SEARCHING FOR SIMPLICITY AND UNITY IN THE COMPLEXITY OF LIFE

CELLS TO CITIES, COMPANIES TO ECOSYSTEMS, MILLISECONDS TO MILLENIA

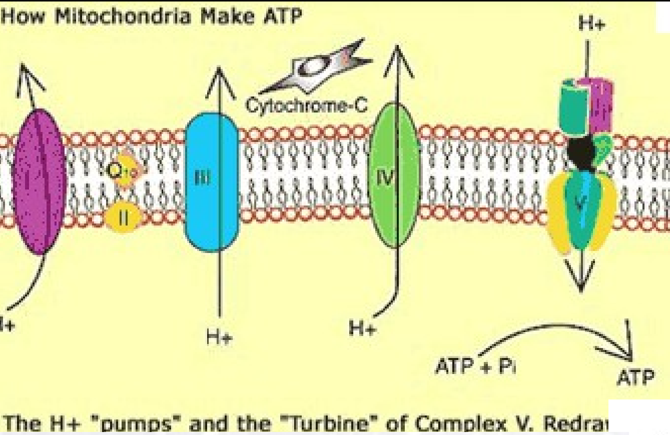
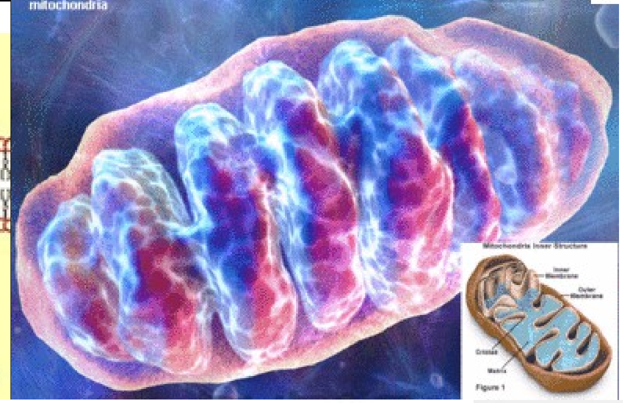
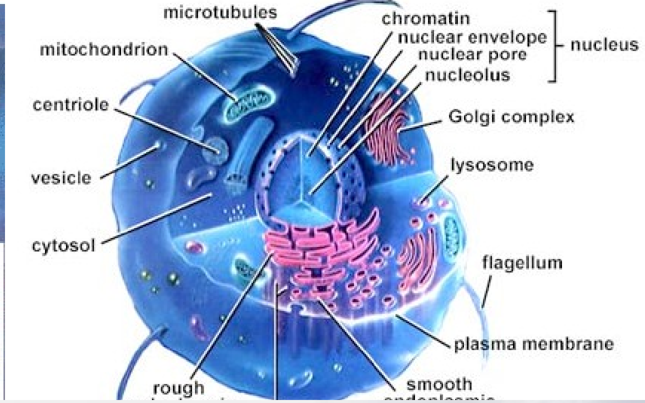
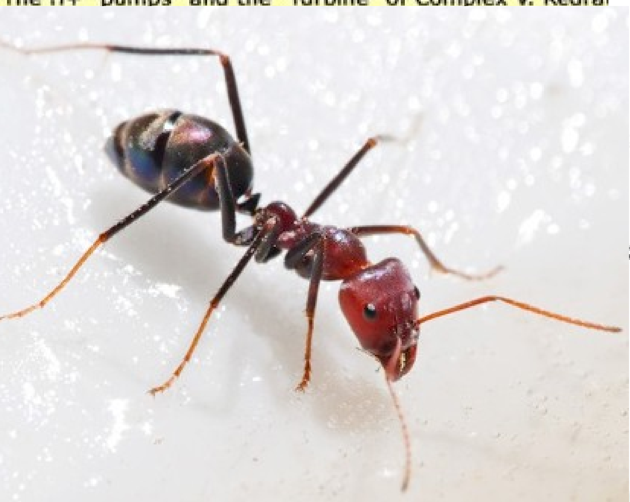
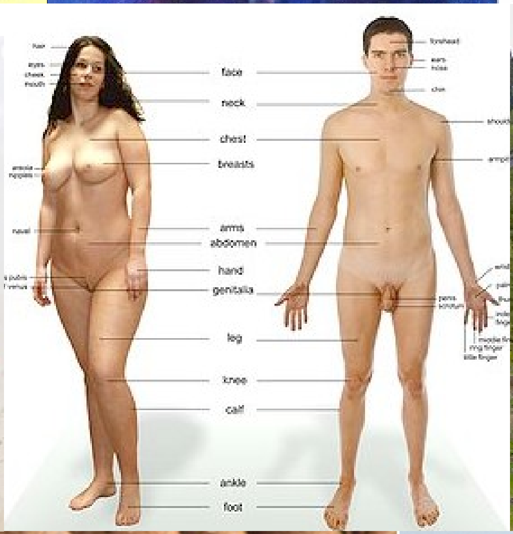
GEOFFREY WEST

SANTA FE INSTITUTE

THE FUTURE OF THE PLANET:

LIFE, GROWTH AND DEATH IN ORGANISMS, CITIES & COMPANIES

Geoffrey West | Santa Fe Institute


How Mitochondria Make ATP
H+
Cytochrome-C
III
IV
II
V
H+
H+
H+
ATP + Pi
ATP
The H+ "pumps" and the "Turbine" of Complex V. Redra

mitochondria

microtubules
chromatin
nuclear envelope
nuclear pore
nucleolus
nucleus
mitochondrion
centriole
Golgi complex
vesicle
lysosome
cytosol
flagellum
plasma membrane
rough
smooth


face
neck
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hand
genitalia
leg
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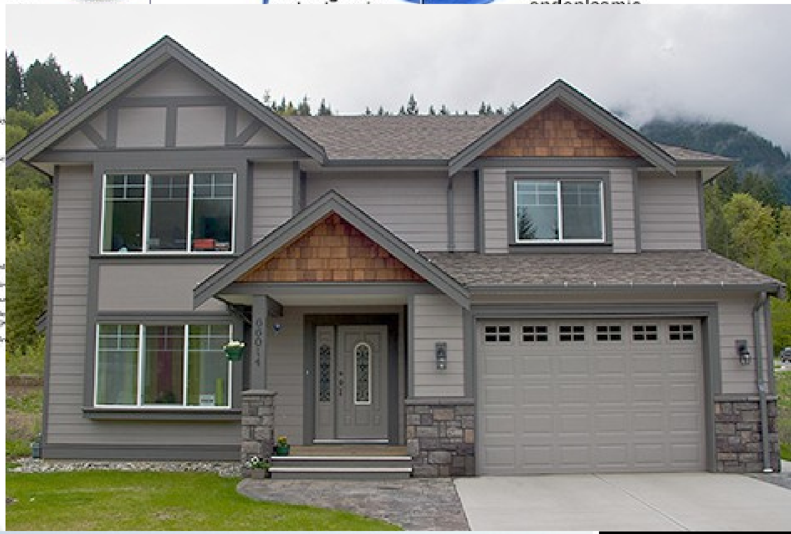
foot


EQUIVALENT TO URBANISING OVER ONE MILLION PEOPLE EVERY WEEK FROM NOW TILL 2050

EQUIVALENT TO URBANISING OVER ONE MILLION PEOPLE EVERY WEEK FROM NOW TILL 2050

OR…….TO ADDING A NEW YORK METROPOLITAN AREA EVERY TWO MONTHS FROM NOW TO 2050

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OR……. A SANTA FE EVERY 12 HOURS!

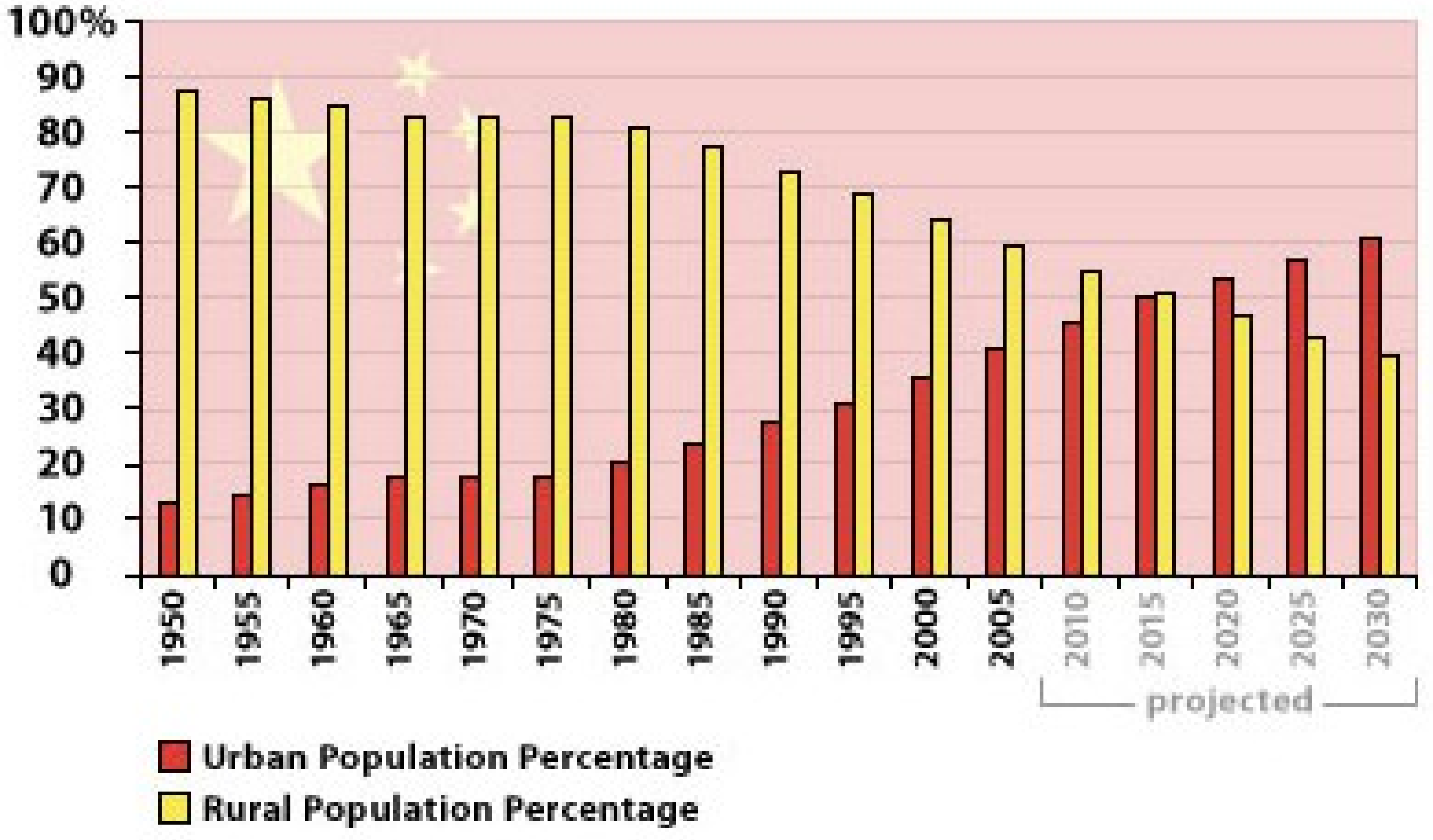
EQUIVALENT TO URBANISING OVER ONE MILLION PEOPLE EVERY WEEK FROM NOW TILL 2050

OR…….TO ADDING A NEW YORK METROPOLITAN AREA EVERY TWO MONTHS FROM NOW TO 2050

OR……. A SANTA FE EVERY 12 HOURS!

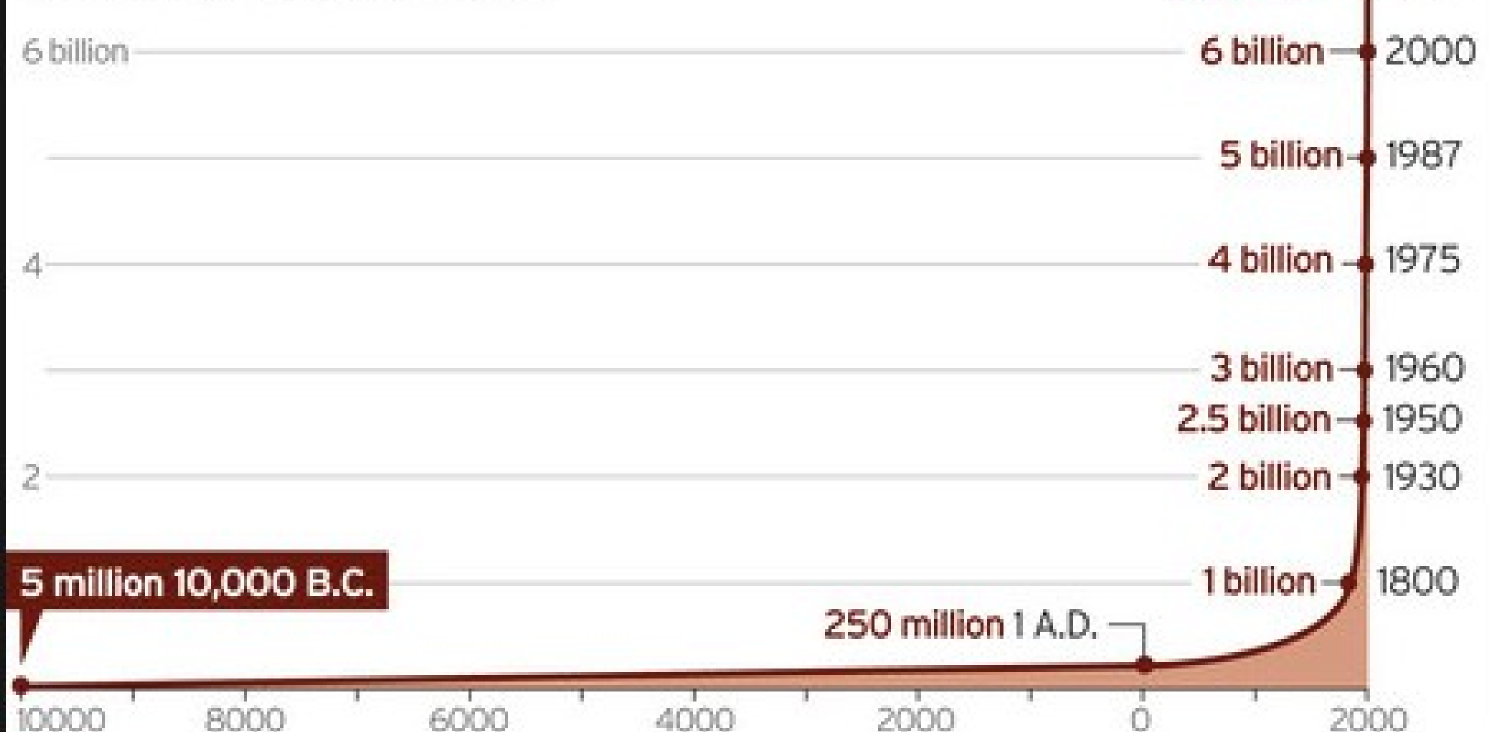
OR……..A FINLAND EVERY MONTH!

CHINA URBAN/RURAL POPULATION GROWTH 1950-2030



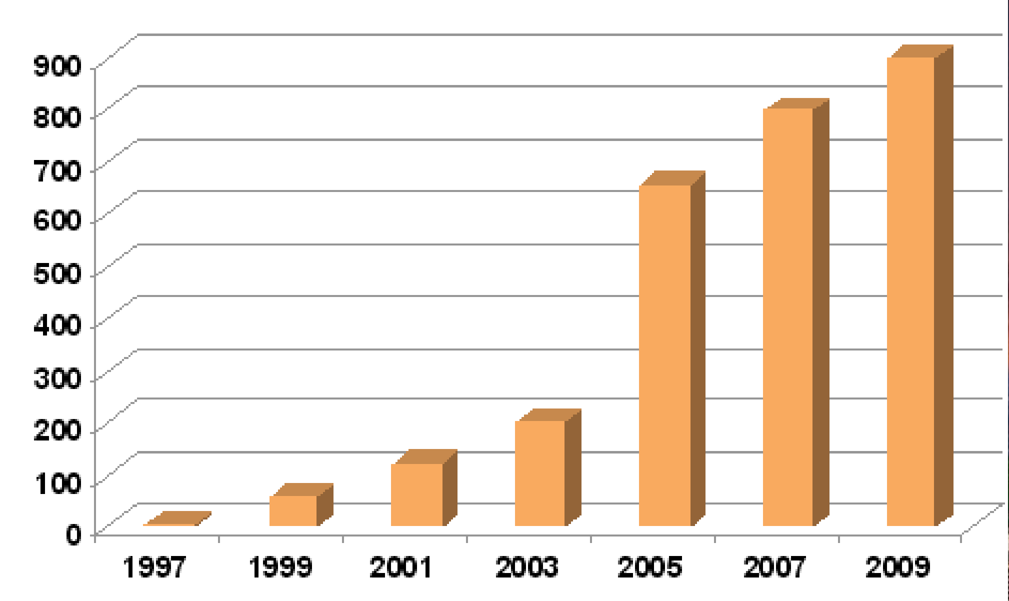
World population growth

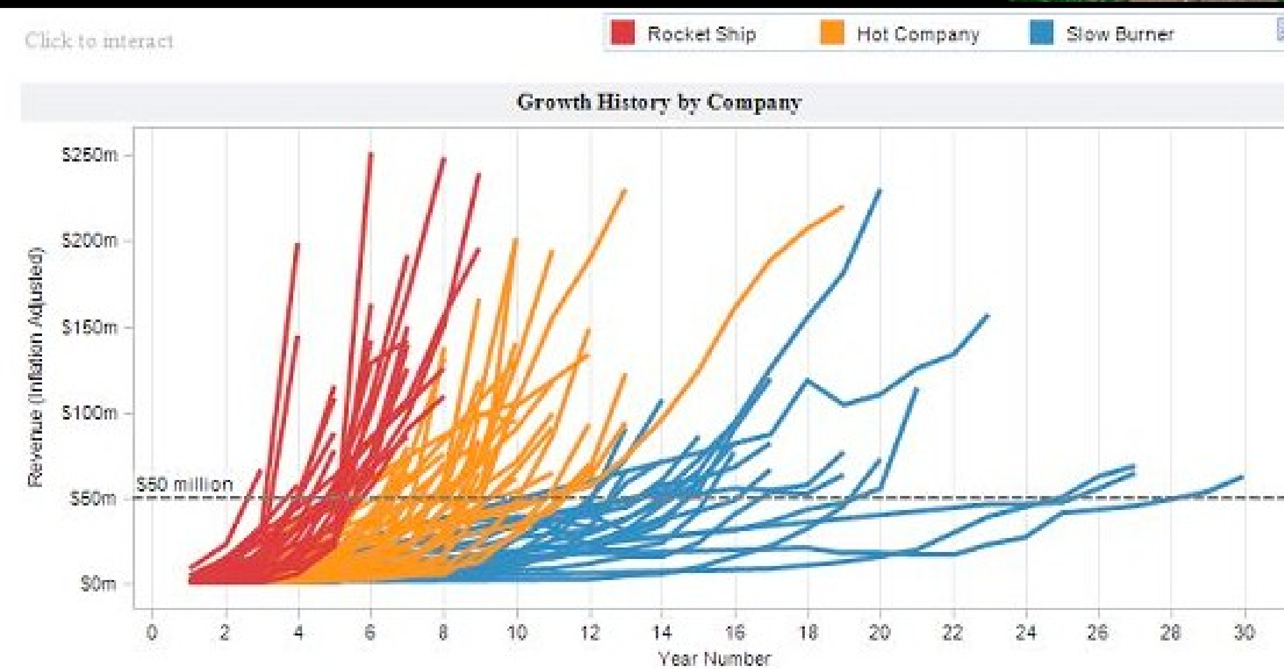
Fertility rates are declining, the United Nations says, but not fast enough to stop population growth. The U.N.'s medium-level projection is for the world's population to reach 9.2 billion by 2050 but still more than 3 billion higher since the turn of the century. Population activists say that's too much for the world to handle.



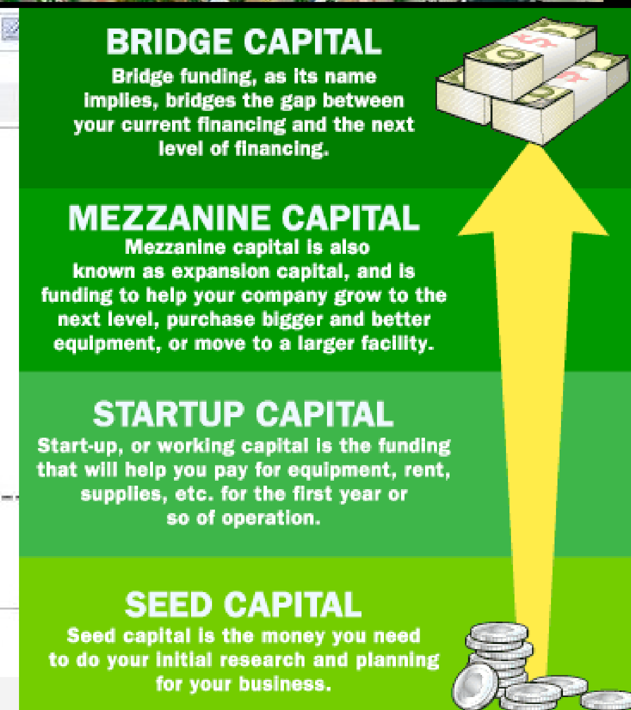
Sources: United Nations; Sustainable Scale Project; World Resources Institute; NationMaster.com

* Projection





Growth rates of 100 software companies from IPO Dashboard



Long-term real growth in US GDP

GDP adjusted for inflation (2005 dollars) 1871–2009

Data from MeasuringWorth.com

VisualizingEconomics.com

FATE OF OUR PLANET IS

the fate of our cities

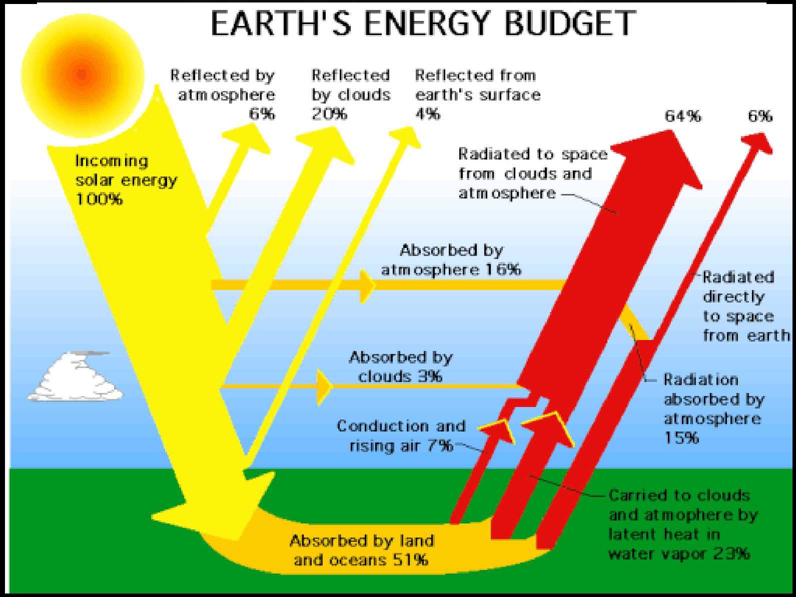




lonelyplanetimages.com


THALDEN•BOYD ARCHITECTS


Missa Papæ Marcelli Cum Sex


EARTH'S ENERGY BUDGET
Reflected by atmosphere 6%
Reflected by clouds 20%
Reflected from earth's surface 4%
64%
6%
Incoming solar energy 100%
Radiated to space from clouds and atmosphere
Absorbed by atmosphere 16%
Radiated directly to space from earth
Absorbed by clouds 3%
Radiation absorbed by atmosphere 15%
Conduction and rising air 7%
Carried to clouds and atmosphere by latent heat in water vapor 23%
Absorbed by land and oceans 51%

SOCIO-ECONOMIC ENTROPY!!


南口
9



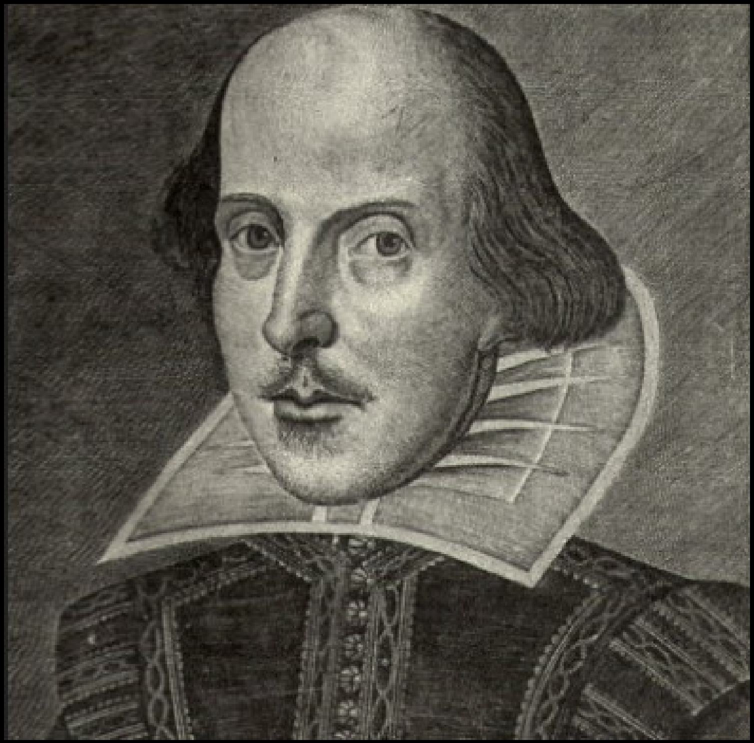

Evening Standard
Classified
FRIDAY
MASSIVE INCREASE IN KNIFE CRIME SURVEYS
Evening Standard




London After Climate Change?

“What is the city but the people?”

William Shakespeare




M·AGRIPPA·L·F·COS·TERTIVM·FECIT

ENERGY & RESOURCES
(METABOLISM, INFRASTRUCTURE)

vs.

INFORMATION
(GENOMICS, INNOVATION)

CITIES AND UBANISATION ARE THE PROBLEM

CITIES AND UBANISATION ARE THE PROBLEM

BUT THEY ARE ALSO THE SOLUTION!!

