How animals use E&M

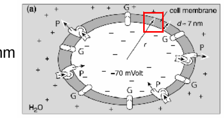
- E-field generation (weakly electric fish)
- E-field detection by predators (sharks)
- Magnetic fields used for navigation (turtles)
- Possible magnetoreception mechanisms

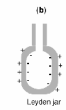
Cells have ion pumps that create voltage potentials

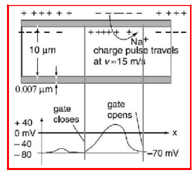
E = V/d

E = 70 mV / 7nm

E = 10^7 V/m







Electrical pulse in a nerve cell
i.e. muscle activation

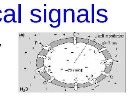
Charges move across membrane

Electrical signal:
Flow of current, J
Change in electric field

Ahlborn, p. 367, 372

Generation of electrical signals

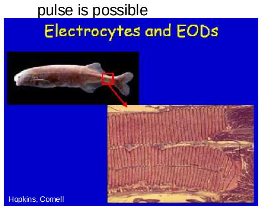
- One cell generates a potential of 70 mV

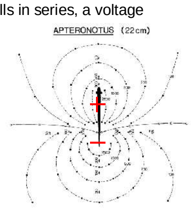


Total source voltage = $\Delta V_n = n\Delta V$

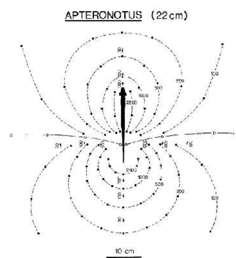
B. Ahlborn. p. 367

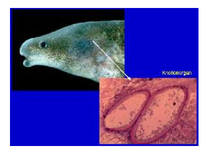
- If an animal can turn on multiple cells in series, a voltage pulse is possible





Electric field around fish

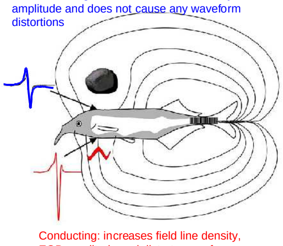




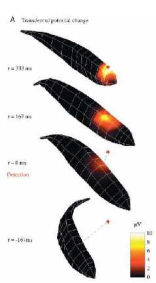
Knudsen, 1975. *J. Comp. Phys. A.*

Electroreception: Electric field dynamics enables objects detection

Nonconducting: decreases field line density, EOD amplitude and does not cause any waveform distortions



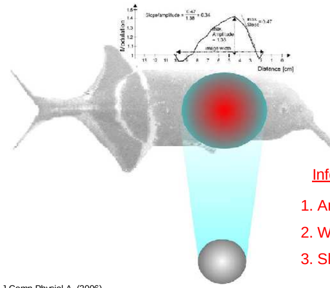
Conducting: increases field line density, EOD amplitude and distorts waveform



Emde. J Comp Physiol A. (2006)

Nelson & Malcolm. 1999. *J. Exp. Biol.*

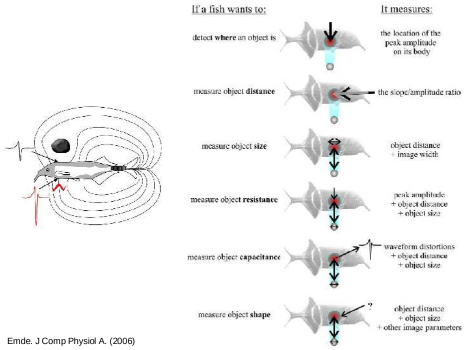
Electrosensory imagery



Information:

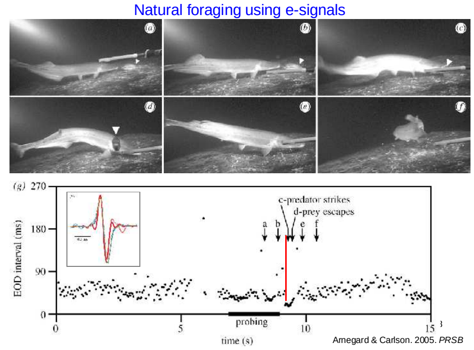
1. Amplitude (V)
2. Width (m)
3. Slope (V/m)

