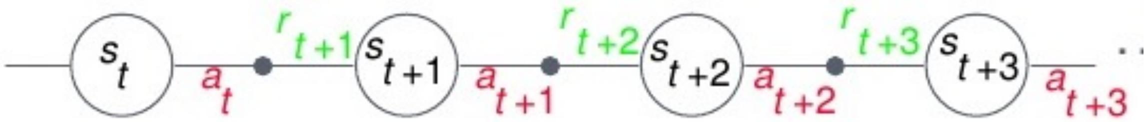
http://www.incompleteideas.net/book/the-book-2nd.html.

(see Section 16.8 p. 453 for thermal soaring)

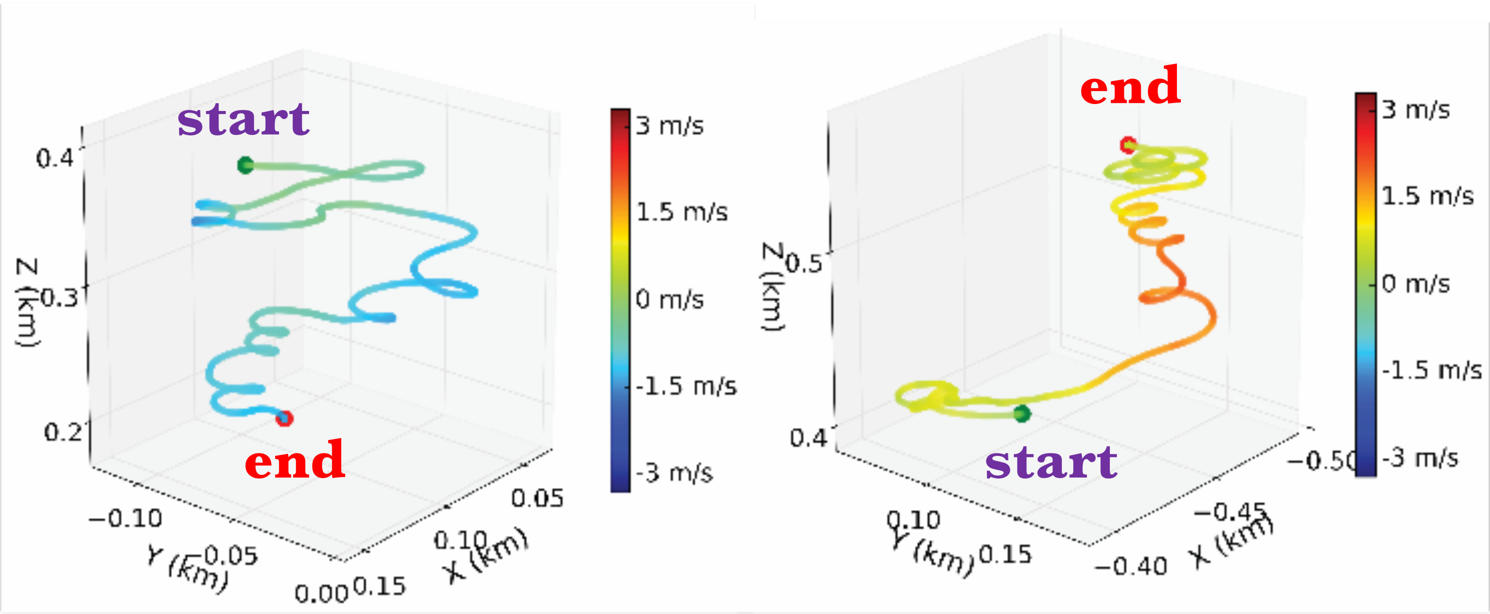
States s — sensorimotor cues + bank angle + angle of attack

Actions a — modify angles

Learning by TD

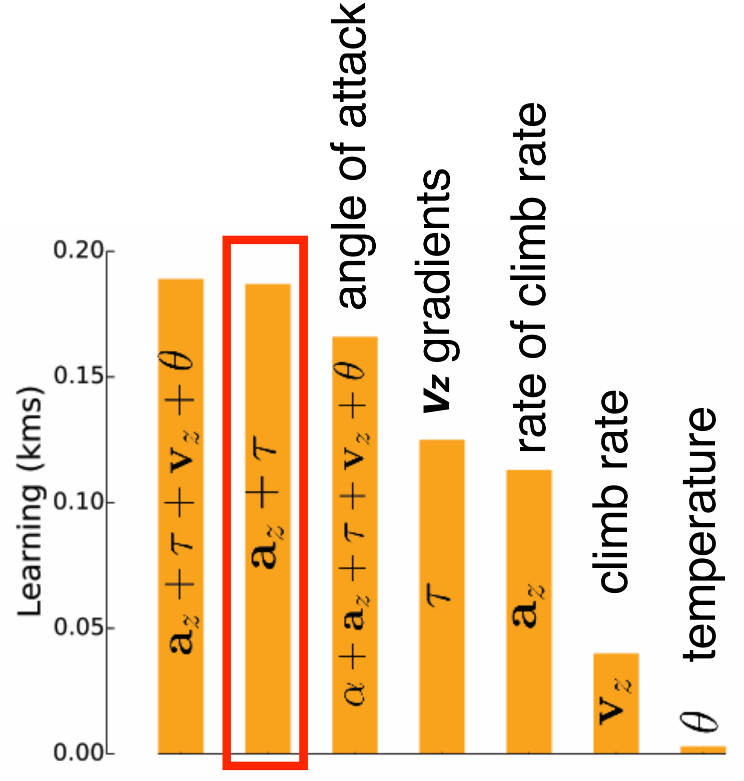


- TD update: $Q(s,a) \rightarrow Q(s,a) + \eta(r + \beta Q(s',a') - Q(s,a))$
- Policy: $\pi_s^a \propto \exp\big(-\hat{Q}(s,a)/\tau\big)$