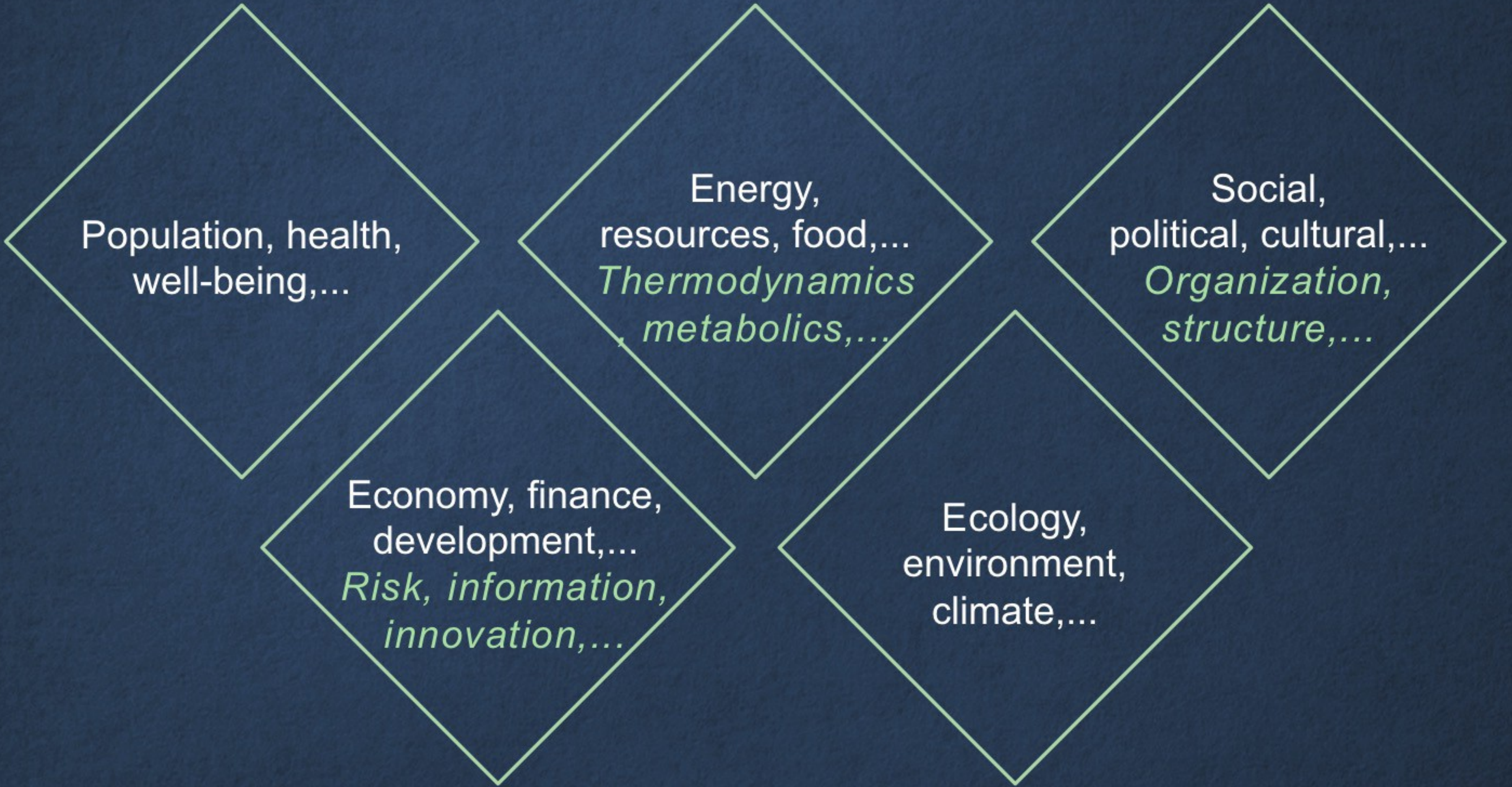
URGENTLY NEED A QUANTITATIVE, PREDICTIVE SCIENCE OF CITIES

RESILIENCE

EVOLVABILITY

GROWTH

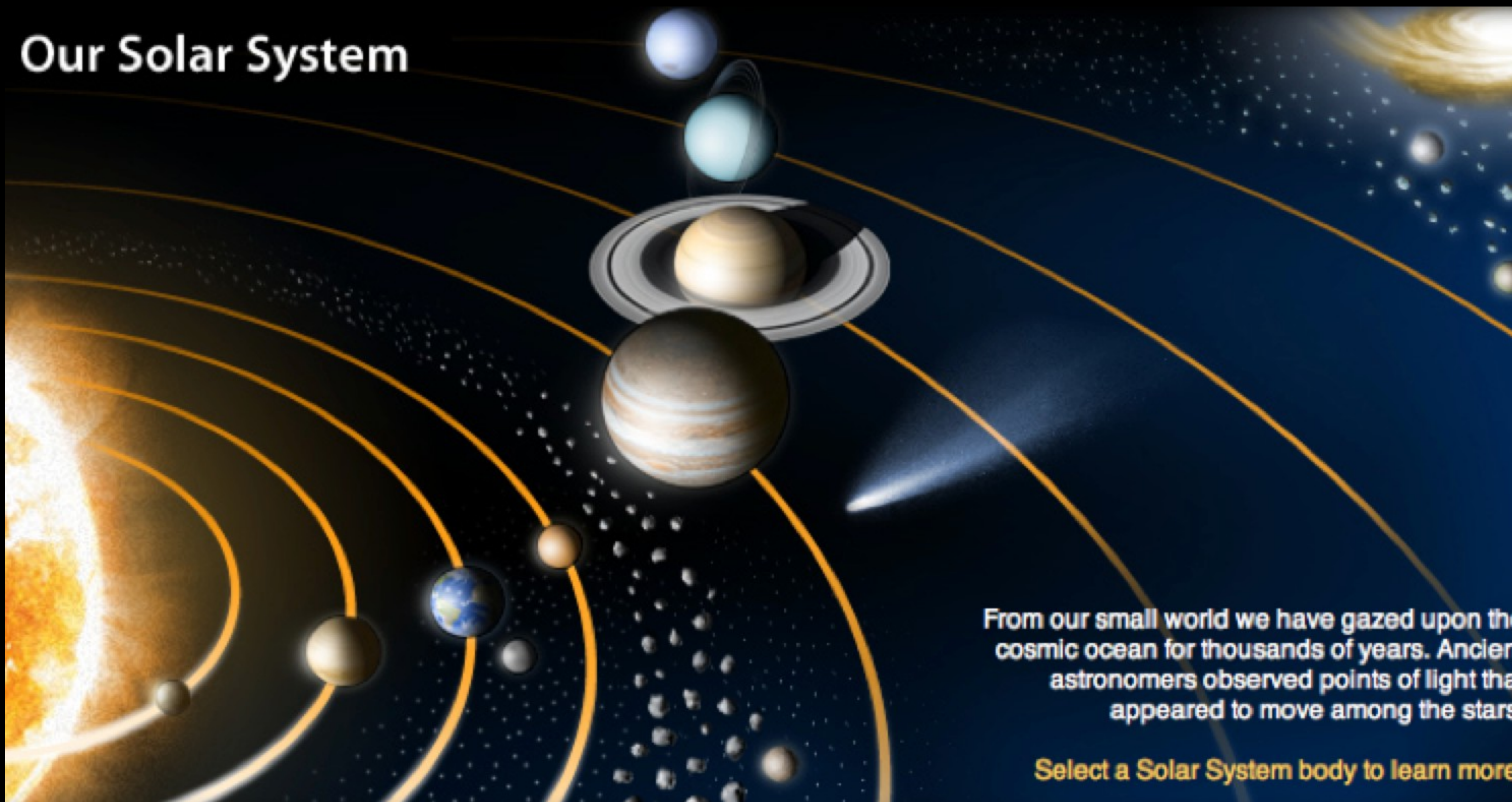
SCALABILITY


Population, health, well-being,...
Energy, resources, food,...
Thermodynamics, metabolics,…
Social, political, cultural,...
Organization, structure,…
Economy, finance, development,...
Risk, information, innovation,…
Ecology, environment, climate,...

THESE ARE NOT INDEPENDENT

They are all highly coupled, inter-related, multi-scale *complex adaptive systems*.

CAN THERE BE “NEWTON’S LAWS OF COMPLEX ADAPTIVE SYSTEMS”?


Our Solar System
From our small world we have gazed upon the cosmic ocean for thousands of years. Ancient astronomers observed points of light that appeared to move among the stars.
Select a Solar System body to learn more.

NEWTON'S LAWS OF MOTION:

$$F = ma = m\frac{d^2\vec{r}}{dt^2}$$

NEWTON'S LAW OF GRAVITATION:

$$F = G\frac{m_1 m_2}{r^2}$$

NEWTON'S LAWS OF MOTION:

$$F = ma = m\frac{d^2\vec{r}}{dt^2}$$

NEWTON'S LAW OF GRAVITATION:

$$F = G\frac{m_1 m_2}{r^2}$$

ENERGY!!

ENCODES AN "INFINITE" AMOUNT OF DATA

MAXWELL'S EQUATIONS

UNIFICATION OF ELECTRICITY AND MAGNETISM

Name	"Microscopic" equations	"Macroscopic" equations
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$	$\nabla \cdot \mathbf{D} = \rho_f$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t}$

MAXWELL'S EQUATIONS

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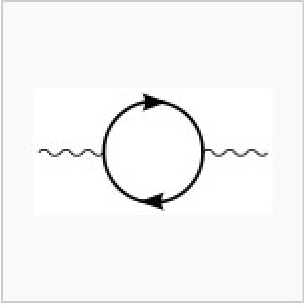
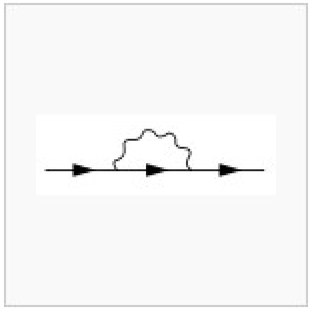
ELECTROMAGNETIC WAVES!!

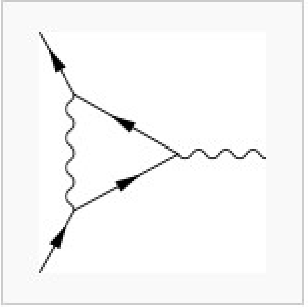
QUANTUM ELECTRODYNAMICS

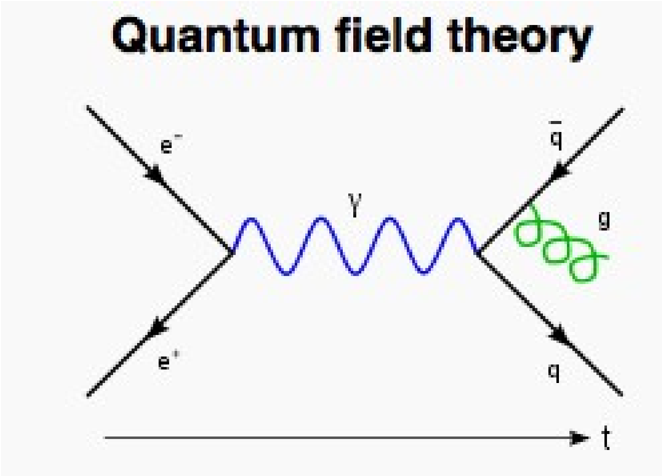
$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

FEYNMAN DIAGRAMS









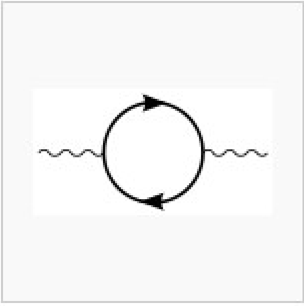
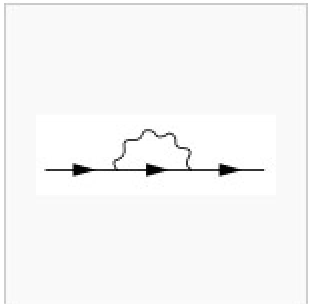
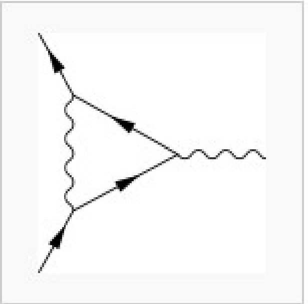
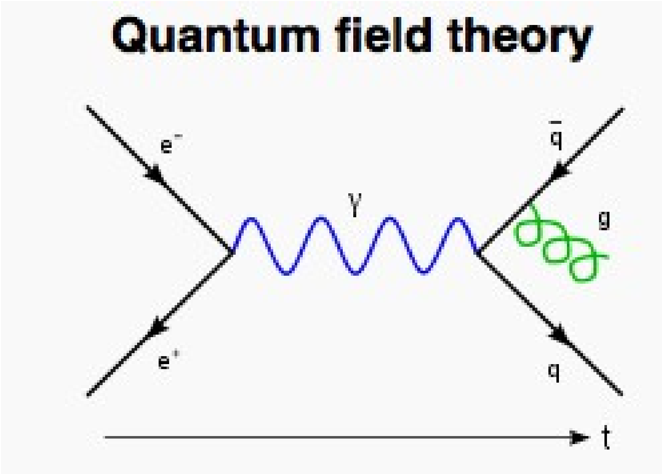
MAGNETIC MOMENT OF THE ELECTRON

THEORY g/2 = 1.001 159 652 177 60 (520) [4.4 ppt]

QUANTUM ELECTRODYNAMICS

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

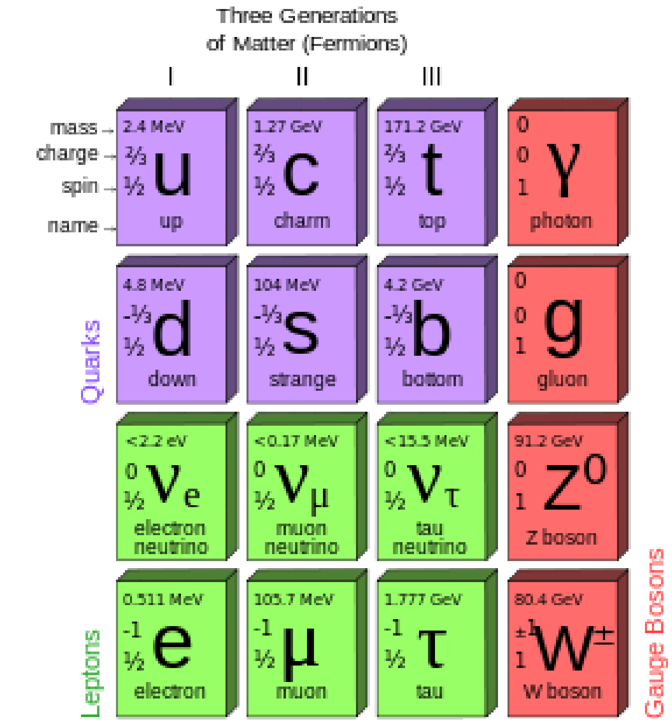
FEYNMAN DIAGRAMS

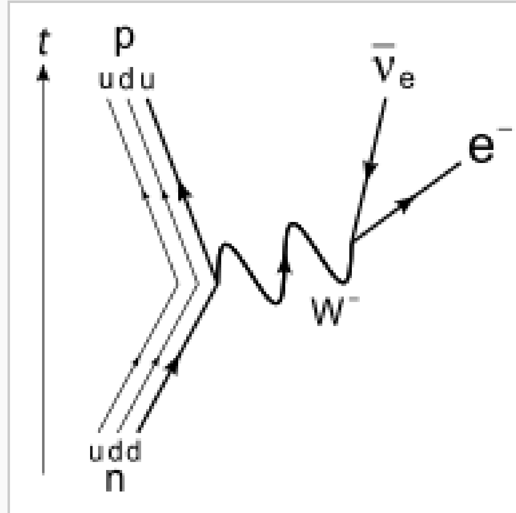
MAGNETIC MOMENT OF THE ELECTRON

THEORY g/2 = 1.001 159 652 177 60 (520) [4.4 ppt]

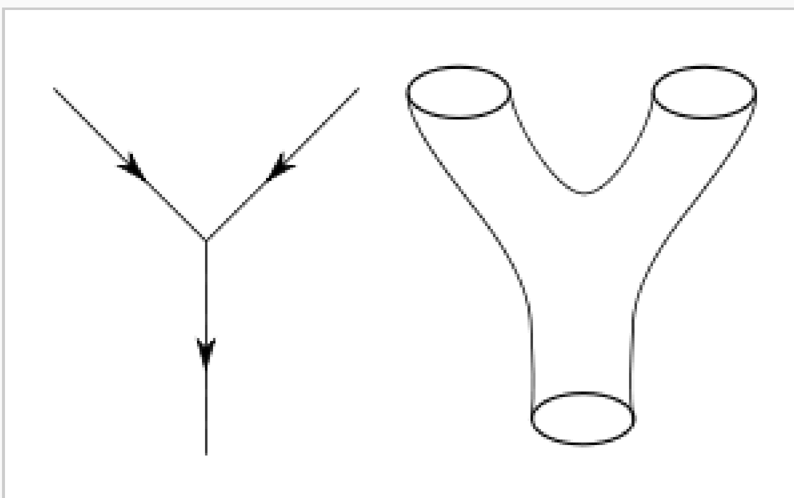
EXPERIMENT g/2 = 1.001 159 652 180 73 (28) [0.28 ppt]



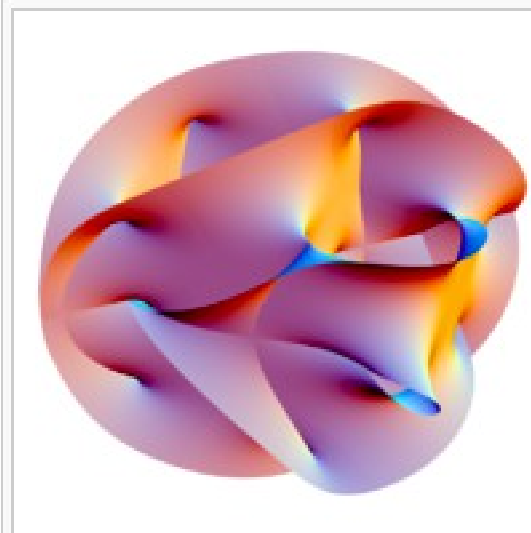
Six of the particles in the Standarc quarks (shown in purple). Each of columns forms a *generation* of ma



Feynman diagram of beta decay with time flowing upwards. The CKM matrix (discussed below) encodes the

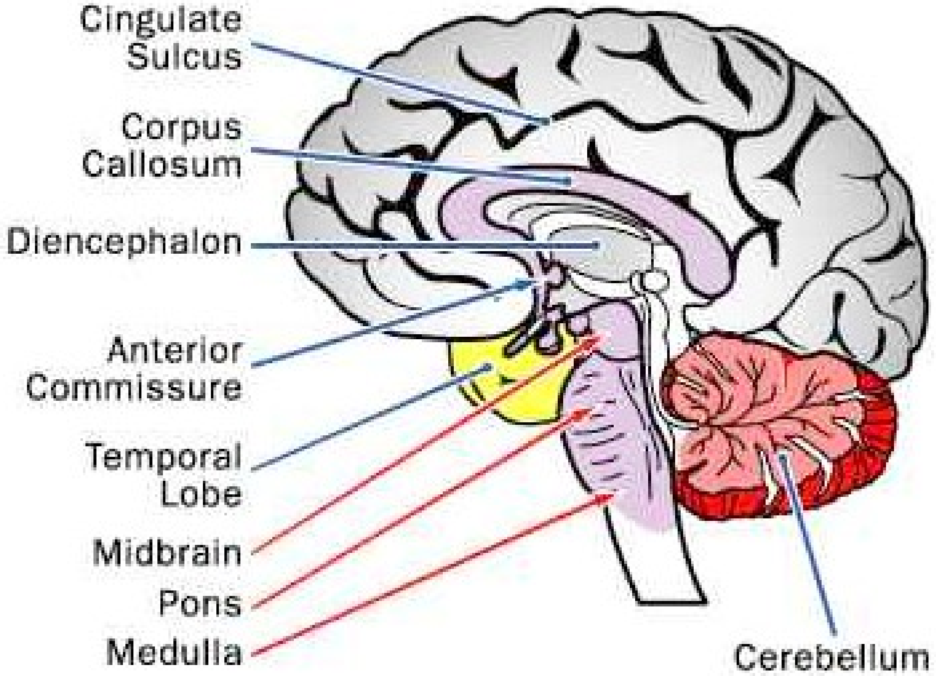


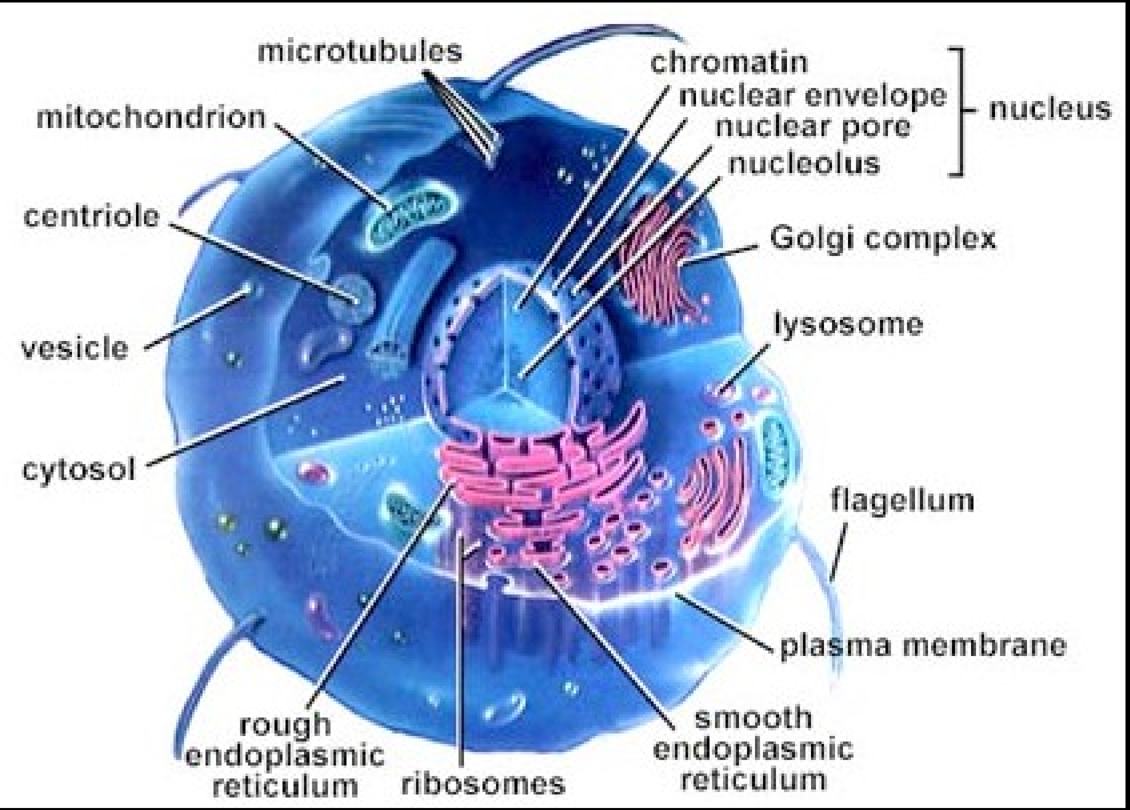
Interaction in the subatomic world: world lines of point-like particles in the Standard Model or a world sheet swept up by closed strings in string theory

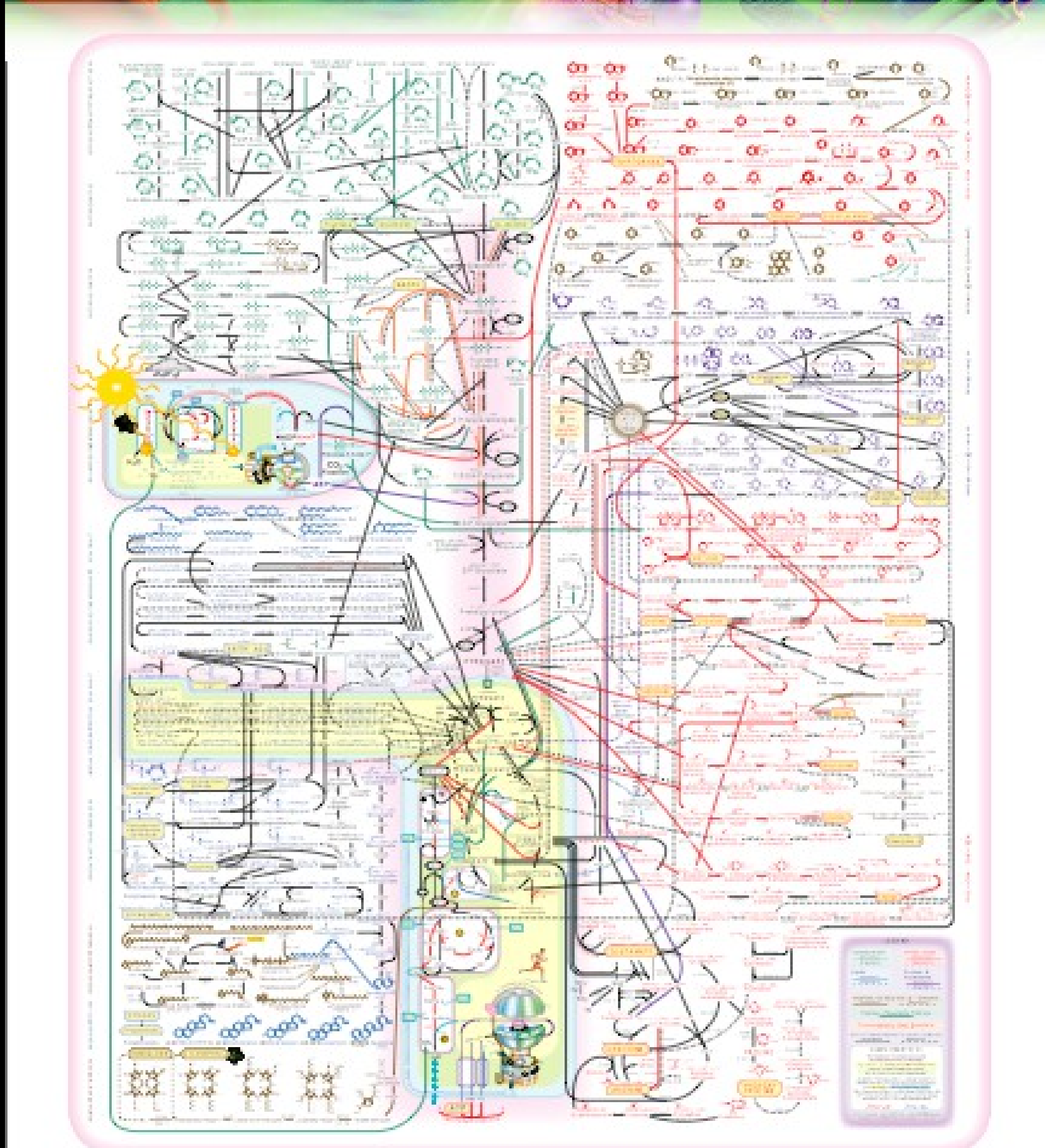


Calabi–Yau manifold (3D projection)

Major Internal Parts of the Human Brain




microtubules
mitochondrion
chromatin
nuclear envelope
nuclear pore
nucleolus
nucleus
centriole
Golgi complex
vesicle
lysosome
cytosol
flagellum
plasma membrane
rough
endoplasmic
reticulum
ribosomes
smooth
endoplasmic
reticulum




China fuels resource boom
September 11 Terrorist Attack on the World Trade Center
Start of Iraq War
Energy and Metal shares boom
Industrial and Property boom. First labour government since 1949
Oil, mining & Poseidon booms
Iraq War speculation World economy slows
Strong overseas investment, scrip shortage and property boom
Korean war starts 1950
1929 Crash British lending ceases Export prices collapse Industrial activity falls Many businesses close
1939-45 war
Oil found in Bass Strait
World Share price collapse Bank credit fuels property boom
1960 credit squeeze
Commodity prices recover, new mineral discoveries Industrial rationalisation
Start of 1914-18 War
Pearl Harbour USA enters war
Strong inflow of overseas capital
TIME - 130 years

SOME CHARACTERISTICS OF COMPLEX SYSTEMS

- *MANY COMPONENTS*
- *MANY INDIVIDUAL ACTORS / AGENTS*
- *MULTI SPATIAL AND TEMPORAL SCALES*
- *STRONGLY COUPLED / INTERACTING*
- *NON-LINEAR*
- *SENSITIVITY TO BOUNDARY CONDITIONS (CHAOS)*
- *MORE IS DIFFERENT*
- *EMERGENT PHENOMENA / MULTIPLE PHASES*
- *UNINTENDED CONSEQUENCES*
- *ADAPTIVE / EVOLVING*
- *ENERGY/INFORMATION*
- *HISTORICALLY CONTINGENT / PATH DEPENDENT*
- *ROBUST / RESILIENT*
- *NON-EQUILIBRIUM*
- *UNDERLYING SIMPLICITY*
- *COMPLICATED vs COMPLEX*

- ***SEARCH FOR UNDERLYING LAWS AND PRINCIPLES LEADING TO A QUANTITATIVE (MATHEMATISABLE) PREDICTIVE CONCEPTUAL FRAMEWORK***

- ***CAN THERE BE "NEWTON'S LAWS OF COMPLEX ADAPTIVE SYSTEMS"?***

COARSE - GRAINED DESCRIPTION

WITH INCREASING RESOLUTION AND GRANULARITY

STATISTICAL/PROBABILISTIC

QUANTITATIVE, PREDICTIVE

WHY DO WE STOP GROWING?

WHY DO WE LIVE ~100 YEARS AND NOT 1000, OR 2-3 YEARS LIKE A MOUSE?

WHERE DOES A TIME-SCALE OF 100 YEARS COME FROM?

HOW IS IT GENERATED FROM FUNDAMENTAL MICROSCOPIC MOLECULAR TIME-SCALES OF GENES AND RESPIRATORY ENZYMES?


WHY DO WE SLEEP ~8 HOURS A DAY AND NOT 15 LIKE MICE AND BABIES OR JUST 3 LIKE ELEPHANTS?

WHY DO CITIES KEEP GROWING WHEREAS ALL COMPANIES EFFECTIVELY STOP?

WHY DO (ALMOST) ALL COMPANIES EVENTUALLY DISAPPEAR - LIKE WE DO - WHEREAS (ALMOST) ALL CITIES SURVIVE?


TWA
TWA
TWA
TWA


GM


LEHMAN BROTHERS

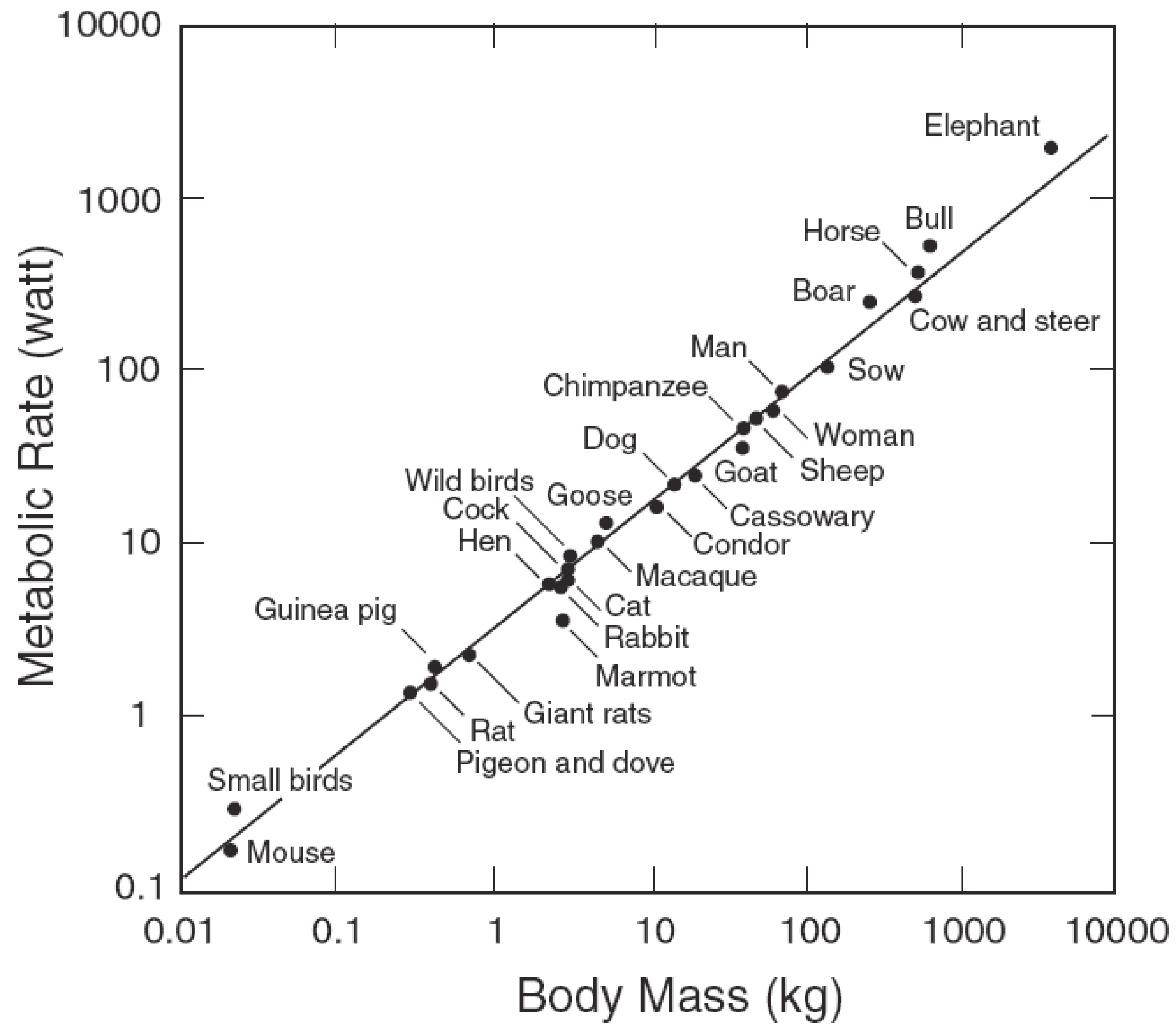

© Alex Hinds
Acclaim Images.com
This Business
is now
CLOSED

WHY DOES THE PACE OF LIFE CONTINUE TO GET FASTER?

