T Symmetry and Its Violation

Part 4: P and T in Biology

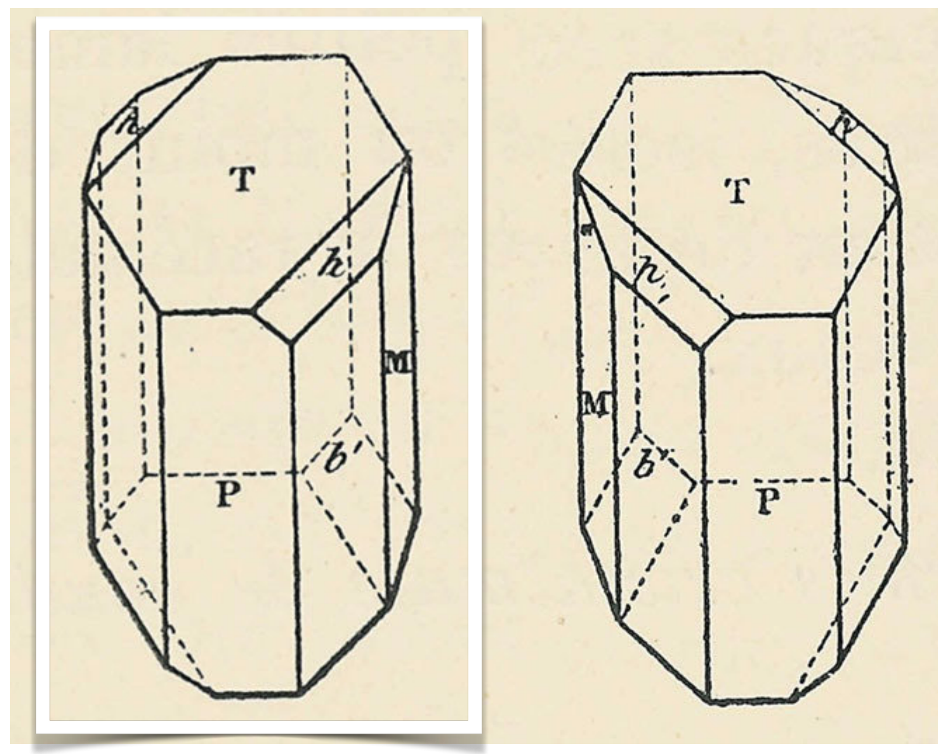
(1) Parity in Biology

An Instructive and Inspiring Story

(1a) Pasteur

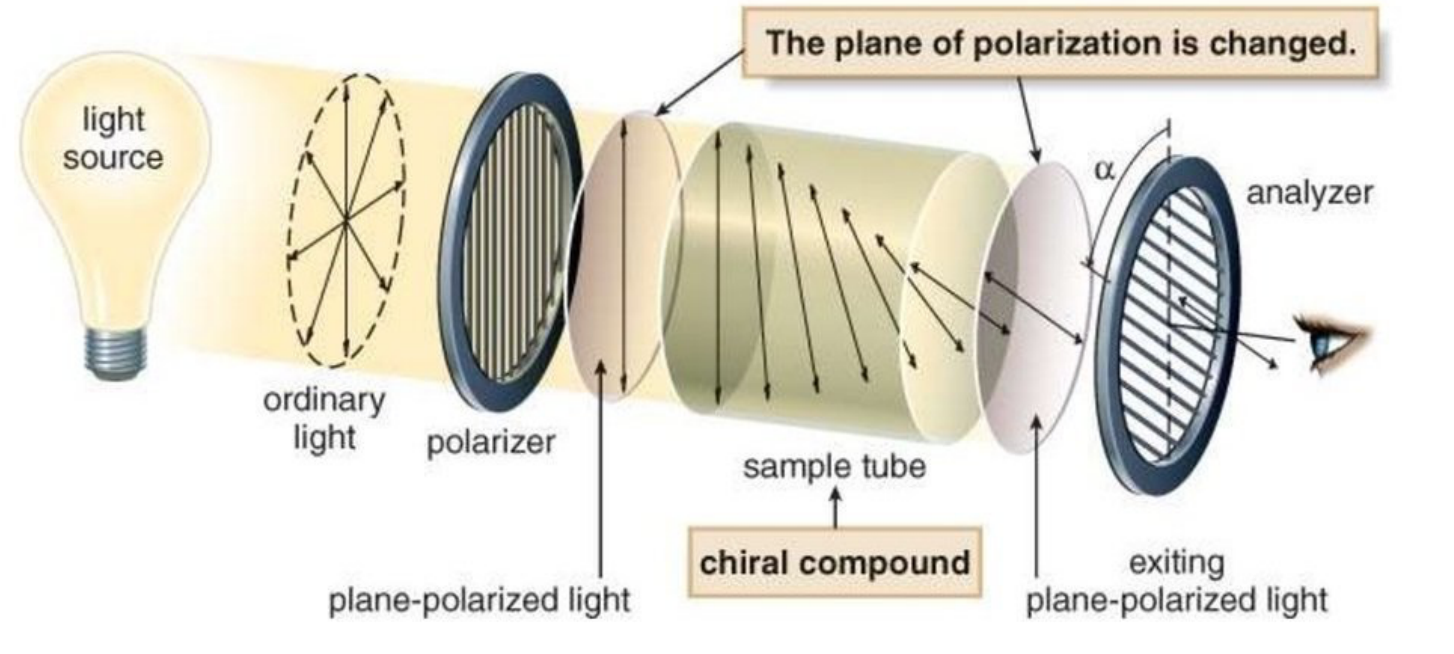
Wine, Crystallization and Optical Activity

The fact that biological systems generally work with molecules of a specific chirality was a famous discovery of Pasteur.



