Bio-Inspired Design

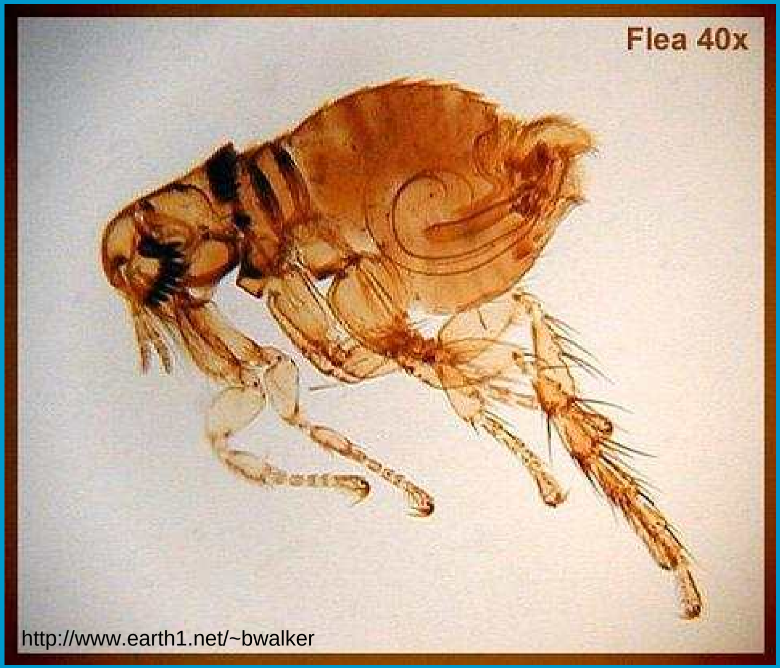
Bioscaling: does size matter?

Just Herder

Faculty of Mechanical, Maritime, and Materials Engineering
Department of BioMechanical Engineering

Delft University of Technology

Scaling effects



"Fleas can jump 130 times as high as their height (St Paul's for a human) and 350 times as far as their body length (football field for a human)"

Kangaroos can jump only around 10 m far…

Scaling effects

- Fleas can jump > 100 times their body height and length
- Why cannot elephants do the same thing?

- Very often: Area to volume ratio

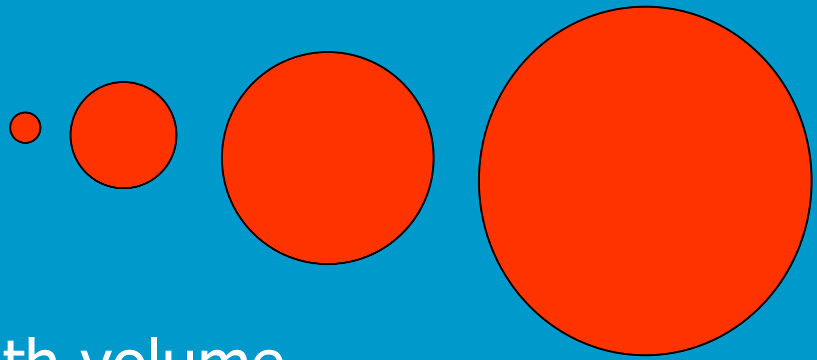
Scaling effects

Example: spherical organisms (0.4 um – 14 mm)

$A=4\pi R^2$

$V= 4\pi R^3/3$

Hence $A/V=3/R$



Oxygen uptake proportional with volume

Oxygen transport proportional with area

From: W. Nachtigall, Biomechanik, 2000

TU Delft

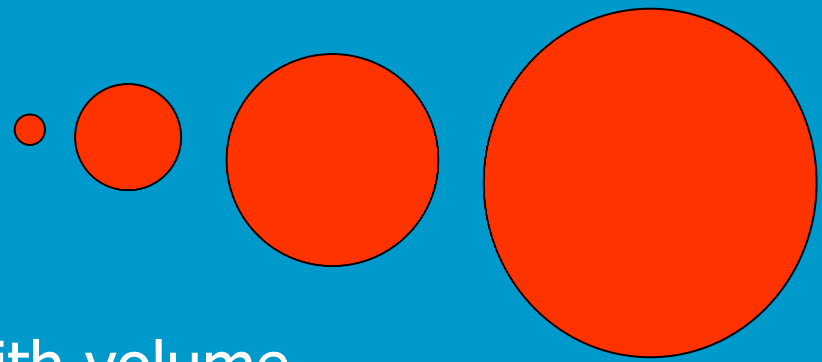
Scaling effects

Example: spherical organisms (0.4 um – 14 mm)

$A=4\pi R^2$

$V= 4\pi R^3/3$

Hence $A/V=3/R$



Oxygen uptake proportional with volume

Oxygen transport proportional with area

→ Organisms greater than around 20 mm need organs dedicated to oxygen uptake (e.g. lungs).