IS ANY OF THIS SUSTAINABLE?

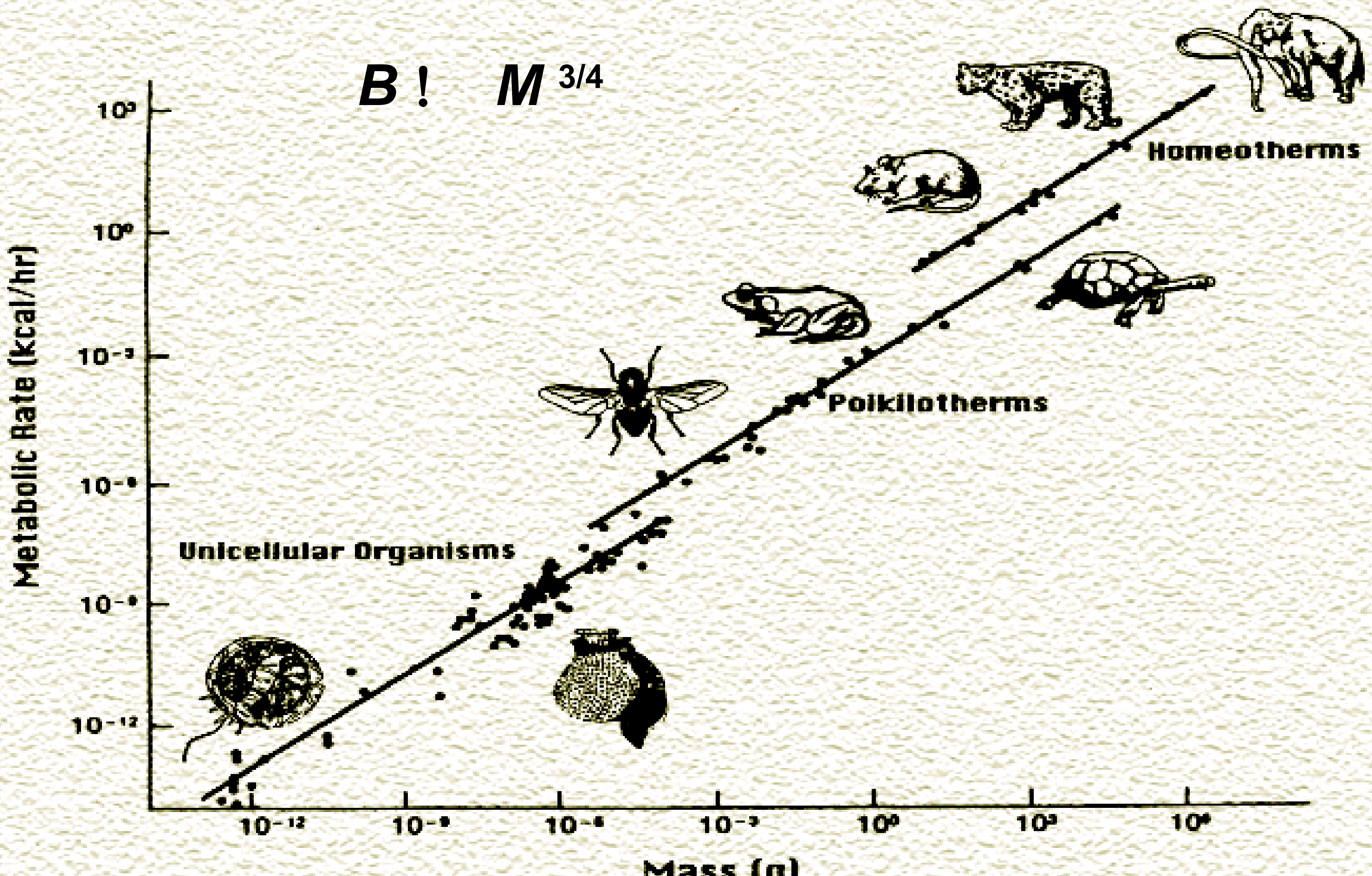
IS THERE AN END TO (SOCIO-ECONOMIC) TIME?

Mammals vary in size by 8 orders of magnitude



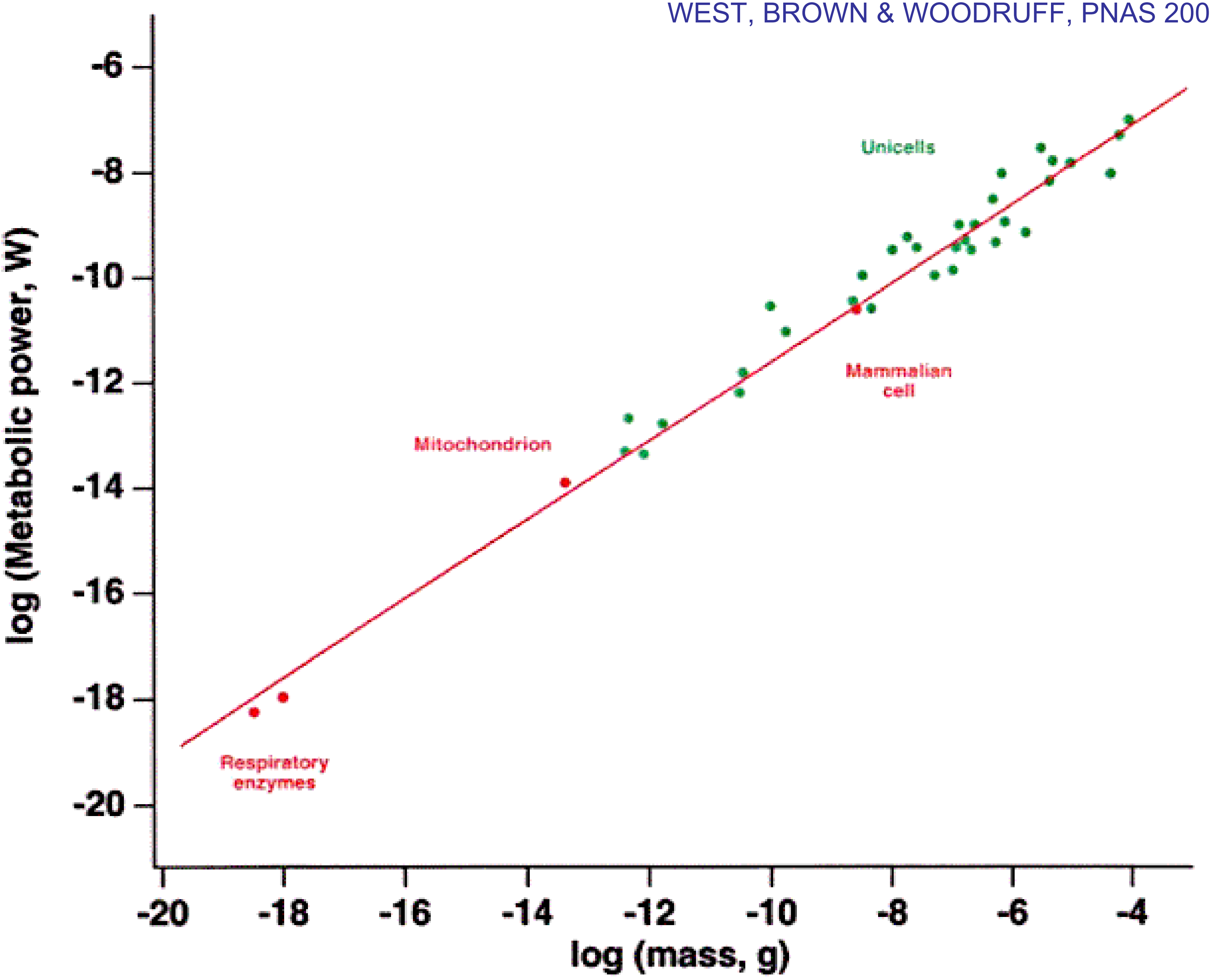
SLOPE = ¾ < 1 SUB-LINEAR ECONOMY OF SCALE

Whole-organism metabolic rate (*B*) scales as the 3/4 power of body mass (*M*)

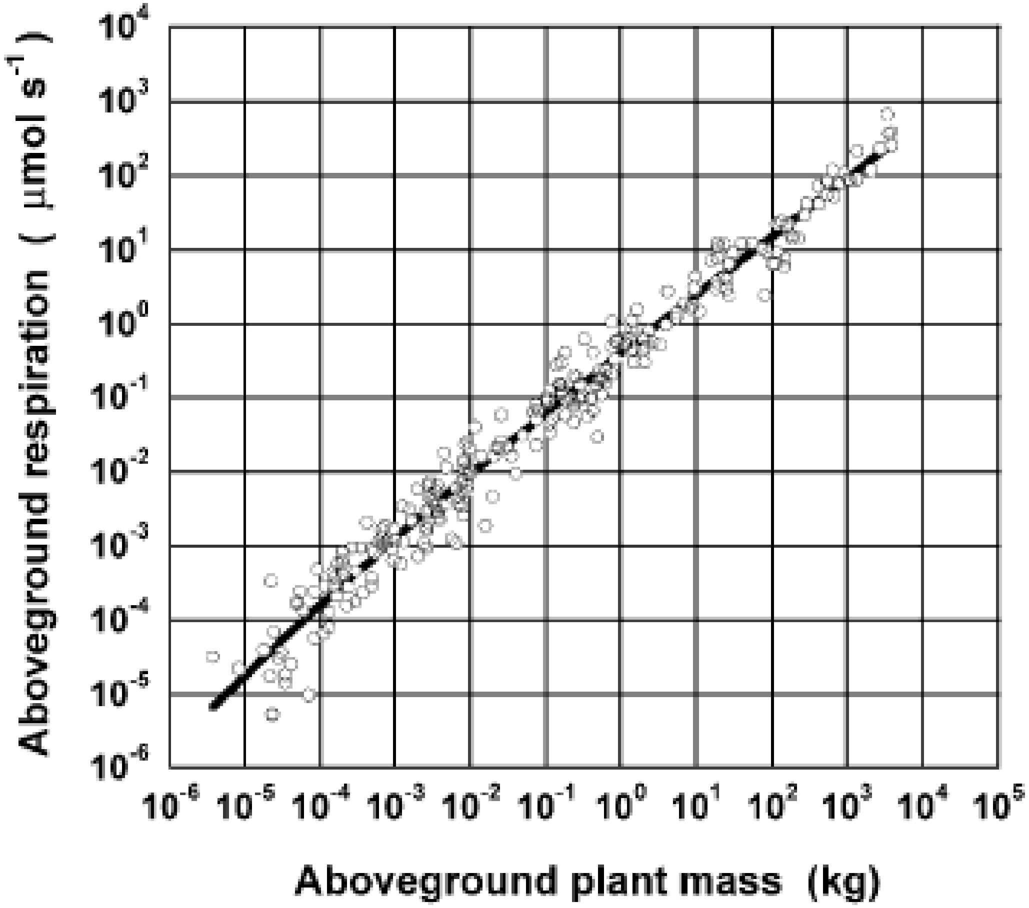


Hemmingson 1960

WEST, BROWN & WOODRUFF, PNAS 2001



PLANTS/TREES



$$B \propto M^{0.780 \pm 0.037}$$

SINCE N_{cells} ~ M NAIVELY MIGHT EXPECT B ~ M

HOWEVER, $$B \sim M^{3/4}$$

OVER 27 ORDERS OF MAGNITUDE

SPECIFIC METABOLIC RATE (PER UNIT MASS)

$$\frac{B}{M} \propto M^{21/4}$$

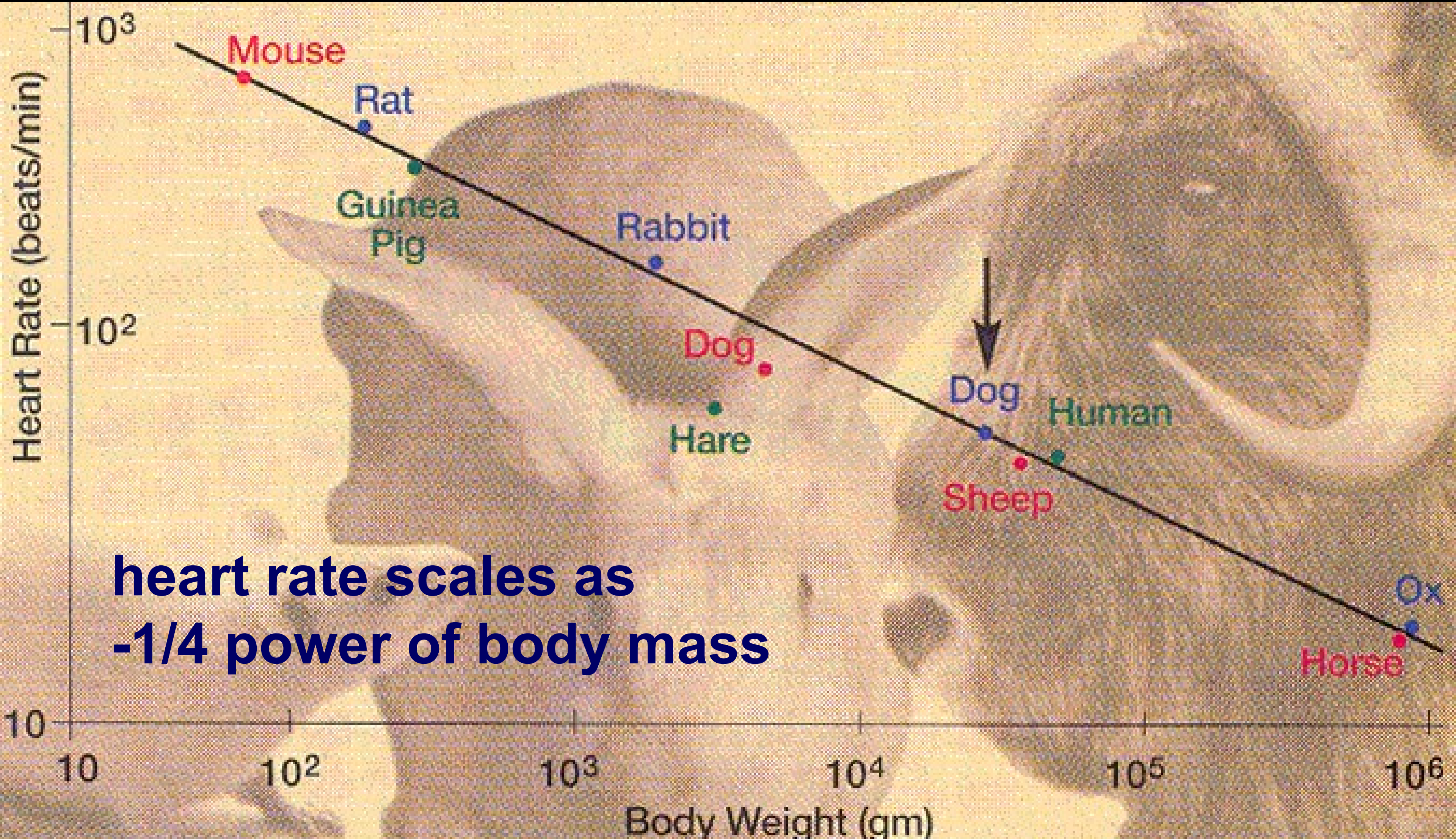
SO METABOLIC RATE OF AVERAGE CELL

$$B_{cell} \propto M^{21/4}$$

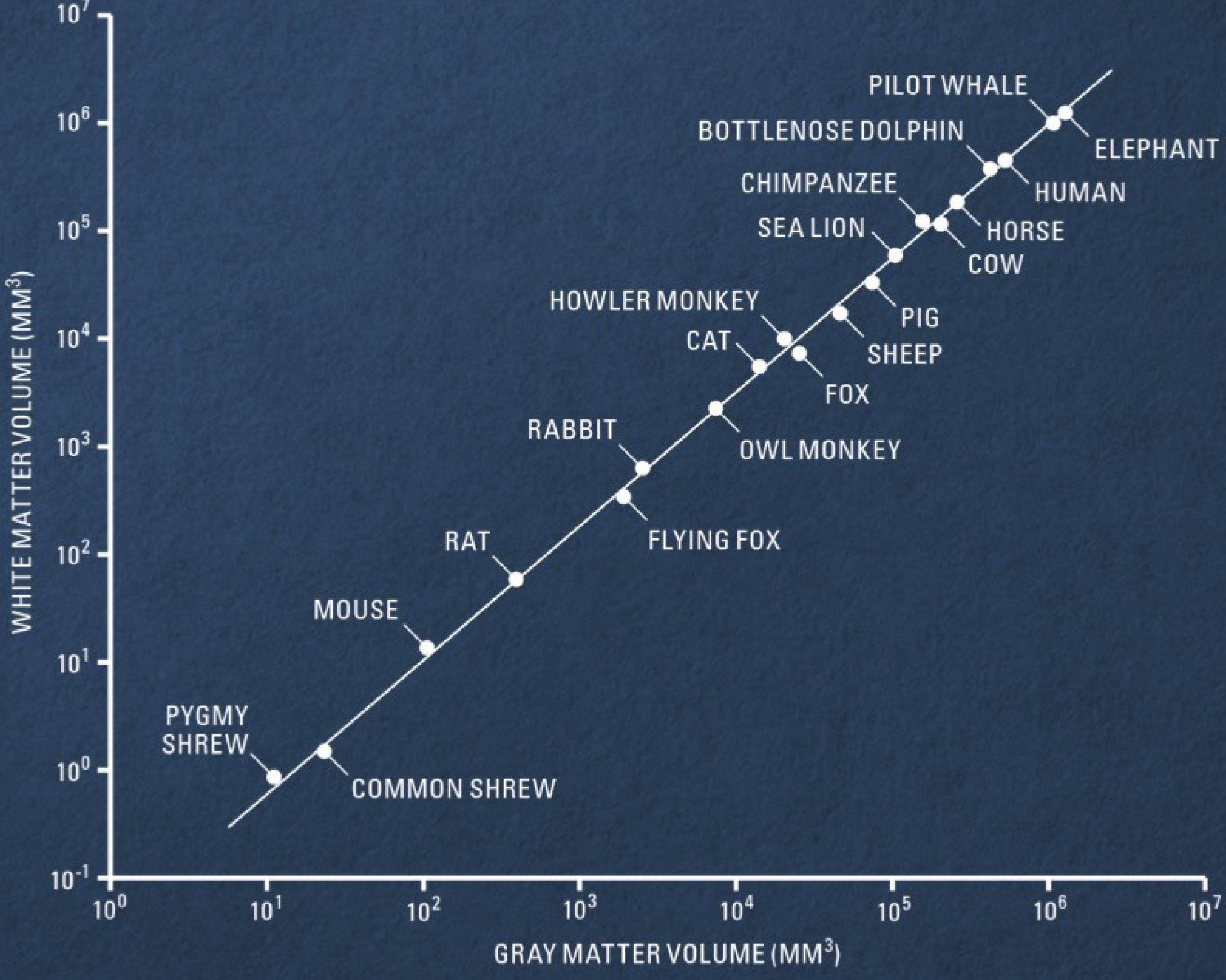
EXTRAORDINARY SYSTEMATIC ECONOMY OF SCALE (THE BIGGER YOU ARE, THE LESS NEEDED PER "CAPITA")

SIMILAR SCALING HOLDS TRUE FOR ALL PHYSIOLOGICAL PROCESSES AND LIFE HISTORY EVENTS OVER THE ENTIRE SPECTRUM OF LIFE

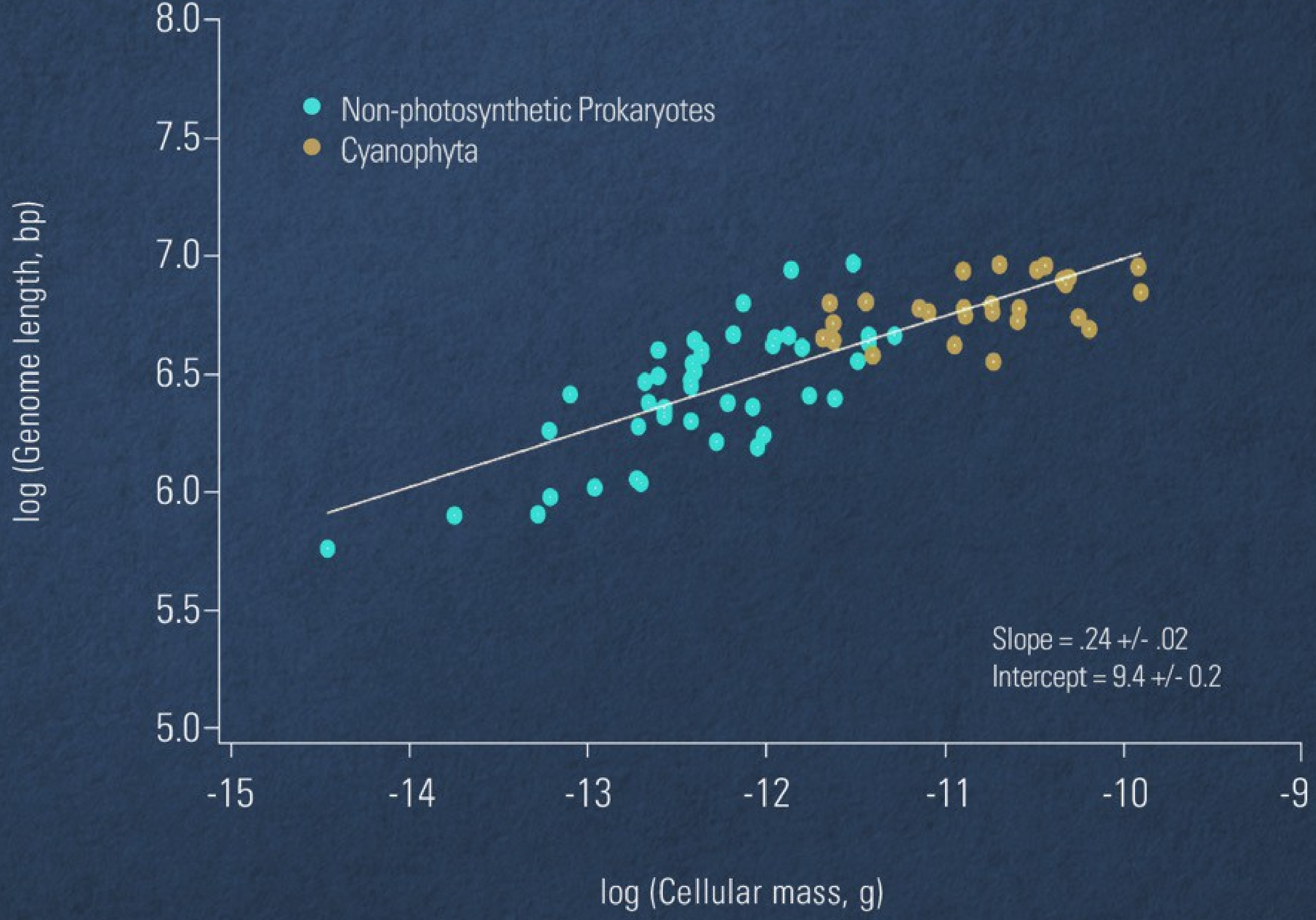
Metabolic rate sets the pace of life
Small animals live fast and die young



WHITE AND GRAY MATTER OF BRAINS



DEPENDENCE OF GENOME LENGTH ON CELLULAR MASS



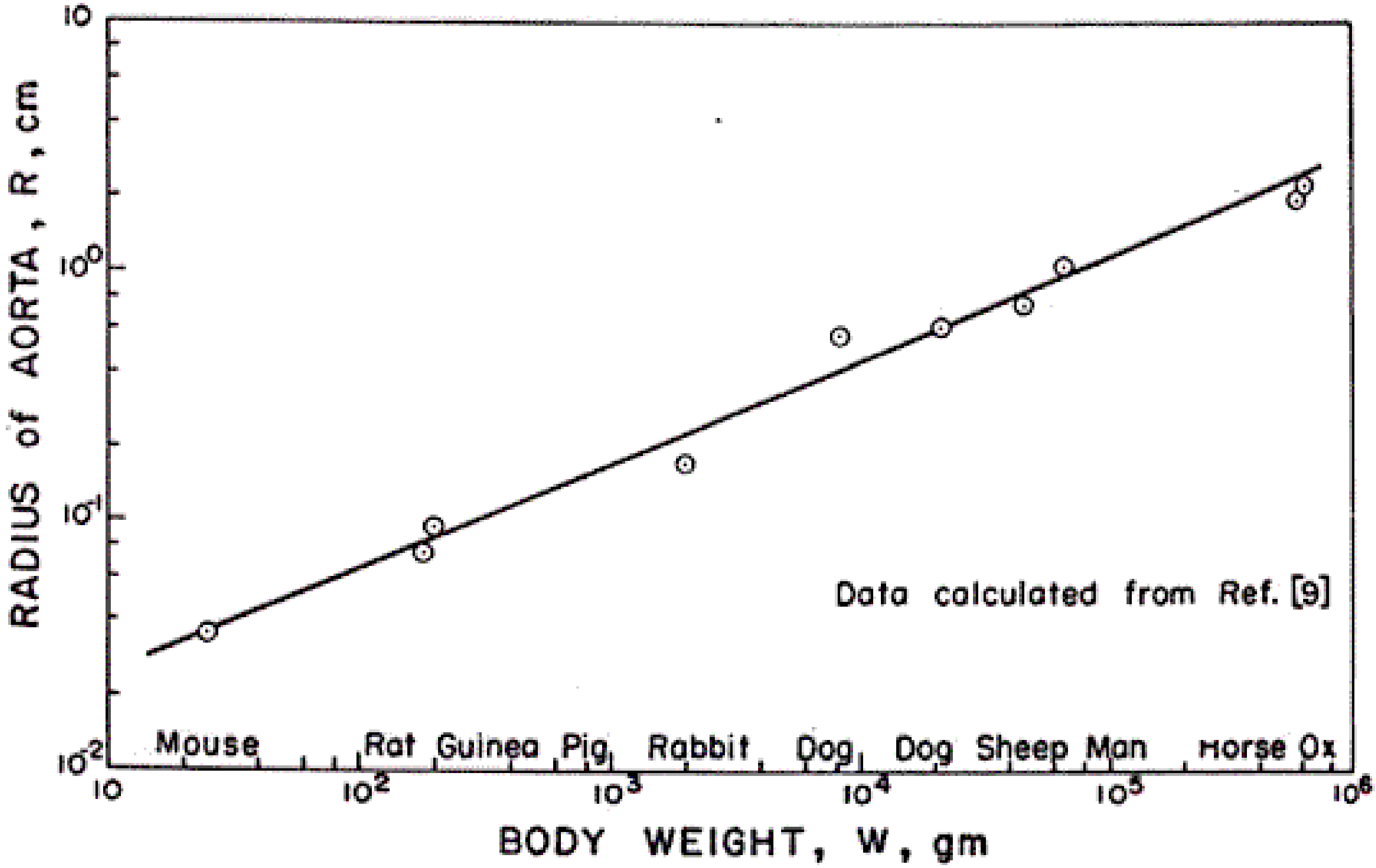


FIG. 4 – VARIATION IN RADIUS OF AORTA WITH BODY WEIGHT

$r \sim M^{3/8}$

SAME SCALING FOR TREE TRUNKS

Slopes (exponents) are typically sub-linear and simple multiples of ¼

“quarter-power scaling”

LIFESPAN

$$T \sim M^{1/4}$$

IF HEART-RATE (NUMBER OF BEATS PER SEC.)