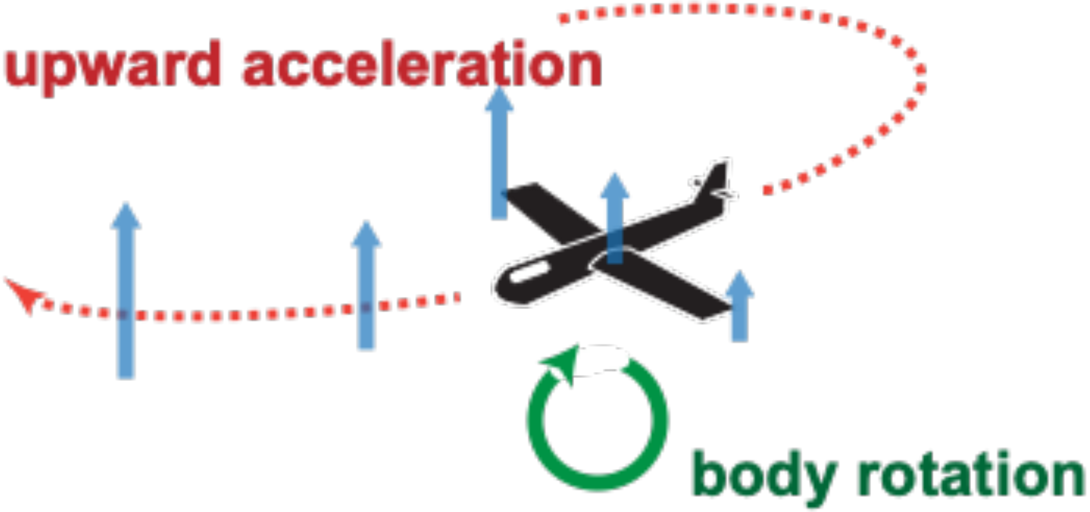


After ~200 5-minute "training episodes" in different simulated thermal environments (Reddy et al., PNAS)