From: W. Nachtigall, Biomechanik, 2000

Scaling effects

The world's most slender chimney (Halsbrucke Esse near Freiberg, Sachsen, compared with grass and upscaled Fagus Sylvatica

The Giant Trees of the Styx Valley in Souther Tasmania

TU Delft

Scaling effects

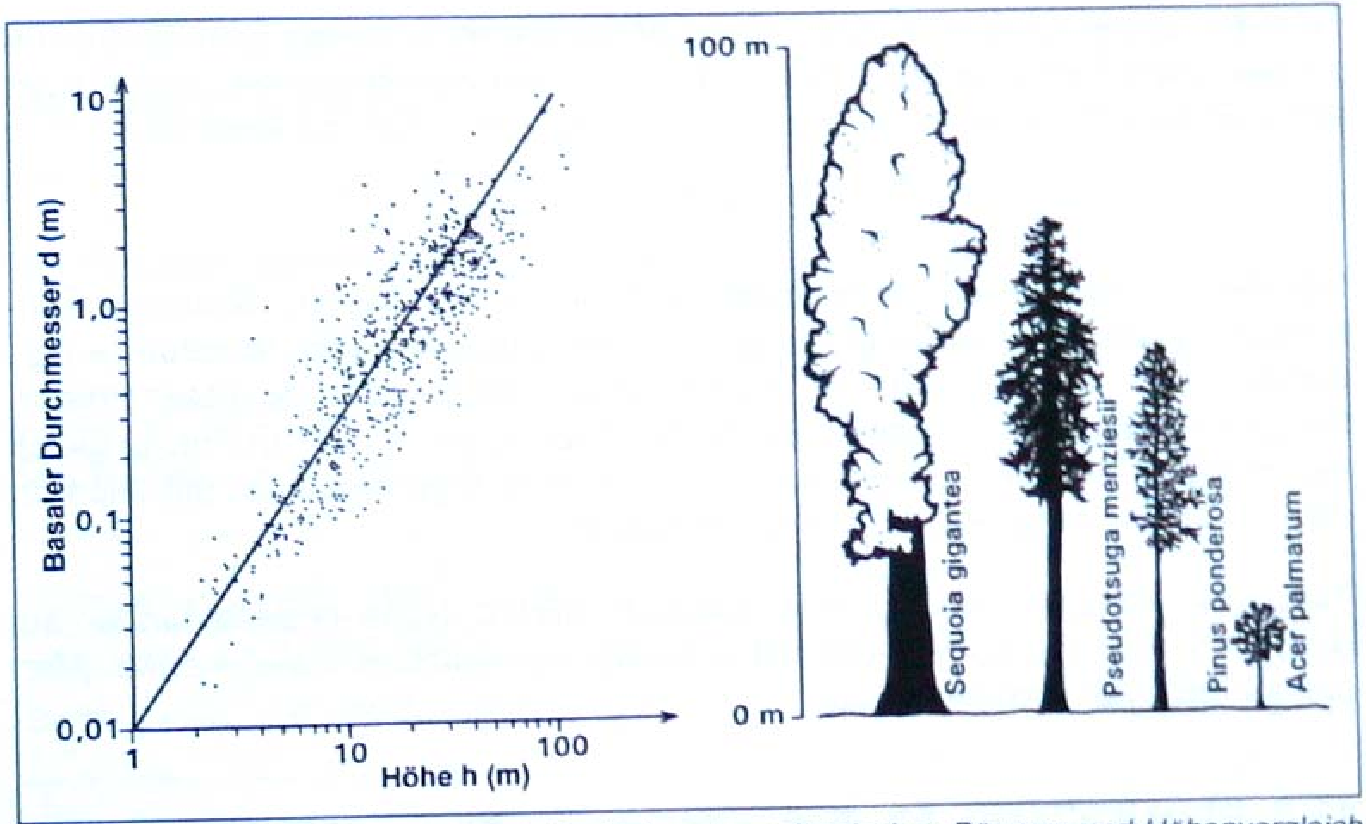
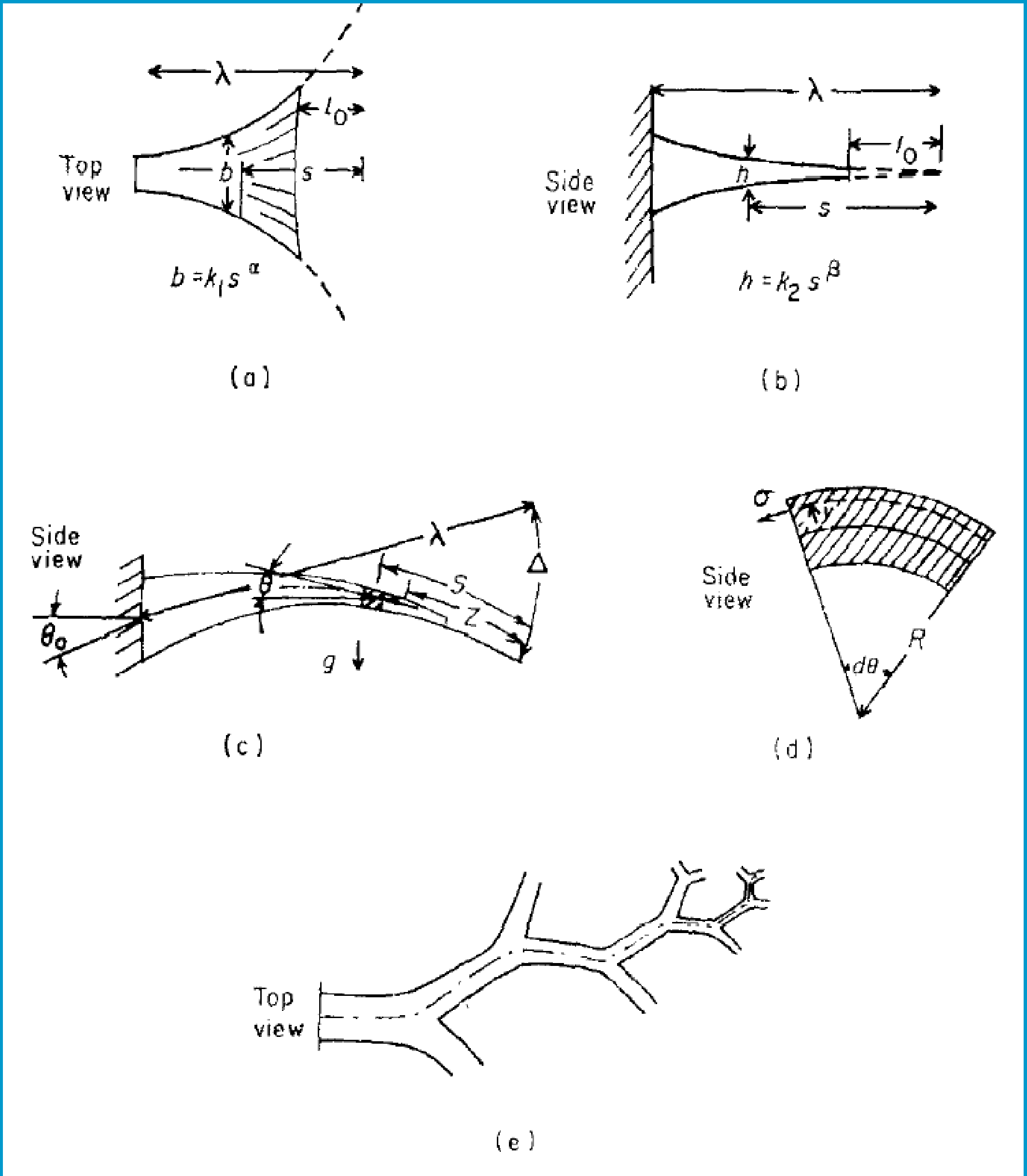


Abb. 16-9: Durchmesser-Höhen-Relation bei nordamerikanischen Bäumen und Höhenvergleich einiger dieser Bäume