Emde. J Comp Physiol A. (2006)



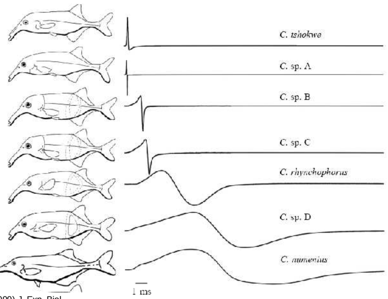
Emde. J Comp Physiol A. (2006)

Natural foraging using e-signals



Amegard & Carlson. 2005. *PRSB*

Diversity of E-signals for sympatric fish



Hopkins (1999) J. Exp. Biol.

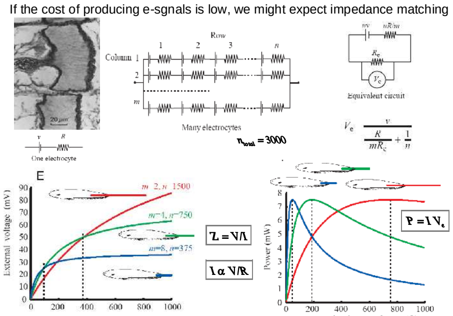
Energetic cost to producing e-signals?

We can roughly calculate the cost of a single **electric organ discharge (EOD)** as approx. 10^{-5} J (**Bell, et al.** (1976). *J. Comp. Physiol.*)

When discharging continuously at 10 EODs s-1, this is equivalent to 8.64 J day^{-1}.

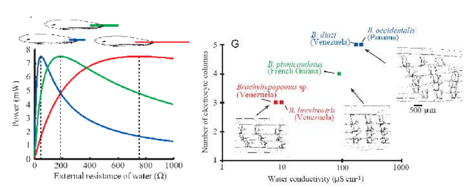
For a 10 g fish with an expected basal metabolic rate (BMR) of 1006 J day^{-1} (Schmidt-Nielsen, 1970), this represents only 1% of its BMR.

If the cost of producing e-sgnals is low, we might expect impedance matching

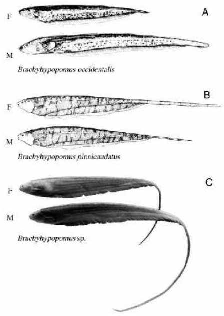


Hopkins (1999) J. Exp. Biol.

Species distribution correlates with water conductivity & e-organ morphology



Energetic cost of signaling?



Females prefer long calls from males

Male EODs 2x long duration (Δt) as Female

Male calls should require more E (longer call may be lower in amplitude)

Males try to accommodate extra cost by growing longer tails

Long tails also represent a larger risk in terms of predation

Field observations: fish with longer tails are killed or injured more often

What happens when a shark swims over a dipole…

Body functions involve weak electrical potentials and leak out into the environment (i.e. *via* gill surface)

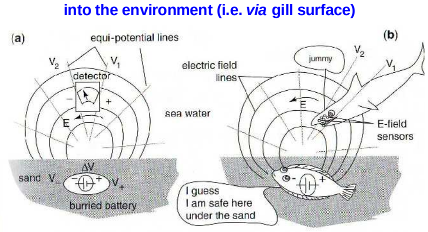


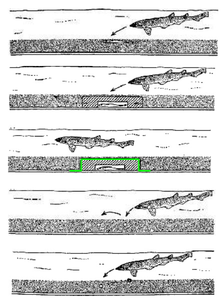
Fig. 10.8. (a) Electrical field of battery buried under sand. (b) Shark and flounder

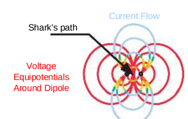
$E_{prey} \approx$ 1 mV/cm at distance of 8 cm