Anti-Racemic Crystallization

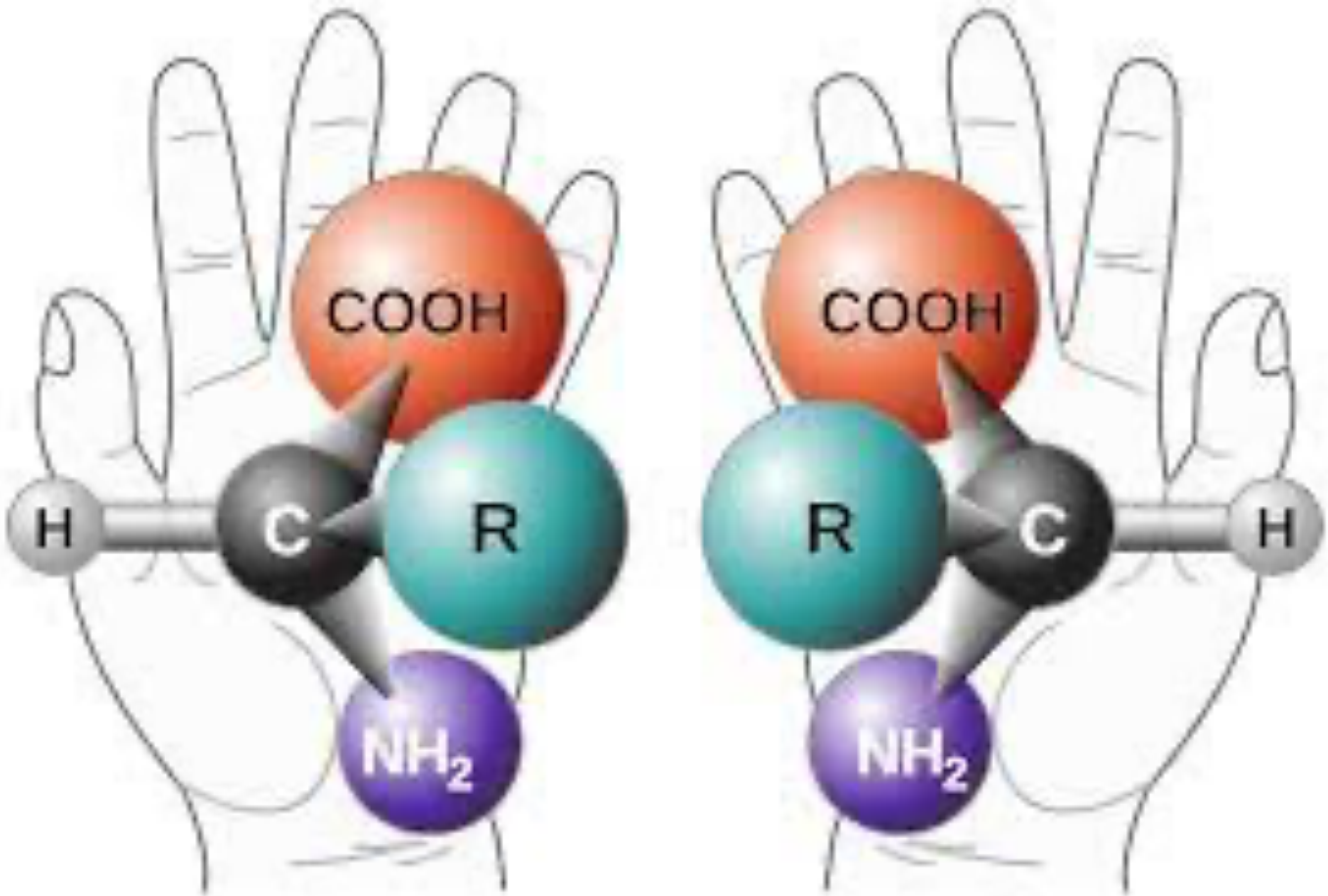
Pasteur also pioneered the study of optical activity.