Sensory-motor cues

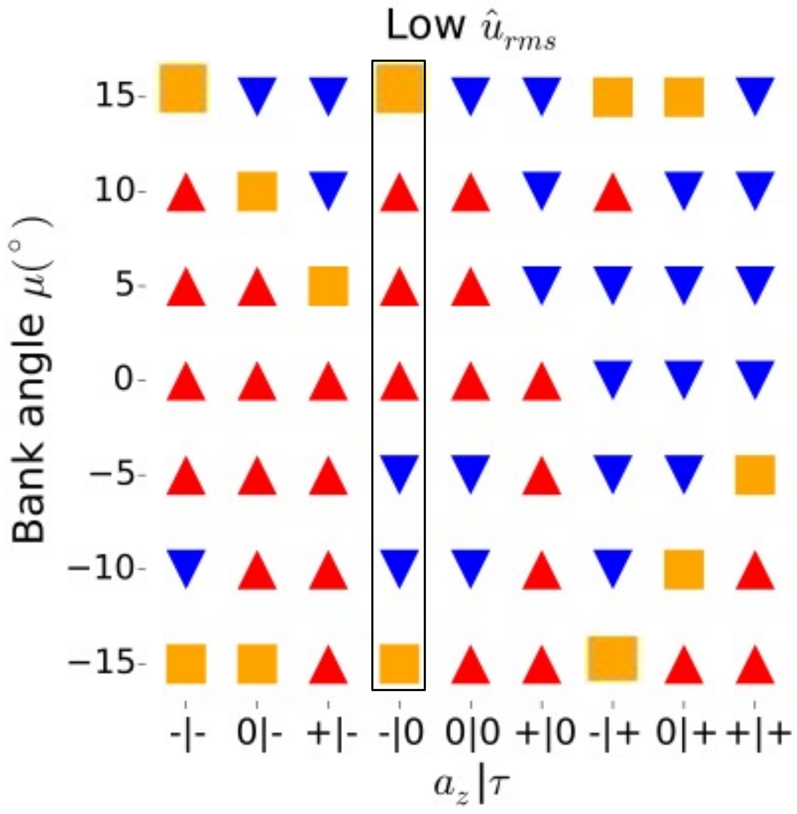


Upward acceleration and body rotation are the most useful cues

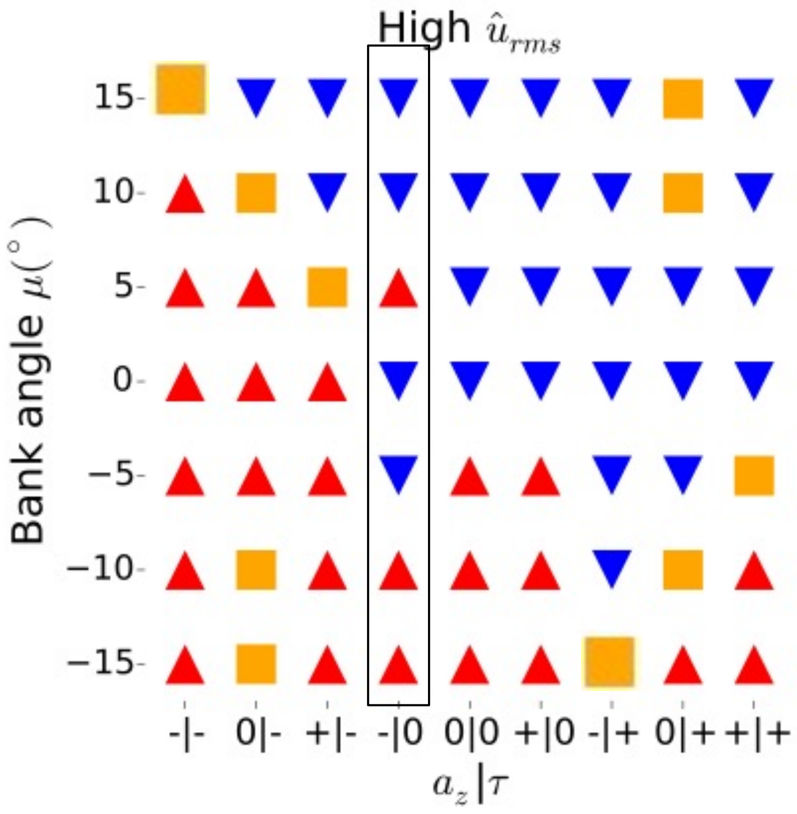


Learned flight policy

Weak fluctuations

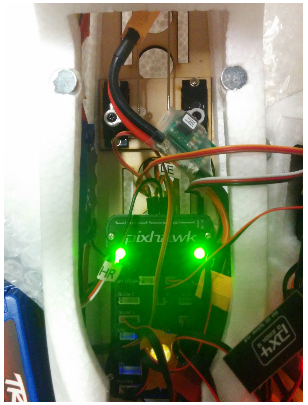


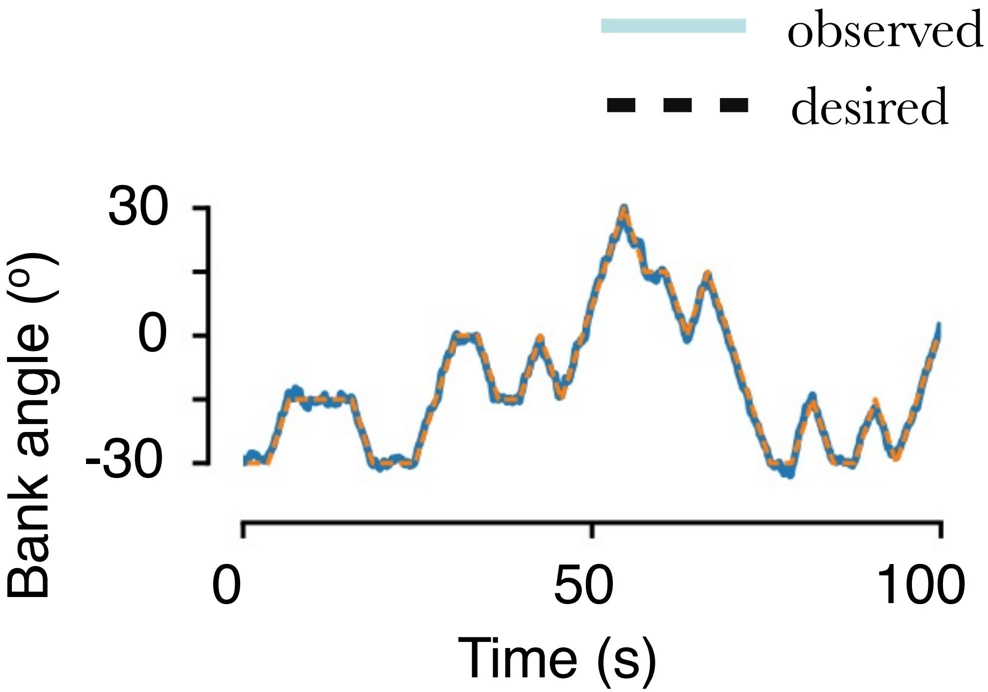
Strong fluctuations



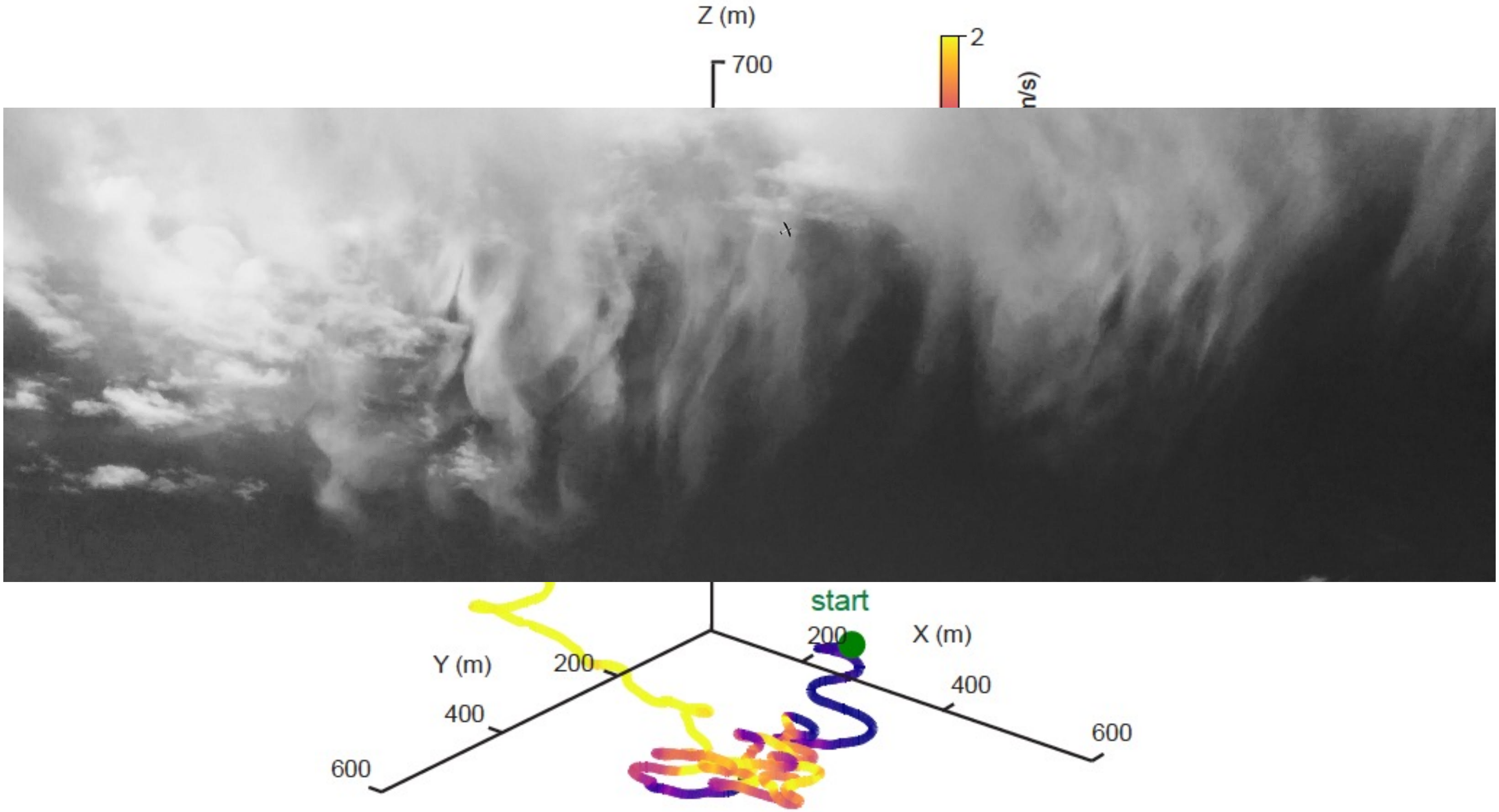
More risk-averse policy for strong fluctuations