Shark detection threshold $\approx 10^{-9}$ V/cm

Ahlborn, p. 375

Sharks can detect electric fields

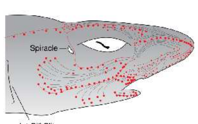


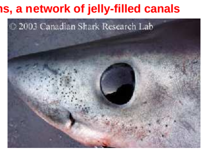


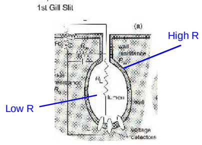
Kalmijn. (1971) *J. Exp. Biol.*

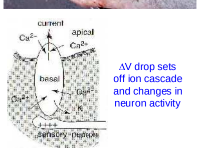
Kajiura & Holland. (2002) *J. Exp. Biol.*

Ampullae of Lorenzini: special sensing organs, a network of jelly-filled canals







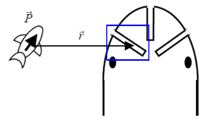


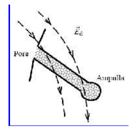
The ampullae detect electric fields in the water by measuring the voltage drop between the skin pore and the base of the voltage detectors .

The ampullae are not sensitive to absolutely static electric fields.

Instead, they are sensitive to changes in the electric field that occur in the range 0.1–10 Hz, relevant biological frequencies for prey swimming movements or even gill movements

Since the strength of even a static field emanating from stationary prey will drop off quickly with distance, a predator approaching the prey will perceive a changing electric field.





Coulomb's Law

$$\vec{E}_d = \frac{1}{4\pi\varepsilon}\frac{1}{r^3}[3(\vec{P}\cdot\hat{r})\hat{r}-\vec{P}]$$

Electric field at a distance ($\vec{E}_d$):
$\vec{P}$ = dipole vector
r = separation vector
$\hat{r}$ = unit direction vector
r = magnitude of seperation vector.

$$V = -\int \vec{E}_d \cdot d\vec{l}$$

Potential difference between ampulla & sea water (V)
$d\vec{l}$ = infinitesimal segment of the canal

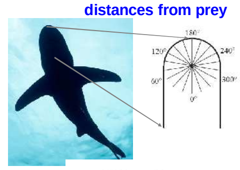
$$\Delta V = V(t_0+\Delta t) - V(t_0)$$

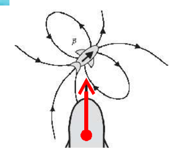
Voltage drop detected over time difference (Δt)

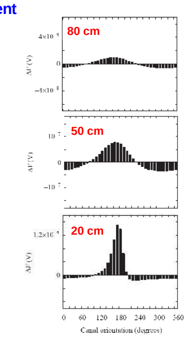
19

B. R. Brown. (2002). *J. Exp. Biol.*

Voltage drop over time, at different distances from prey

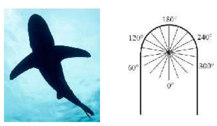


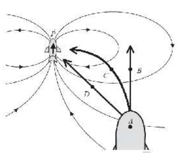


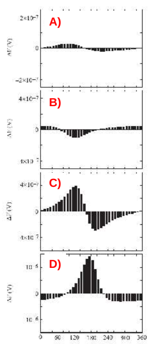


B. R. Brown. (2002). *J. Exp. Biol.*

Different paths towards prey





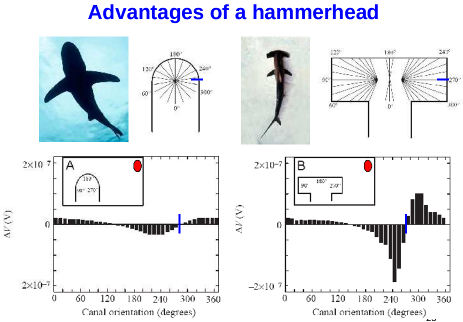


B. R. Brown. (2002). *J. Exp. Biol.*

Why the big head?

22

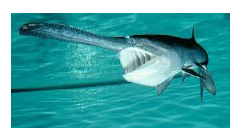
Advantages of a hammerhead



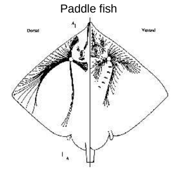
B. R. Brown. (2002). *J. Exp. Biol.*

Diversity of form & function

Small-tooth sawfish



Paddle fish



Skates & Rays

24

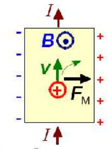
Magnetoreception: what's the evidence?