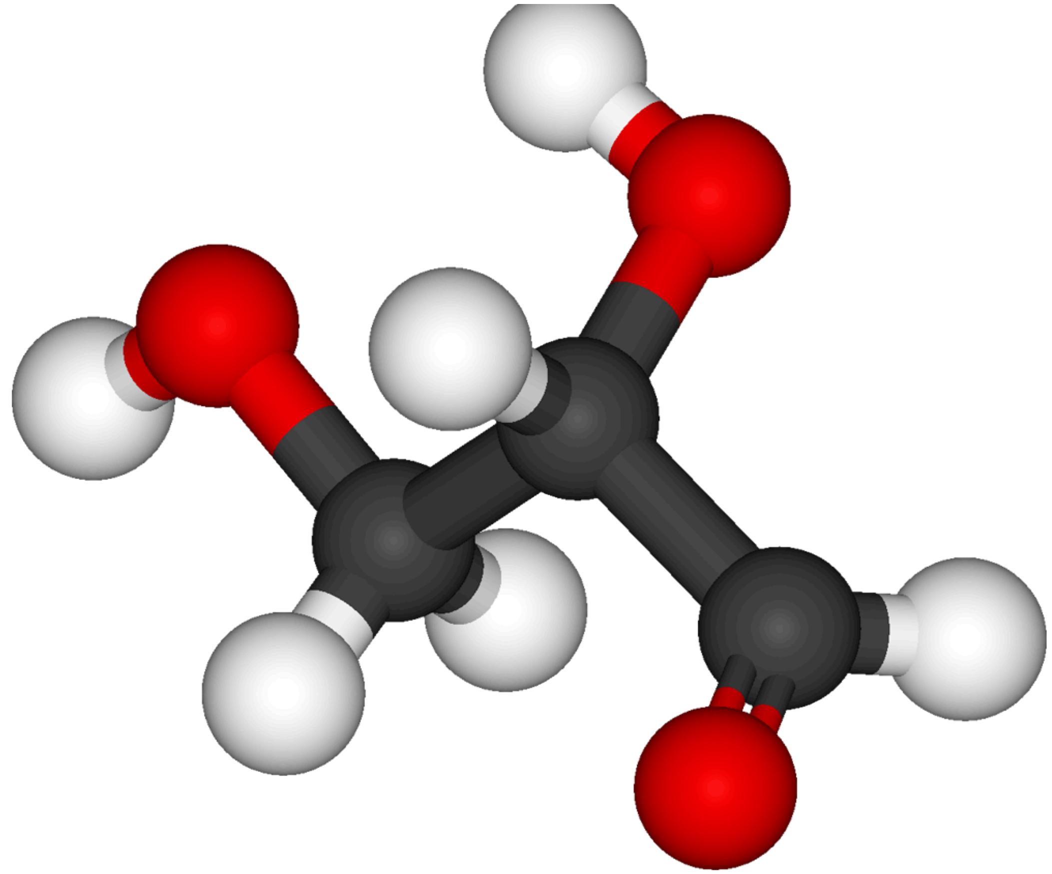


Optical Activity: A Signature of P Violation

(1b) Chirality in Biology: Phenomena

Examples and Universality


COOH
H
C
R
NH2
COOH
R
C
H
NH2



All the amino acids other than glycine ($R \to \{\,\}$) are chiral, and only one enantiomer of each is widely utilized in proteins throughout the biological world. The preferred forms all can be synthesized using L glyceraldehyde, shown above.

The universality of biological chirality makes sense, intuitively, if we think of biology as an industrial economy.

It useful to have universal agreement about what sort of screws to use!

“Dissenters” will lack infrastructure, and it will be hard for them to compete.

This is an example of competitive symmetry breaking.

Chirality is passed on from generation to generation, in the form of templates that govern early development.

Though parity is (weakly) broken in fundamental law, no one has made a convincing connection between that small effect and biological chirality, and to me the existence of such a connection seems far-fetched.

More reasonable, but seemingly less explored, is the hypothesis that parity breaking in local conditions (e.g., magnetized mineral substrate) at the unique origin of existing life favored one isomer in some key process.

(Here the CISS effect, discussed below, is instructive.)

(2) T Violation in Biology?

A Beautiful Question

(2a) Posing the Question

Definition and an Important Contrast

Clearly, there is a strong sense in which “Biology Breaks P”.

What do we mean, more precisely, by biological P breaking?

- *Systematic choice of one chirality of an enantiomer for a given use, in a significant piece of the living world.*

Note: This is generally not the molecular ground state. (Formally, that is the superposition.) Nevertheless the choice is stable, because of the watched kettle effect - or, in our preceding language - environmental selection of interaction states.

By analogy, (hypothetical) biological T breaking would be

- *Systematic choice of one of a pair of* T *related molecules (or systems) for given use, in a significant piece of the living world.*

(2b) Biomolecular T Violation: Utility

Sensing and Storage

Evolution of biomolecular T violation makes sense, intuitively, if we think of biology as an industrial economy. It could be useful to have universal agreement about what kind of clocks to use!

(Do the hands progress clockwise, or anti-clockwise?)

Of course, biology manifestly violates time-reversal symmetry in very big ways: development, evolution, adaptive behavior, … .

Most or all of this T-violation can be traced to entropy and energy gradients, ultimately driven by the Sun's radiance.

Much less obvious is the role, if any, of non-dissipative T breaking, occurring at the molecular level

More specifically, it can be handy to have labelled compass needles, for magnetic field sensing.

Perhaps more profoundly, correlation of moments would facilitate transfer of information between “charge world” and “spin world”.

That can be useful, because those worlds bring in different strengths and weaknesses.

Broadly speaking, charge world is good for processing while spin world is good for storage.

We see precisely that division of labor in many computer architectures: charge-based bits in the processor, spin-based bits in the memory.

(2c) Biomolecular T Violation: Possible Embodiment

Templates and Copying

For heredity, and in general to have a stable references, we need templates …

Multiferroics will do the trick!

Thus, it is suggested to look for the occurrence of preferred Tisomer multiferroics …

… together with machinery for using them as templates, and for passing (seeds for) them on in heredity.

(2d) Biomolecular T Violation: Signatures

The Reveal

We’ve discussed several possible “scalable” signatures already, in Part 3.

Of course, those observable effects can be downstream of heredity and imprinting by templates, so they do not require identification of natural Tisomeric ferroelectrics, and could involve evanescent Tisomers.

(3) Adjacent Phenomena: Magnetic Navigation

An Ancient Achievement, Still Evolving

(3a) Magnetotactic Bacteria

Labelled Compasses!

Figure 2: TEM image of a magnetotactic bacterium

Note the chain of twelve magnetite (Fe_3O_4) nanoparticles that are arranged along the long axis of the cell. The magnetic magnetite chain allows the organism to behave as a tiny motile compass needle. Scale bar is provided in the lower right corner.

