Biophysics: A conversation between Physics and Biology

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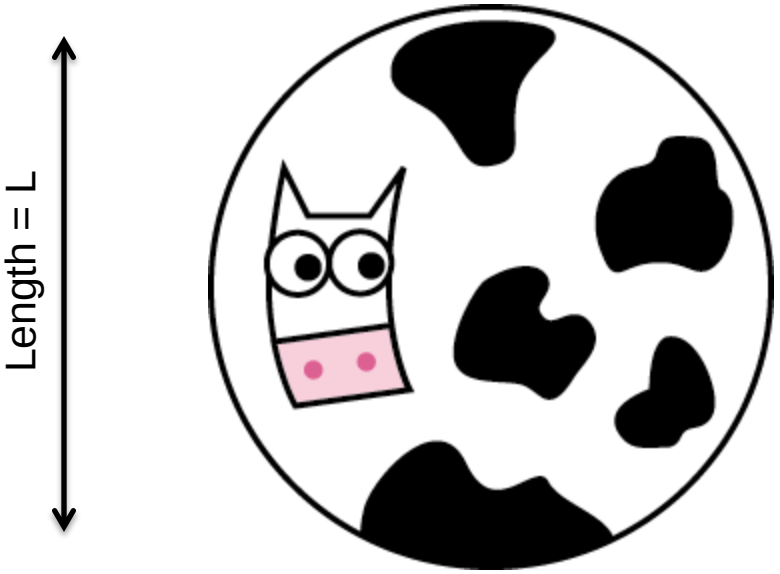
Physics constrains Biology

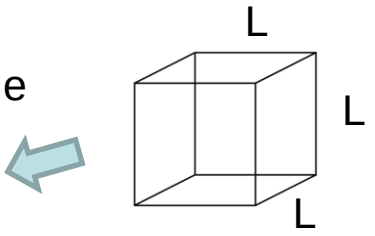
- Can big bird fly?
- Can you swim in honey?
- Can we program life?

How do things scale with size?

Consider a spherical cow … how does an organism's height depend on mass?



Mass is proportional to Volume



Mass ~ Volume ~ L^3

So

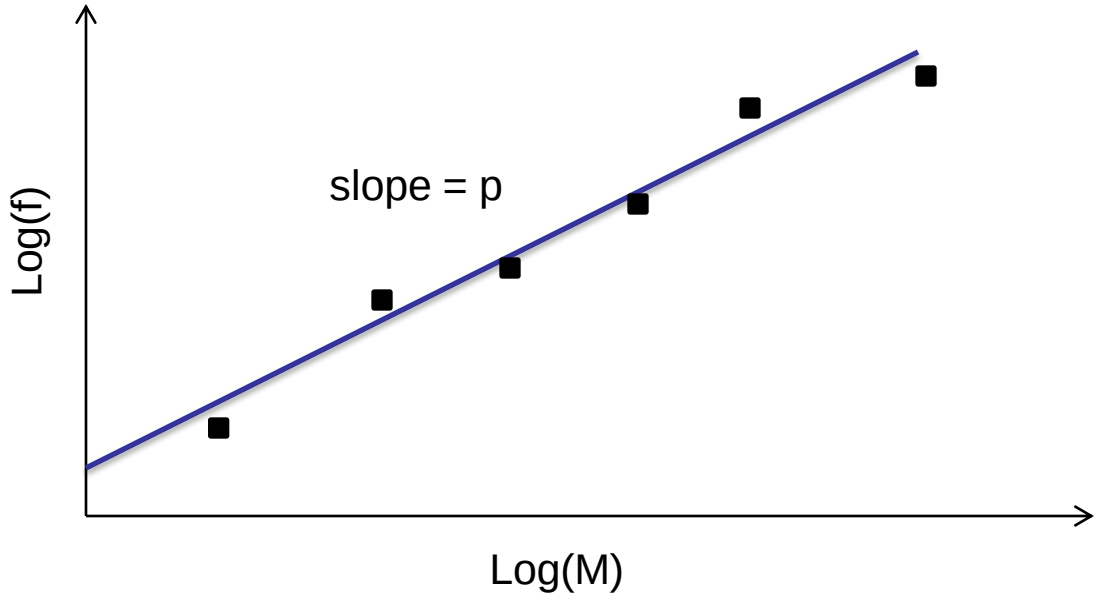
$$L \sim (\text{Mass})^{1/3}$$

Study of scaling behaviour = Allometry

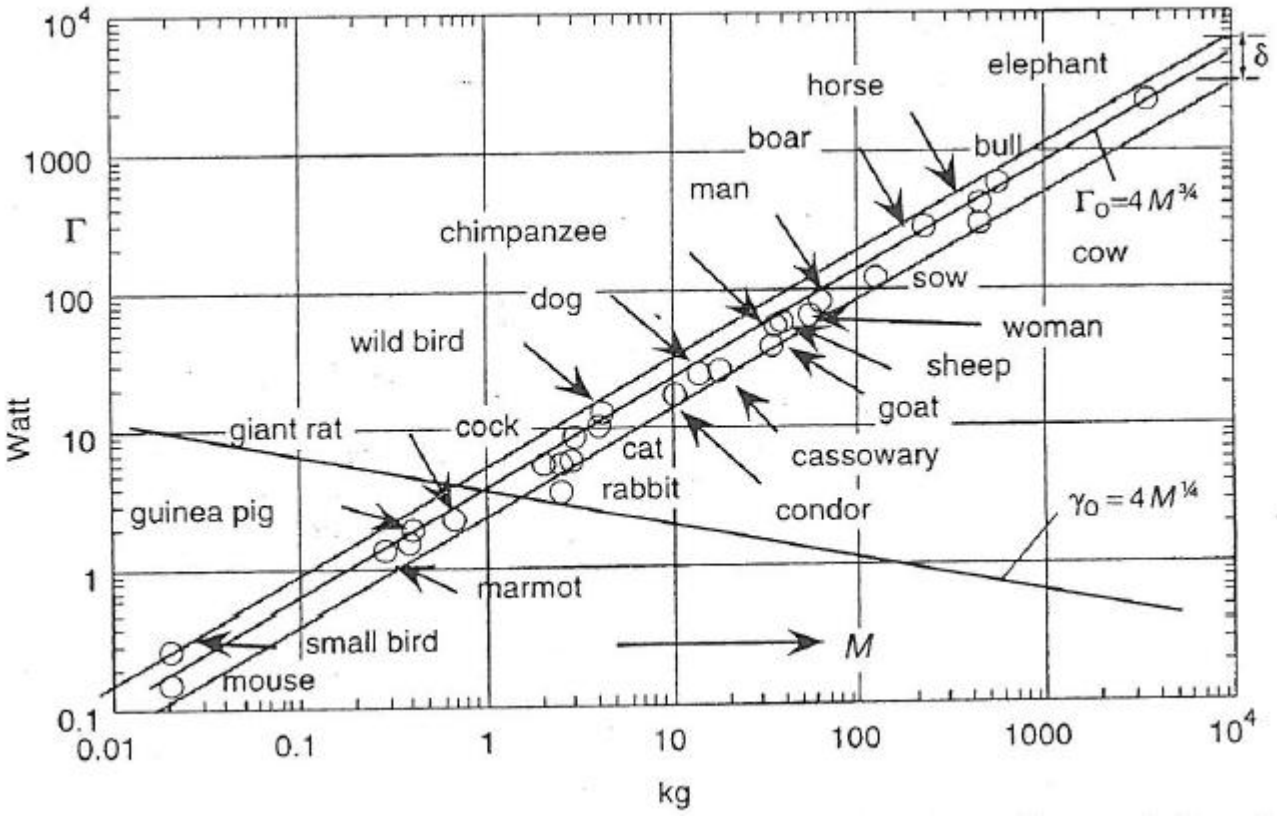
Physical properties of organisms that scale with mass = allometric scaling