Meyer, C. G., Holland, K. N. & Papastamatiou Y. P. Sharks can detect changes in the geomagnetic field. *J. R. Soc. Interface* **2**, 129–130 (2005).

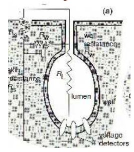
What's the mechanism?

Electromagnetic induction *via* the Lorentz force & Hall effect:

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$



If E-conductive bar moves through B:
+/- charges move to opposite sides of the bar
constant voltage is generated
If the bar is immersed in a conductive medium that is stationary relative to the field, an electric circuit is formed and current flows through the medium and the bar.



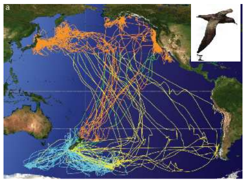
Jelly-filled ampullae of Lorenzini = conducting bars
Surrounding sea water functions = motionless conducting medium,
and the highly resistive and sensitive electroreceptors at the inner end of the ampullae detect the voltage drop of the induced current.

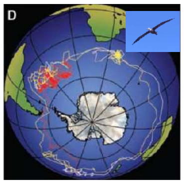
Johnsen & Lohmann (2005). The physics and neurobiology of magnetoreception. *Nature Reviews Neuroscience* 6: 703-712.

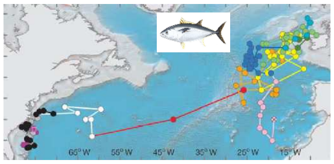
Problems with electromagnetic induction

- The water surrounding marine fish is seldom motionless
- Ocean currents are also conductors moving through the Earth's magnetic field, and so create electric fields of their own.
- Must be able to determine which component of the total field that it experiences is attributable to its own motion and which is due to the motion of water (Head movements during swimming?)

- This can't happen in air (not a conductive medium), so what about terrestrial animals or aquatic animals with no ampullae?

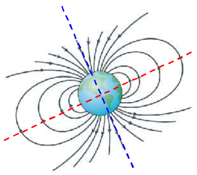




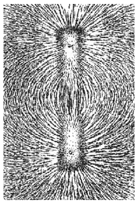


Natural variation of magnetic fields: Earth's general dipole

Equator: parallel & weak (60 µT)



Poles: field lines are <u>steep</u> and <u>strong</u> (30 µT)

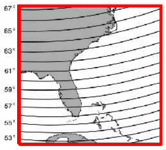


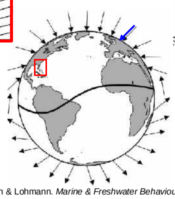
Iron filings on magnet

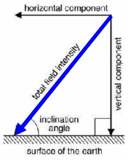
Types of information available to animals from changes in magnetic field:

1. **Directional or compass information**: from polarity of the magnetic field
2. **Position (Biological GPS)**: inclination angle and intensity of magnetic field

Inclination angle (the angle formed between magnetic field lines and the surface of the Earth) varies with latitude.

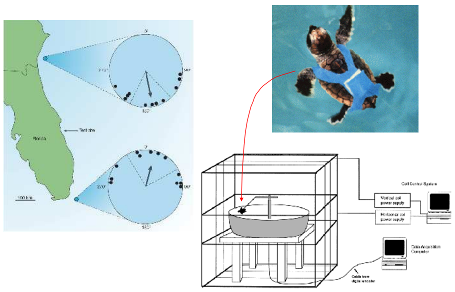






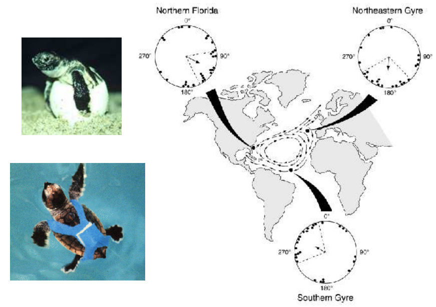
Lohmann & Lohmann. *Marine & Freshwater Behaviour & Physiology*. 2006; **39**: 49–64