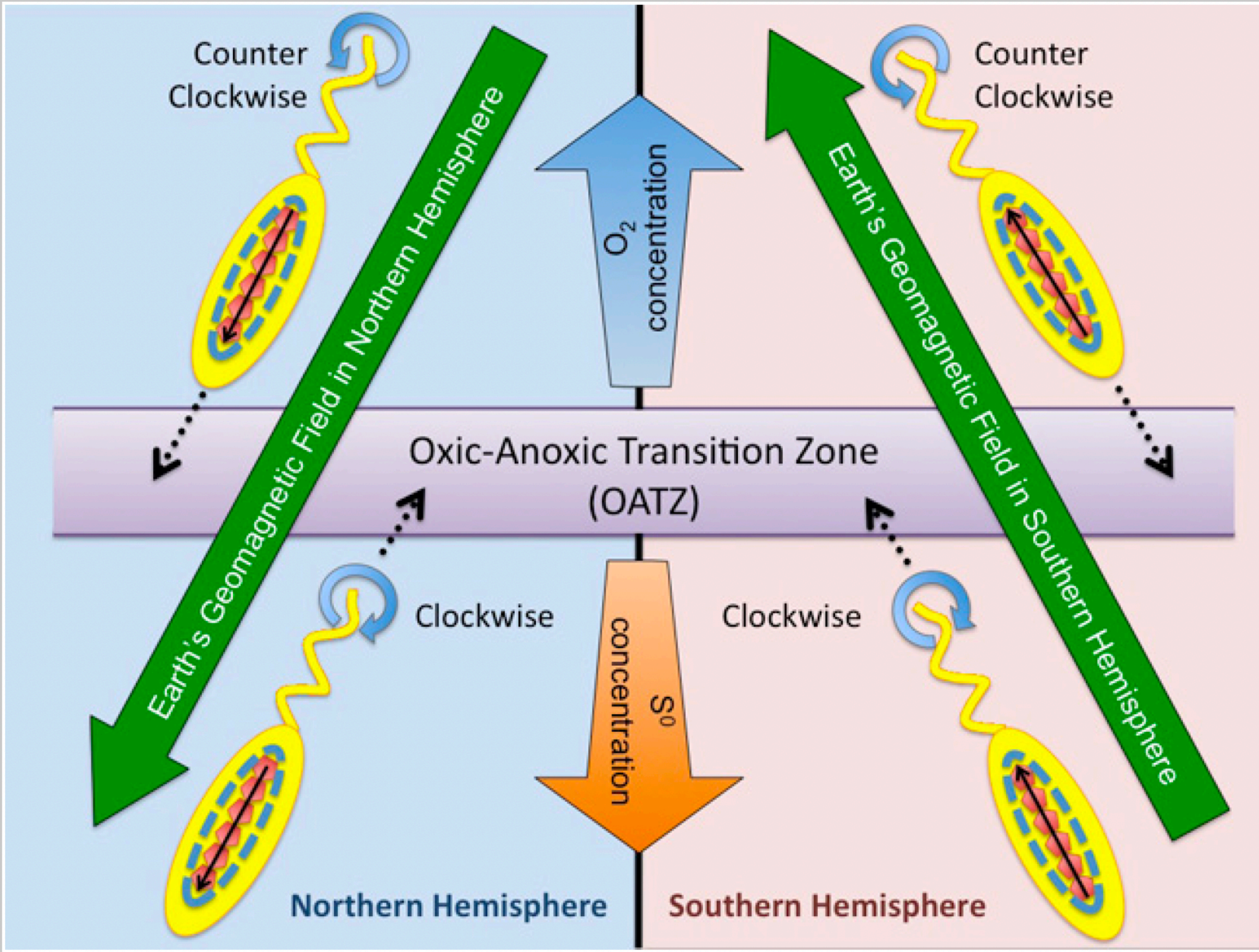
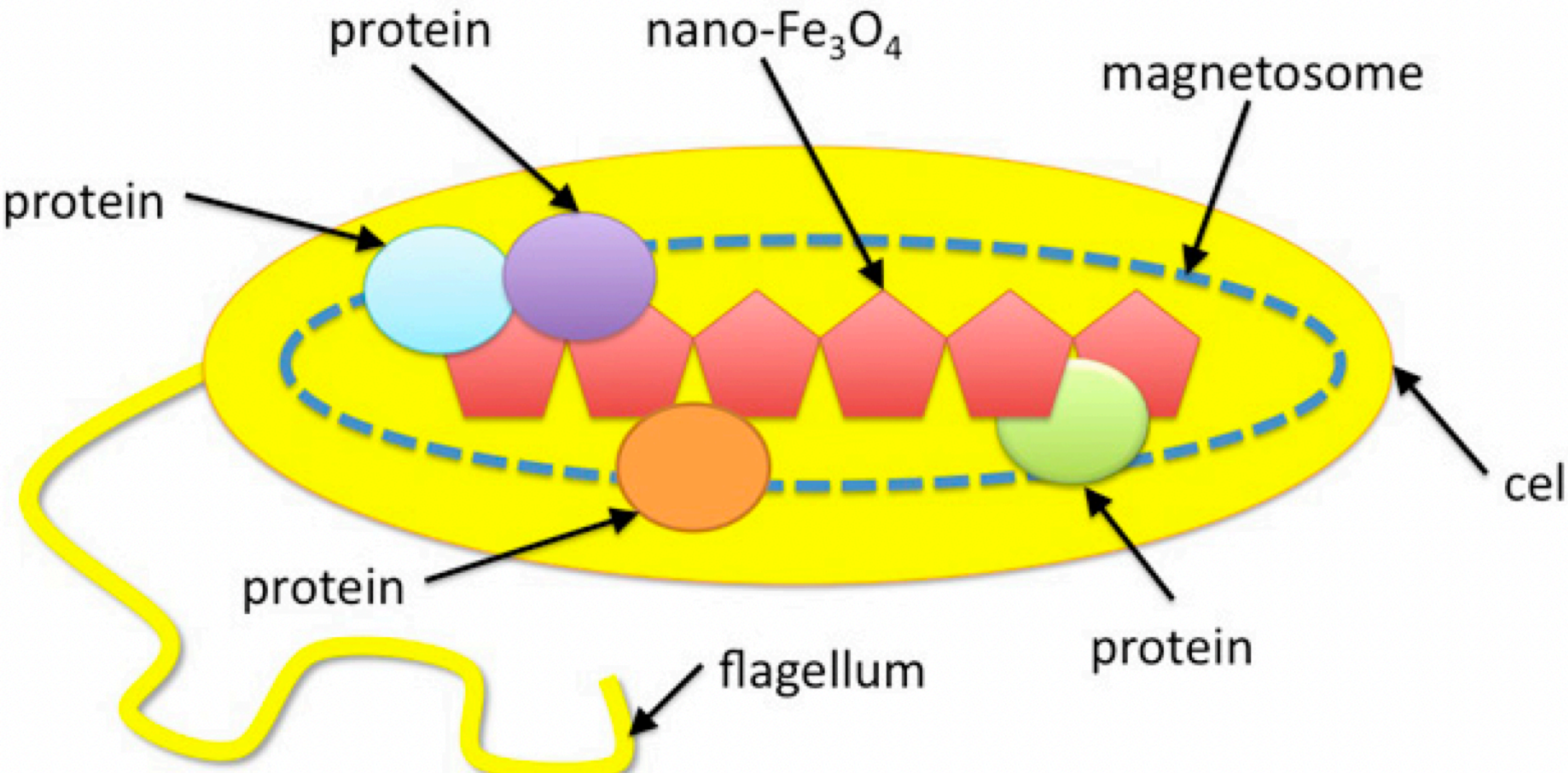