In the field (Reddy et al., Nature, 2018)





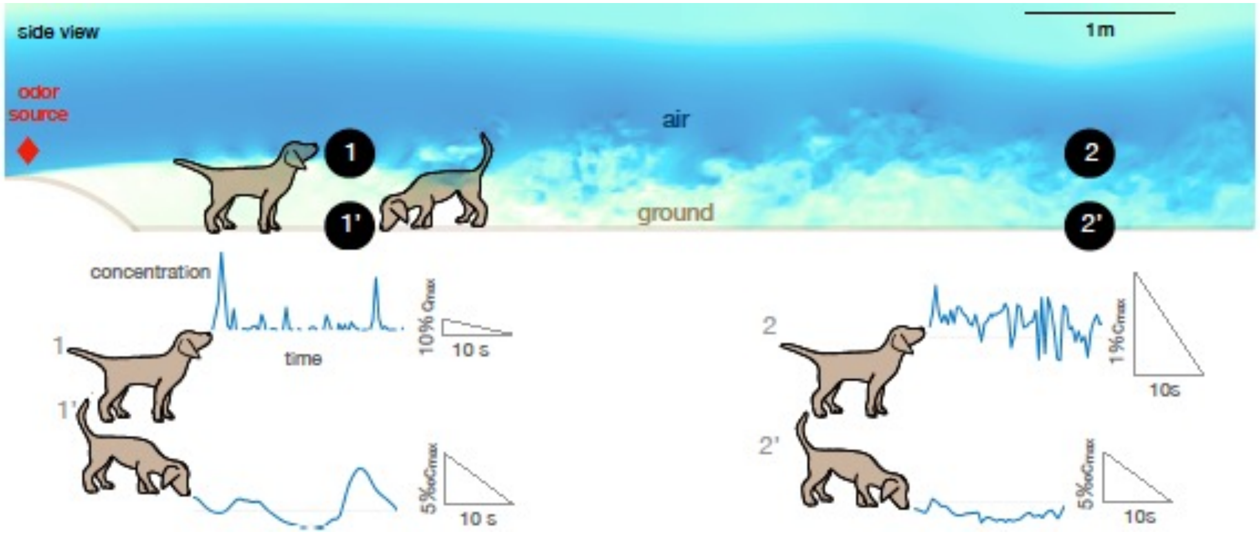
Learning works in the field



Alternation in olfactory searches

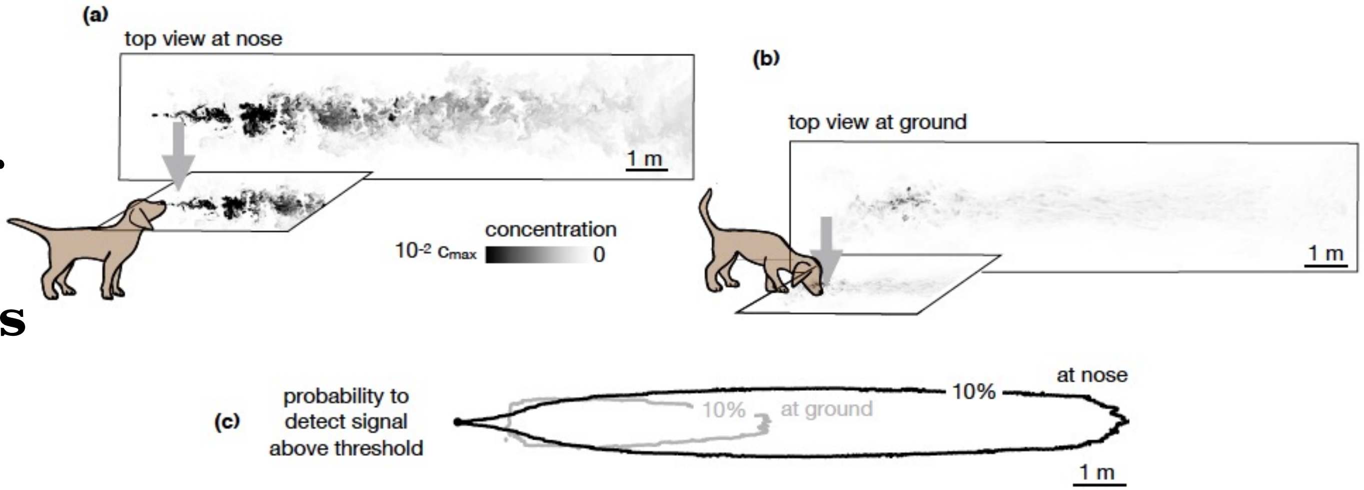
(Rigolli et al., eLife, 2022)