$$f = a M^{p}$$

For f = Length, p = 1/3



How does energy consumption scale with mass?

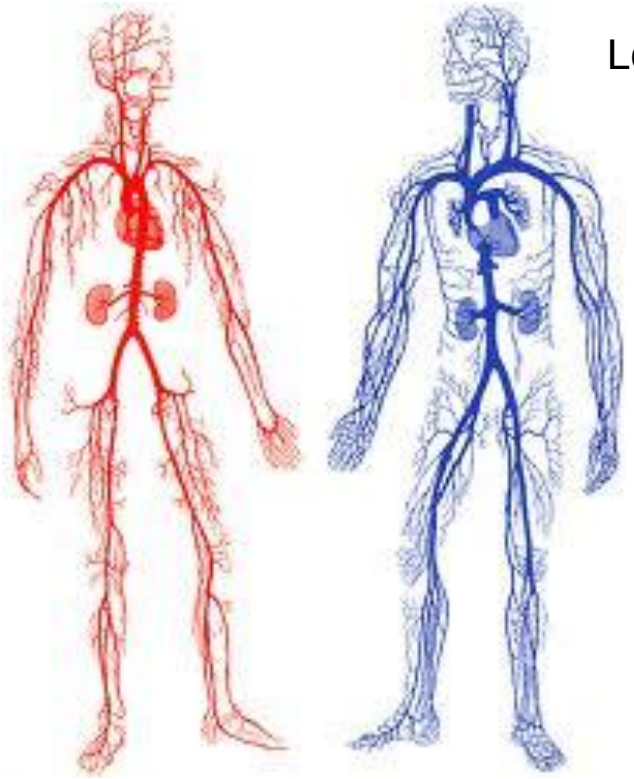


From *Zoological Physics*, Boye Ahlborn

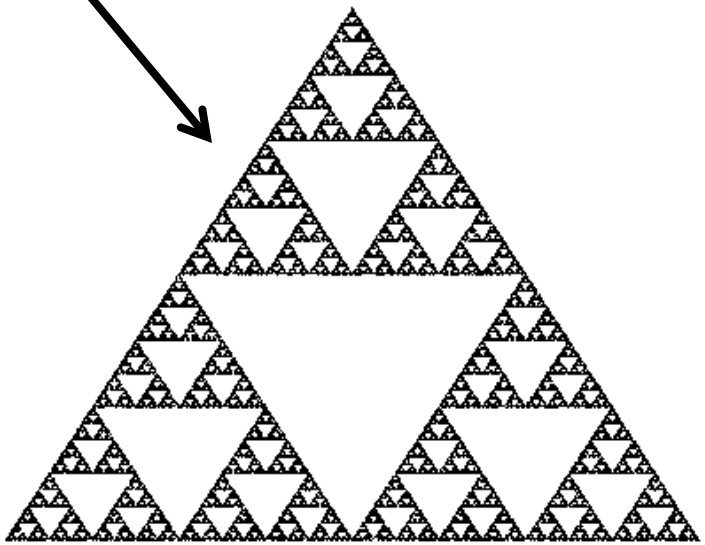
Organism's metabolism gets bigger with the mass of organism, p = ¾

BUT why is p = ¾ and not p = 1 that might be expected if Power ~ Mass ?

Circulatory system and fractals



Looks the same on all scales = fractal



Circulatory system has a fractal character – not quite 3D, not quite 2D

Physicists showed that this leads to p = ¾ for energy consumption.