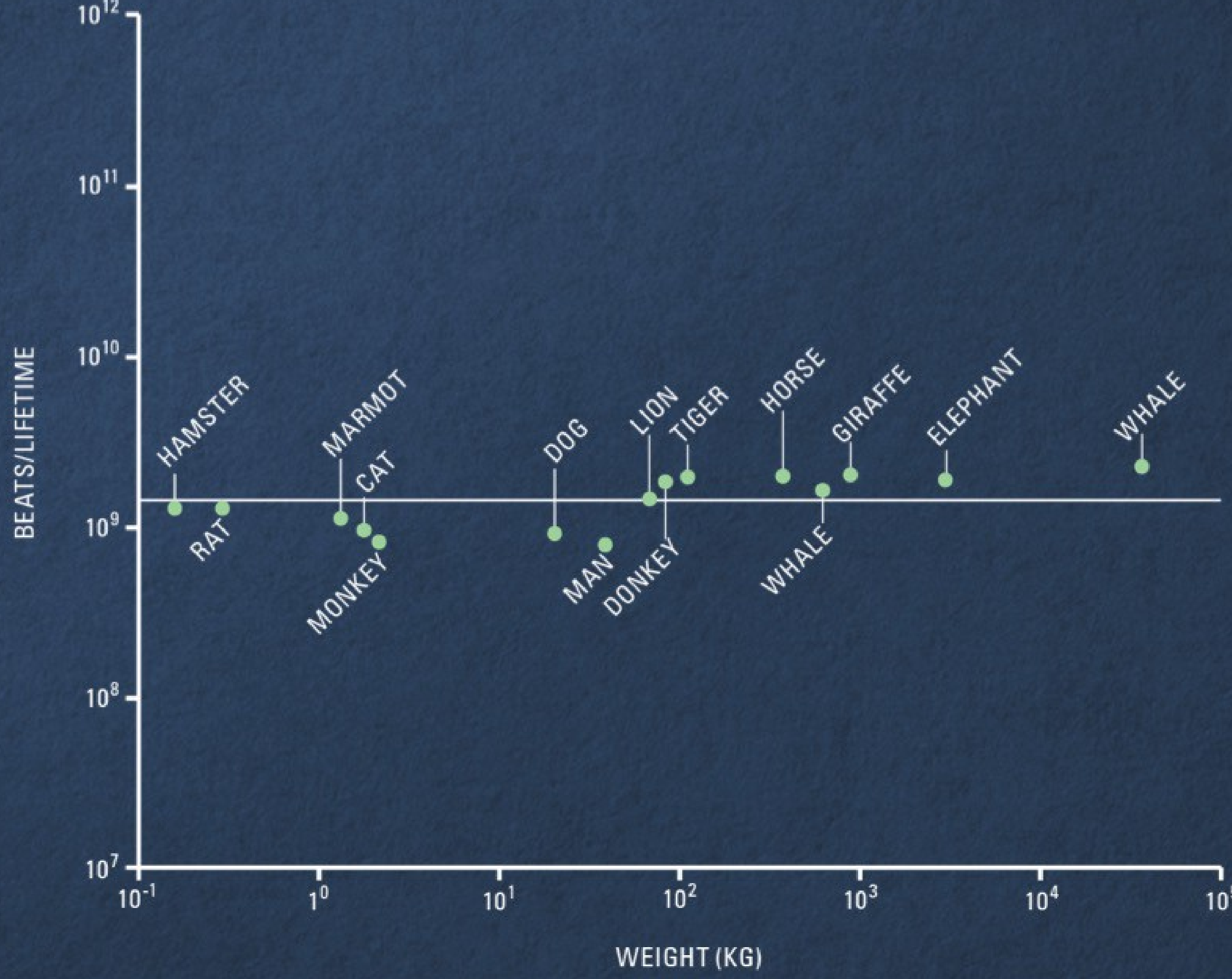
$$\sim M^{-1/4}$$

$\Rightarrow$ TOTAL NUMBER OF HEART-BEATS IN A TYPICAL LIFE-TIME IS INDEPENDENT OF SIZE!

$$\approx 1.5 \times 10^9$$

EACH ANIMAL SPECIES REGARDLESS OF SIZE HAS APPROXIMATELY THE SAME NUMBER OF HEART-BEATS IN ITS LIFE-TIME (ROUGHLY 1 BILLION)

NUMBER OF HEARTBEATS PER LIFETIME OF ANIMALS



RECALL SPECIFIC METABOLIC RATE

$$\bar{B} = \frac{B}{M} \propto M^{-1/4}$$

$\Rightarrow$ TOTAL ENERGY NEEDED TO SUPPORT UNIT MASS OF AN ANIMAL DURING A LIFETIME IS THE SAME FOR ALL ANIMALS REGARDLESS OF SIZE :

$$E_{TOT} \approx 1.2 \times 10^{6} \text{ JOULES / gm}$$

$$\approx 300 \text{ kcals / gm}$$

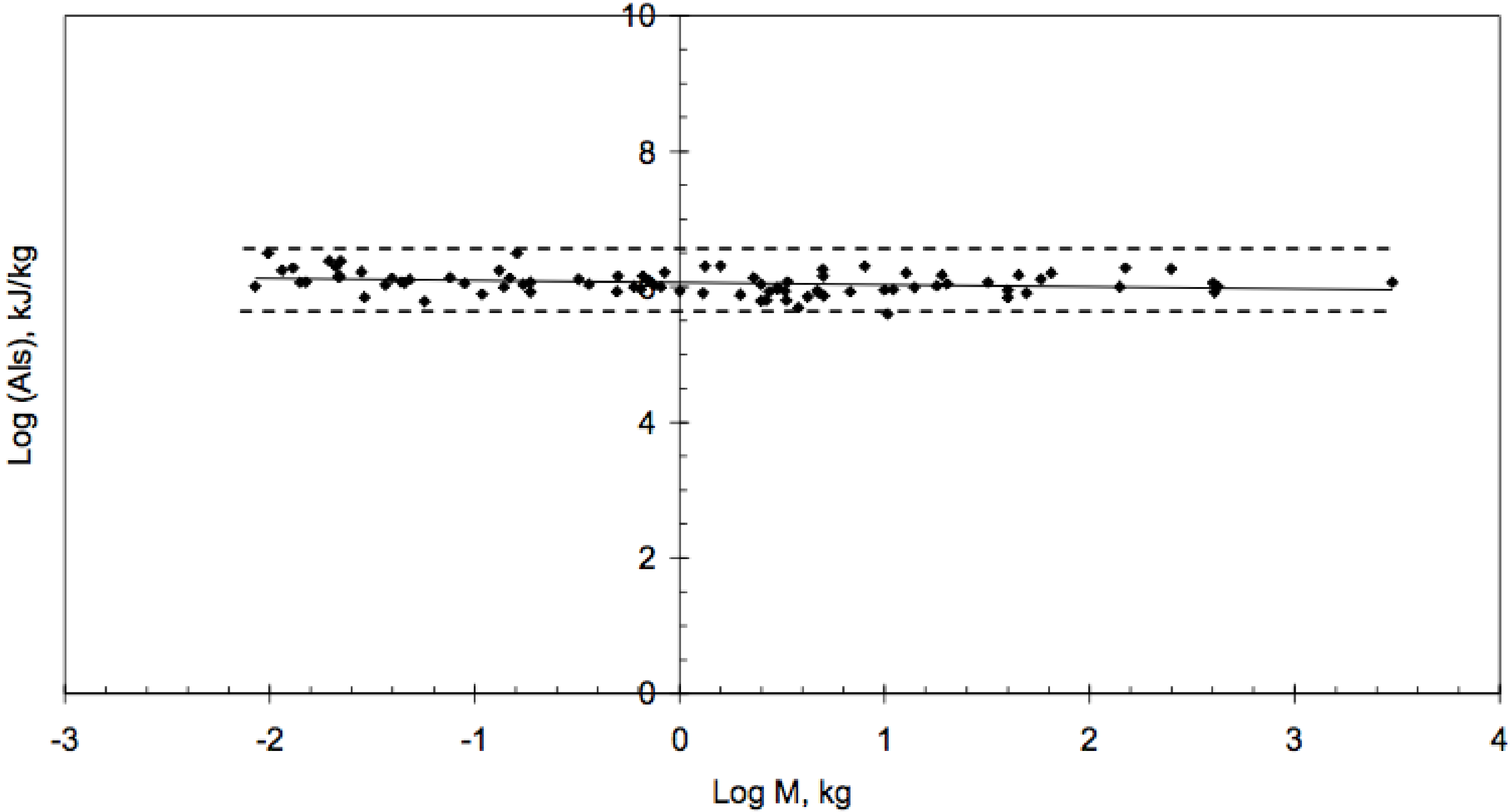


Fig. 2. Relationship between the total metabolic energy per life span per unit body mass ($A_{ls}=PT_{ls}/M$ kJ/kg) and the body mass (M, kg) for 86 terrestrial mammals in captivity (Prototheria, Metatheria and Eutheria). The 95% confidence limits are shown by dashed lines.

A. T. Atanasov, Bulg. J. of Vet. Med. (2006), 9, No 3, 159−174

LIFE IS THE MOST COMPLEX SYSTEM

SCALING LAWS ARE REMARKABLE BECAUSE

i) THEY EXIST

ii) THEY ARE VERY SIMPLE } DOMINANCE OF 1/4 POWER

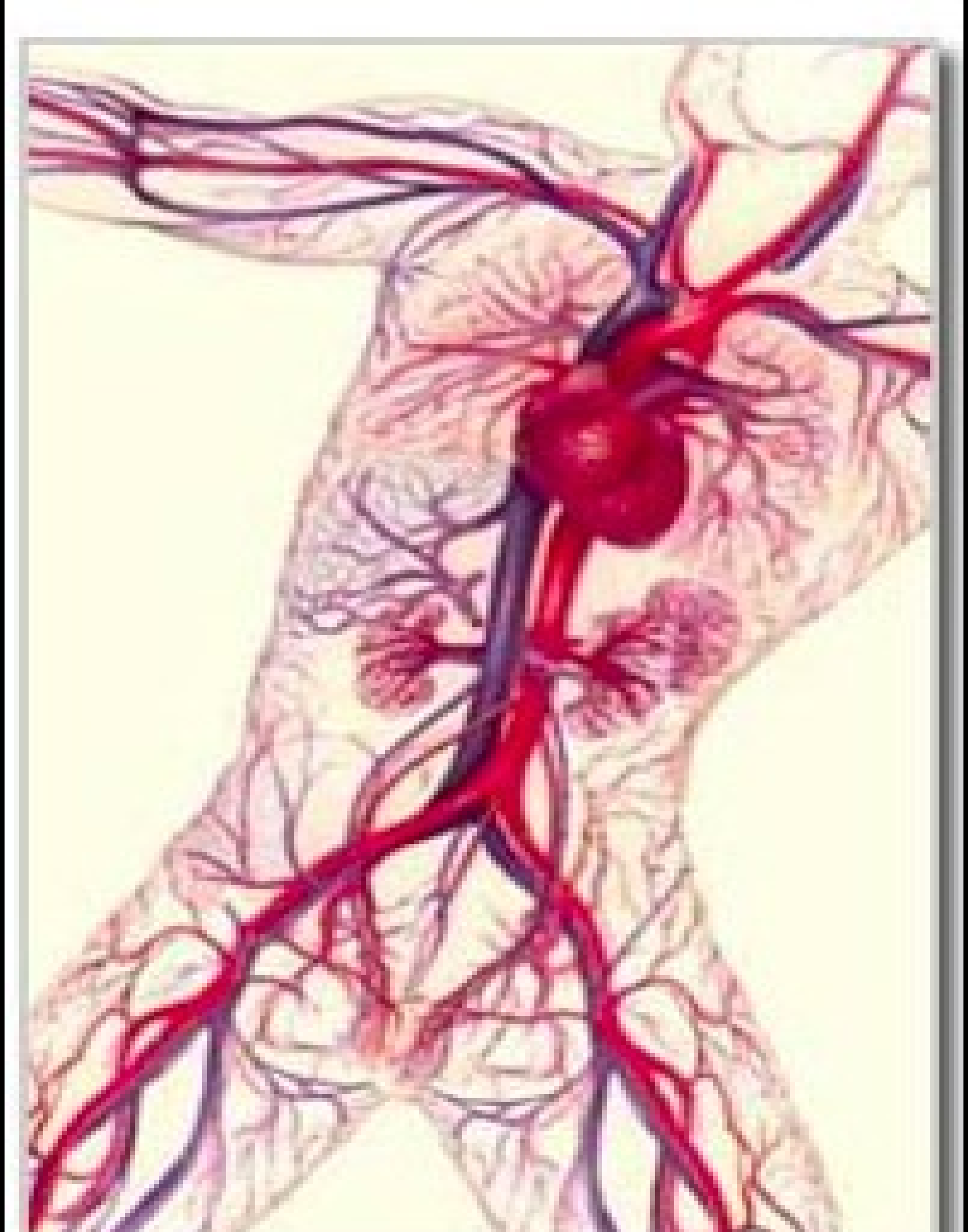
iii) THEY ARE UNIVERSAL

iv) ⇒ BIGGER IS MORE EFFICIENT

v) FEW QUANTITATIVE "LAWS" IN BIOLOGY

EXPLAINED BY THE GENERIC MATHEMATICAL AND PHYSICAL PROPERTIES OF.......

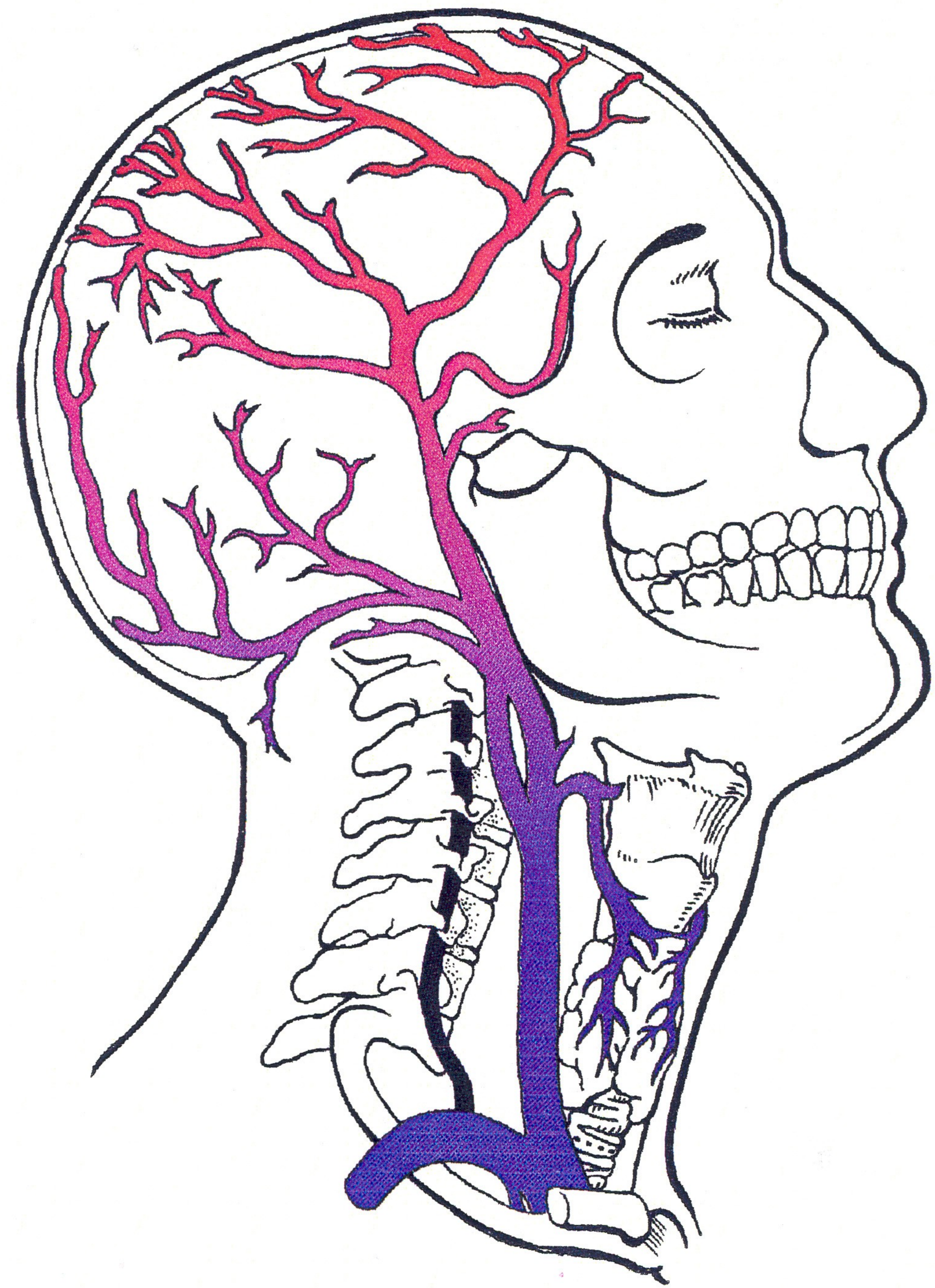
NETWORKS

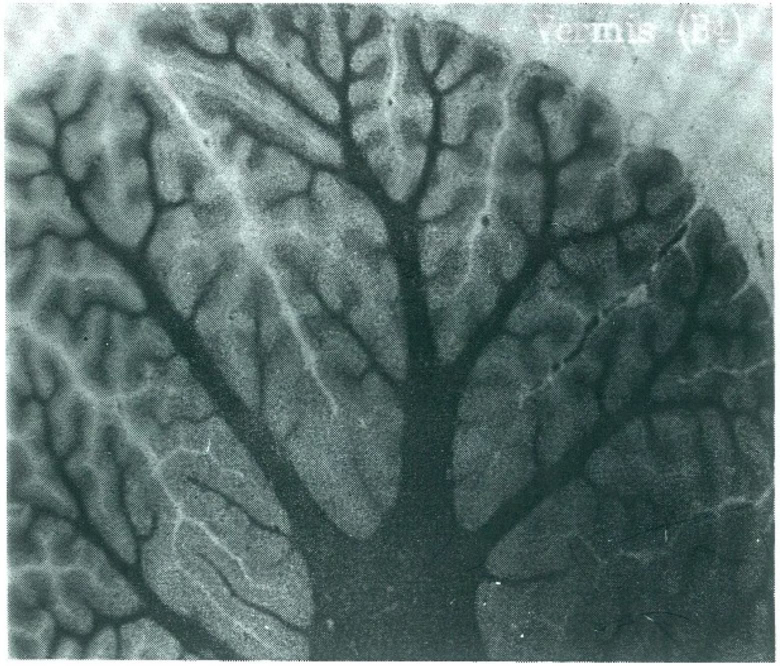


Large vessels branch into smaller ones

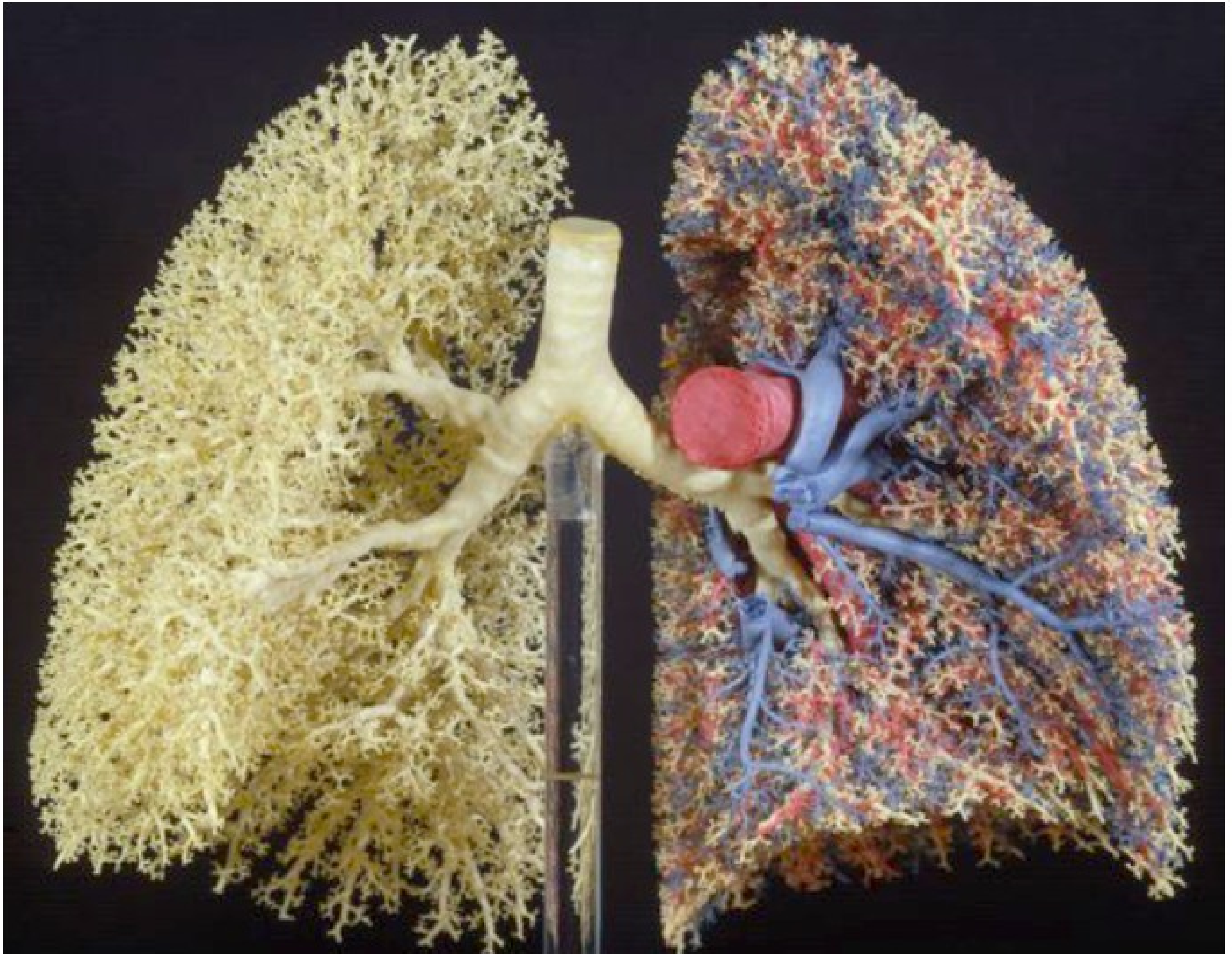
Beating heart

Pulse wave propagates through elastic vessels

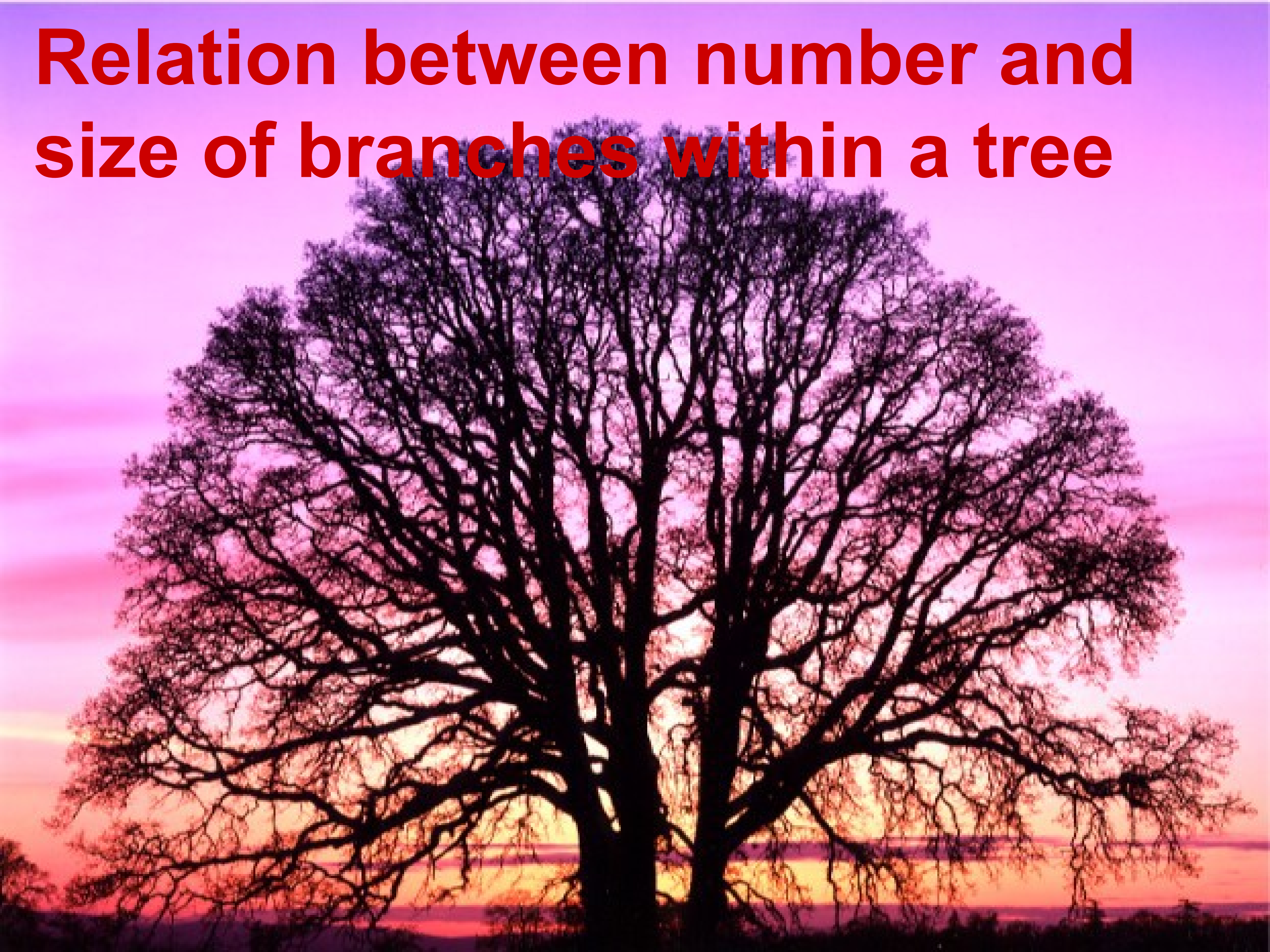


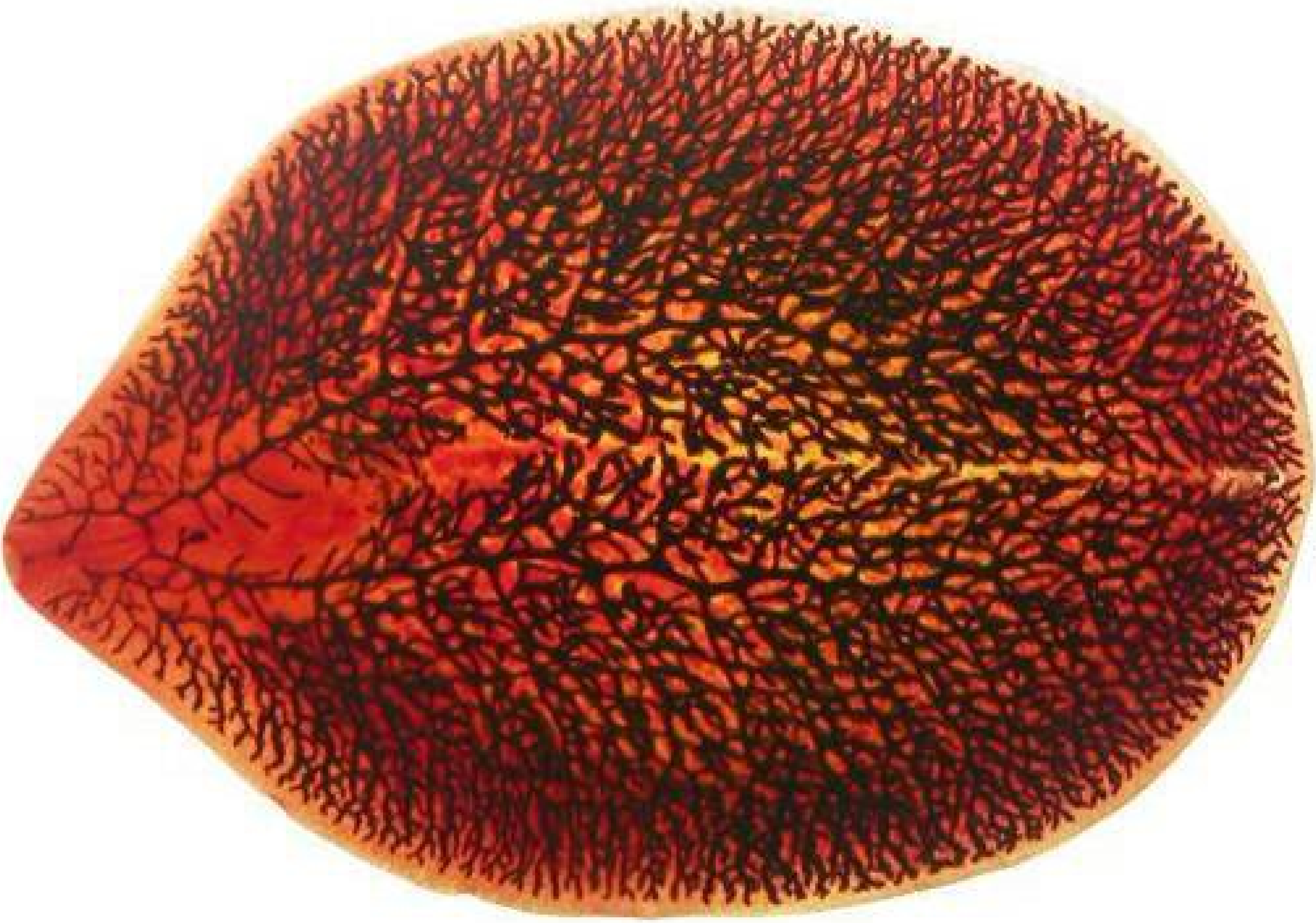


: 5 A slice through the cerebellum showing the progressive branching structure
vhite matter is distributed throughout the cerebellar volume. The geometric
:ity of these structures provides for rapid dissemination of information (or
e) via a large surface area in a compact space. This feature is a hallmark of
tructures which maximize the surface area within a finite volume.