Figure 3: Diagram showing how magnetotactic bacteria use magnetotaxis to swim to the OATZ in the Northern versus the Southern Hemisphere on Earth



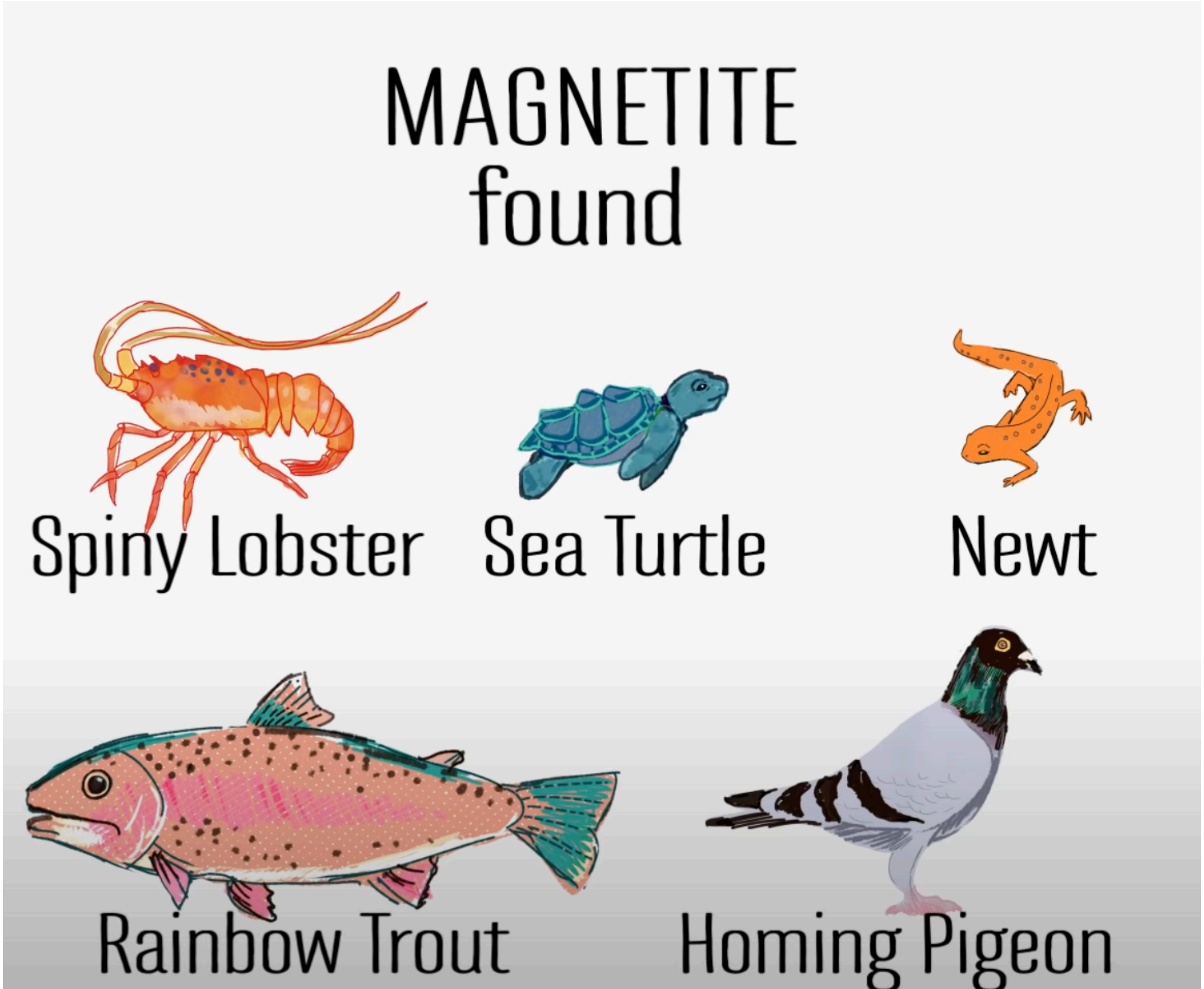
A *Labelled* Magnetic Moment!