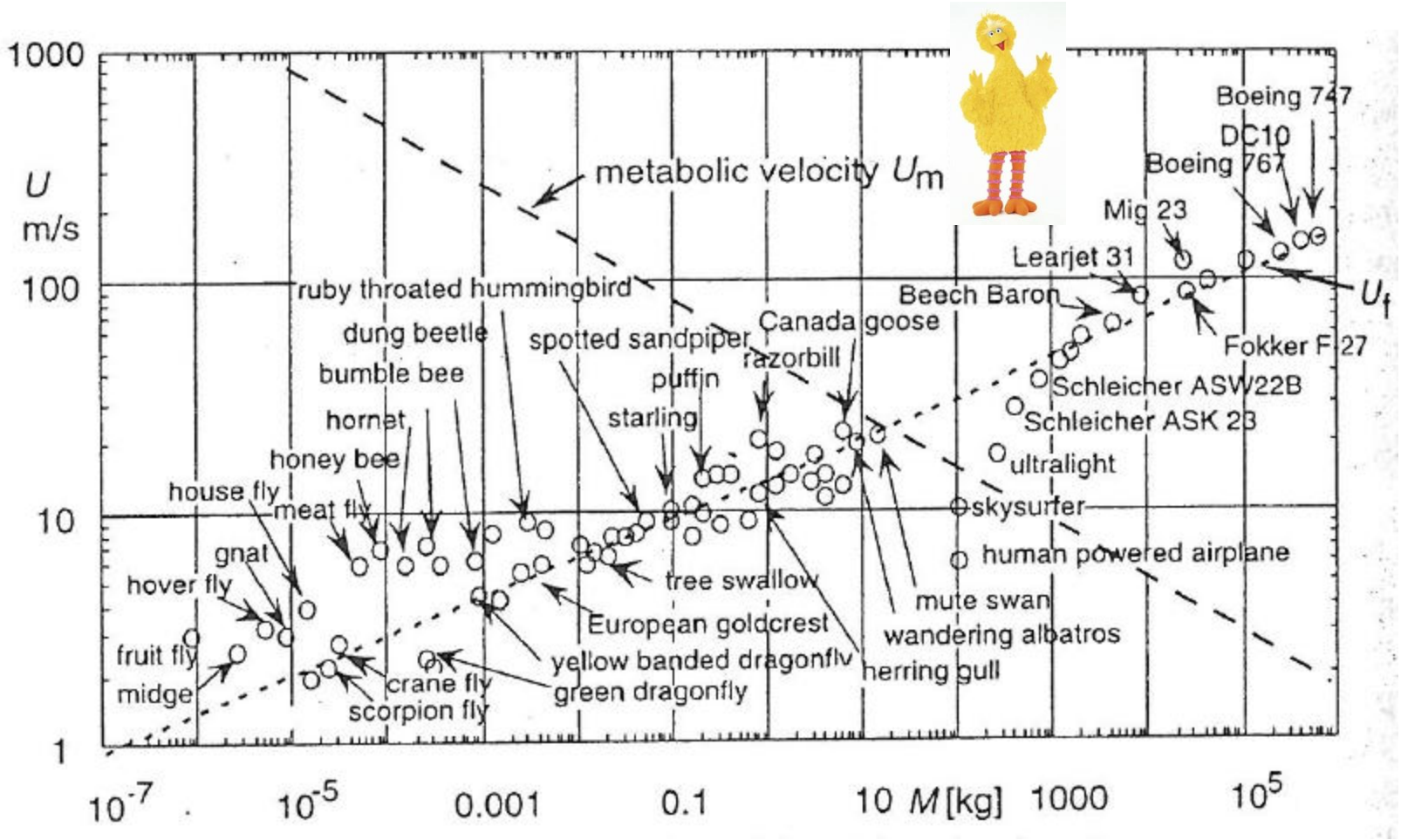
Curious scalings:

parameter	factor a	exponent α
body surface in m^2	0.11	0.65
brain mass (man) in kg	0.085	0.66
brain mass (non primates) in kg	0.01	0.7
breathing frequency in Hz	0.892	−0.26
cost of transport (running) in J/m · k	7	−0.33
cost of transport(swimming) in J/m · kg	0.6	−0.33
effective lung volume in m^3	$5.67 \cdot 10^{-5}$	1.03
frequence of heartbeat in Hz	4.02	−0.25
heart mass in kg	$5.8 \cdot 10^{-3}$	0.97
life time in years	11.89	0.20
metabolic rate in W	4.1	0.75
muscle mass in kg	0.45	1.0
skeletal mass (cetaceans) in kg	0.137	1.02
skeletal mass (terrestrial) in kg	0.068	1.08
speed of flying in m/s	15	1/6
speed of walking in m/s	0.5	1/6

Number of heart beats in a lifetime = (frequency) x (life time) = 1 x 10^9 beats

a constant independent of size!!!

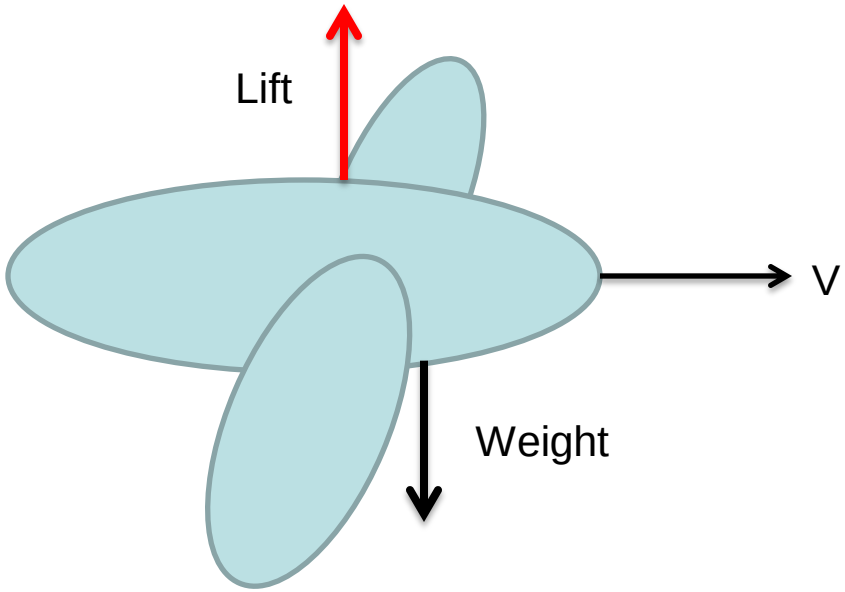
Can Big Bird fly???



Flight velocity = speed needed to fly ~ $M^{1/6}$ WHY???

Metabolic velocity = speed that body can supply ~ $M^{-1/4}$ WHY???

Speed to fly



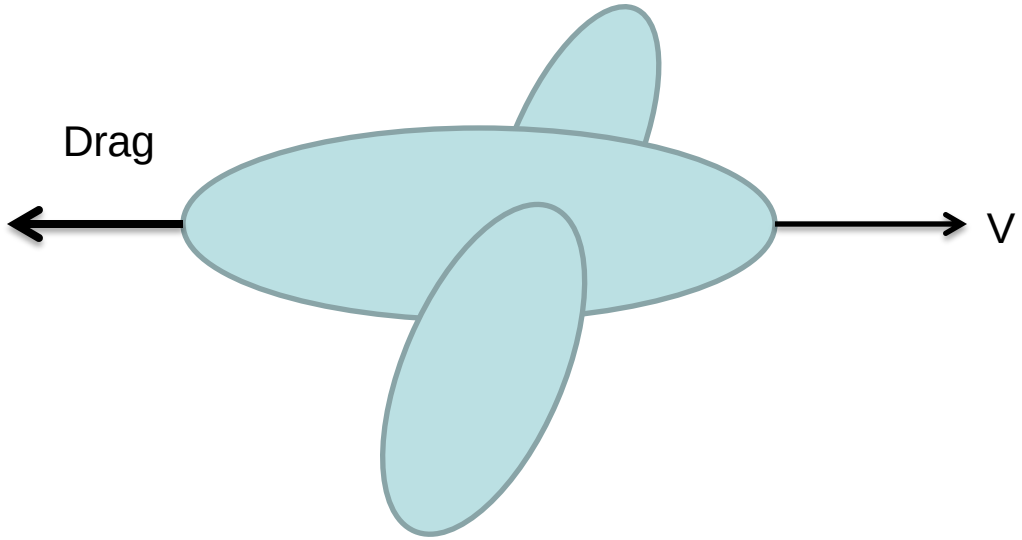
To just fly, the weight needs to be balanced by lift.