Relation between number and size of branches within a tree





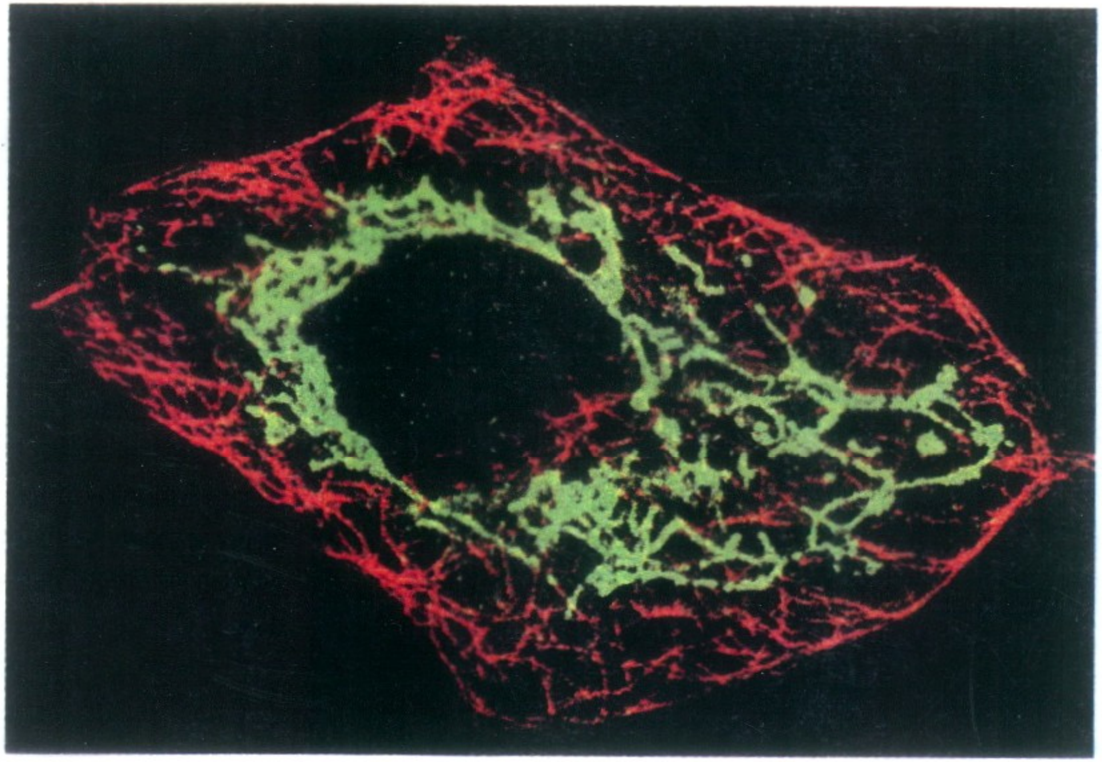
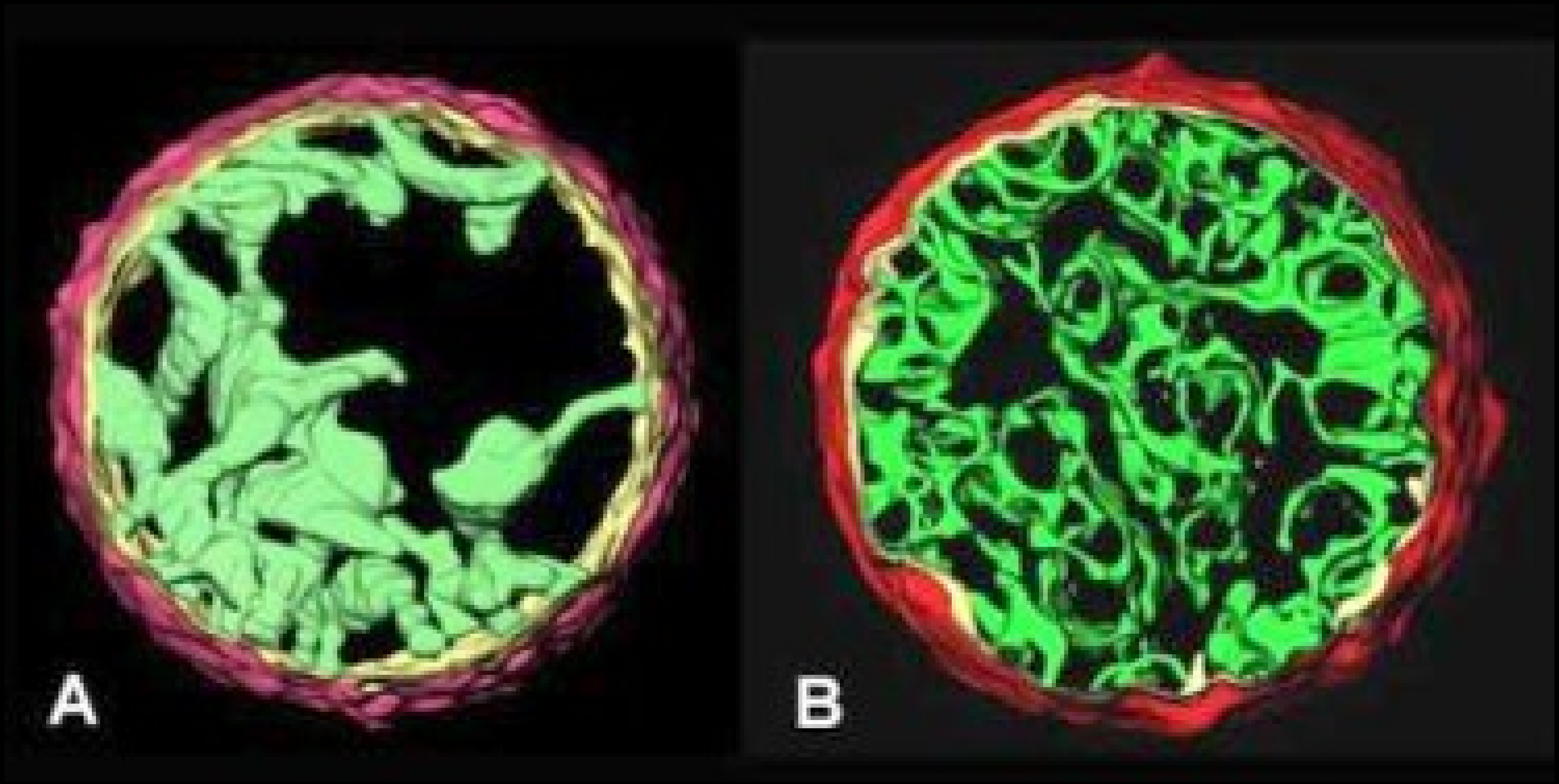


Fig. 1. Mitochondrial network in a mammalian fibroblast. A COS-7 cell labeled to visualize mitochondria (green) and microtubules (red) was analyzed by indirect immunofluorescence confocal microscopy. Mitochondria were labeled with antibodies to the β subunit of the F_1-ATPase and a rhodamine-conjugated secondary antibody. Microtubules were labeled with antibody to tubulin and a fluorescein-conjugated secondary antibody. Pseudocolor was added to the digitized image. Scale: 1 cm = 10 μm.

From M. P. Yaffe, *Science,* **283,** 1493 (1999).


A
B

FUNDAMENTAL PRINCIPLES

(NATURAL SELECTION)

I. AT ALL SCALES ORGANISMS ARE SUSTAINED BY THE TRANSPORT OF ENERGY AND ESSENTIAL MATERIALS THROUGH HIERARCHICAL BRANCHING NETWORK SYSTEMS IN ORDER TO SUPPLY ALL LOCAL PARTS OF THE ORGANISM

II. THESE NETWORKS ARE SPACE-FILLING

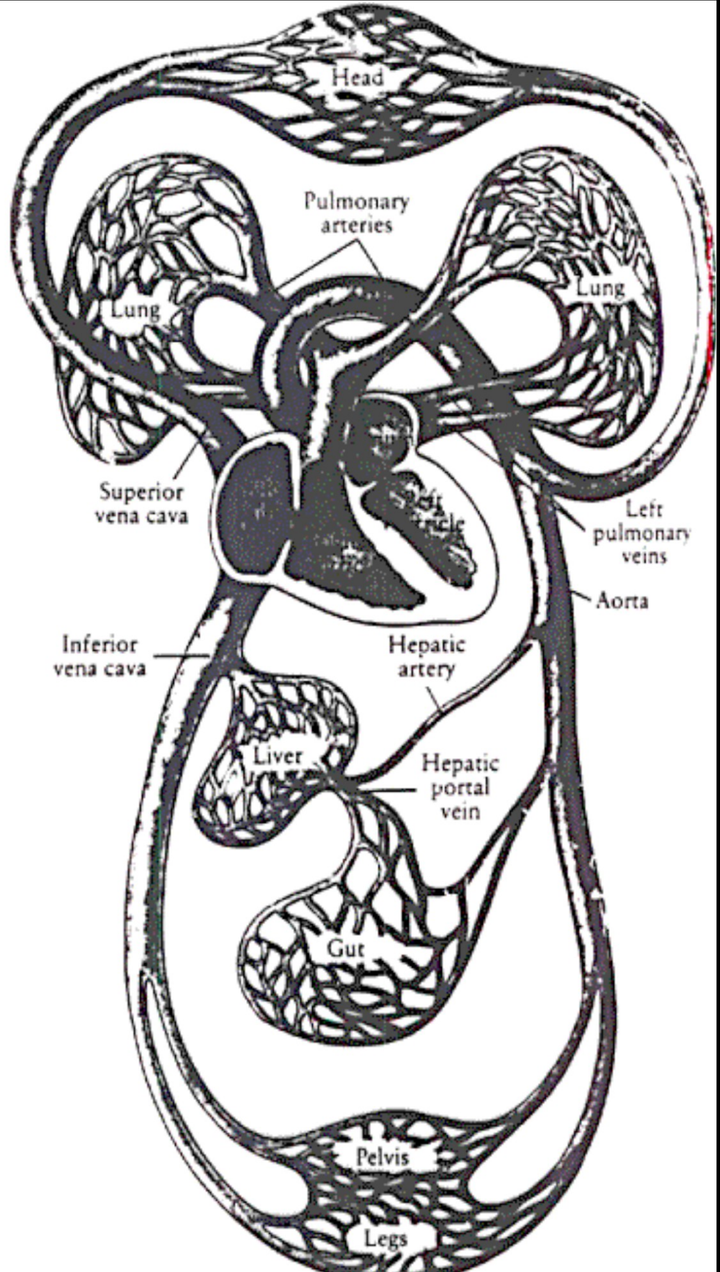
III. THE TERMINAL BRANCHES OF THE NETWORK ARE INVARIANT UNITS

IV. ORGANISMS HAVE EVOLVED BY NATURAL SELECTION SO AS TO

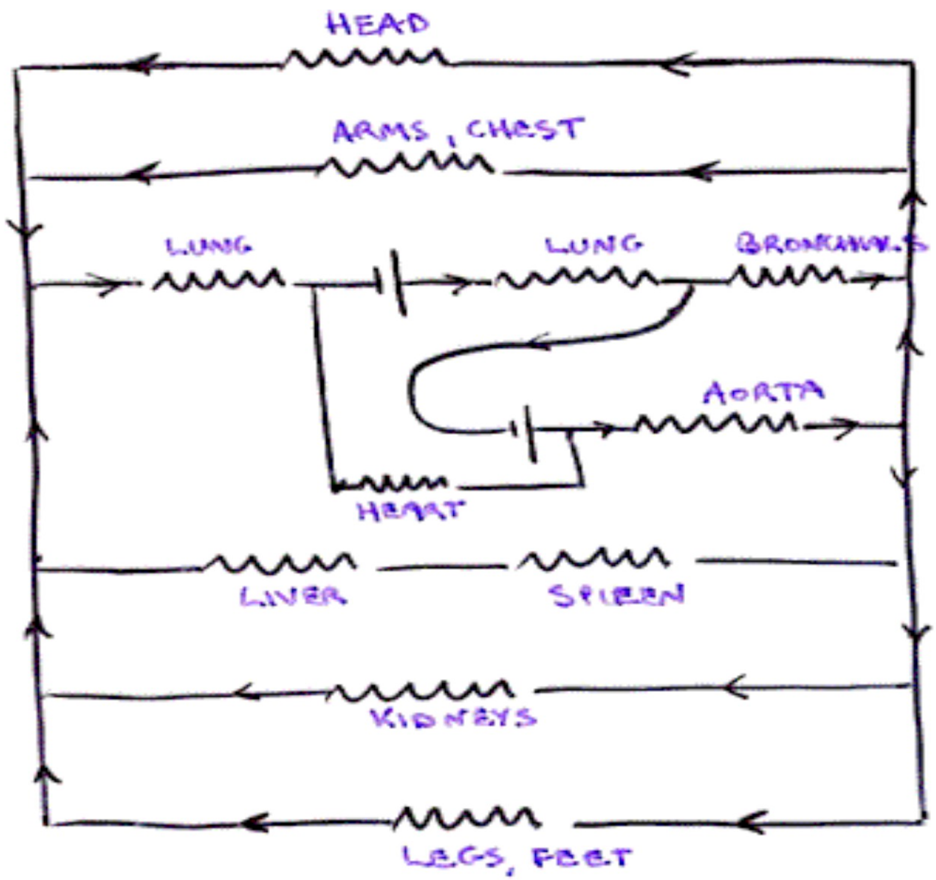
i) MINIMISE ENERGY DISSIPATED IN THE NETWORKS

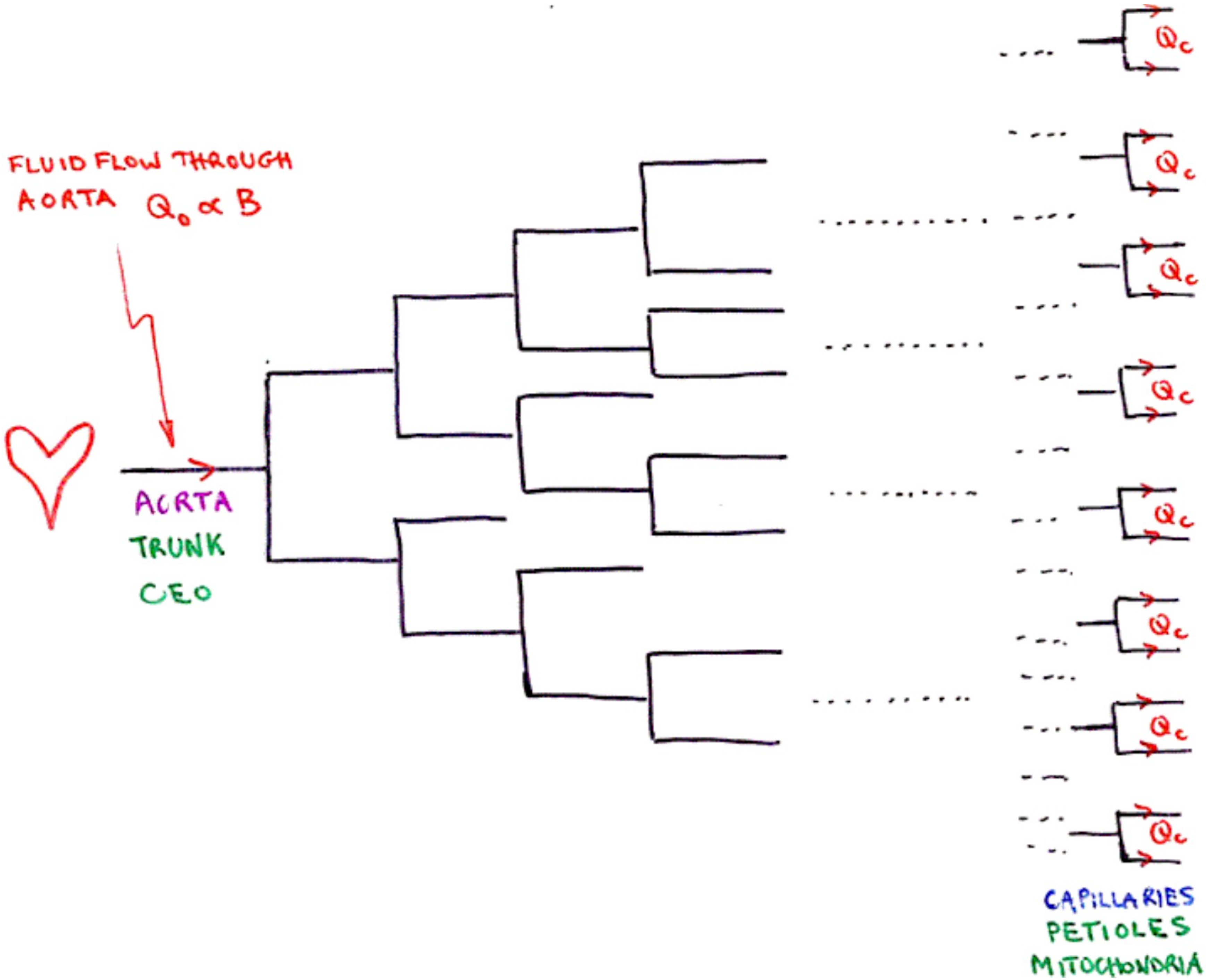
AND/OR ii) MAXIMISE THE SCALING OF THEIR AREA OF INTERFACE WITH THEIR RESOURCE ENVIRONMENT

West, Brown & Enquist, Science 1997, 1999,…., Nature, 1999, 2001,……..



THE VASCULAR CIRCUITRY


HEAD
ARMS, CHEST
LUNG
LUNG
AORTA
HEART
LIVER
SPLEEN
KIDNEYS
LEGS, FEET



FLUID FLOW THROUGH
AORTA $Q_0 \propto B$
AORTA
TRUNK
CEO
Q_c
Q_c
Q_c
Q_c
Q_c
Q_c
Q_c
Q_c
CAPILLARIES
PETIOLES
MITOCHONDRIA

SINCE THE FLUID (BLOOD) TRANSPORTS OXYGEN, NUTRIENTS, ETC FROM THE AORTA TO THE CAPILLARIES

METABOLIC RATE $\propto$ VOLUME FLOW RATE

$$B \propto Q_0$$

BUT THE CONSERVATION OF FLUID (BLOOD)

$$\Rightarrow \quad Q_0 = N_c Q_c$$

N_c: TOTAL NUMBER OF CAPILLARIES

Q_c: VOLUME FLOW RATE IN AVERAGE CAPILLARY

CAPILLARY IS AN INVARIANT UNIT

(Q_c IS SAME FOR ALL MAMMALS)

$\Rightarrow$ NUMBER OF CAPILLARIES (N_c) MUST SCALE IN SAME WAY AS THE METABOLIC RATE ($B \propto Q_0$)

SO, IF $B \sim M^{3/4}$ THEN

$N_c \sim M^{3/4}$ (NOT $N_c \sim M$)

TOTAL NUMBER OF CELLS

$$N_{cell} \sim M \qquad \text{(LINEAR)}$$

TOTAL NUMBER OF CAPILLARIES

$$N_c \sim M^{3/4}$$

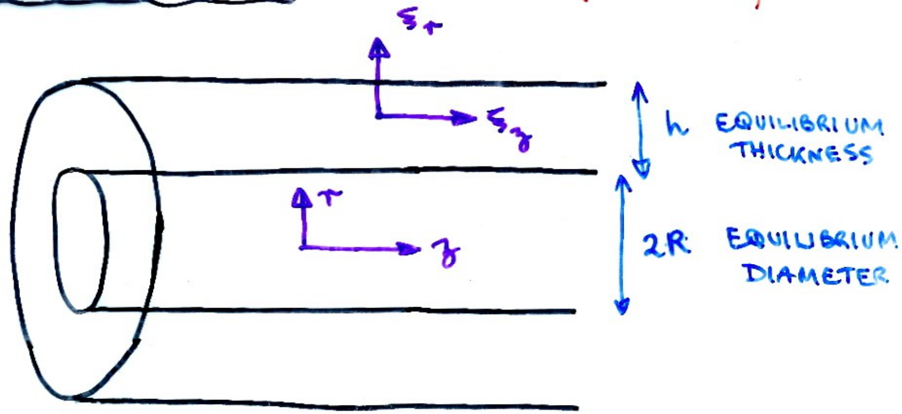
MISMATCH!

⇒ NUMBER OF CELLS FED BY A SINGLE CAPILLARY INCREASES AS $M^{1/4}$

(ANOTHER MANIFESTATION THAT EFFICIENCY INCREASES WITH SIZE)

IMPORTANT IMPLICATIONS FOR GROWTH AND DEATH!

) PULSATILE TREATMENT (WOMERSLEY)



a) FLUID :

COEFFICIENTS OF VISCOSITY

STRESS TENSOR : $\theta_{ij} = \lambda e_{kk} \delta_{ij} + 2\mu e_{ij} - p\,\delta_{ij}$

(NEWTONIAN) PRESSURE

STRAIN TENSOR : $e_{ij} = \frac{1}{2}(\partial_i v_j + \partial_j v_i)$

VELOCITY

EQ^{N}. OF MOTION : $\rho \frac{D v_i}{Dt} = \partial_j \theta_{ij}$ NAVIER-STOKES EQ^{N}.

COVARIANT DERIVATIVE $\frac{D}{Dt} = \frac{\partial}{\partial t} + v_i \partial_i$

EQ^{N}. OF CONTINUITY : $\frac{\partial \rho}{\partial t} + \partial_i(\rho v_i) = 0$

b) WALLS :

ELASTIC MODULI

$$\theta^{W}_{ij} = \lambda e^{W}_{kk}\,\delta_{ij} + 2B\,e^{W}_{ij} - p\,\delta_{ij}$$ HOOKE'S LAW

$$e^{W}_{ij} = \tfrac{1}{2}(\partial_i \xi_j + \partial_j \xi_i)$$

$$\rho_W \frac{Du_i}{Dt} = \partial_j \theta^{W}_{ij} \quad ; \quad u_i \equiv \frac{\partial \xi_i}{\partial t}$$ NAVIER EQ^NS.

$$\partial_i \xi_i = 0$$

NEGLECT NON-LINEARITIES :

$$\rho_W \frac{\partial^2 \xi_i}{\partial t^2} = B\,\partial^2 \xi_i - \partial_i p$$

SOLVE USING FOURIER AS WITH FLUID, WALLS AND FLUID COUPLED VIA BOUNDARY CONDITIONS : CONTINUITY OF VELOCITY AND FORCE : $u_r = \dfrac{\partial \xi_r}{\partial t}$

AND $\int_{\text{SURFACE}} \theta_{ij}\, dS_j$ CONTINUOUS

CAN BE SOLVED : BIG MESS!

SIMPLIFY USING THIN WALL APPROXIMATION

i.e. $\dfrac{h}{R} \ll 1$

IMPEDANCE: $$Z(\omega) = \frac{\rho c_0^2}{\pi R^2 c} \frac{1}{J_0(ikR)}$$

WHERE $c = \frac{\omega}{k}$ PHASE VELOCITY

AND $$c_0 = \left(\frac{Bh}{2\rho R}\right)^{1/2} \qquad B = \frac{E}{1-\sigma^2}$$

YOUNG'S MODULUS (E); POISSON RATIO (σ)

[KORTEWEG - MOENS VELOCITY, FIRST DERIVED BY YOUNG]

TYPICALLY $kR = \frac{2\pi R}{\lambda} \ll 1$ SO

$$Z(\omega) \approx \frac{\rho c_0^2}{\pi R^2 c}$$

WITH $$\left(\frac{c}{c_0}\right)^2 = -\frac{J_2(i^{3/2}\alpha)}{J_0(i^{3/2}\alpha)}$$ DISPERSION RELATION

WHERE $$\alpha \equiv \left(\frac{\omega\rho}{\mu}\right)^{1/2} R$$ DIMENSIONLESS WOMERSLEY NUMBER

$\Rightarrow$ ATTENUATION AND DISPERSION

ii) OPTIMISATION (ENERGY MINIMISATION)

EX.: FOR GIVEN VOLUME OF BLOOD MINIMISE ENERGY OUTPUT (THEREFORE MINIMISE RESISTANCE) SUBJECT TO SPACE FILLING GEOMETRY. USE LAGRANGE MULTIPLIERS AND CONSIDER:

$$F(r_k, l_k, n_k) = Z(r_k, l_k, n_k) + \lambda V_b(r_k, l_k, n_k) + \sum_{k=0}^{N} \lambda_k n_k^k l_k^3$$

DEMAND $\frac{\partial F}{\partial r_k} = \frac{\partial F}{\partial l_k} = \frac{\partial F}{\partial n_k} = 0$ LAGRANGE EQ^{NS}

USE: $Z(r_k, l_k, n) = \sum_{k=0}^{N} \frac{8 \mu l_k}{\pi r_k^4 n^k}$

$$V_b(r_k, l_k, n) = \sum_{k=0}^{N} \pi r_k^2 l_k n^k$$

e.g. $\frac{\partial F}{\partial r_k} = 0 \Rightarrow r_k^6 n^{2k} = \text{CONSTANT}$

i.e. $\beta_k = \frac{r_{k+1}}{r_k} = \frac{1}{n^{1/3}}$ INDEP. OF k. NOT $\frac{1}{n^{1/2}}$!

NOW VARY MASS : MINIMISE ENERGY LOSS ($\dot{Q}_0$ CHANGES)

$$F(r_k, l_k, n, M) = \dot{E}(M) + \lambda \left[\sum_{k=0}^{N} \pi r_k^2 l_k n^k - V_b(M) \right]$$

$\dot{E}(M) \to M^a$; $V_b(M) \to M^b$

$$+ \sum_{k=0}^{N} \lambda_k \left[n^k l_k^3 - V_N(M) \right] + \lambda_M M$$

$V_N(M) \to N_c l_c^3 \sim M^a$

FOR FIXED M, AS ABOVE ;

$$\frac{\partial F}{\partial M} \sim a M^{a-1} + \lambda b M^{b-1} + \left(\sum \lambda_k\right) a M^{a-1} + \lambda_M$$

$$= 0 \quad \Rightarrow \quad \underline{b = 1}$$

i.e. $\underline{V_b \sim M}$

IN d DIMENSIONS

$$B \propto M^{\frac{d}{d+1}}$$

WE LIVE IN 3 SPATIAL DIMENSIONS SO $B \propto M^{3/4}$

⇒ "3" REPRESENTS DIMENSIONALITY OF SPACE

"4" INCREASE IN DIMENSIONALITY DUE TO FRACTAL-LIKE SPACE FILLING

LIFE HAS TAKEN ADVANTAGE OF THE POSSIBILITY OF USING SPACE-FILLING FRACTAL-LIKE SURFACES (WHERE ENERGY AND RESOURCES ARE EXCHANGED) TO MAXIMISE ENERGY TRANSFER FROM THE ENVIRONMENT

NON-FRACTAL : $M^{2/3}$ (2 → AREA; 3 → DIMENSIONALITY OF SPACE (VOLUME))

BIOLOGICAL (FRACTAL) $M^{3/4}$

BY ANALOGY : LIFE EFFECTIVELY OPERATES IN FOUR SPATIAL DIMENSIONS

[FIVE IF TIME IS INCLUDED]

Cardiovascular		
Variable	Exponent	
	Predicted	Observed
Aorta radius r_o	3/8 = 0.375	0.36
Aorta pressure Δp_o	0 = 0.00	0.032
Aorta blood velocity u_o	0 = 0.00	0.07
Blood volume V_b	1 = 1.00	1.00
Circulation time	1/4 = 0.25	0.25
Circulation distance l	1/4 = 0.25	ND
Cardiac stroke volume	1 = 1.00	1.03
Cardiac frequency ω	−1/4 = −0.25	−0.25
Cardiac output $\dot{E}$	3/4 = 0.75	0.74
Number of capillaries N_c	3/4 = 0.75	ND
Service volume radius	1/12 = 0.083	ND
Womersley number α	1/4 = 0.25	0.25
Density of capillaries	−1/12 = −0.083	−0.095
O_2 affinity of blood P_{50}	−1/12 = −0.083	−0.089
Total resistance Z	−3/4 = −0.75	−0.76
Metabolic rate B	3/4 = 0.75	0.75

Respiratory

Variable	Exponent	
	Predicted	Observed
Tracheal radius	3/8 = 0.375	0.39
Interpleural pressure	0 = 0.00	0.004
Air velocity in trachea	0 = 0.00	0.02
Lung volume	1 = 1.00	1.05
Volume flow to lung	3/4 = 0.75	0.80
Volume of alveolus V_A	1/4 = 0.25	ND
Tidal volume	1 = 1.00	1.041
Respiratory frequency	−1/4 = −0.25	−0.26
Power dissipated	3/4 = 0.75	0.78
Number of alveoli N_A	3/4 = 0.75	ND
Radius of alveolus r_A	1/12 = 0.083	0.13
Area of alveolus A_A	1/6 = 0.083	ND
Area of lung A_L	11/12 = 0.92	0.95
O_2 diffusing capacity	1 = 1.00	0.99
Total resistance	−3/4 = −0.75	−0.70
O_2 consumption rate	3/4 = 0.75	0.76

Table 1 Predicted values of scaling exponents for physiological and anatomical variables of plant vascular systems.