A few noteworthy aspects of bacterial magnetotaxis:

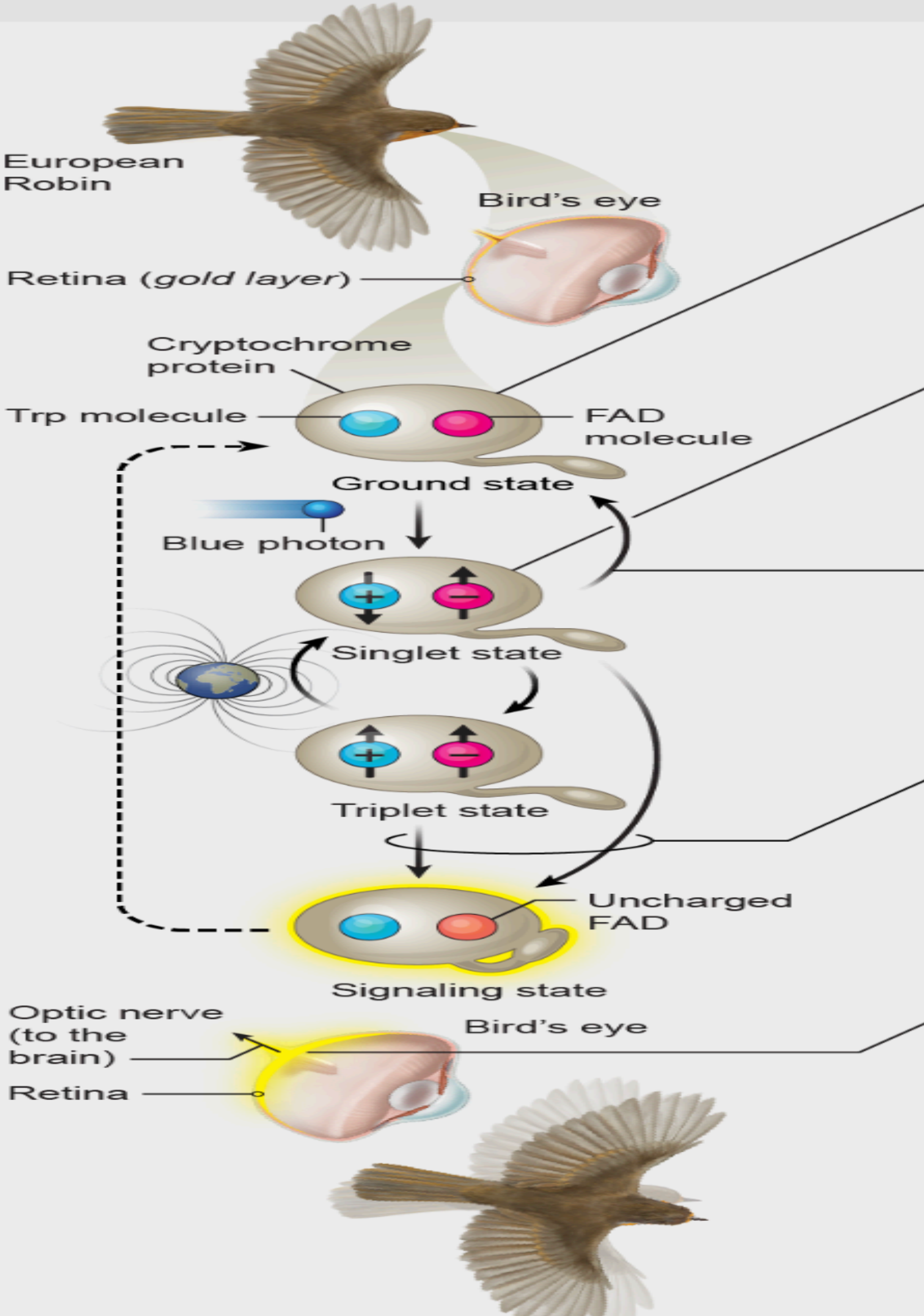
- Uses magnetite (Fe_3O_4), the most powerful naturally occurring ferromagnetic material.
- Product engineering is very efficient - high purity, uniform size!
- Use by “primitive” prokaryotic organisms to achieve anoxic environments suggests a very early evolutionary origin.
- Iron is used as a cofactor in many important pathways, throughout the biological world, often in closely related (but different packaged) forms.

(3b) Magnetic Navigation in Complex Animals

Bringing in Brains - and Quantum Chemistry?


MAGNETITE
found
Spiny Lobster
Sea Turtle
Newt
Rainbow Trout
Homing Pigeon

Studies suggest that the magnetic compass of migratory birds relies on quantum effects in short-lived molecular fragments known as radical pairs that are formed photochemically in the eyes. In this way, the birds can perceive Earth's magnetic field lines and use that information to navigate their long-haul trips.



1. Cryptochrome proteins—located in the retinal cells of the bird's eye—include a flavin adenine dinucleotide molecule (FAD) and a tryptophan amino acid (Trp). In the stable state, these molecules are electrically neutral, and a small section of the protein probably extends like a tail.

2. When a photon of blue light hits the cryptochrome, an electron jumps from the Trp onto the FAD. The resulting molecules—each with an odd number of electrons—are known as a radical pair. In this singlet state, the molecules' unpaired electrons spin in opposition.

3. The activated protein oscillates rapidly back and forth between the singlet state and the triplet state, in which the unpaired electrons spin in parallel. Earth's magnetic field influences the spin, impacting the likelihood of each state dominating.

4. Both states can undergo chemical reactions that transform them into the "signaling state"—in which a hydrogen ion has been added to the FAD radical—and the tail seems to move closer to the body of the protein. The singlet state can also simply return to the ground state. The proportion of outcomes depends on the bird's orientation in Earth's magnetic field.

5. The signaling state of the cryptochrome turns on a biochemical cascade that triggers the release of neurotransmitter molecules in the retina. Signals continue to the bird's brain, where the magnetic information they contain is integrated with information from other directional cues, informing the direction of the bird's flight.