From: W. Nachtigall, Biomechanik, 2000

Scaling effects

Constant ratio of deflection/length would require β=2

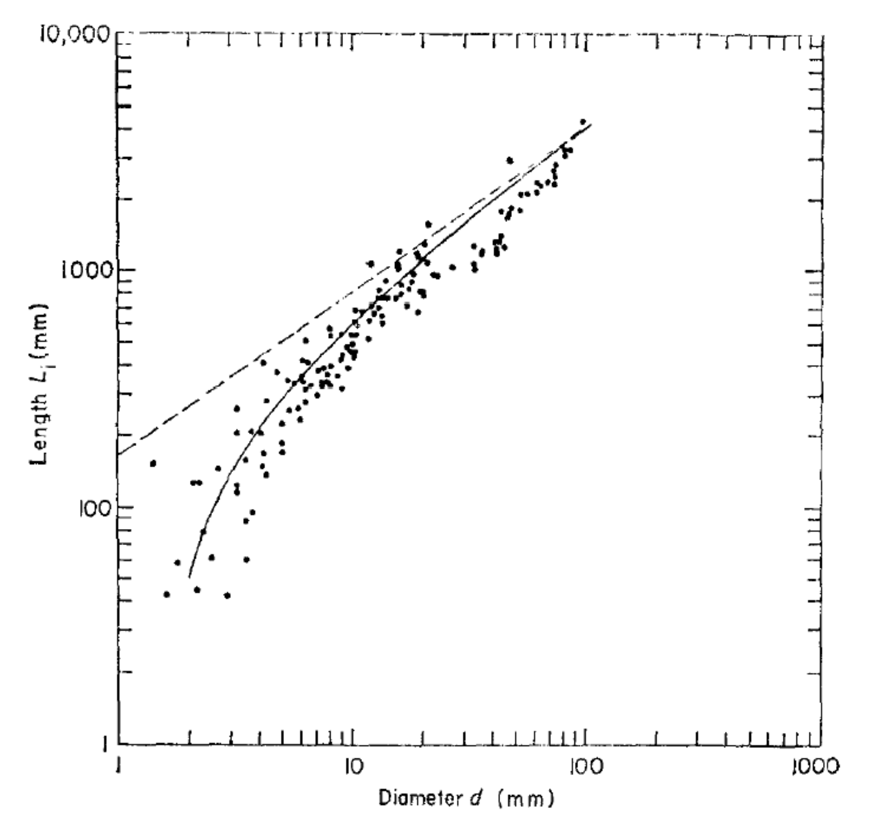


McMahon and Kronauer, 1976

TUDelft

Scaling effects

Models	Depth taper exponent β, $d \propto \lambda^{\beta}$	
Geometric similarity	1·0	
Elastic similarity	3/2	
Static stress similarity	2	
No taper	0	
Experiments		
White pine	1·37	average ≃ 1·50
Red oak	1·51	
Large white oak	1·41	
Small white oak	1·66	
Cherry	1·50	
AFA record specimens (Fig. 5)	1·50	



However, measurements (via eigenfrequency) suggest $D=L^{3/2}$ or $L=D^{2/3}$

McMahon and Kronauer, 1976

TU Delft

Scaling effects

Heart beat versus body mass
Simplifying assumption: Assume scaling law for accellerating mass:

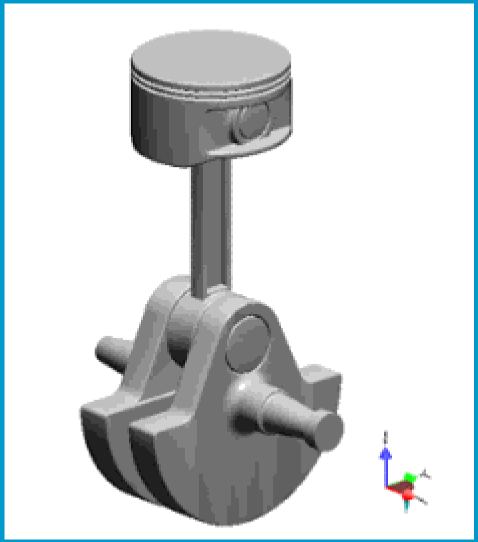
$$F = m\ddot{x} = mr\omega^2 = \rho V r\omega^2$$