Variable	Plant mass: Exponent predicted	Plant mass: Symbol	Branch radius: Symbol	Branch radius: Exponent Predicted	Branch radius: Exponent Observed
Number of leaves	$\frac{3}{4}$ (0.75)	n_0^L	n_k^L	2 (2.00)	2.007 (ref. 12)
Number of branches	$\frac{3}{4}$ (0.75)	N_0	N_k	−2 (−2.00)	−2.00 (ref. 6)
Number of tubes	$\frac{3}{4}$ (0.75)	n_0	n_k	2 (2.00)	n.d.
Branch length	$\frac{1}{4}$ (0.25)	l_0	l_k	$\frac{2}{3}$ (0.67)	0.652 (ref. 6)
Branch radius	$\frac{3}{8}$ (0.375)	r_0			
Area of conductive tissue	$\frac{7}{8}$ (0.875)	A_0^{CT}	A_k^{CT}	$\frac{7}{3}$ (2.33)	2.13 (ref. 8)
Tube radius	$\frac{1}{16}$ (0.0625)	a_0	a_k	$\frac{1}{6}$ (0.167)	n.d.
Conductivity	1 (1.00)	K_0	K_k	$\frac{8}{3}$ (2.67)	2.63 (ref. 12)
Leaf-specific conductivity	$\frac{1}{4}$ (0.25)	L_0	L_k	$\frac{2}{3}$ (0.67)	0.727 (ref. 17)
Fluid flow rate			$\dot{Q}_k$	2 (2.00)	n.d.
Metabolic rate	$\frac{3}{4}$ (0.75)	$\dot{Q}_0$			
Pressure gradient	$-\frac{1}{4}$ (−0.25)	$\Delta P_0/l_0$	$\Delta P_k/l_k$	$-\frac{2}{3}$ (−0.67)	n.d.
Fluid velocity	$-\frac{1}{8}$ (−0.125)	u_0	u_k	$-\frac{1}{3}$ (−0.33)	n.d.
Branch resistance	$-\frac{3}{4}$ (−0.75)	Z_0	Z_k	$-\frac{1}{3}$ (−0.33)	n.d.
Tree height	$\frac{1}{4}$ (0.25)	h			
Reproductive biomass	$\frac{3}{4}$ (0.75)				
Total fluid volume	$\frac{25}{24}$ (1.0415)				

PLANTS

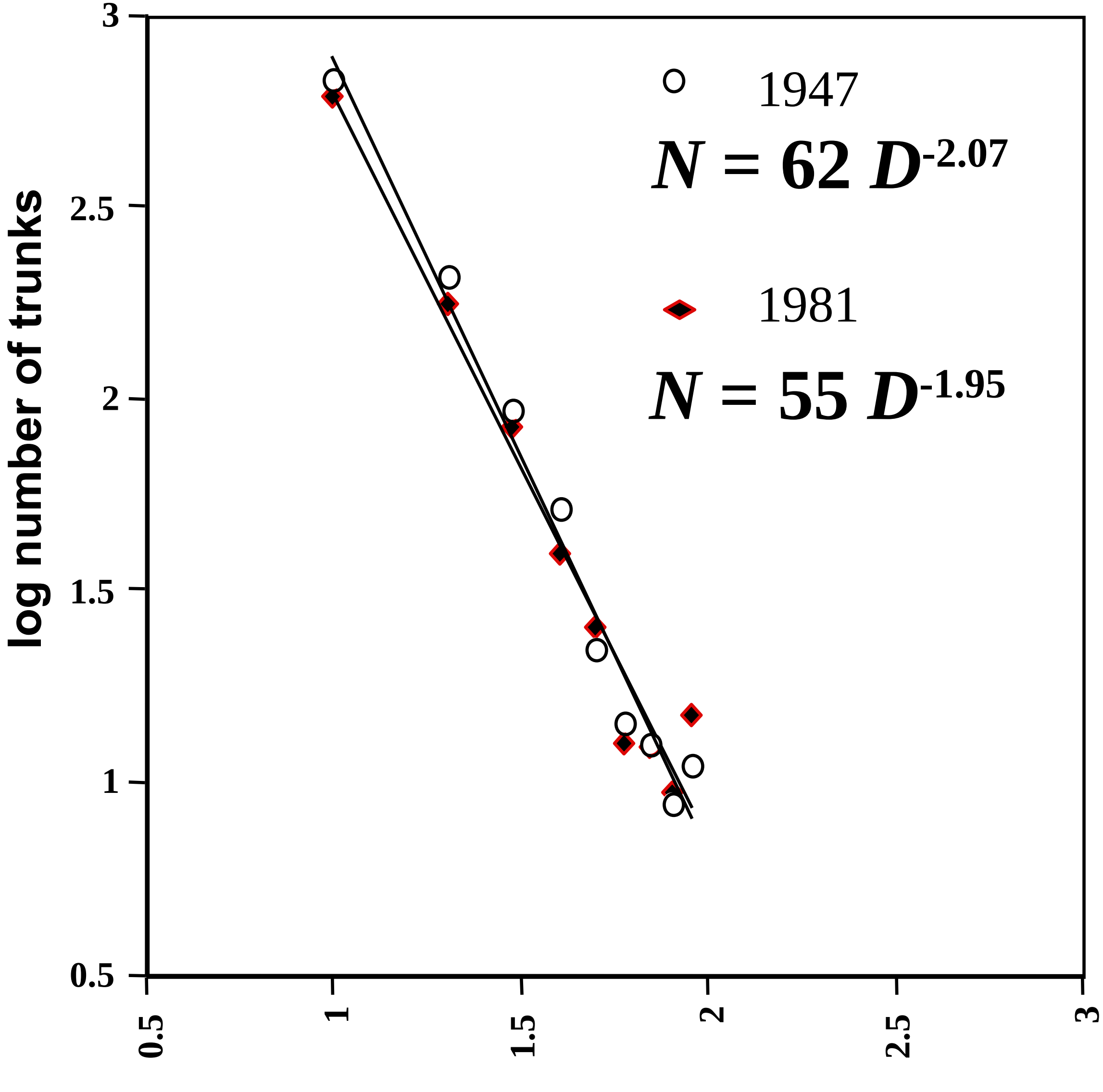
VERY DIFFERENT EVOLVED ENGINEERING DESIGN (NON-PULSATILE FIBRE BUNDLES) BUT SAME NETWORK PRINCIPLES

Table 1. Similarity of predicted scaling relations for branches within a tree [quantities denoted by uppercase symbols and subscripts *i* (20)], and for trees within a forest (denoted by lowercase symbols and subscripts *k*)*

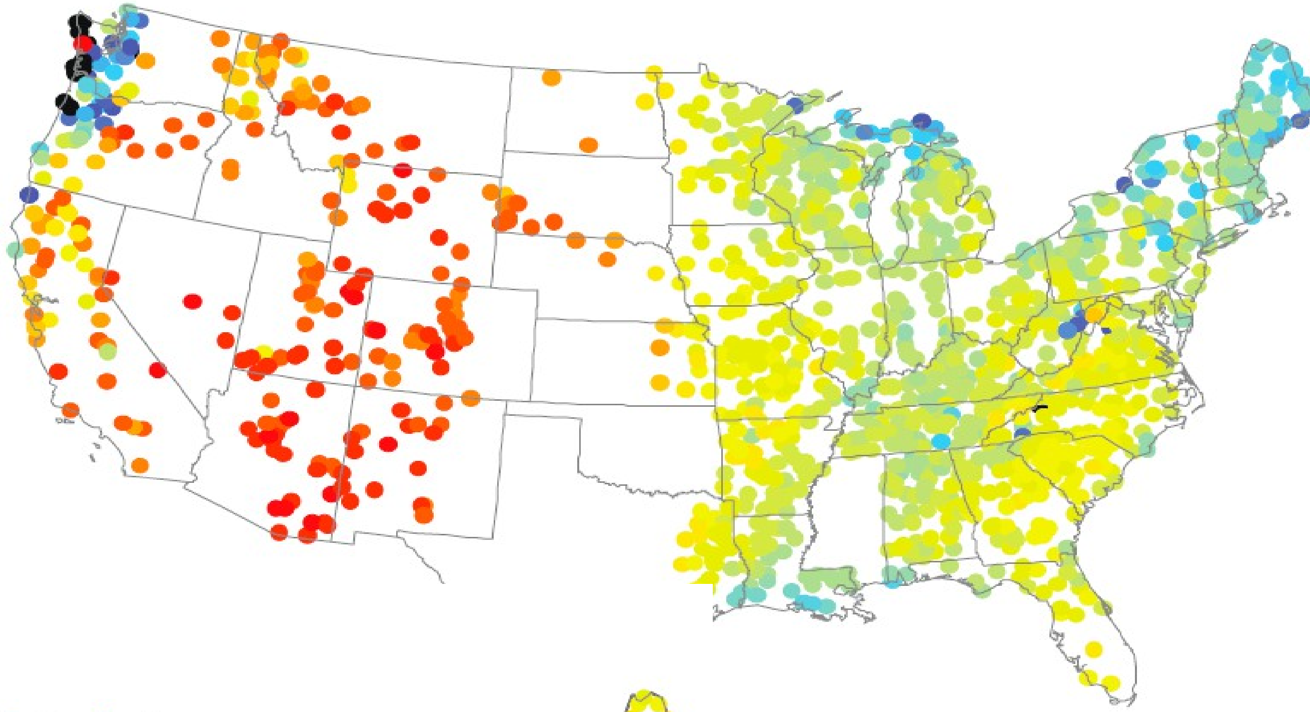
Scaling quantity	Individual tree	Entire forest
Area preserving	$\frac{R_{i+1}}{R_i} = \frac{1}{n^{1/2}}$	$\frac{r_{k+1}}{r_k} = \frac{1}{\lambda^{1/2}}$
Space filling	$\frac{L_{i+1}}{L_i} = \frac{1}{n^{1/3}}$	$\frac{l_{k+1}}{l_k} = \frac{1}{\lambda^{1/3}}$
Biomechanics	$R_i^2 = L_i^3$	$r_k^2 = l_k^3$
Size distribution*	$\Delta N_i \propto R_i^{-2} \propto M_i^{-3/4}$	$\Delta n_k \propto r_k^{-2} \propto m_k^{-3/4}$
Energy and material flux*	$B_i \propto R_i^2 \propto N_i^L \propto M_i^{3/4}$	$B_k \propto r_k^2 \propto n_k^L \propto m_k^{3/4}$

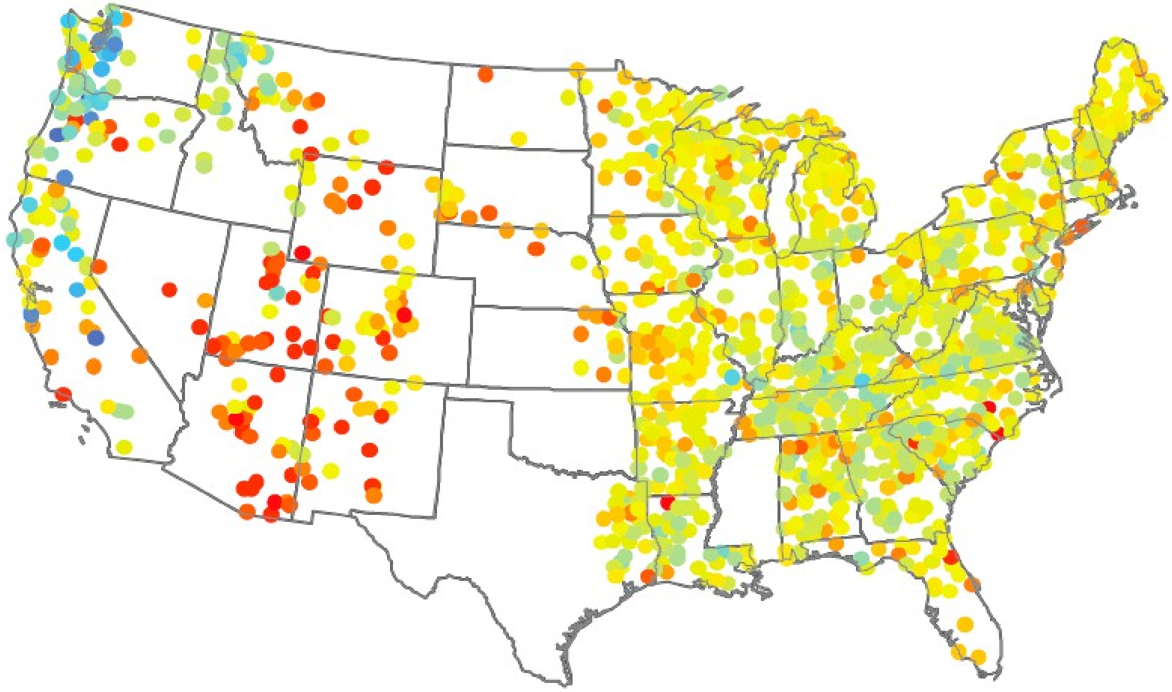
Stand property	Predicted stem radius, r_k, based scaling function
Size class neighbor separation	$d_k \propto r_k$
Canopy scaling	$r_k^{can} \propto r_k^{2/3}$
Canopy spacing	$d_k^{can} = c_1 r_k \left[1 - \left(\frac{r_{\bar{k}}}{r_k} \right)^{1/3} \right]$
Energy Equivalence	$\Delta n_k B_k \propto r_k^0$
Total forest resource use	$B_{Tot} \propto \sum \Delta n_k r_k^2 \leq \dot{R}$
Mortality rate	$\mu_k \approx A r_k^{-2/3}$
Size distribution	$N_k \approx \frac{\dot{R}}{(K+1) b_0} r_k^{-2}$

INTERSPECIFIC SIZE DISTRIBUTION
All species in a Malaysian Rainforest



Manokaran and Kochummen (1987)





HYDRODYNAMIC RESISTANCE OF THE NETWORK

$$\sim \frac{1}{M^{3/4}}$$

TOTAL RESISTANCE DECREASES WITH SIZE !!

SMALL MAY BE BEAUTIFUL BUT LARGE IS MORE EFFICIENT !!

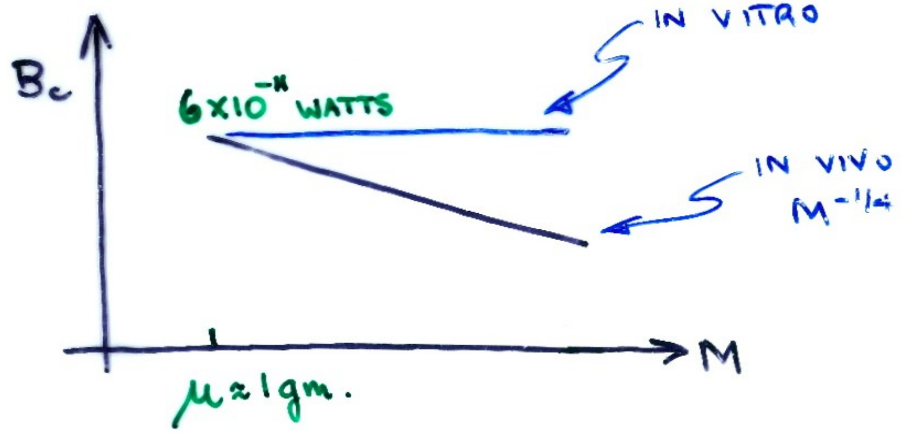
BLOOD PRESSURE $\sim M^0$
AORTA BLOOD VELOCITY $\sim M^0$
} INVARIANT !

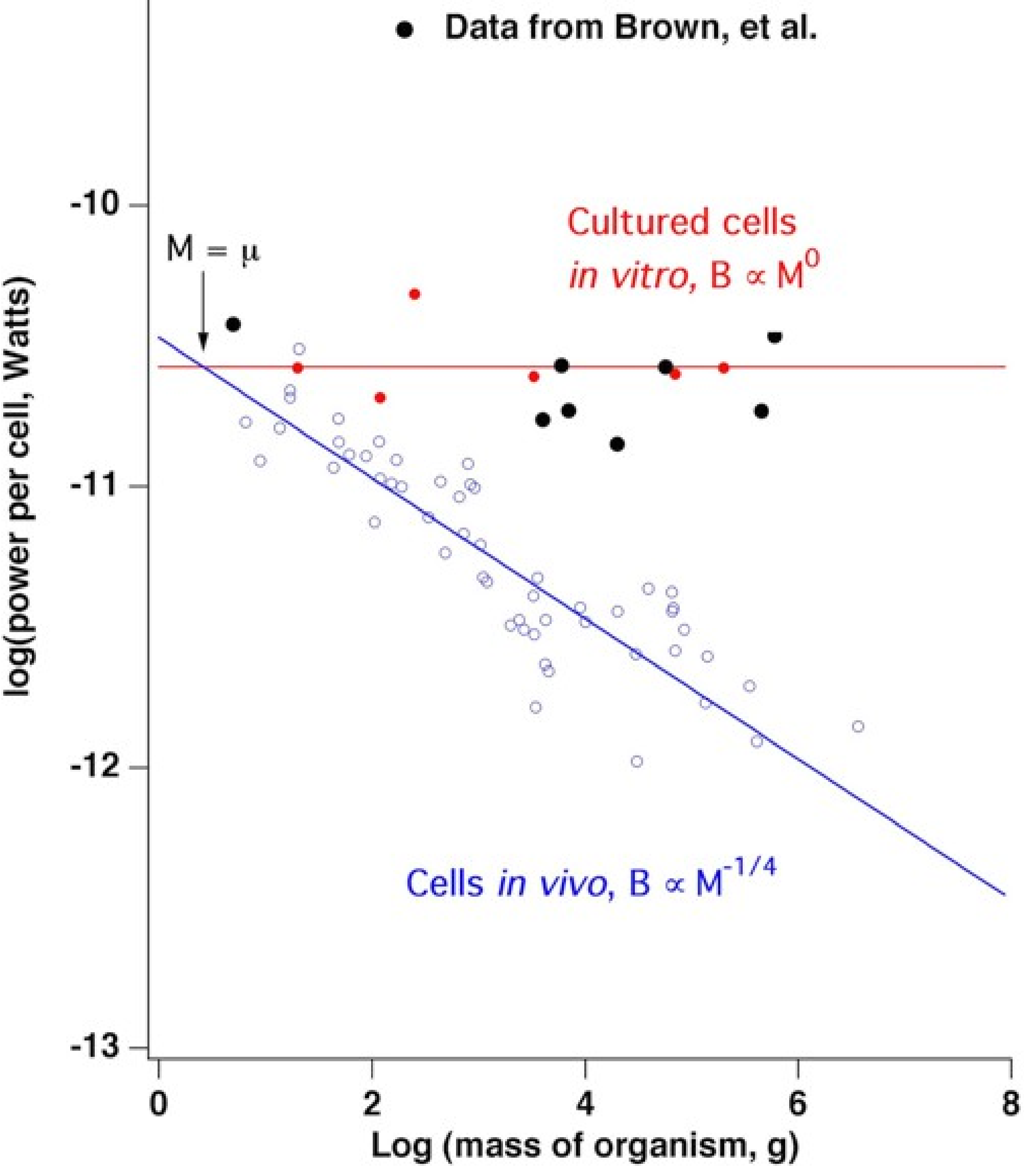
RADIUS OF A WHALE'S AORTA $\sim$ 30 CM

RADIUS OF A SHREW'S AORTA $\sim \frac{1}{10}$ MM

THIS DECREASE OF B_c WITH SIZE IS DRIVEN BY THE HEGEMONY OF THE NETWORK (CONTROLS FUNDAMENTAL BIOCHEMICAL RATES)

⇒ IF THE NETWORK WERE REMOVED SO CELLS BECOME FREE (IN VITRO) B_c SHOULD BECOME INDEPENDENT OF WHAT MAMMAL THEY ORIGINATED IN: PREDICT





Data from Brown, et al.
Cultured cells
in vitro, B ∝ M^0
M = μ
Cells in vivo, B ∝ M^-1/4
log(power per cell, Watts)
-10
-11
-12
-13
0
2
4
6
8
Log (mass of organism, g)

NETWORK GEOMETRY AND DYNAMICS CONTROLS THE PACE OF LIFE AT ALL SCALES LEADING TO AN EMERGENT "UNIVERSAL" TIME SCALE

$$B_{cell} \square \frac{B}{M} = B_0 M^{21/4}$$

THE PACE OF LIFE SYSTEMATICALLY SLOWS WITH INCREASING SIZE

ALL RATES ~ $M^{-1/4}$

METABOLISM
GROWTH
EVOLUTION
LONGEVITY
DIFFUSION
FLUXES
....

ALL TIMES ~ $M^{1/4}$

LIFESPANS
TURNOVER TIMES
TIMES TO MATURITY
CIRCULATION TIMES
....

TEMPERATURE DEPENDENCE

METABOLIC RATE IS THE SUM OF ALL CONTRIBUTING REACTION SUB-PROCESSES (IN PARALLEL):

$$B = \sum_i P_i$$

P_i ~ (CONCENTRATIONS) x (FLUXES) x (KINETICS)

(CONCENTRATIONS) x (FLUXES) ~ NETWORK ~ $M^{3/4}$

(KINETICS) ~ BOLTZMANN - ARRENHIUS ~ $e^{-E/kT}$

E = AVERAGE ACTIVATION ENERGY FOR RATE-LIMITING PROCESS IN RESPIRATORY COMPLEX (PRODUCTION OF ATP) ~ 0.7 eV ~ $2x10^{-20}$ cal

ALL RATES ~ $M^{-1/4}$

METABOLISM
GROWTH
EVOLUTION
LONGEVITY
DIFFUSION
FLUXES

....

ALL TIMES ~ $M^{1/4}$

LIFESPANS
TURNOVER TIMES
TIMES TO MATURITY
CIRCULATION TIMES

....

TEMPERATURE

REACTION RATES GOVERNED BY STATISCAL PHYSICS (BOLTZMANN-ARRENHIUS)

ALL RATES ~ $M^{-1/4}e^{-E/kT}$

METABOLISM
GROWTH
EVOLUTION
LONGEVITY
DIFFUSION
FLUXES
....

ALL TIMES ~ $M^{1/4}e^{E/kT}$

LIFESPANS
TURNOVER TIMES
TIMES TO MATURITY
CIRCULATION TIMES
....

MASS AND TEMPERATURE ARE THE MAJOR DETERMINANTS OF THE MEASURABLE TRAITS OF ORGANISMS

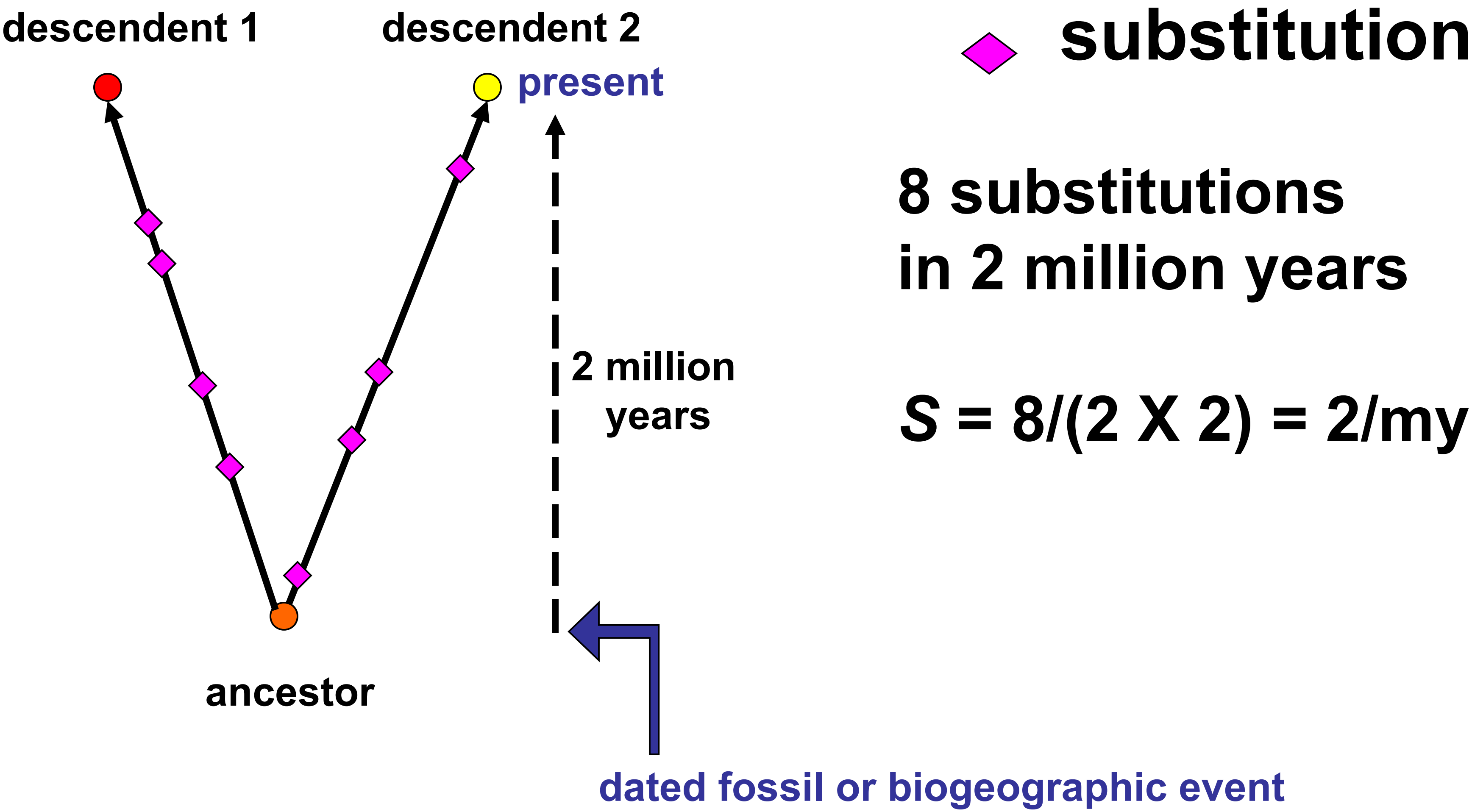
IF THE MASS AND TEMPERATURE DEPENDENCIES ARE ACCOUNTED FOR THEN:

$$(TIMES) \times M^{-1/4}e^{-E/kT}$$
$$(RATES) \times M^{1/4}e^{E/kT}$$

ARE INVARIANT, IMPLYING A "UNIVERSAL" RATE OF LIVING, DYING, GROWING, REPRODUCING, EVOLVING, …….GOVERNED BY JUST TWO PARAMETERS:

1/4 AND E ~ 0.7 ev

Evolution: measuring nucleotide substitution rate (*S*)