Alternation between sniffing in the air and on the ground



RL and theory to show that

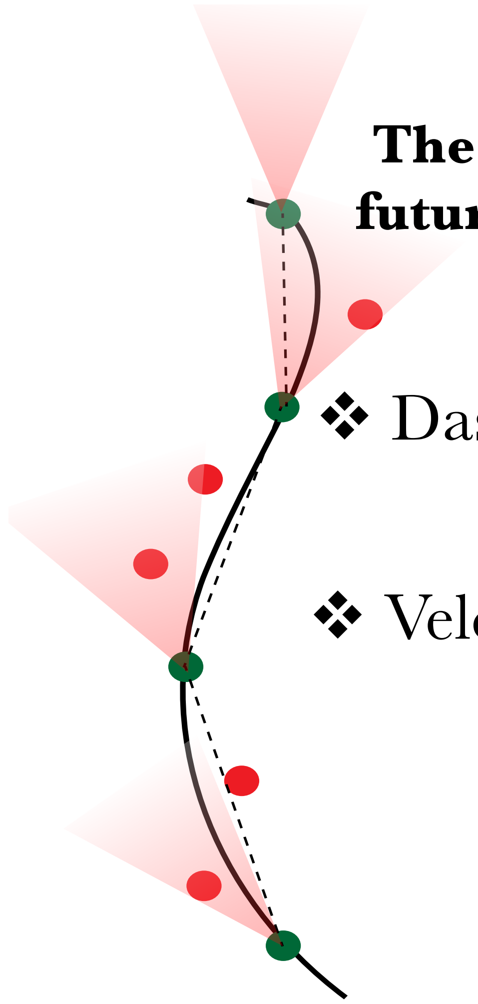
Far downwind of the source, the benefits of higher encounters with rare airborne cues outweigh the cost of pausing its movement.



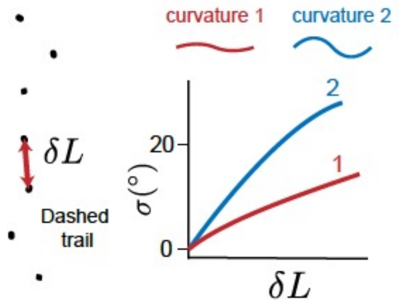
A new paradigm for trail tracking

(Reddy, Shraiman, MV, PNAS, 2022)

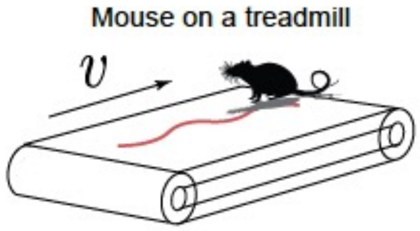
The animal uses past detections to build an estimate of the future trail's heading and searches the corresponding sector

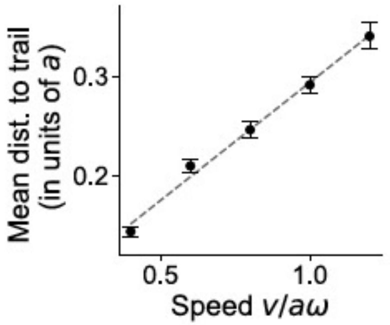


❖ Dashed trails: aperture of the search sector

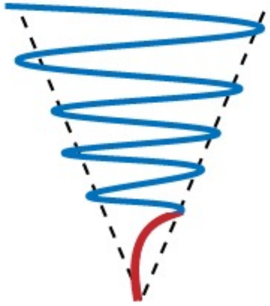


❖ Velocity-accuracy tradeoff





❖ Surge-casting



Time giving up is $\propto$ estimated trail's correlation length

1794
ENS
ÉCOLE NORMALE
SUPÉRIEURE

SIMONS FOUNDATION

cnrs


N. Rigolli (U. Genoa;
ENS Paris)


A. Celani
(ICTP)


V. Murthy
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G. Reddy (UCSD;
Harvard)


B. Shraiman
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Institut
Pasteur)

UC SANTA BARBARA
Kavli Institute for
Theoretical Physics

INSTITUT PASTEUR

NIH
National Institutes
of Health

UCSD

Soaring energetics

$$\dot{E} = \mathrm{v}\left(T - D\right) + mg\mathbf{w}_z - m\mathbf{v}.\frac{d\mathbf{w}}{dt}$$

u ground; **v** air; **w** wind velocities: **u=v+w**

If flapping: $T = D \approx \frac{1}{2}\rho S C_D \mathrm{v}^2$

Steppe eagle

For migration of a 1000km:

$$\Delta E \approx 5000 \text{ kcal}$$

$S \approx 0.5\mathrm{m}^2$

$C_D \approx 0.3$

$\mathrm{v} \approx 15 \text{ m/s}$

$m \approx 2 \text{ kg}$

About 500 grams of fat
> 25% of body mass

G.K.Taylor, K. Reynolds, A. Thomas, Phil. Trans. B, 2016

Measuring vertical wind accelerations

GPS/baro

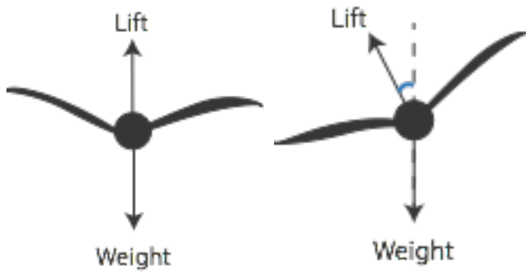
Wind vel.