$$\text{Lift} \sim (\text{Area} \sim M^{2/3}) \times (V^2) = (\text{Weight} \sim M)$$

So

$$V_{fly} \sim M^{1/6}$$

Speed body can generate



Body must supply power to overcome the drag force

$$\text{Power} = (\text{Drag}) \times V = (\text{Metabolic Power}) \sim M^{3/4}$$

Now when flying

$$\text{Drag} \sim (\text{Lift}) \sim (M)$$

So

$$V \sim M^{-1/4}$$

Summary I:

Many of an organism’s characteristics can be related to its mass

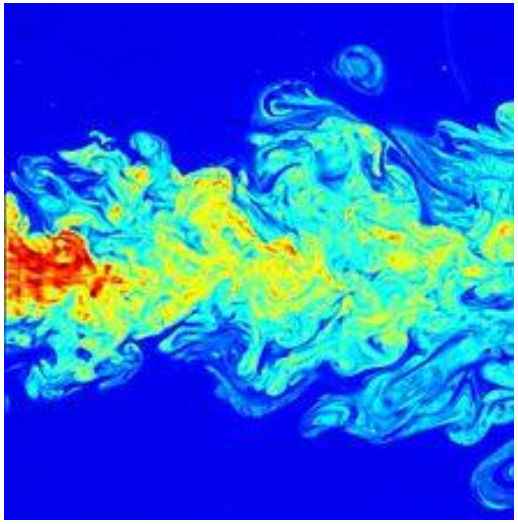
Body plans must operate under physical constraints

We have seen how physics constrains the size of flying animals

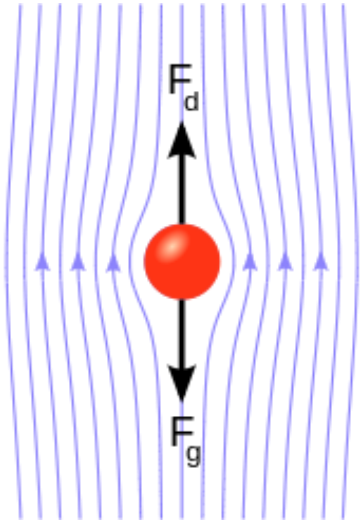
So, Big Bird can not fly, but the Kory Bustard can

Can you swim in honey???

Turbulent



Laminar



What determines whether flow is turbulent or laminar?

Reynold's number = *Re* = (liquid density) x (size) x (speed) / (viscosity)

So it also depends on how big you are and how fast you are swimming through the liquid!

Re > 1000 = Turbulent *Re* < 100 = laminar

Swimming: turbulent or laminar?

Swimming in water:

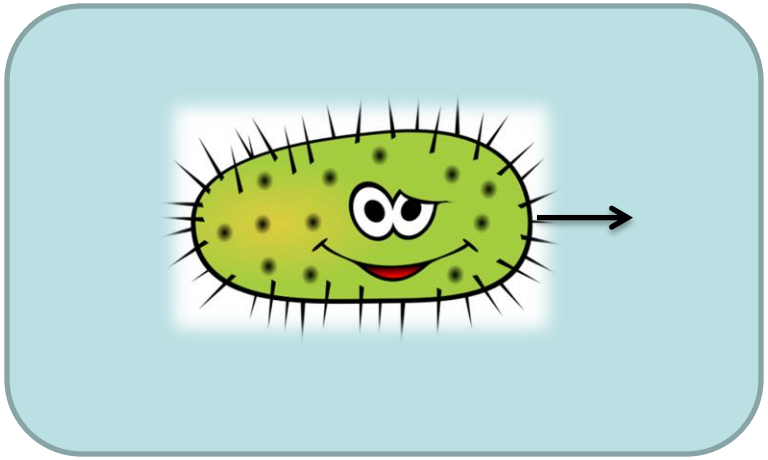
speed ~ 1 m /s ; size ~ 1 m

Re ~ 1 x 10^5 = turbulent

Swimming in honey:

Honey viscosity ~ 10000 x water

Re ~ 10 = laminar



Bacteria swimming in water:

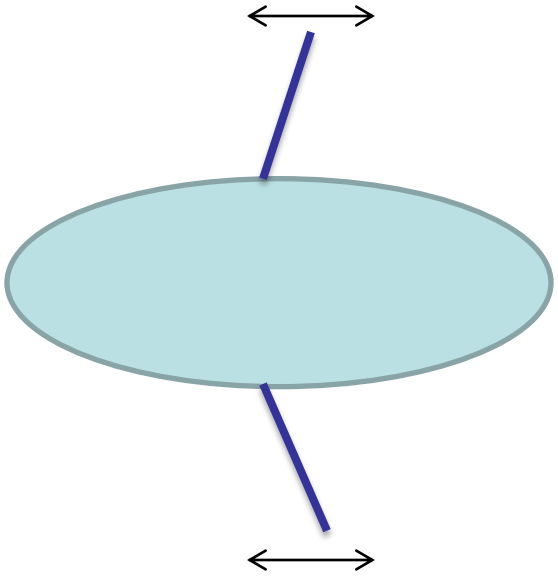
Speed ~ 30 x 10^{-6} m/s ; size ~ 1 x 10^{-6} m

Re ~ 1 x 10-5 = laminar

So bacteria swimming in water is like us in honey

Strategies for swimming I

If you kick your feet in honey (as you would in water) will you move???