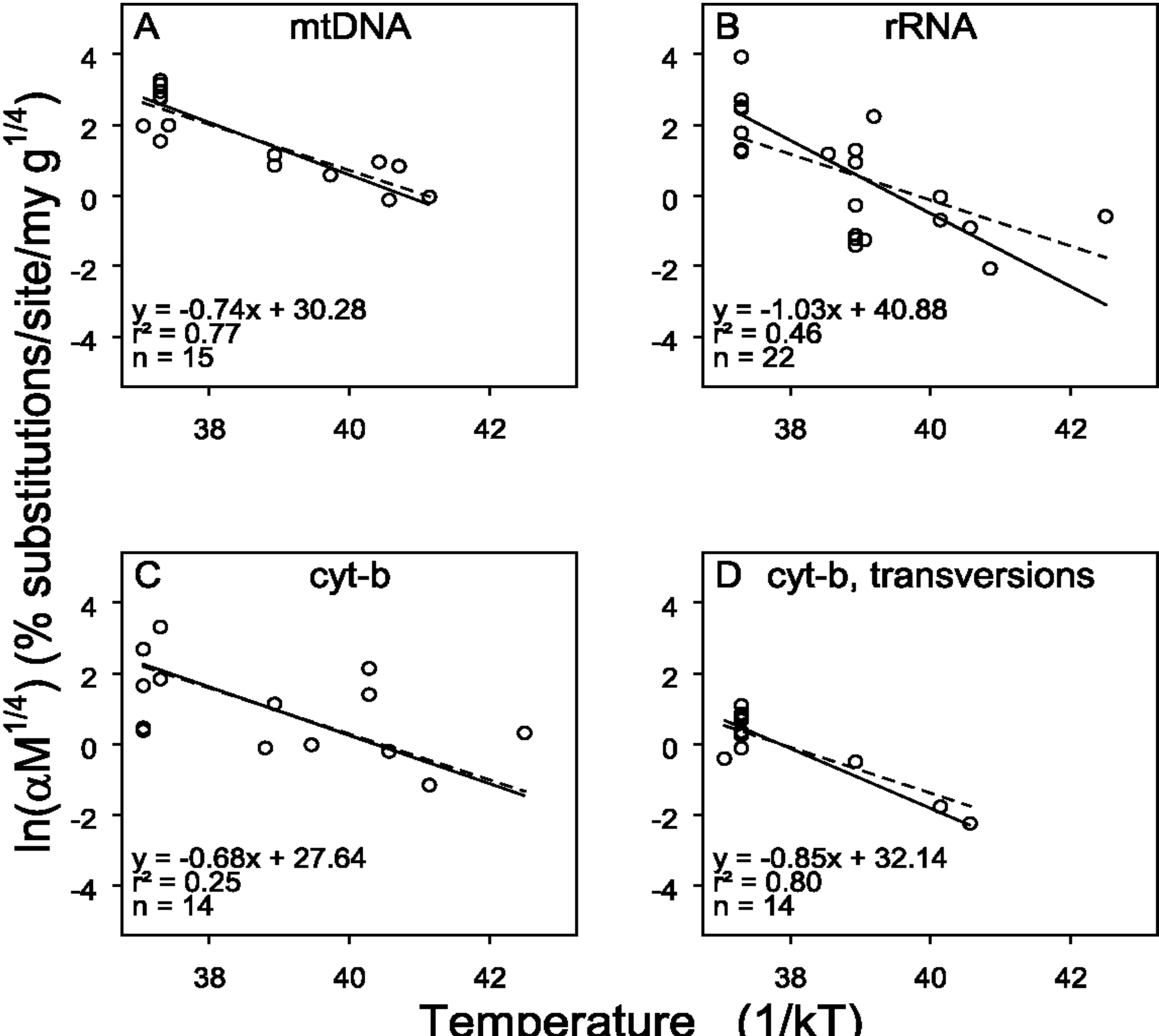


8 substitutions
in 2 million years

$S = 8/(2 \text{ X } 2) = 2/\text{my}$

Rates of molecular evolution

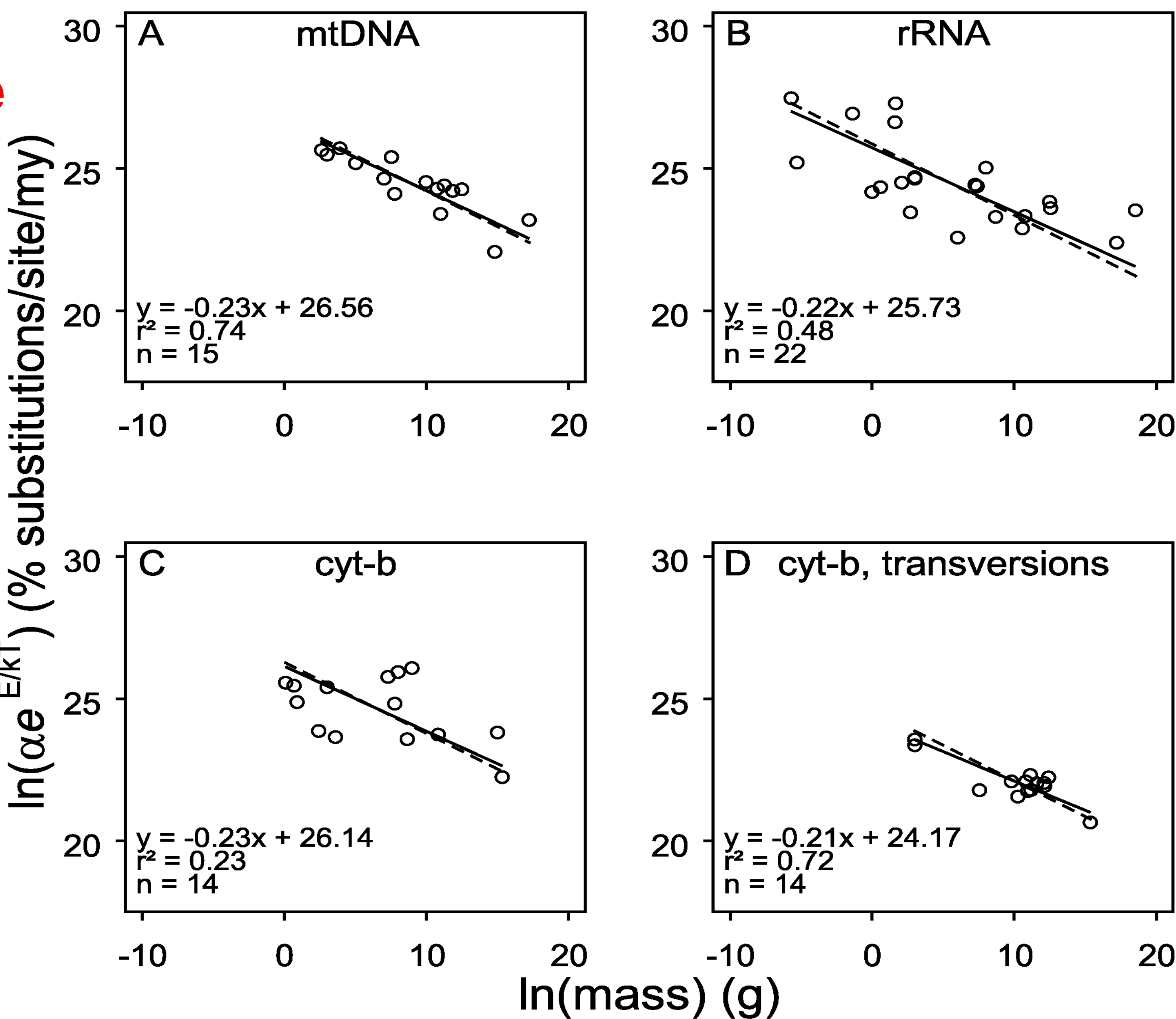
temperature dependence



Gillooly et al. 2005

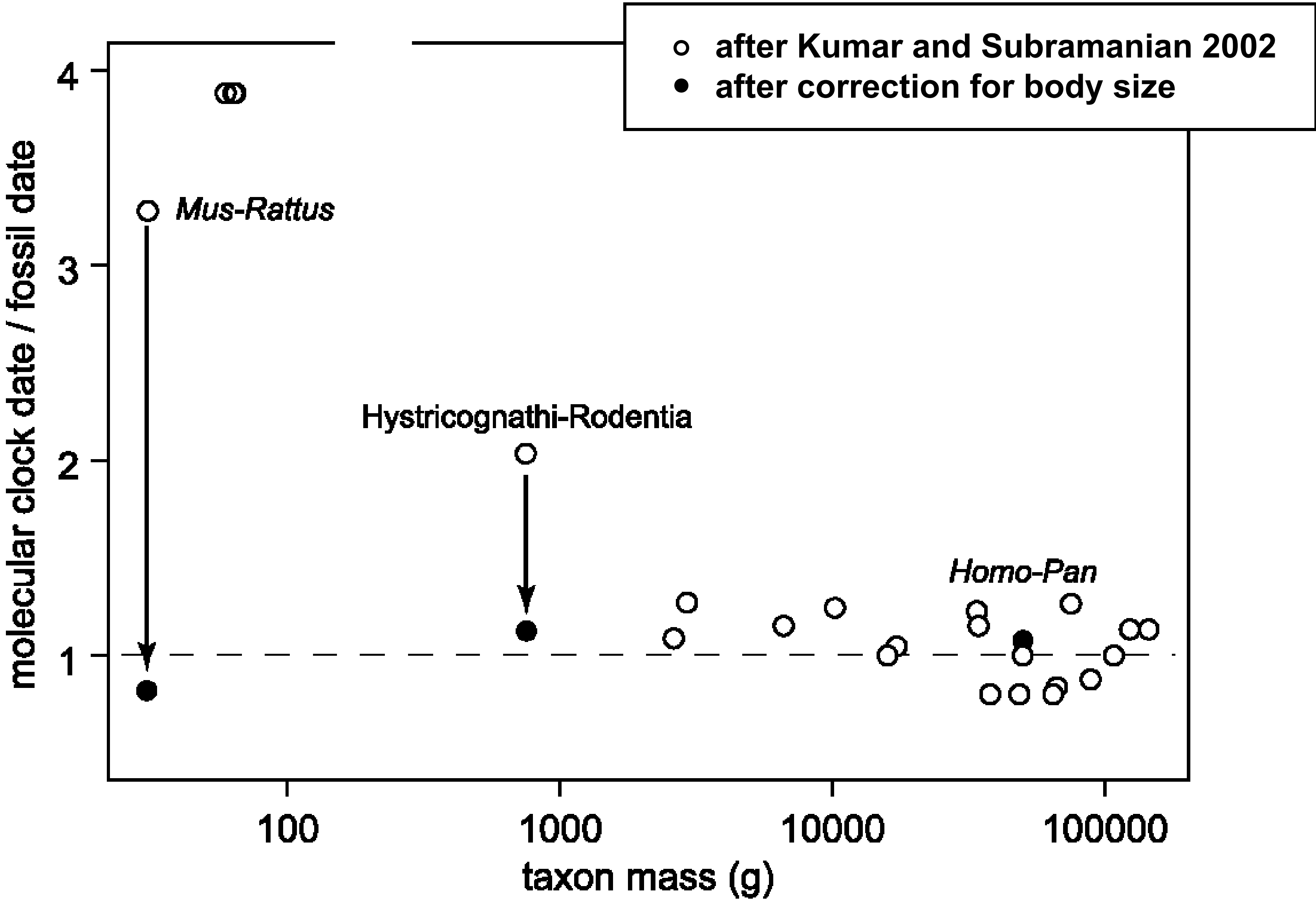
Rates of molecular evolution

body size dependence

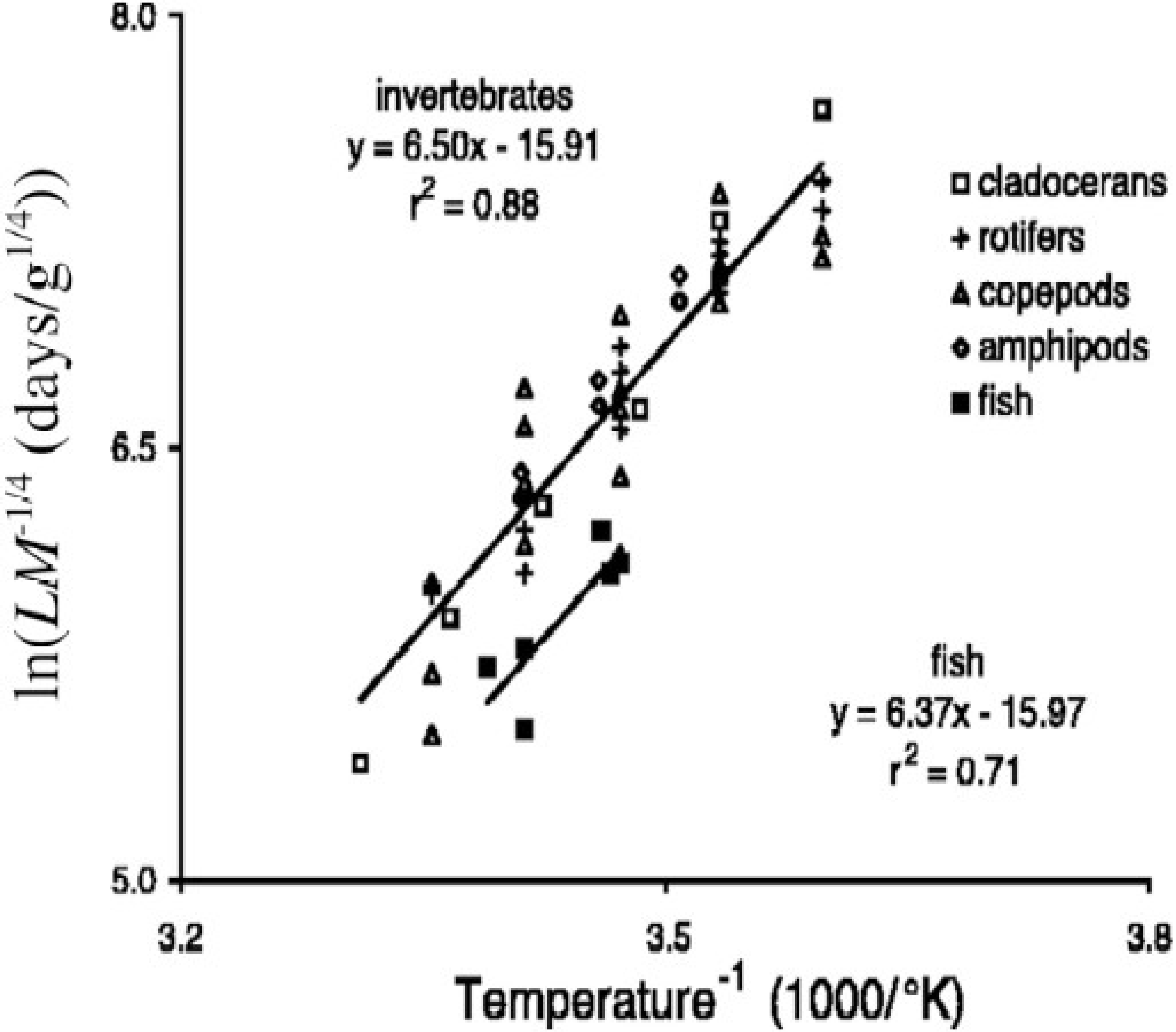


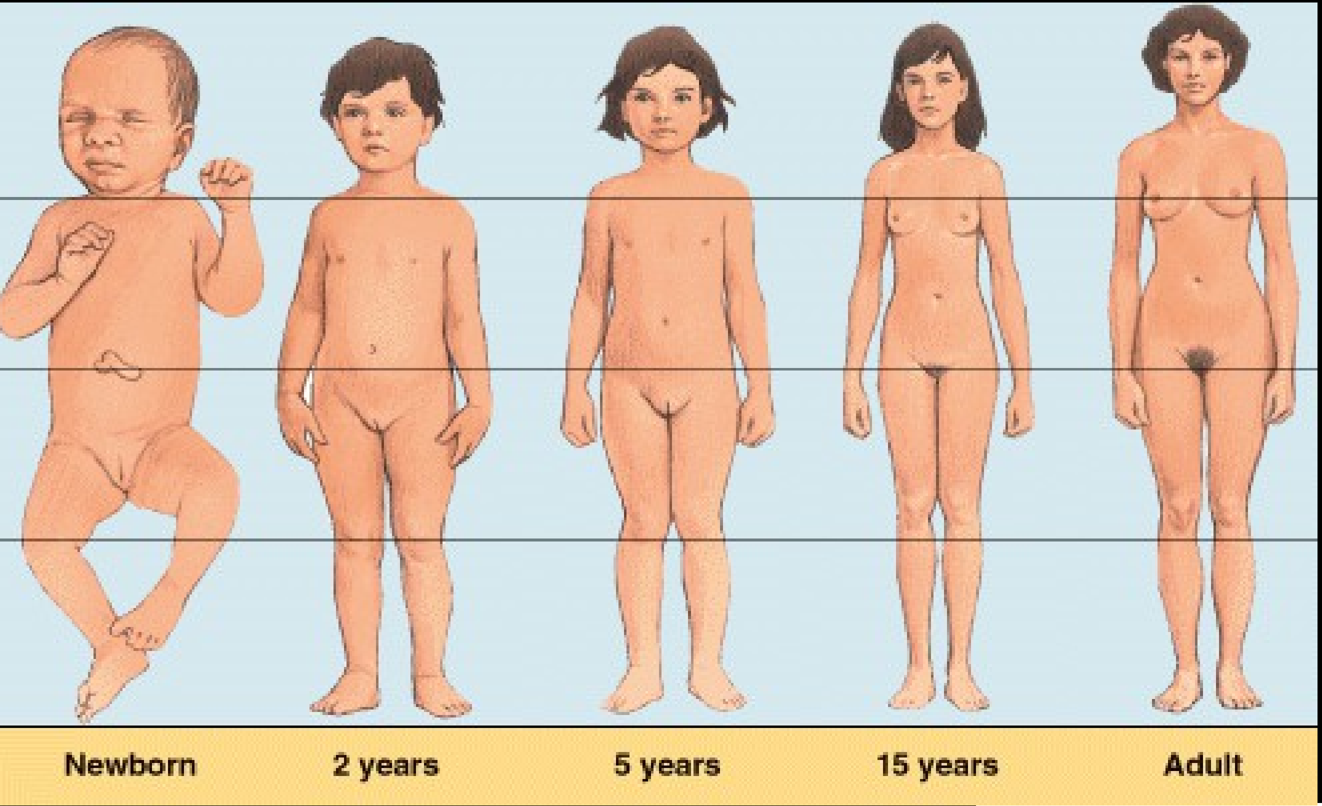
Gillooly et al. 2005

Rates of molecular evolution: size correction reconciles molecular clock with fossil dates

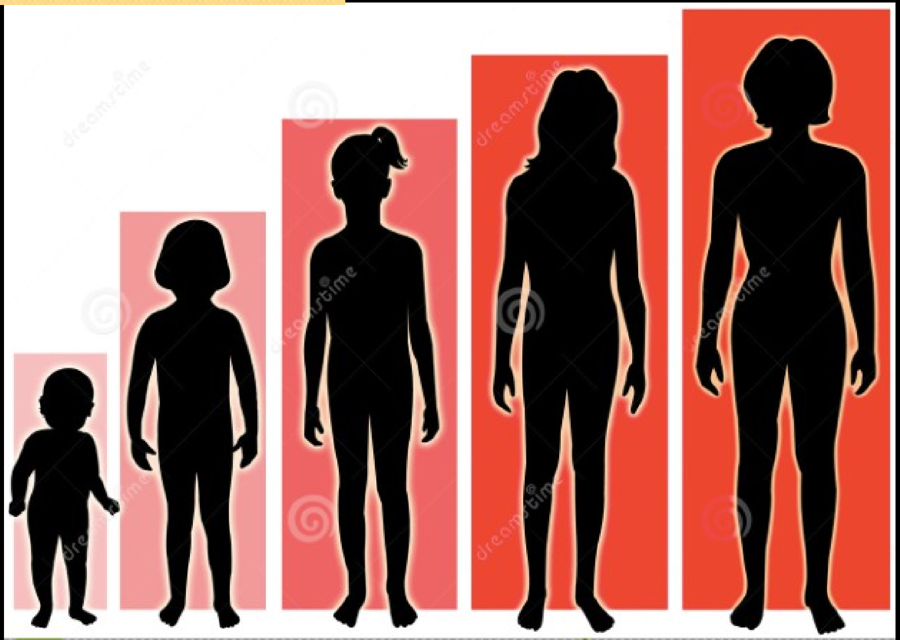


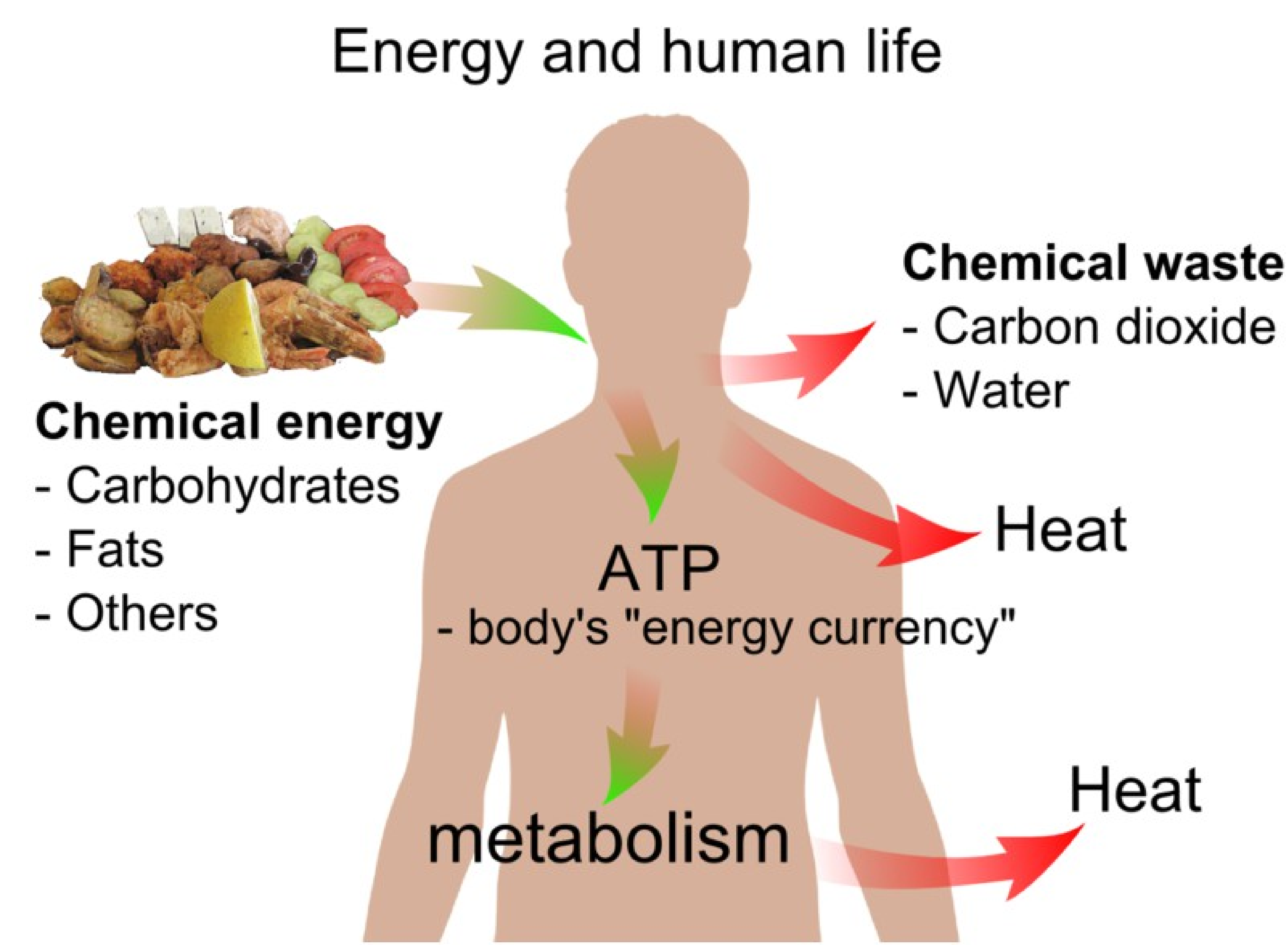
Gillooly et al. 2005


invertebrates
y = 6.50x - 15.91
r2 = 0.88
cladocerans
rotifers
copepods
amphipods
fish
fish
y = 6.37x - 15.97
r2 = 0.71
8.0
6.5
5.0
3.2
3.5
3.8
ln(LM-1/4 (days/g1/4))
Temperature-1 (1000/°K)



GROWTH




Energy and human life
Chemical energy
- Carbohydrates
- Fats
- Others
Chemical waste
- Carbon dioxide
- Water
Heat
ATP
- body's "energy currency"
metabolism
Heat

Growth

Incoming
Metabolized Energy

↓

Maintenance
(of Existing Cells)

+

New Growth
(of New Cells)

$$B = N_{cells} B_{cell} + E_{cell} \frac{dN_{cell}}{dt}$$

IN TERMS OF MASS AT AGE t

$$\square \quad \frac{dm}{dt} = am^{3/4}\ 2\ bm$$

where

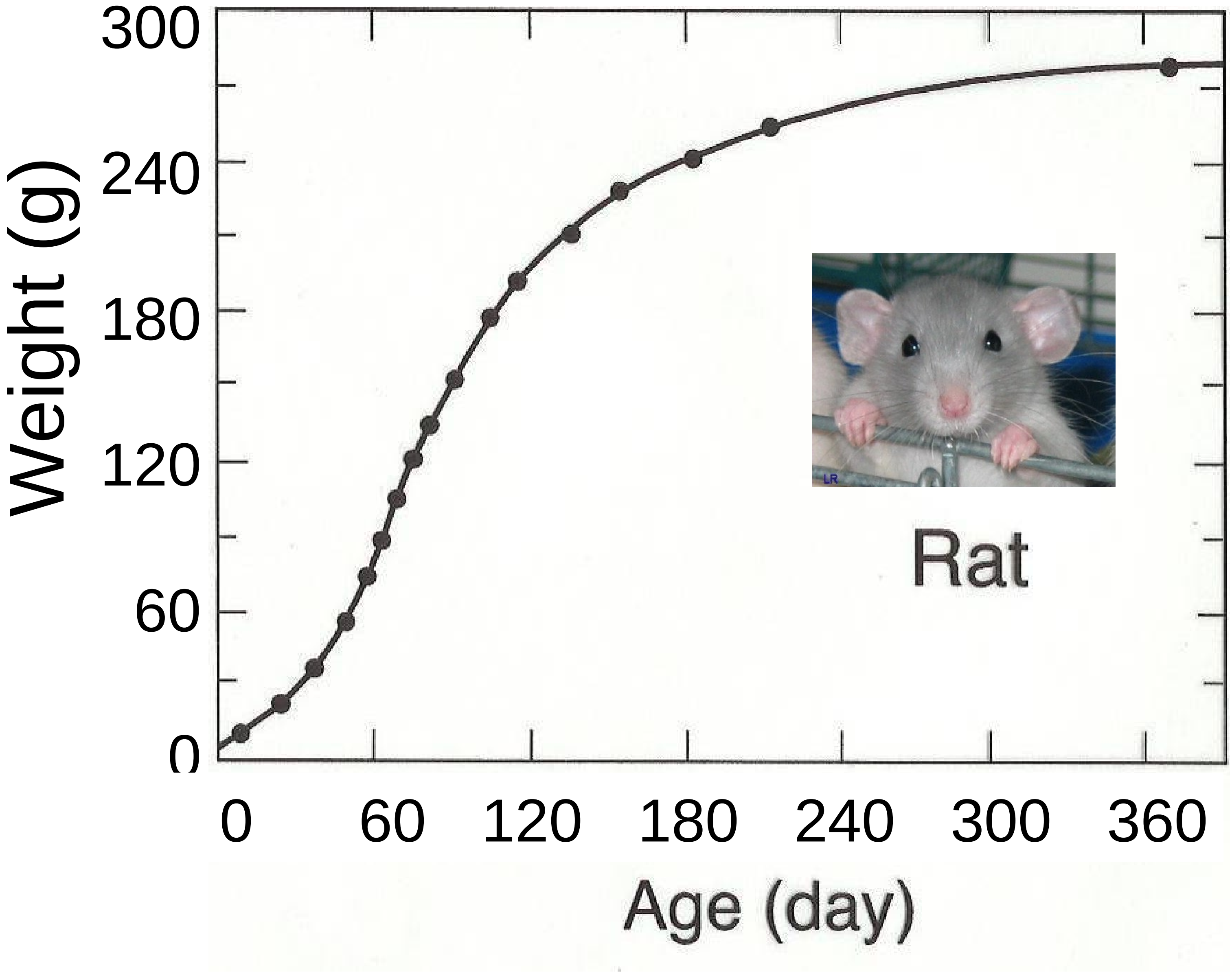
$$a\ \vartheta \frac{B_0 m_c}{E_c}$$

$$b\ \vartheta \frac{B_c}{E_c}$$

SOLUTION:

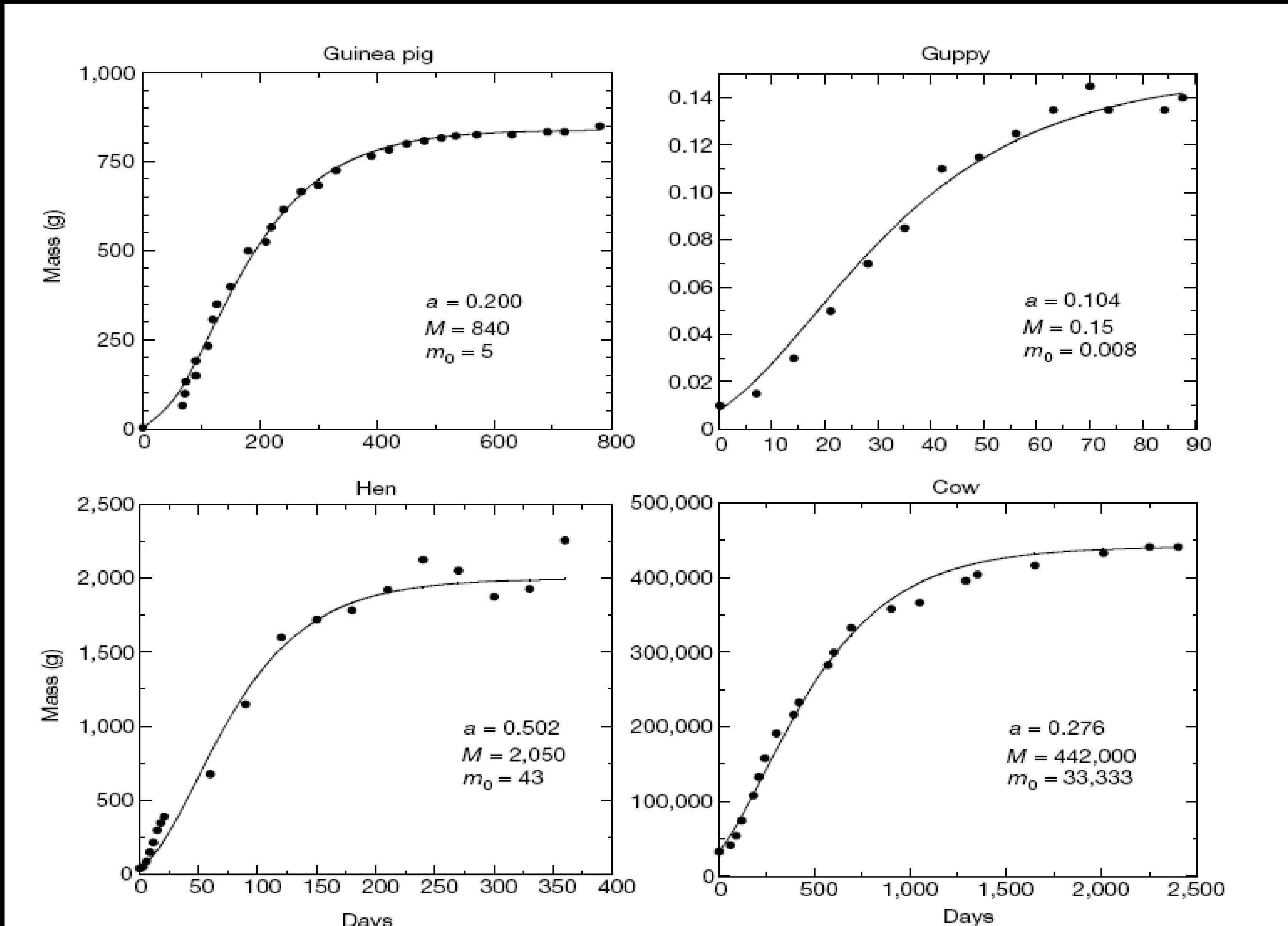
$$\left(\frac{m}{M}\right)^{1/4} = 1 - \left[1 - \left(\frac{m_0}{M}\right)^{1/4}\right] e^{-at/4M^{1/4}}$$

WHERE m_0 = MASS AT BIRTH ($m = m_0$ WHEN $t = 0$)



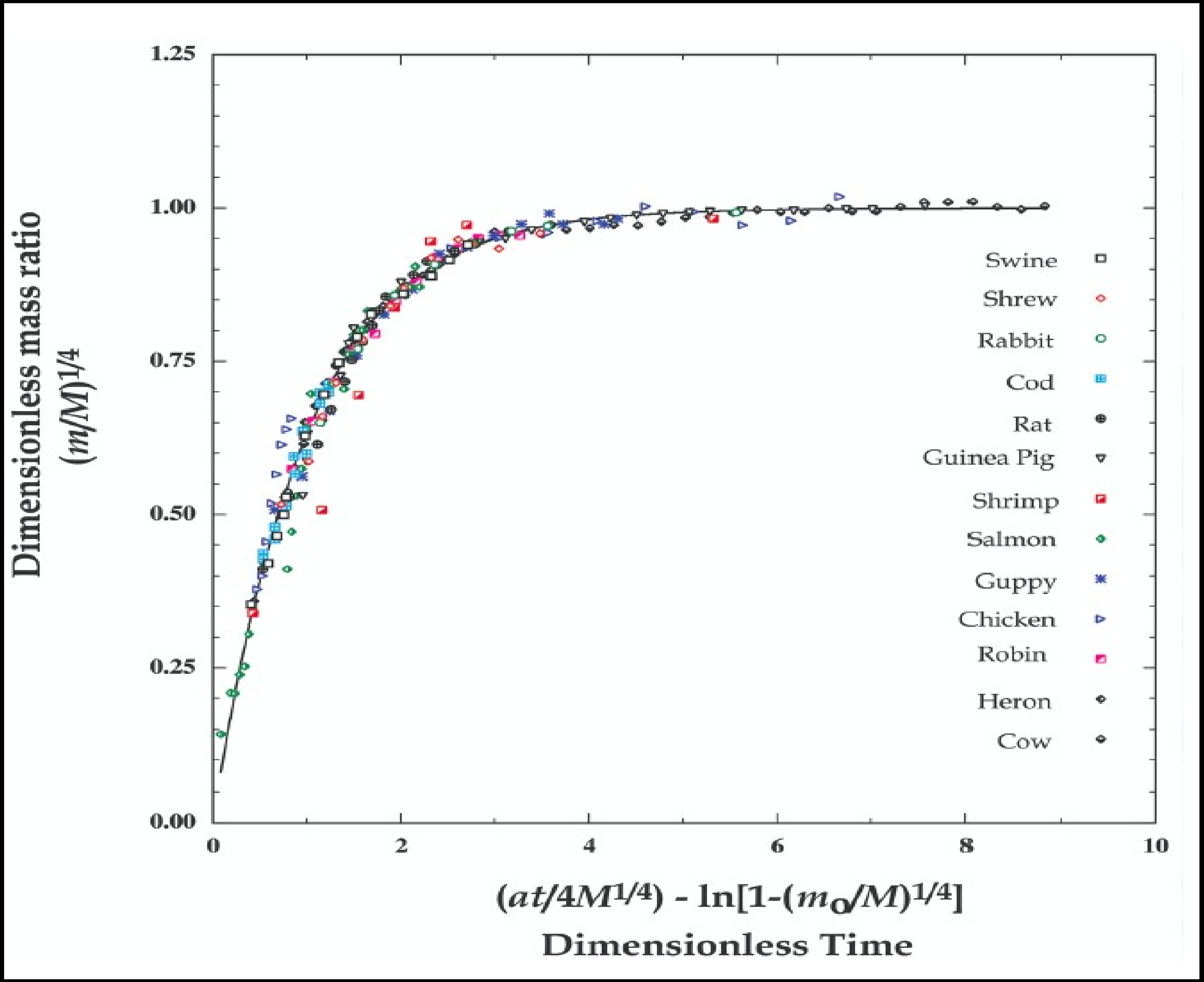
SUB-LINEAR SCALING LEADS TO BOUNDED GROWTH