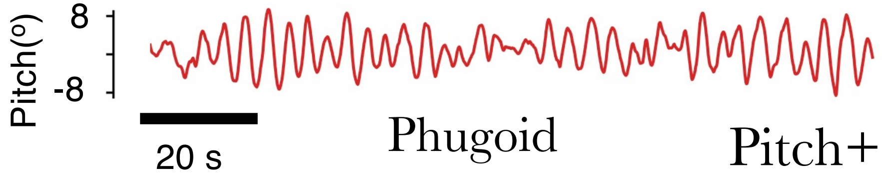
Glider vel.

$$w_z = u_z - v_z$$

Ground vel.

modeling



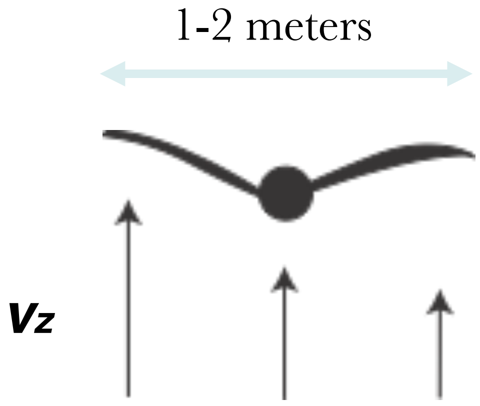


Phugoid

Pitch+angle of attack

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

Measuring vertical wind velocity gradients



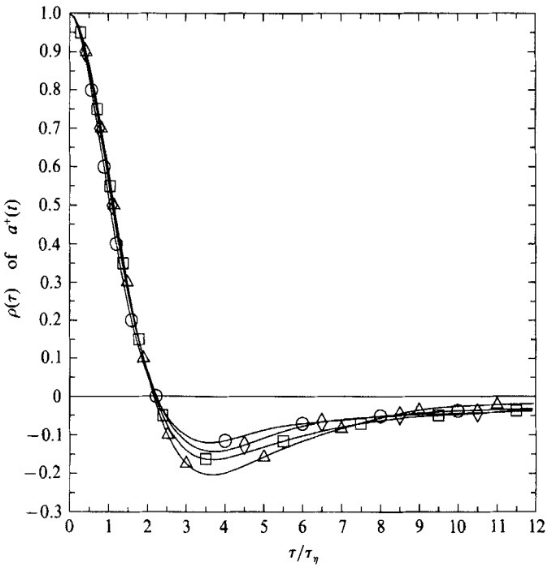
change in bank = feedback control + aerodynamics + wind gradients

Credit assignment and reward shaping

Vertical velocity as a reward would be the natural choice, yet it does not work while vertical accelerations do

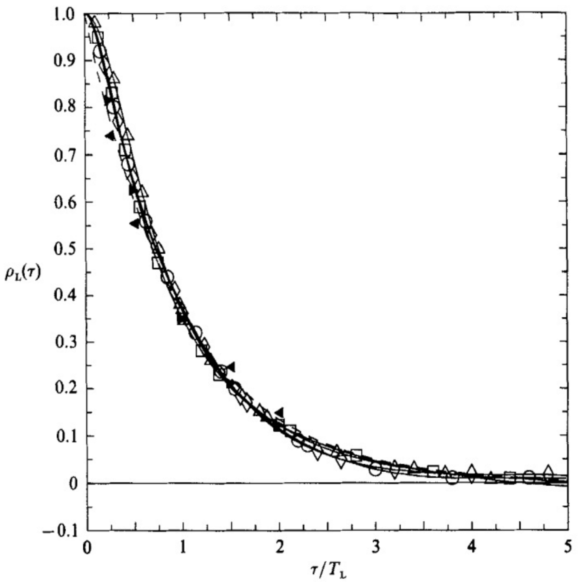
Accelerations

Autocorrelation



t/(kolmogorov scale)

Velocities

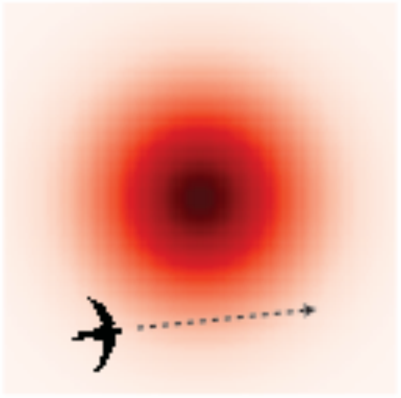


t/(integral scale)

Yeung and Pope, JFM, 1989

Policy optimal for a given reward is also optimal when taking “discrete time derivatives” of the reward

Can a bird sense the relevant cues?



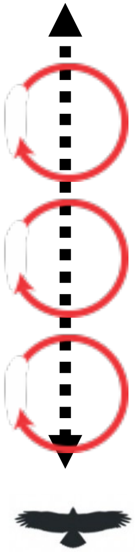
$$\omega \sim l\,?$$

“artistic” view of turbulence

The predicted behavior for torque sensing is $l^{1/6}$ due to the stronger fluctuations generated by bigger eddies over the wingspan as l increases