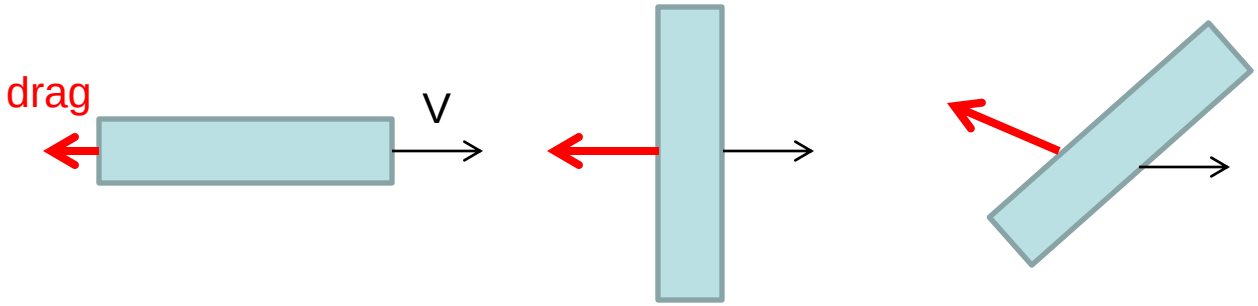


Symmetric, back-and-forth motion

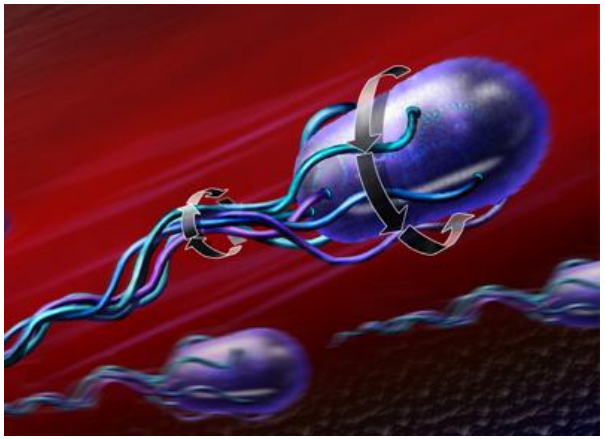
Strategies for swimming II

So performing symmetric swimming motion will get you no where in honey.

How to swim in honey??? Need to perform asymmetric motion.



Many bacteria swim by using a helical propeller that exploits asymmetry in drag forces



See Life at Low Reynold's Number, Berg and Purcell

Summary II:

How we swim depends very much on how the fluid will flow

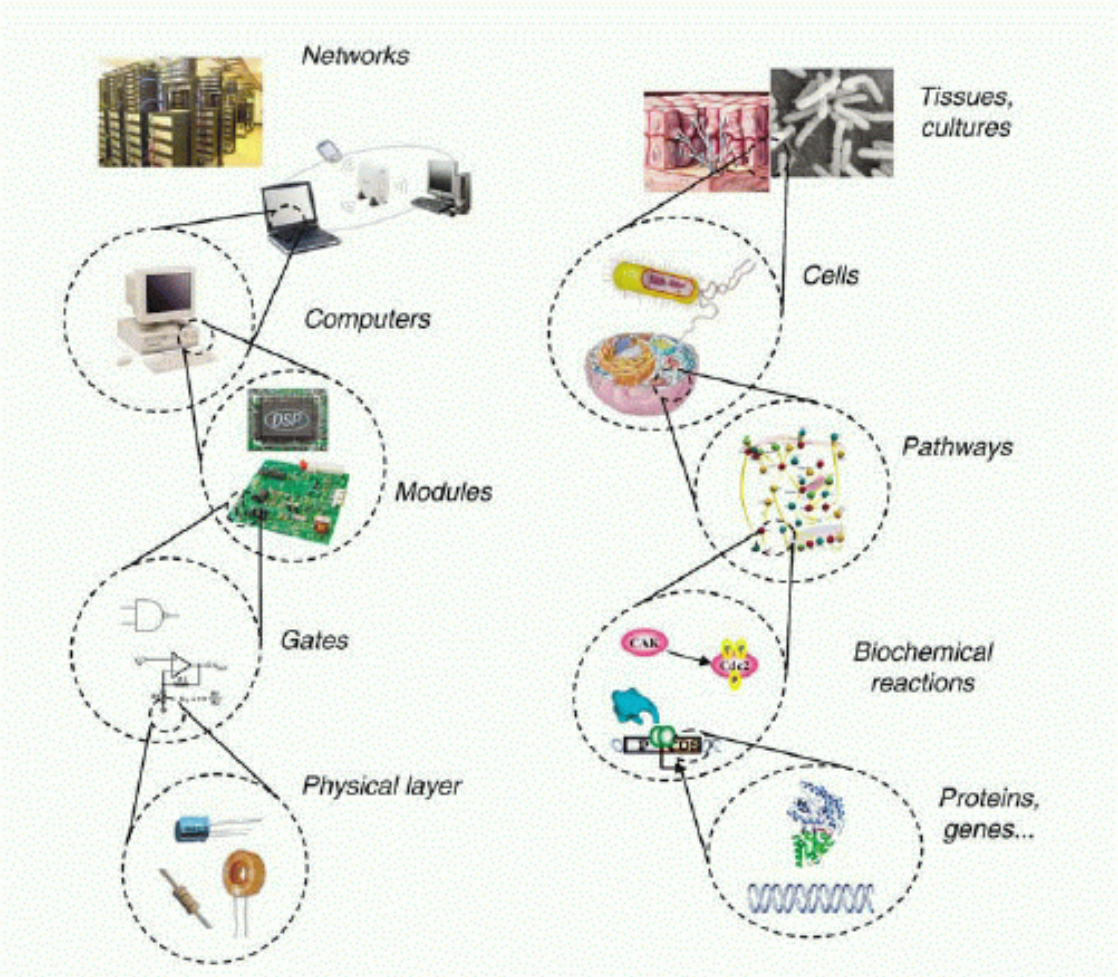
We can swim in H20 by doing symmetric motion because flow is turbulent

We could not swim that way in honey

Bacteria swimming in water is like us swimming in water

Bacteria move by exploiting asymmetry in drag forces when flow is laminar

Cells compute:

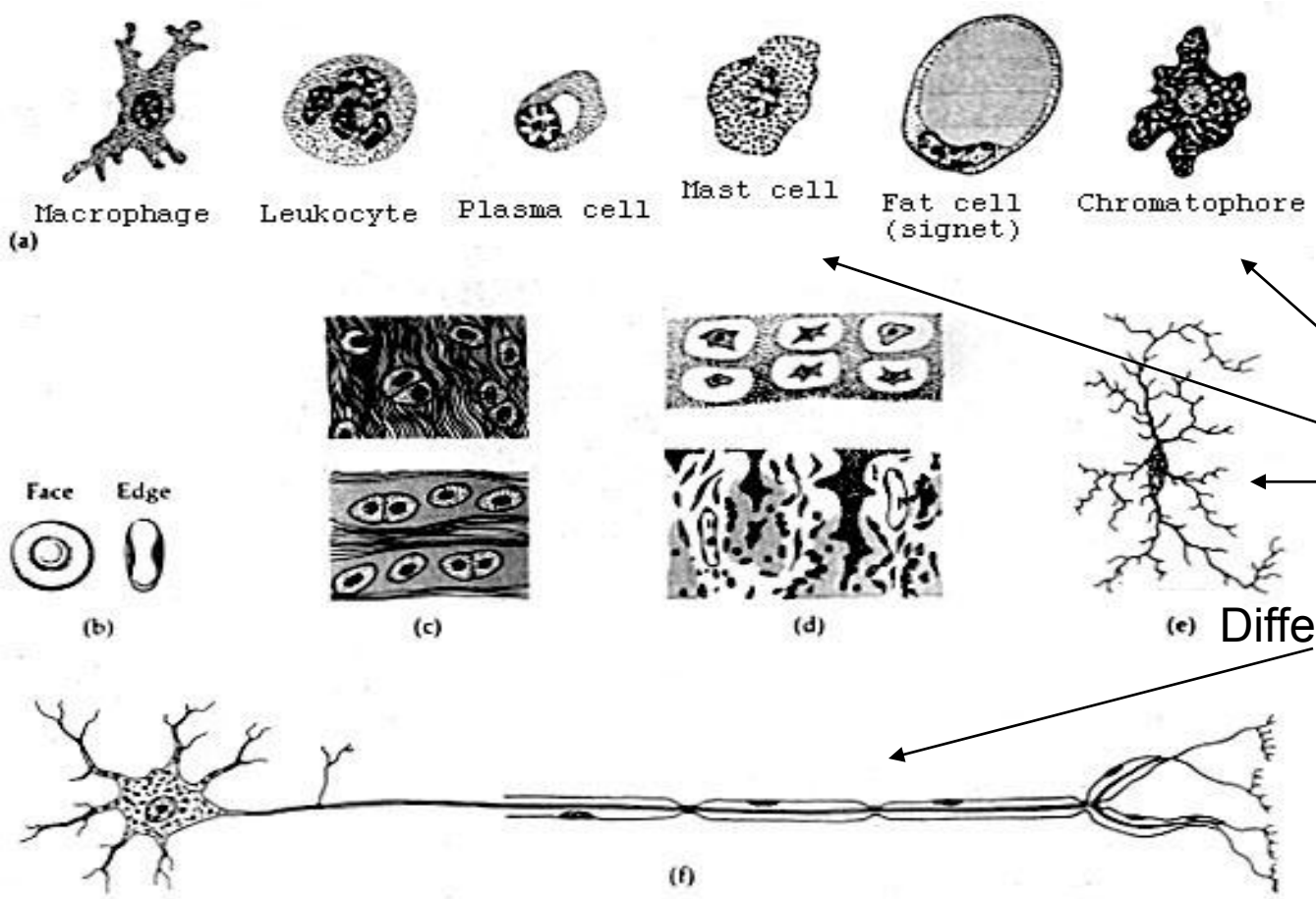


(Andrianantoandro, Basu, Karig, Weiss (2006))

Can we decipher the biological hardware and software?

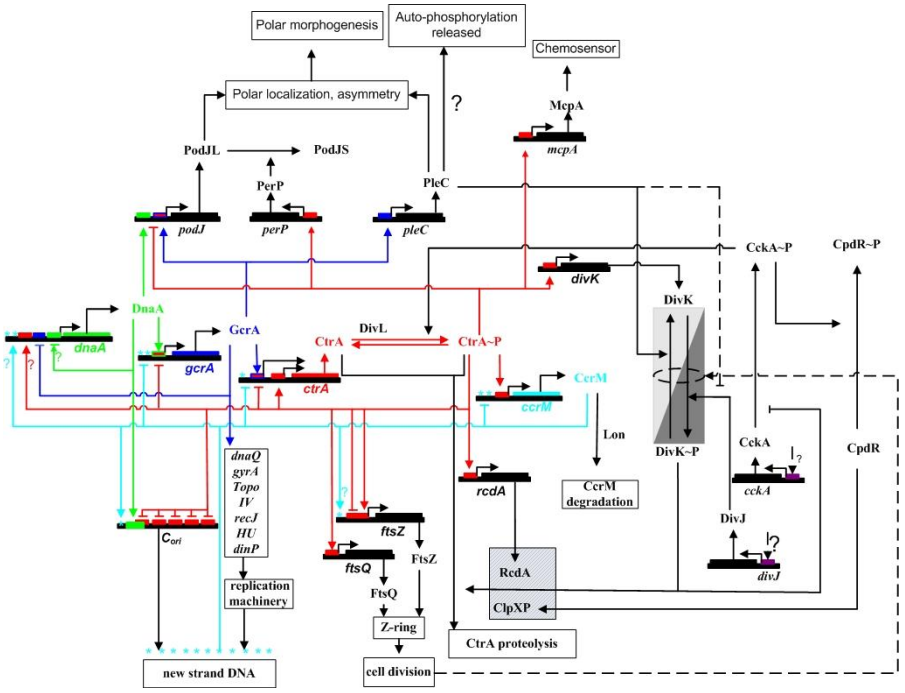
Cellular “states”:

- Cellular state is determined by which genes=proteins are “ON”

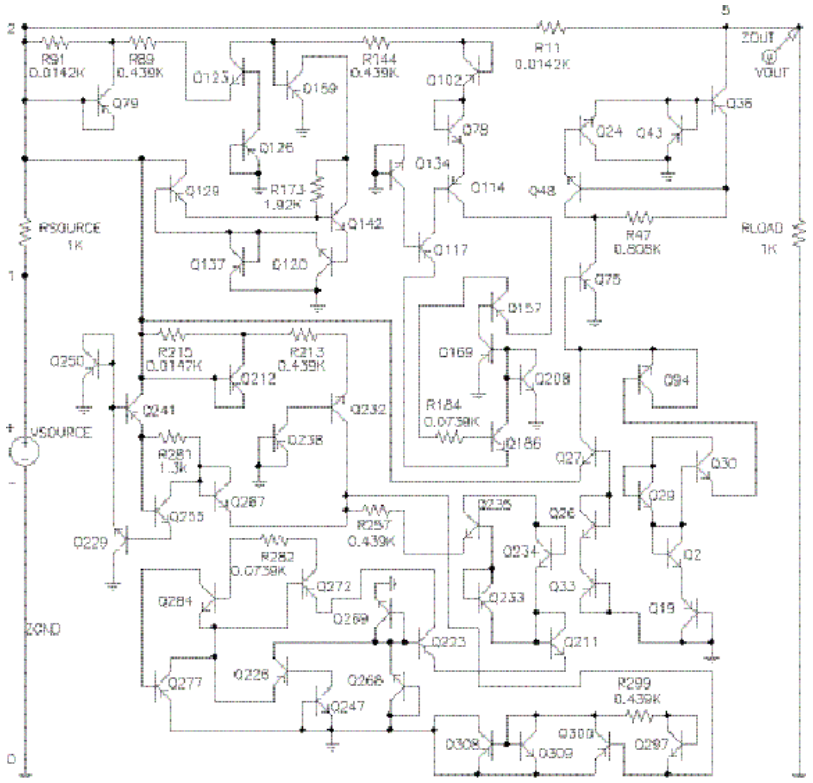


- Different cell types = different genetic programs that are being run

Genetic circuits and the logic of cells



(genetic circuit)



(electrical circuit)

genetic circuits can implement many forms of logical operations found in computation

…. if we can understand how cells implement logic, can we then program them???