Geomagnetic map used in sea-turtle navigation: Biological GPS system



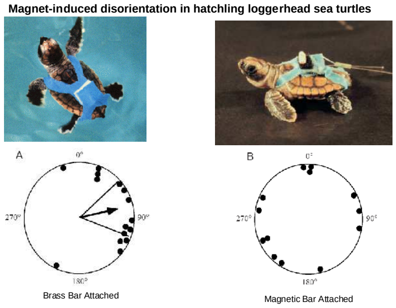
Lohmann, K. J. *et al.* Geomagnetic map used in sea-turtle navigation. *Nature* **428**, 909–910 (2004).

Loggerhead sea turtles respond to cite specific magnetic field differences



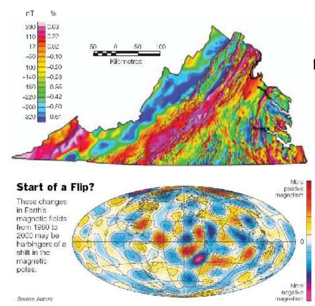
Lohmann et al. 2001. *Science* **294**:364–366.

Magnet-induced disorientation in hatchling loggerhead sea turtles



Irwin & Lohmann. 2003. *J. Exp. Biol.* **206**, 497-501.

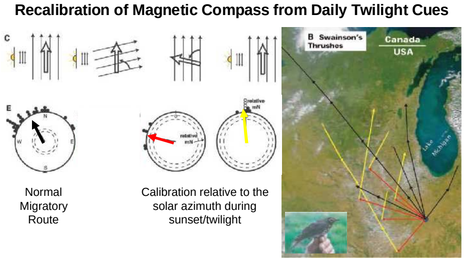
How do animals deal with changes in the Earth's magnetic field?



Local anomalies from ferromagnetic minerals in the earth's crust

Geomagnetic reversals and changes over time

Recalibration of Magnetic Compass from Daily Twilight Cues



Normal Migratory Route

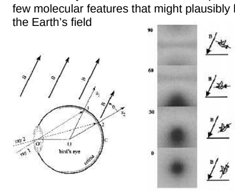
Calibration relative to the solar azimuth during sunset/twilight

In addition, other studies observe changes in magnetic orientation behavior that are elicited by different wavelengths and intensities of light.

Cochran, et al., *Science* (2004).

Alternative mechanisms for magnetoreception: chemical

Earth-strength magnetic fields influence **correlated spin states of paired radical ions**. Electron spins are largely unaffected by thermal noise, and so represent one of only a few molecular features that might plausibly be influenced by the Earth's field



Many of the best-known radical pair reactions begin with electron transfers that are induced by light absorption. This consideration has led to the suggestion that chemical magnetoreceptors, if they exist, might also be photoreceptors.

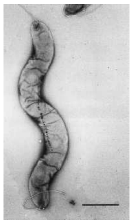
There is **no direct evidence** for chemical magnetoreception, but there is a link between magnetoreception and the visual system (behavior dependent on \ and λ).

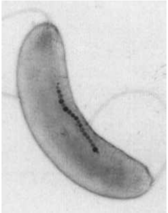
Ritz, T. *et al. Biophys. J.* **78**, 707–718 (2000).

Johnsen & Lohmann (2005). *Nature Reviews Neuroscience*

Magnetite

Many animals biologically synthesize the ferromagnetic mineral, magnetite (Fe_3O_4).





Single-domain crystals are minute (~50 nm in diameter), permanently magnetized magnets that twist into alignment with the Earth's magnetic field if allowed to rotate freely

Magnetite has been found in honeybees, birds, salmon, sea turtles and a number of other animals that are known to orient to the Earth's magnetic field

The crystals might exert torque or pressure on secondary receptors (such as stretch receptors, hair cells or mechanoreceptors)

OR

The rotation of intracellular magnetite crystals might open ion channels directly if they are directly connected to the cell membrane

No One Knows!