6. Cryptochrome returns to its ground state, and the process starts again (*dashed arrow*).

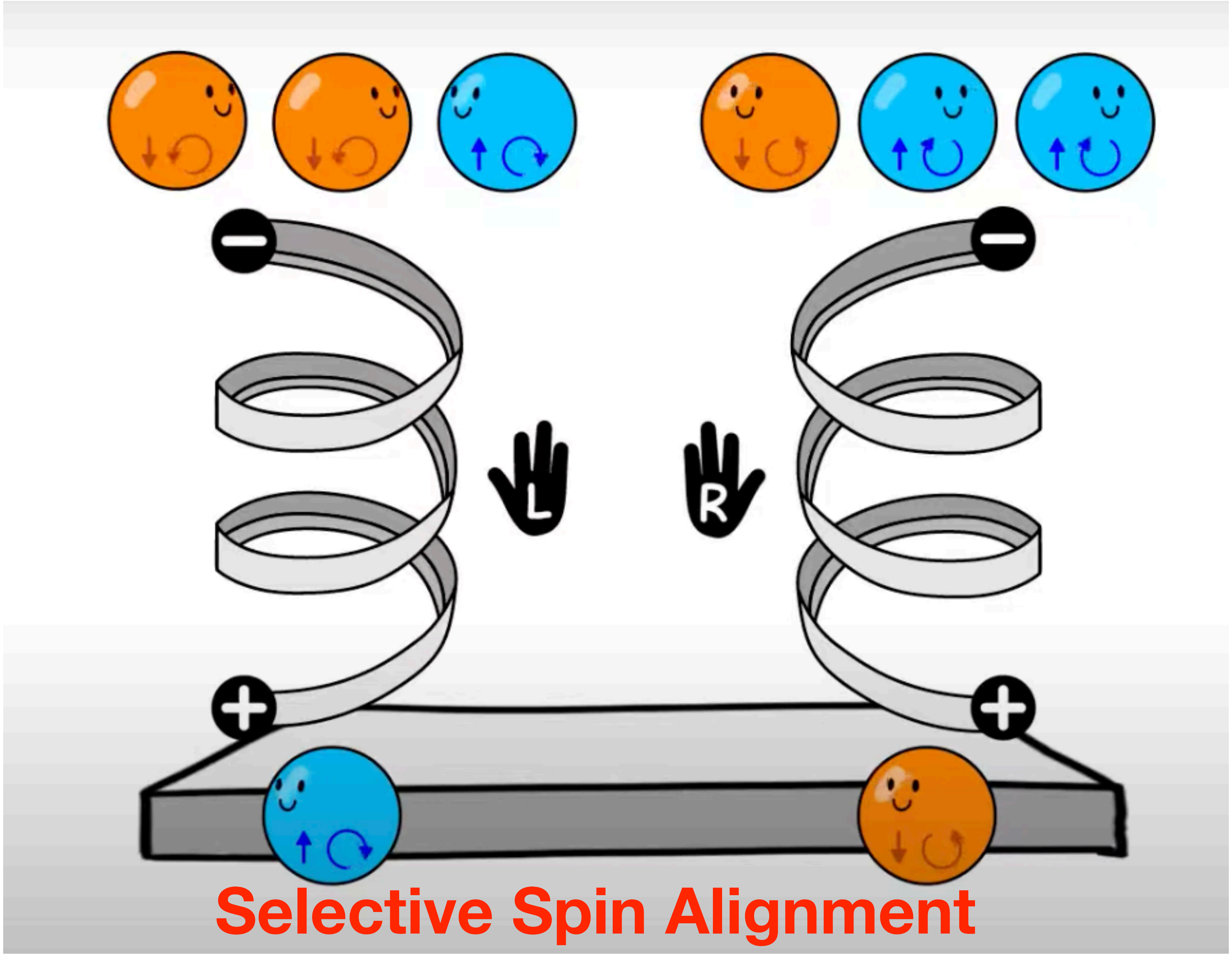
(3c) Humans?