Can we program cells?

We have learned some of the ways in which cells compute

Can engineer genetic switches, oscillators, …

If you can think of an electronic circuit, chances are it can be implemented

The new field of *synthetic biology* promises to program cells

- bacteria that eat oil, detect hazardous material
- stem cells that become what you want when and where

Synthetic spatial patterns using biology

A synthetic multicellular system for programmed pattern formation

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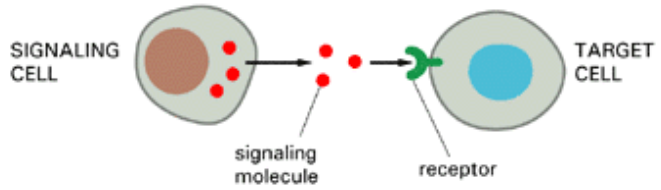
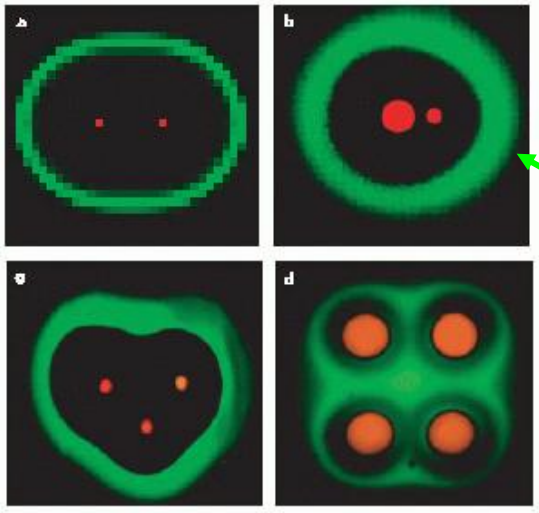
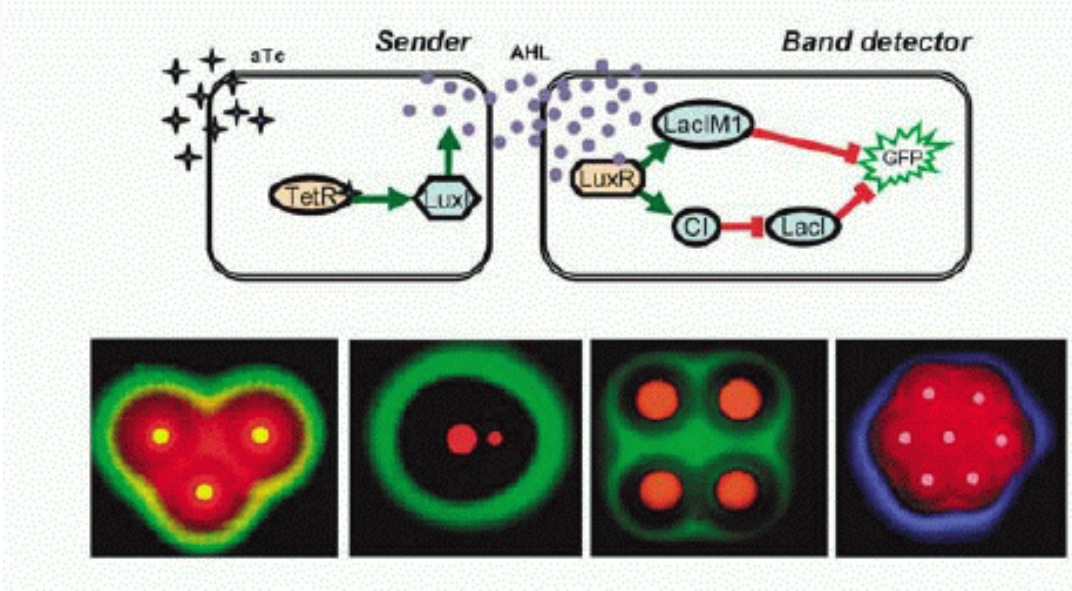
[3]Division of Chemistry and Chemical Engineering, California Institute of Technology 210-41, Pasadena, California 91125, USA





"band detector" network in receiver cells

Designed circuit = band detector

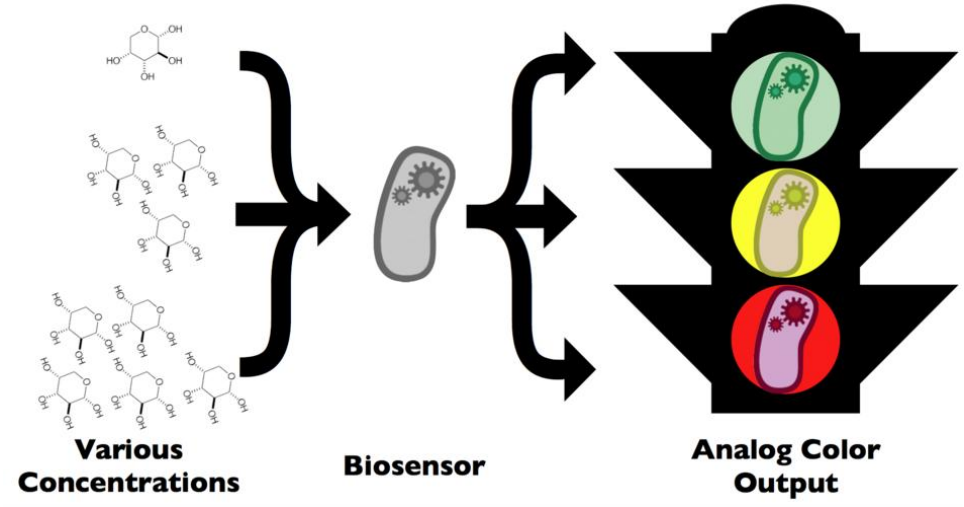


Q: What can we do with cells that we have reprogrammed?