$$l/l^{1/3} * (VT/l)^{1/2}$$

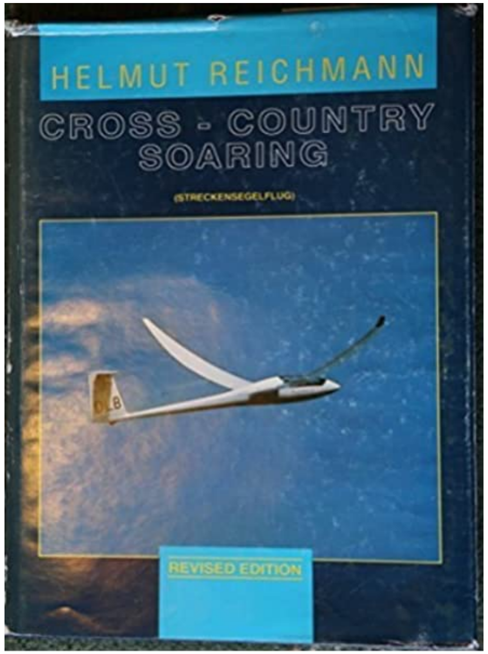
$$\delta v \sim l^{1/3}$$



$$n \sim VT/l$$

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

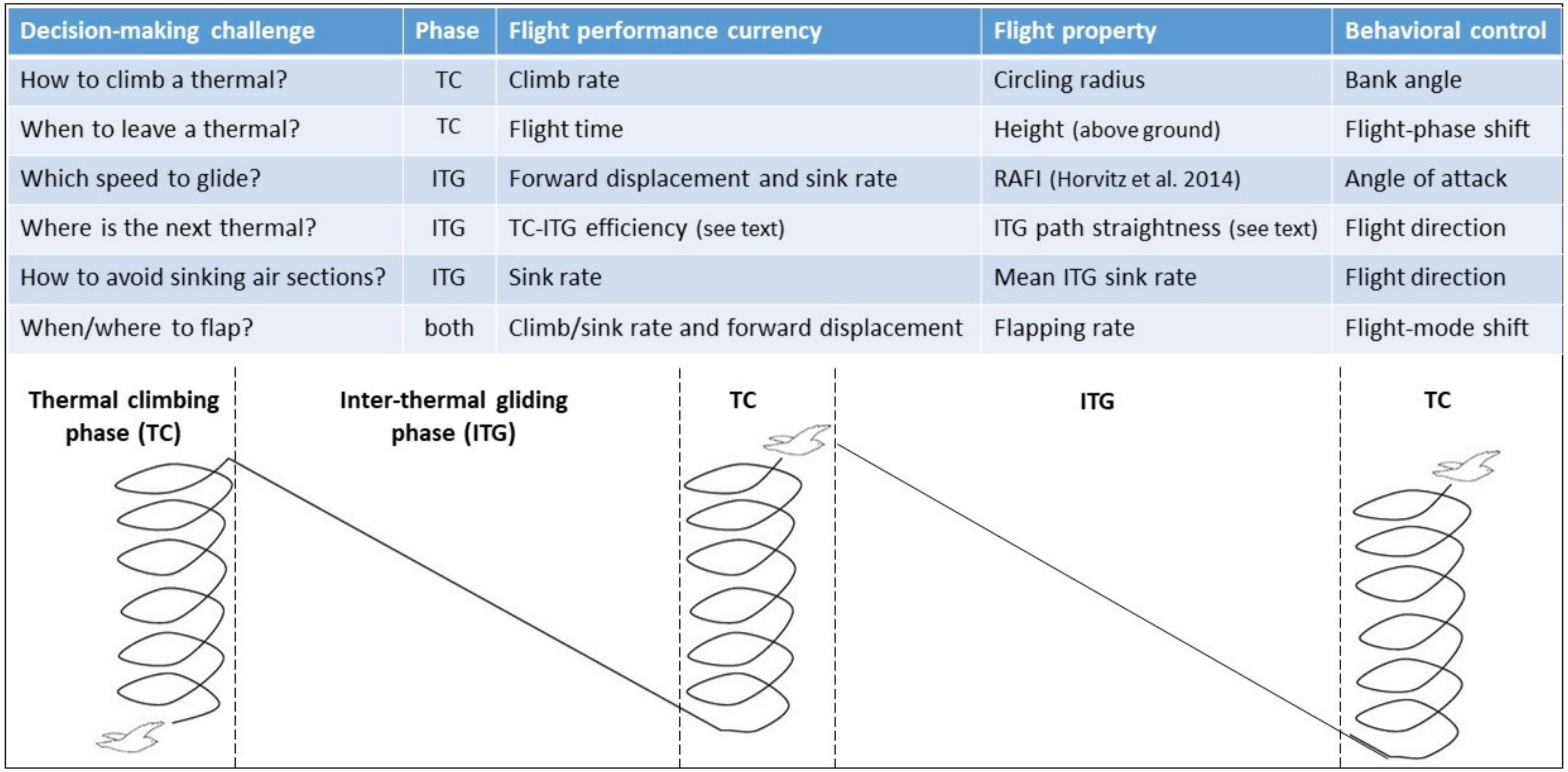
$$\frac{a_z}{\delta a_z} \sim (VT)^{2/3}$$



Cross-country

The goal is not just to stay aloft, but use soaring to fly between two predetermined locations rapidly and without engine (or using it as little as possible)

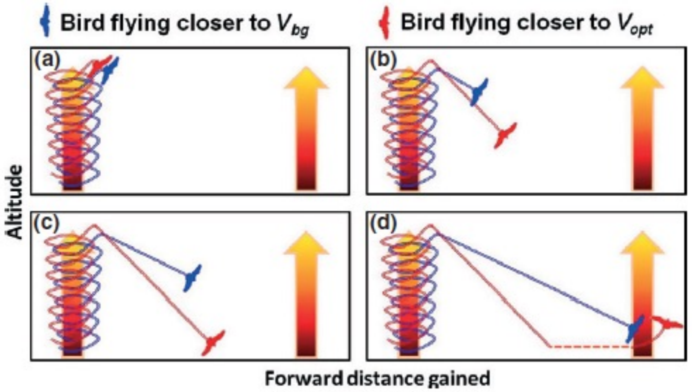
With Mirko Indumi, William Stewart & Davide Zambrano at EPFL