youtube.com/watch?v=tdXb_4EkYtU&ab_channel=ScienceMagazine

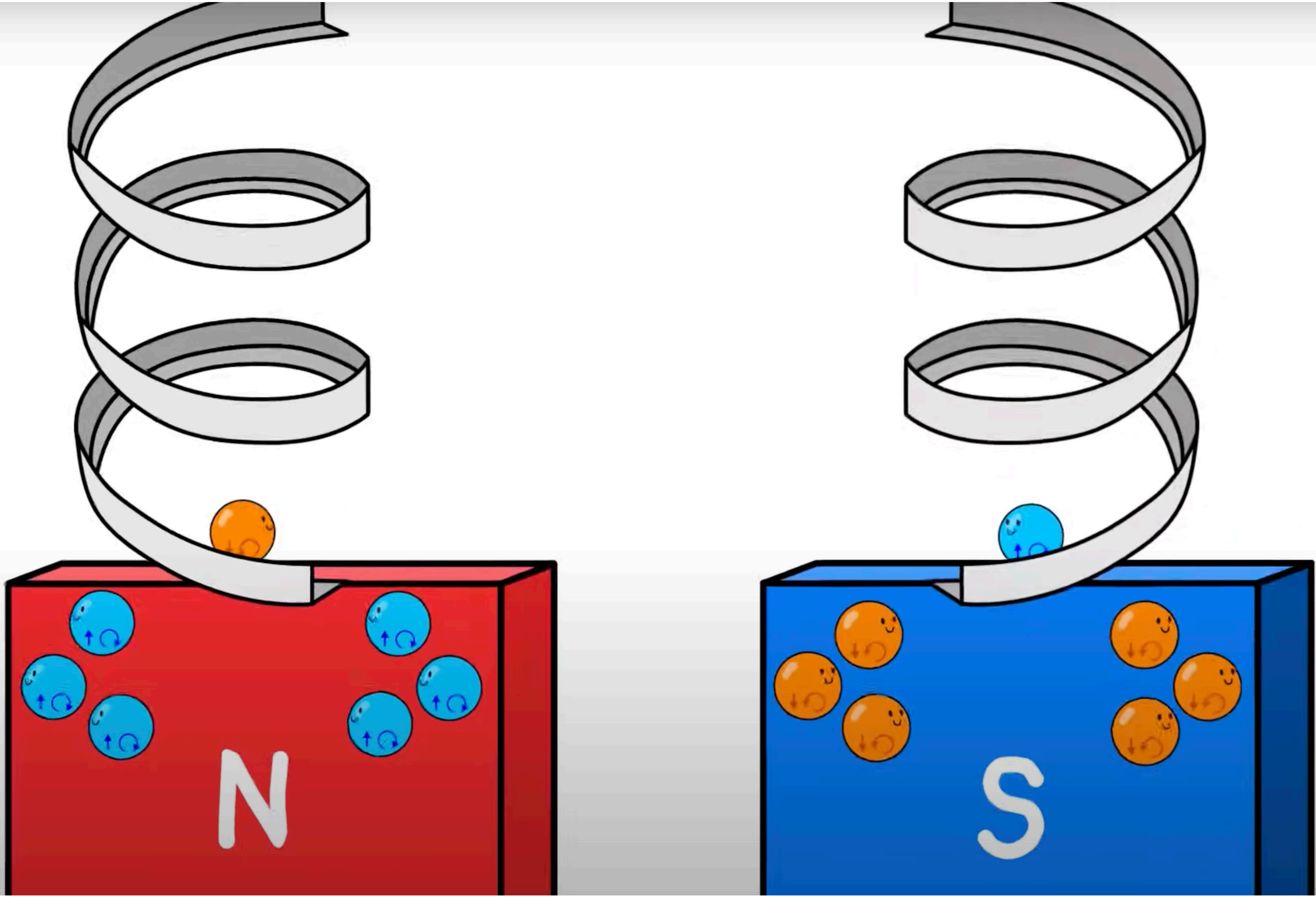
Hints of a very weak magnetic sense

(4) Adjacent Phenomena: Bio-Spin

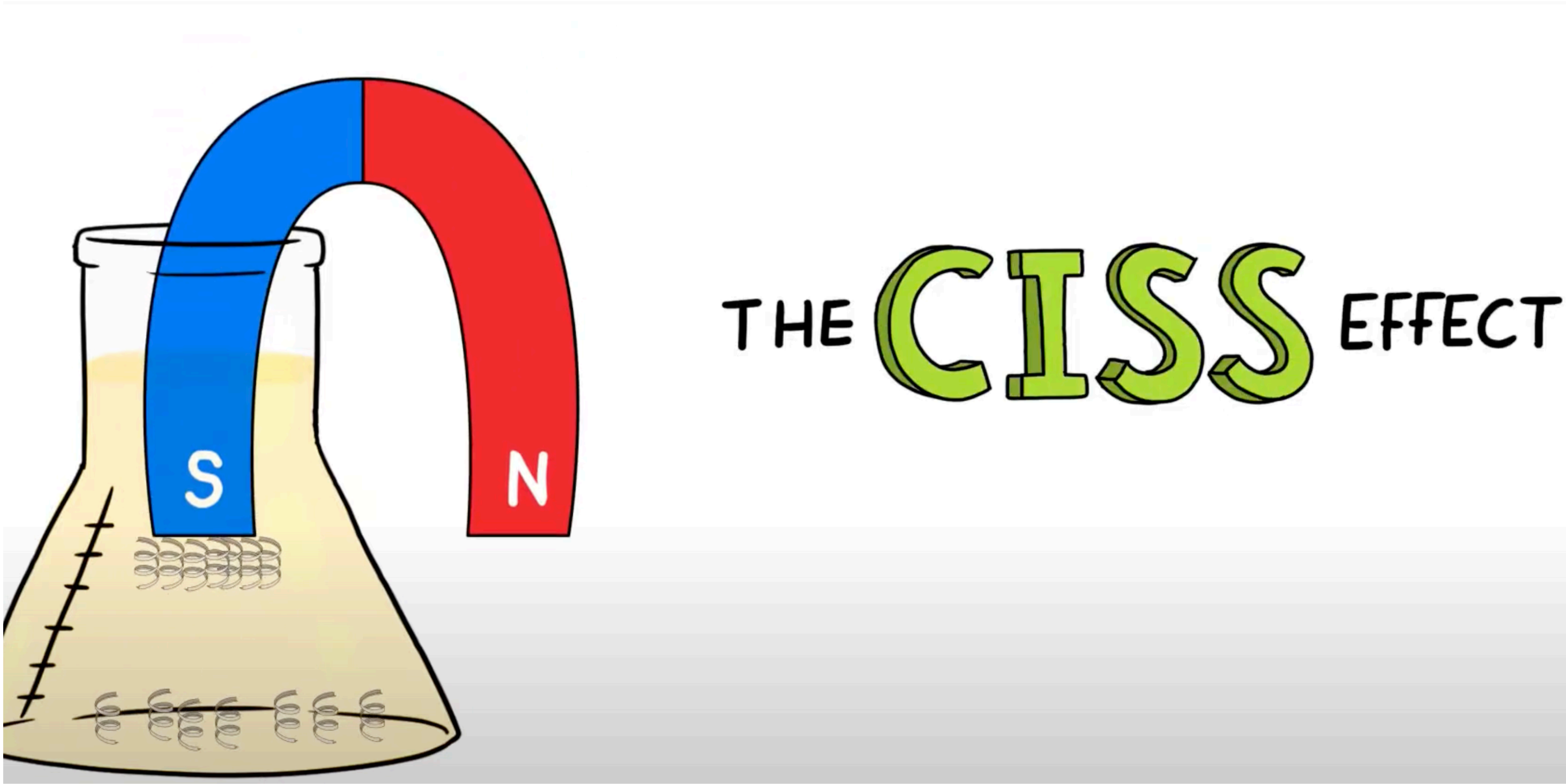
Chirality Induced Spin Selection



www.weizmann.ac.il/sites/CISS/#:~:text=The chiral-induced spin selectivity,spin-selective processes in biology.



Selective Attraction



Sorting Enantiomers

A nice problem is to analyze the implications of T for this process.

A more general question in the same spirit: Does evolution design recognizable quantum dots, nanoparticles, and metamaterials?