Biological Robots

iGEM = international Genetically Engineered Machines competition

teams of undergrad teams compete to design cells with novel behaviour



(UBC iGEM team design)

Some final comments…

- Nature contains many examples of circuits which have analogues in electrical engineering
- Can engineer synthetic circuits to carry out specific tasks
- How to design robust circuitry?
- How to evolve circuitry?
- Should we evolve/make synthetic circuitry?

Acknowledgements:

References:

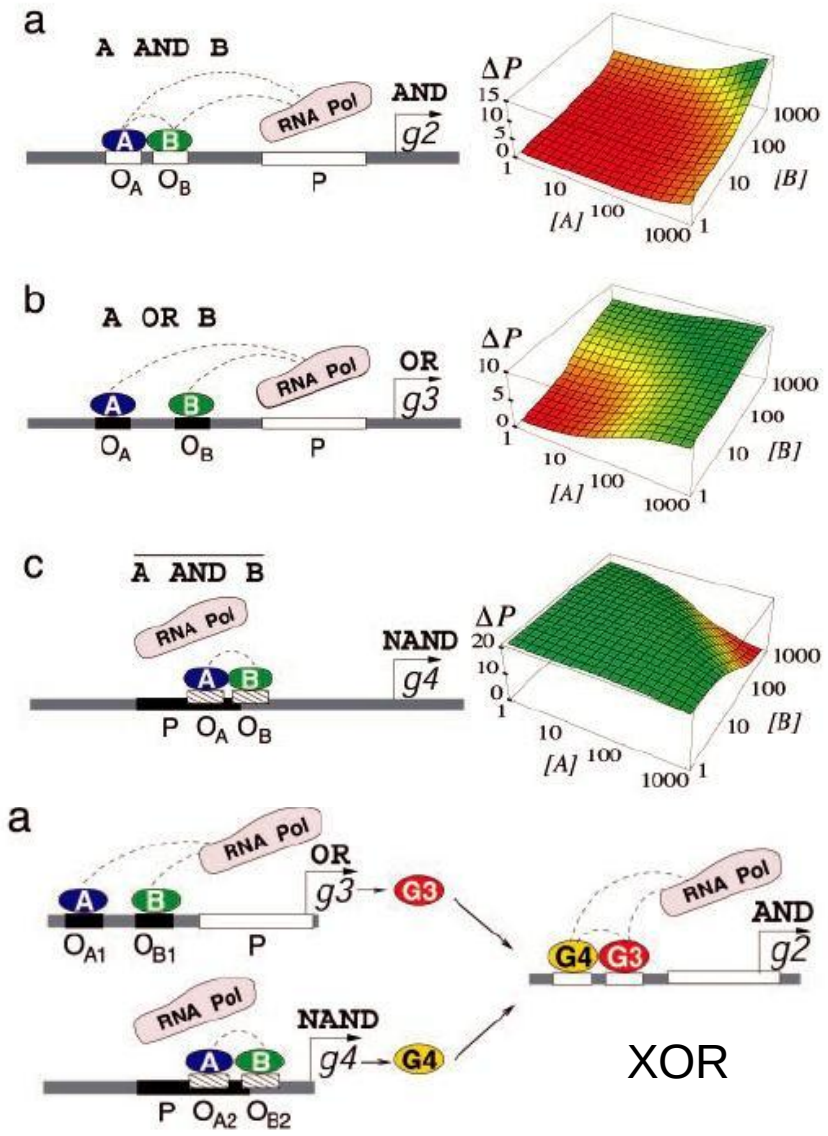
Zoological Physics, Boye Ahlborn

Life at Low Reynold's Number, Berg and Purcell

and

YouTube™

A toolkit of logic operations:



XOR

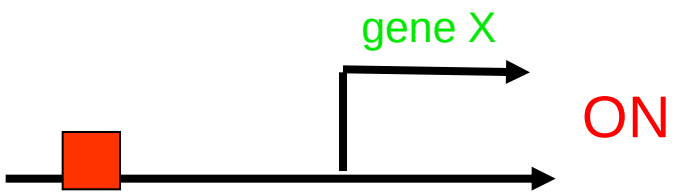
(Buchler, Gerland, Hwa, PNAS **100**, 5136 (2003))

- Use thermodynamics to compute probability of transcription

- Can cascade functions to generate new functions

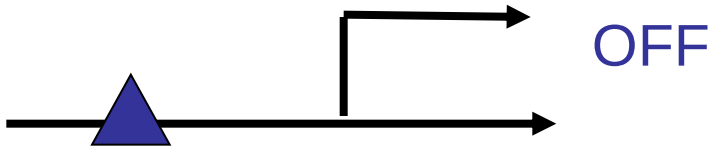
Regulatory Logic of Genes

- Genes are regulated by proteins termed transcription factors
- Transcription factors can activate and repress gene expression



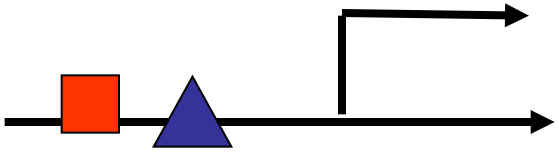
ON

Activators help turn genes on



OFF

Repressors help turn genes off



ON? OFF?

Combinations can lead
to a variety of outcomes

From the dictionary …

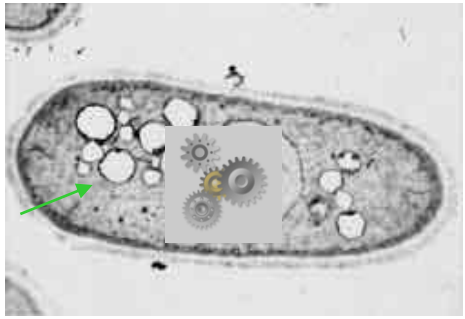
Synthetic biology, *n.* an ambiguous scientific term which is utilized to secure money from granting agencies.

Some guesses …

- tinkering with biological building blocks to measure biological processes
- combining biological building blocks to carry out novel biological processes
- using biological building blocks to do non-biological things

Cellular Computation:

A cell computes by measuring chemical inputs → chemical output



A) What constraints does physics impose on how cells measure their environments?

B) Can the complex biological calculations be decomposed into simpler procedures?

C) Can we understand and predict how these calculations are carried out?

D) Are there common design strategies behind these calculations?