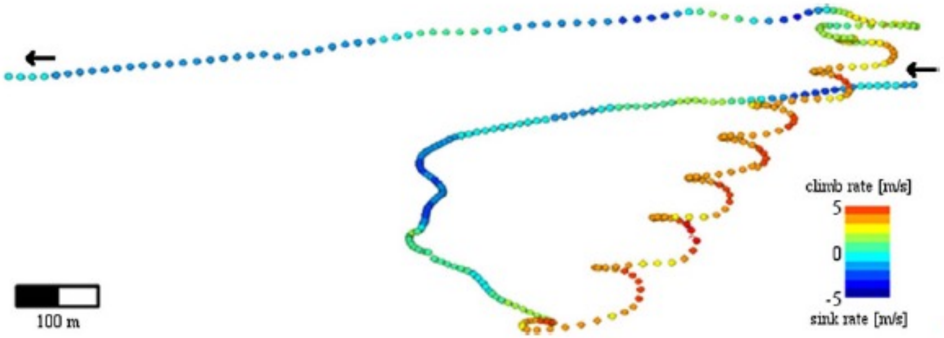
Decision-making challenge	Phase	Flight performance currency	Flight property	Behavioral control
How to climb a thermal?	TC	Climb rate	Circling radius	Bank angle
When to leave a thermal?	TC	Flight time	Height (above ground)	Flight-phase shift
Which speed to glide?	ITG	Forward displacement and sink rate	RAFI (Horvitz et al. 2014)	Angle of attack
Where is the next thermal?	ITG	TC-ITG efficiency (see text)	ITG path straightness (see text)	Flight direction
How to avoid sinking air sections?	ITG	Sink rate	Mean ITG sink rate	Flight direction
When/where to flap?	both	Climb/sink rate and forward displacement	Flapping rate	Flight-mode shift

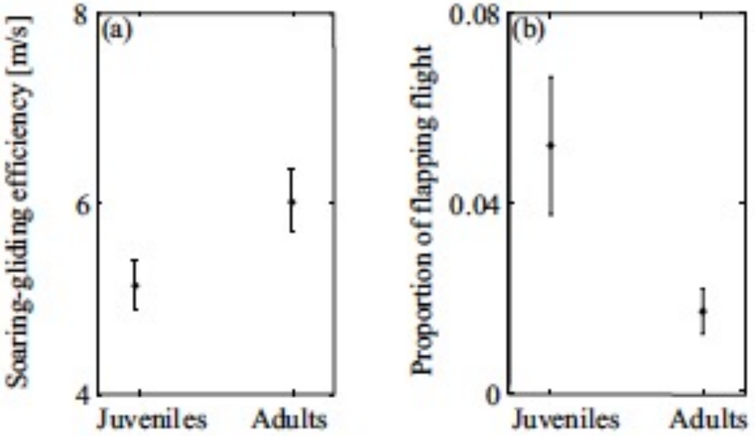
Birds

Williams et al. 2018 JEB



Horvitz et al. Ecology Lett., '14



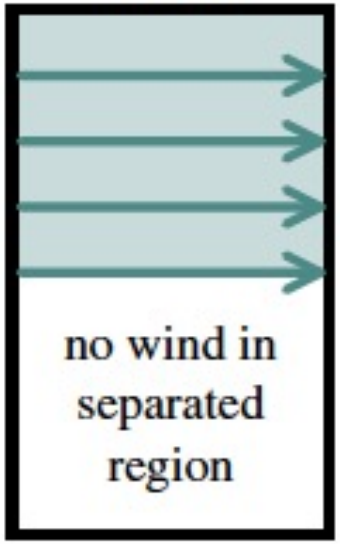


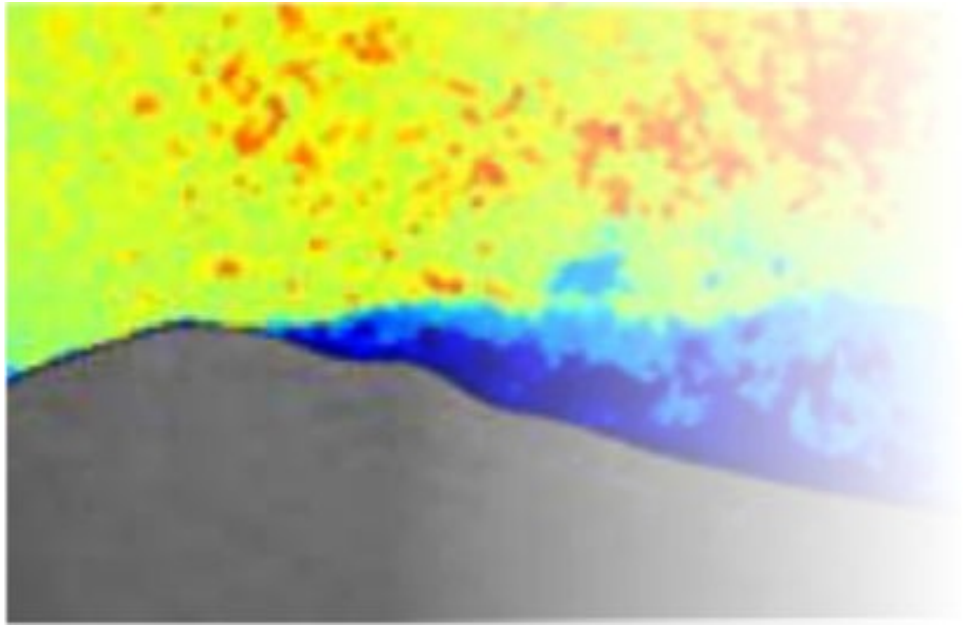
Adult vultures outperform juveniles in challenging thermal soaring conditions

Roi Harel, Nir Horvitz & Ran Nathan

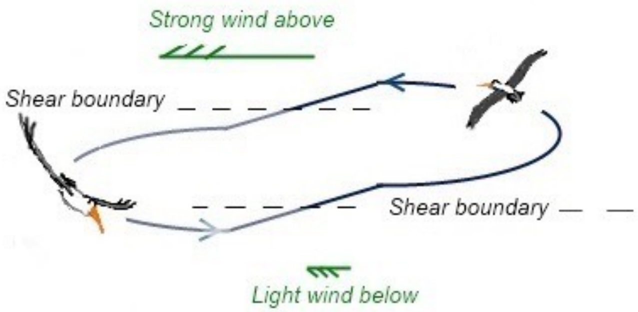
Dynamic soaring

Rayleigh model





Rayleigh Cycle



Rayleigh, Nature, 1883
Richardson, Progr. Oceanography, 2011
Bousquet et al, J. R. Soc. Interface, 2017

Learning works in the field as well