$$\sigma = \frac{F}{A} = \frac{\rho V r\omega^2}{A}$$

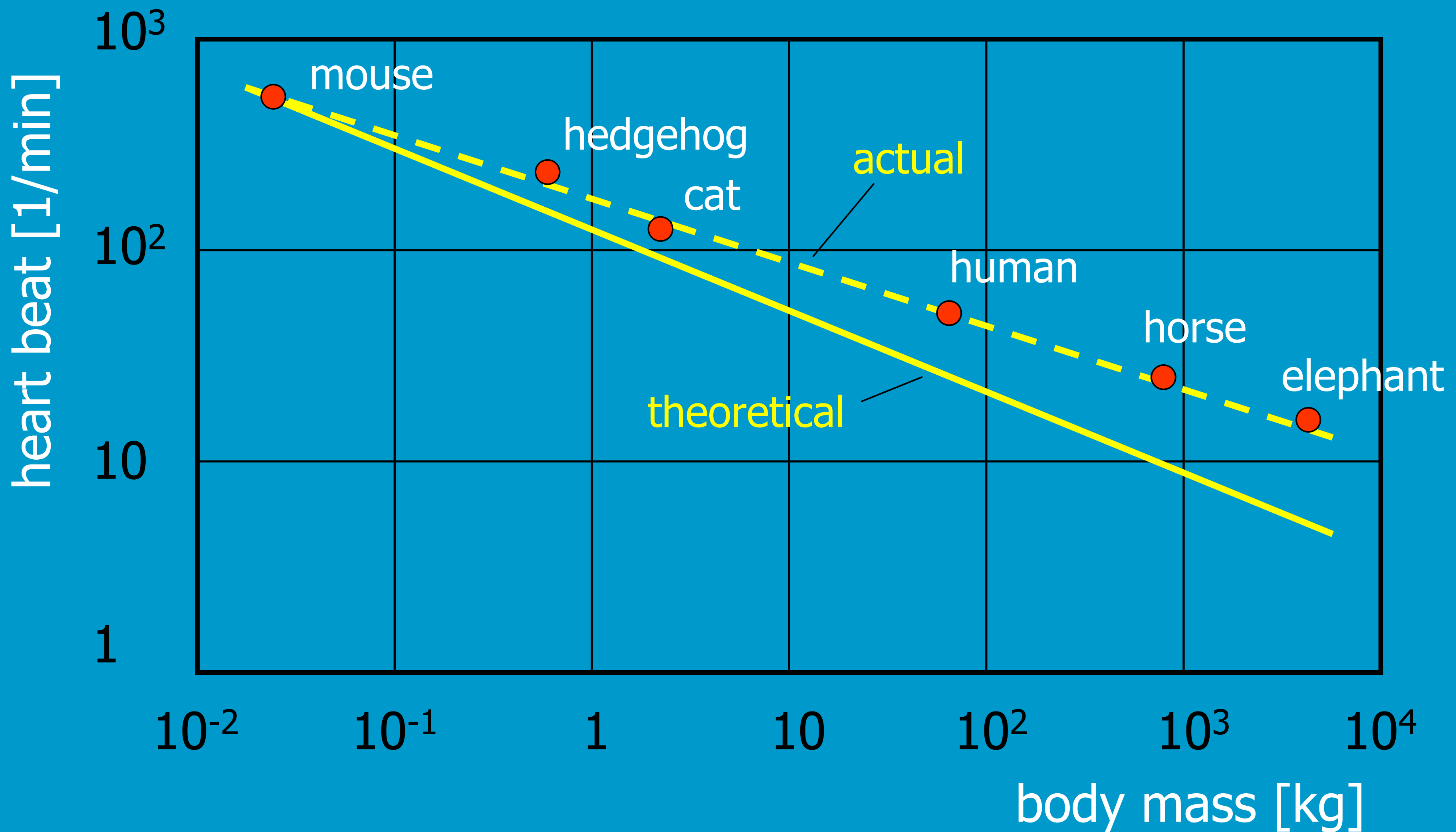
$$S_\sigma = S_\rho S_\omega{}^2 S_\ell{}^2$$

$$Equal\ \sigma\ and\ \rho:$$

$$S_\omega = S_\ell^{-1} = S_m^{-1/3}$$



Scaling effects



JC Cool, 2004

TU Delft

Scaling effects

Energetical scaling laws

Heat production versus heat transfer through skin

$$Demand: \quad S_V = S_\ell^2$$

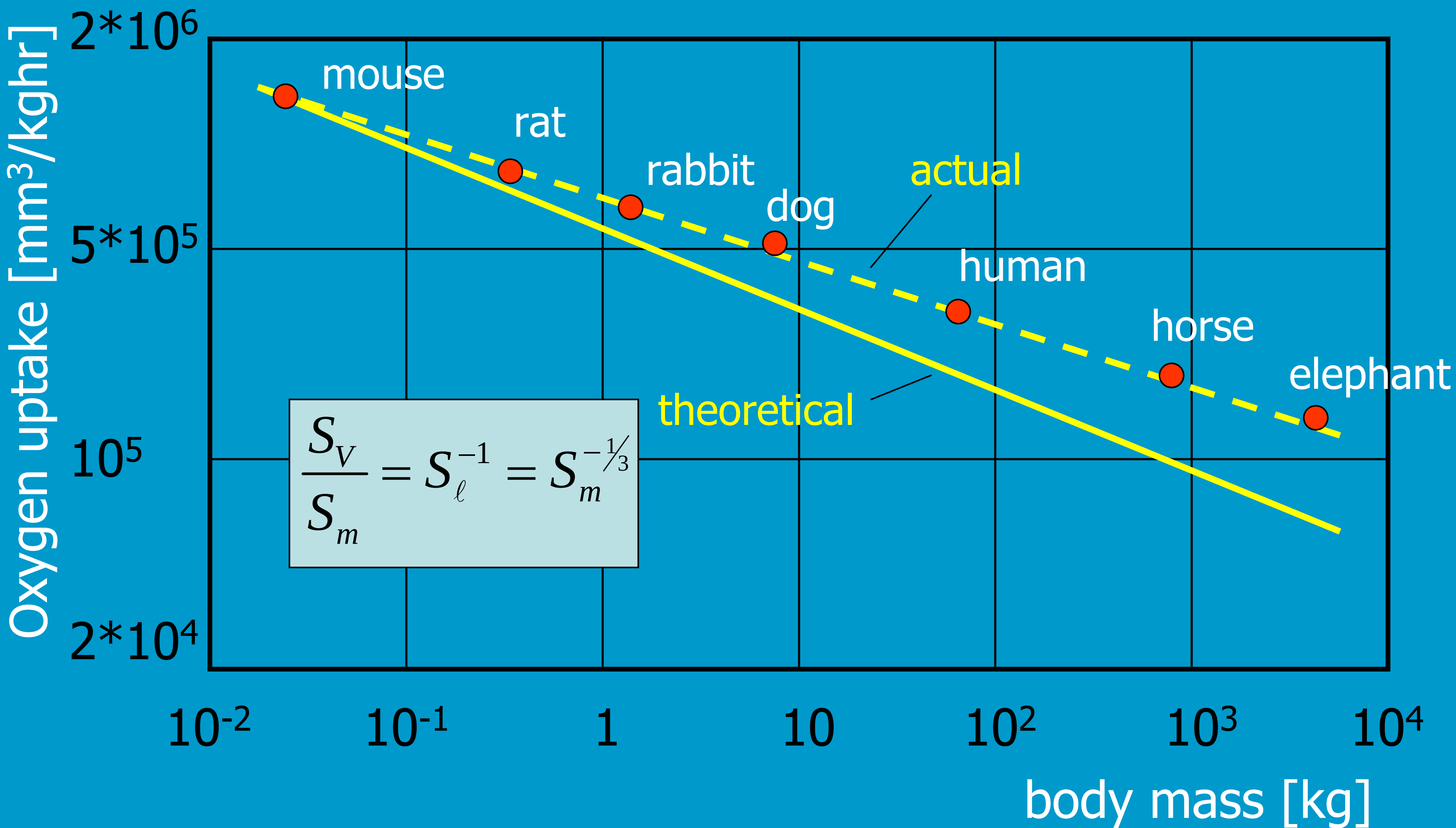
$$Then: \quad \frac{S_V}{S_m} = \frac{S_\ell^2}{S_\ell^3} = S_\ell^{-1}$$

→ Per kg larger animals need less food (more efficient)

→ No warm-blooded animals smaller than ≈ mouse-size

JC Cool, 2004

Scaling effects



JC Cool, 2004

Scaling effects

Gulliver: 12 times bigger than lilliputters. According to the story he needs 12^3 times as much food, is that correct?

http://andrewsullivan.thedailybeast.com/.a/6a00d83451c45669e20120a5ddcabc970c-popup

Scaling effects

Gulliver: 12 times bigger than lilliputters. According to the story he needs 12^3 times as much food, but in ‘reality’ he would need only 12^2.

http://andrewsullivan.thedailybeast.com/.a/6a00d83451c45669e20120a5ddcabc970c-popup

TUDelft