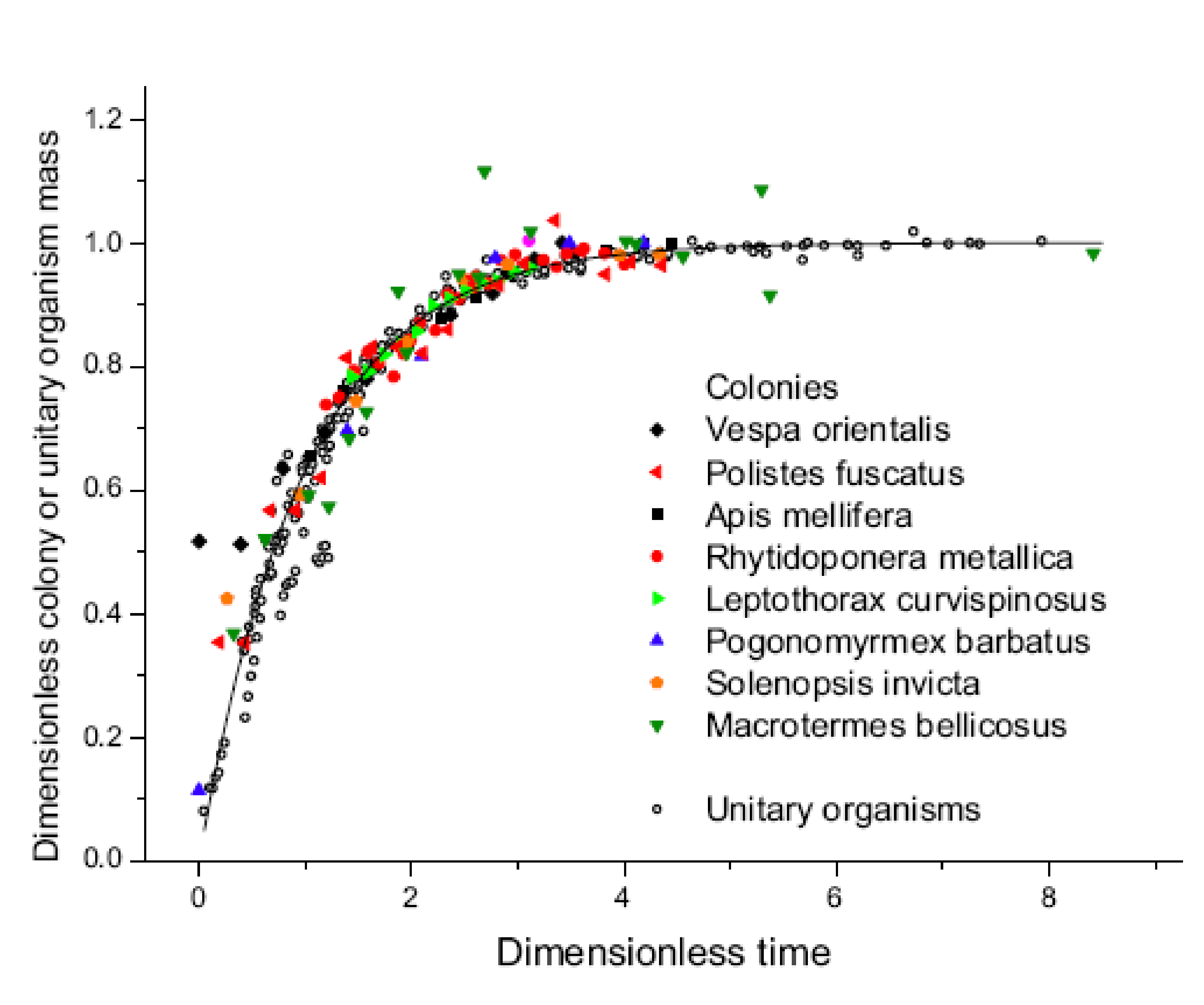
GROWTH CURVES OF ANIMALS



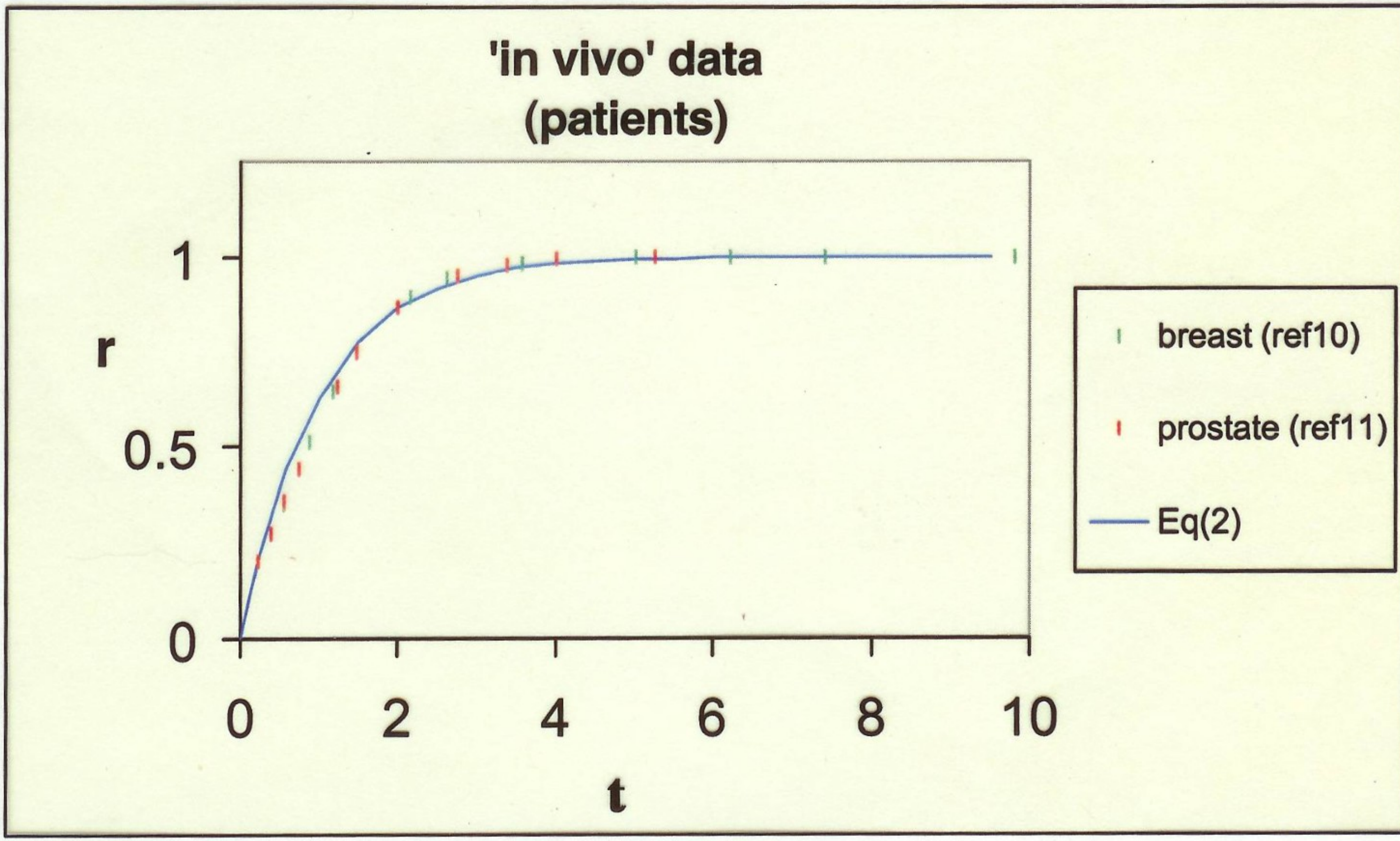
UNIVERSAL COLLAPSED GROWTH CURVE

RESCALED MASS VS. RESCALED AGE

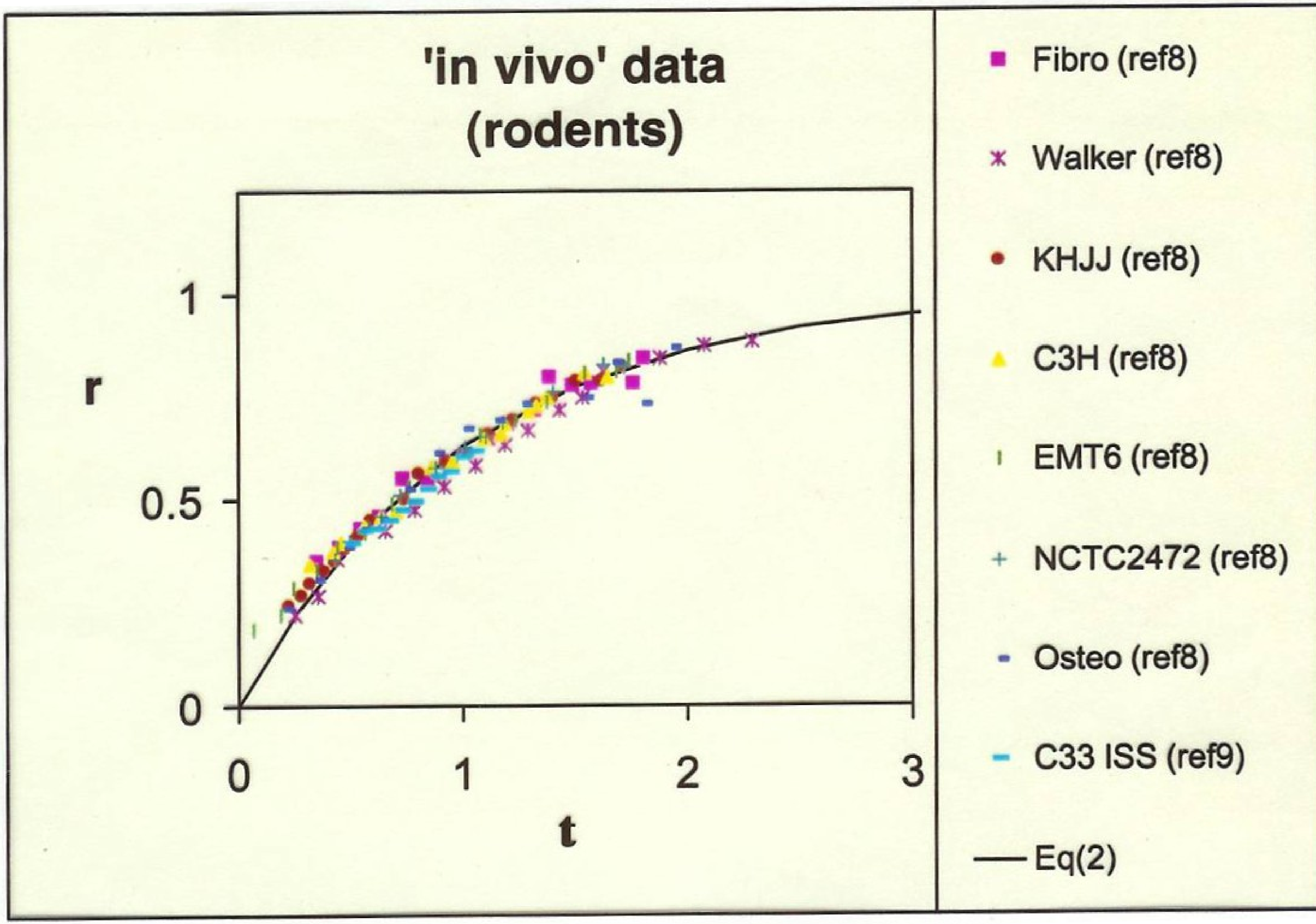




Dimensionless colony or unitary organism mass
Dimensionless time
Colonies
Vespa orientalis
Polistes fuscatus
Apis mellifera
Rhytidoponera metallica
Leptothorax curvispinosus
Pogonomyrmex barbatus
Solenopsis invicta
Macrotermes bellicosus
Unitary organisms
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
2
4
6
8



'in vivo' data
(patients)
r
1
0.5
0
0
2
4
6
8
10
t
breast (ref10)
prostate (ref11)
Eq(2)



'in vivo' data
(rodents)
r
1
0.5
0
0
1
2
3
t
Fibro (ref8)
Walker (ref8)
KHJJ (ref8)
C3H (ref8)
EMT6 (ref8)
NCTC2472 (ref8)
Osteo (ref8)
C33 ISS (ref9)
Eq(2)

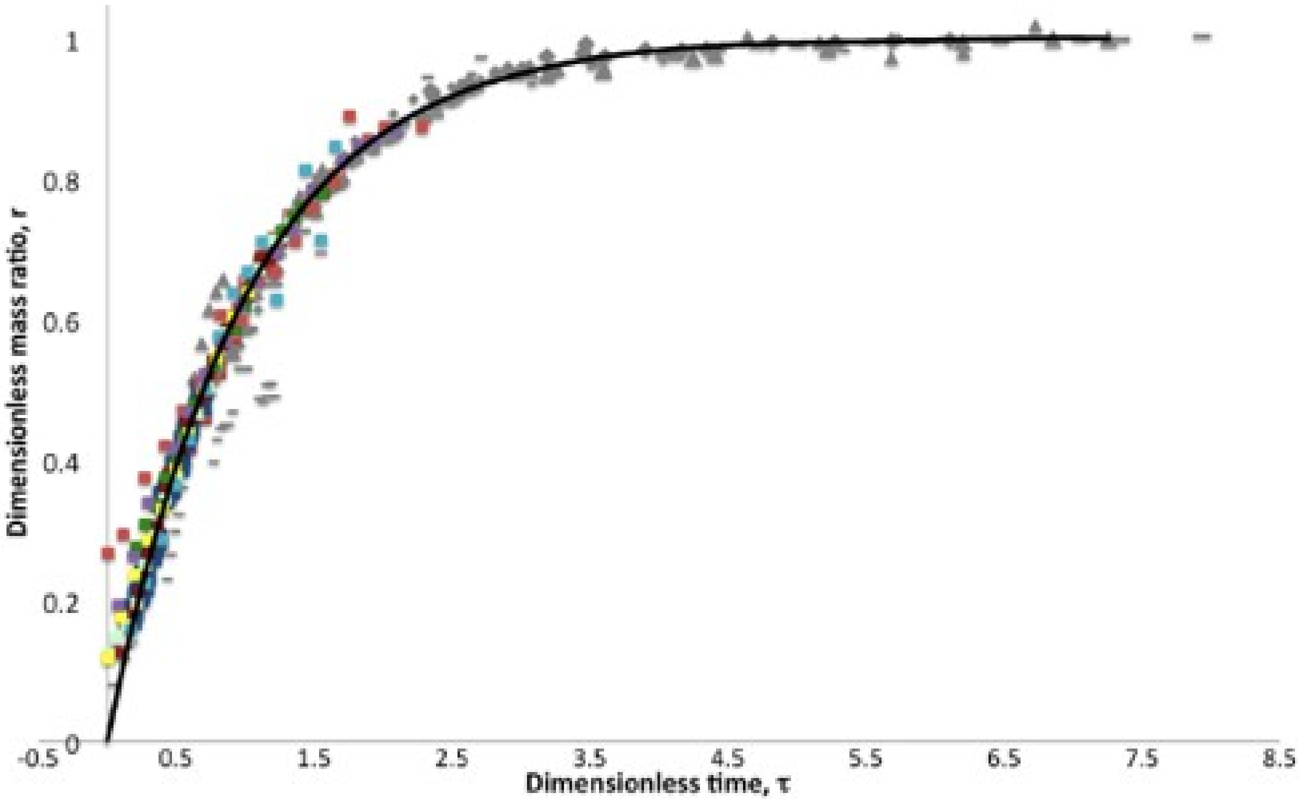


FIGURE 5. Plots of dimensionless ratio versus dimensionless time as defined by Eqs. (29)-(30). Data in grey are for ontogenetic growth from 13 species of animals (see [90] for original data sources), ranging from guppy to cod to guinea pig, and data in color with square symbols are for tumor growth trajectories for C3H mammary carcinoma (dark blue), EMT6 mammary carcinoma (dark red), KHJJ mammary carcinoma (light green), NCTC (dark green), Flank (yellow), Primary fibroadenoma (red), Primary Osteosarcoma (light blue), and Walker Carcinoma (purple) tumor

Herman A.B., Savage V.M., West G.B. *(2012) PLoS ONE*; **6:** e22973


GODZILLA
MAY 16
SEE IT IN realD 3D AND IMAX 3D
MENU
HOME
TICKETS
VIDEOS
DOWNLOADS
GALLERY
STORY
PARTNERS
ULTIMATE FAN CONTEST
IMAX FAN ART CONTEST
MUTOResearch.net
WORLDWIDE RELEASE DATES
GODZILLA SHOP
LEGAL

LENGTH	**350 ft**
WEIGHT	**1.7×10^7 Kg = 1.7×10^4 tons**
BASAL METABOLIC RATE	**2×10^7 calories a day = 1 megawatt**
WEIGHT OF HEART	**10^5 Kg = 100 tons**
RADIUS OF HEART	**30 ft**
HEART RATE	**2.5 times a minute**
VOLUME OF BLOOD	**2×10^6 litres**
DIAMETER OF AORTA	**10 ft**
SLEEP	**< 1 hour a day**
LIFESPAN	**2000 years**

GENERALISED SCALING

i) SUPPOSE THE POPULATION SIZE CHANGES BY A FACTOR λ:

$$N \to \lambda N$$

ii) THIS INDUCES A CHANGE IN SOME METRIC FROM *Y(N)* TO *Y(λN)*:

$$Y(N) \to Y(\lambda N) = Z(\lambda, N) Y(N)$$

GENERALISED SCALING

i) SUPPOSE THE POPULATION SIZE CHANGES BY A FACTOR λ:

$$N \rightarrow \lambda N$$

ii) THIS INDUCES A CHANGE IN SOME METRIC FROM *Y(N)* TO *Y(λN)*:

$$Y(N) \rightarrow Y(\lambda N) = Z(\lambda, N)Y(N)$$

RENORMALISATION GROUP

M. Gell-Mann & F. E. Low (1954) *Physical Review* ***95 (5): 1300–1312***

iii) FOR *ARBITRARY* *Z(λ,N)* THIS CAN BE SOLVED TO GIVE THE GENERAL SOLUTION:

$$Y(N) = Y_0 N^{b(N)}$$

WHERE THE GENERALISED EXPONENT, *b(N)*, DEPENDS ON *N* AND IS GIVEN BY:

$$b(N) = \frac{\int_0^{\ln N} \gamma(N)\, d\ln N}{\ln N}$$

WITH

$$\gamma(N) \equiv \frac{\partial Z(1,N)}{\partial \lambda}$$

iv) THE "NATURAL" VARIABLE IS *ln N*

v) WHEN DO WE GET SIMPLE POWER LAWS WITH EXPONENTS *b(N)* INDEPENDENT OF *N*?

ANSWER: WHEN γ(N) IS INDEPENDENT OF N

➔WHEN *Z(λ,N)* IS INDEPENDENT OF *N:*

$$Y(\lambda N) = Z(\lambda)\, Y(N)$$

SELF-SIMILAR (FRACTALITY)

GENERALISE TO "DYNAMICAL" REPRESENTATION

$$Y(N) \rightarrow Y[N,g(N)]$$

g(N) **"STRENGTH OF INTERACTION"**

THEN RG SOLUTION IS

$$Y(N) \equiv Y[N,g(N)] = Y(N_0)\, e^{\int^{g} \frac{B(g)}{\beta(g)} dg} F\left[N e^{\int^{g} \frac{dg}{\beta(g)}}\right]$$

WHERE

$$\beta(g) \equiv \frac{\partial g(N)}{\partial N}$$

(FIXED POINTS)

BIOLOGY (LIFE)

a) DOMINATED BY SYSTEMATIC, PREDICTABLE, NON-LINEAR (UNIVERSAL) SCALING LAWS

b) ECONOMIES OF SCALE (THE BIGGER YOU ARE, THE LESS YOU NEED PER "CAPITA") - SUBLINEAR

c) PACE OF LIFE SYSTEMATICALLY SLOWS WITH INCREASING SIZE

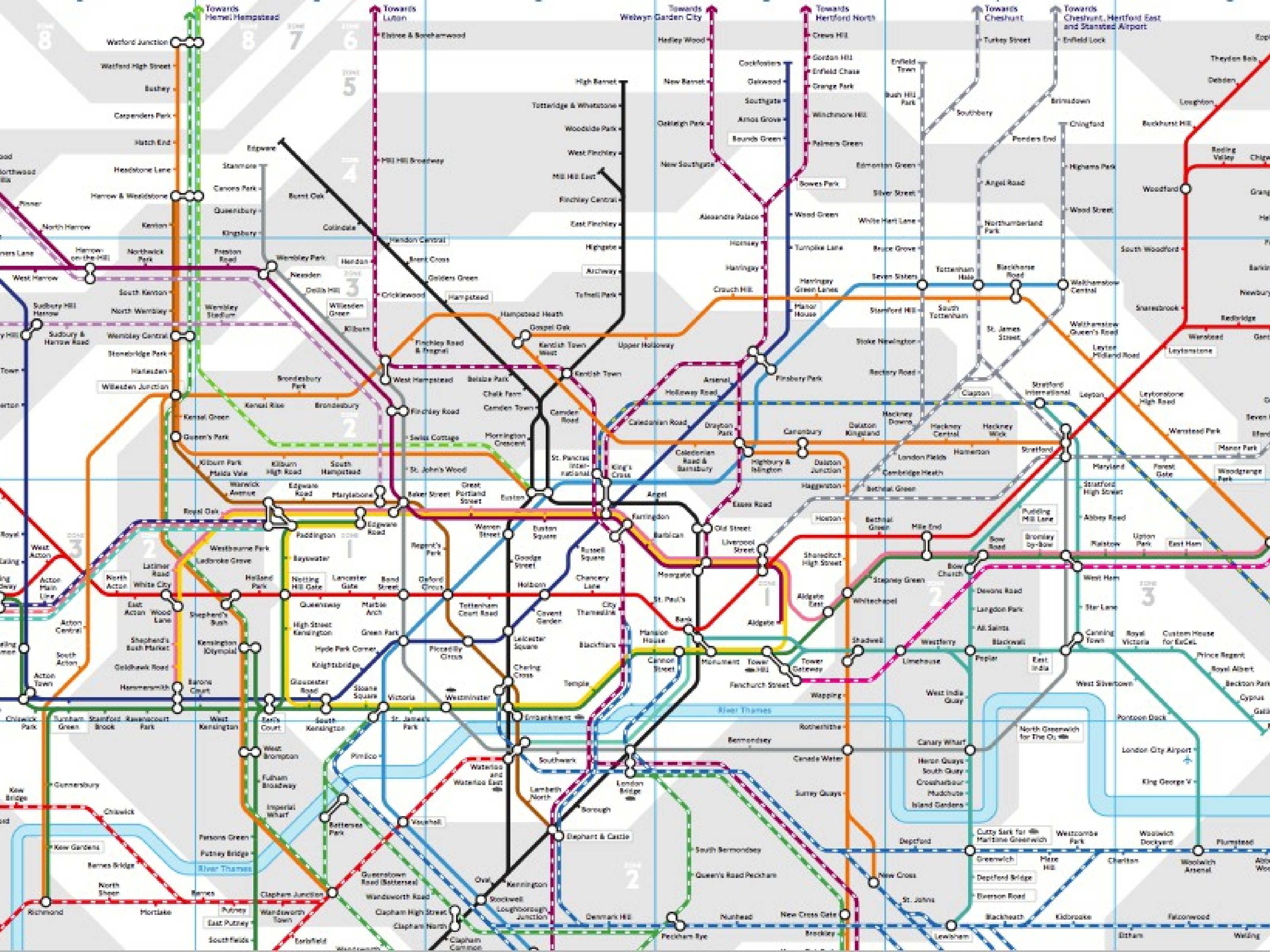
d) GROWTH IS SIGMOIDAL REACHING A STABLE SIZE AT MATURITY

e) FINITE LIFESPAN

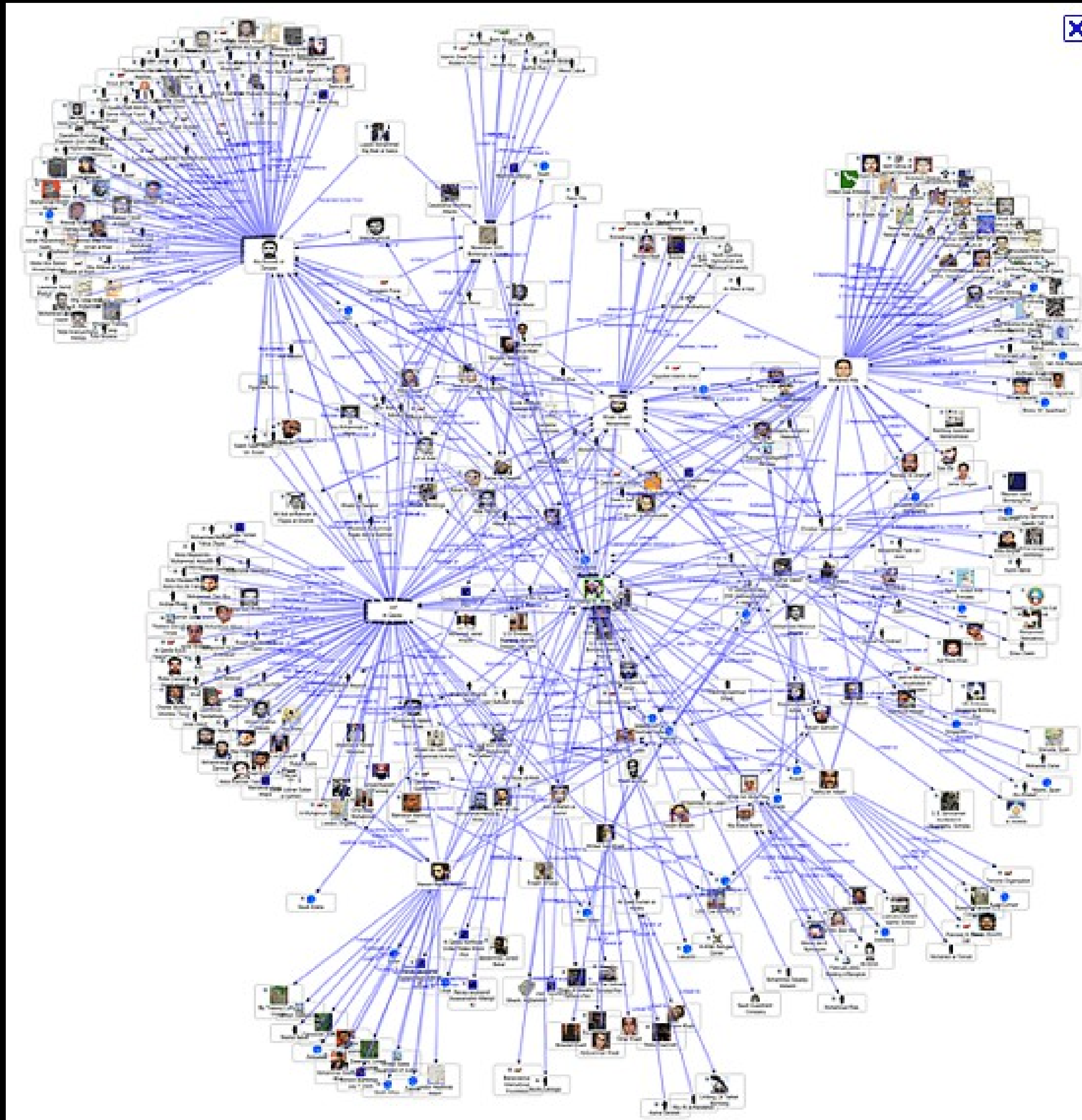
ARE CITIES (AND COMPANIES) SCALED VERSIONS OF EACH OTHER?

DO THEY MANIFEST "UNIVERSALITY"?

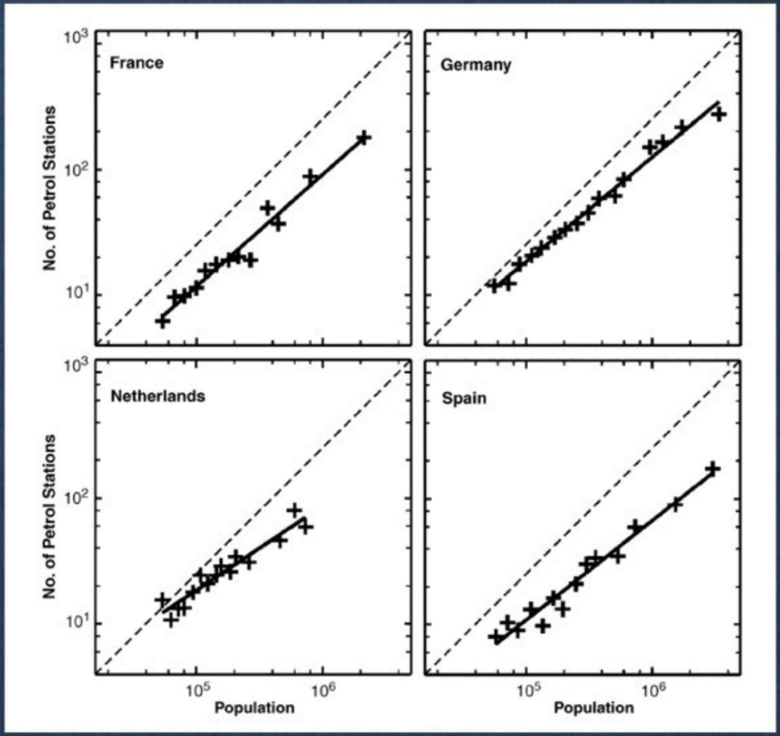

Satellite Imaging Corporation
12777 Jones Road, Suite 370
Houston, Texas 77070-4647 USA
Tel: 1.832.237.2900



Towards Hemel Hempstead
Towards Luton
Towards Welwyn Garden City
Towards Hertford North
Towards Cheshunt
Towards Cheshunt, Hertford East and Stansted Airport
Zone 8
Zone 7
Zone 6
Zone 5
Zone 4
Zone 3
Zone 2
Zone 1
Watford Junction
Watford High Street
Bushey
Carpenders Park
Hatch End
Headstone Lane
Harrow & Wealdstone
Kenton
Northwick Park
Preston Road
Pinner
North Harrow
Harrow-on-the-Hill
West Harrow
South Kenton
North Wembley
Wembley Central
Stonebridge Park
Harlesden
Willesden Junction
Sudbury Hill Harrow
Sudbury & Harrow Road
Wembley Stadium
Wembley Park
Neasden
Dollis Hill
Willesden Green
Kilburn
Stanmore
Canons Park
Queensbury
Kingsbury
Edgware
Burnt Oak
Colindale
Hendon Central
Hendon
Brent Cross
Golders Green
Hampstead
Cricklewood
Mill Hill Broadway
Elstree & Borehamwood
High Barnet
Totteridge & Whetstone
Woodside Park
West Finchley
Mill Hill East
Finchley Central
East Finchley
Highgate
Archway
Tufnell Park
Hadley Wood
New Barnet
Oakleigh Park
New Southgate
Cockfosters
Oakwood
Southgate
Arnos Grove
Bounds Green
Crews Hill
Gordon Hill
Enfield Chase
Grange Park
Winchmore Hill
Palmers Green
Bowes Park
Alexandra Palace
Wood Green
Hornsey
Turnpike Lane
Harringay
Harringay Green Lanes
Crouch Hill
Manor House
Enfield Town
Bush Hill Park
Turkey Street
Southbury
Enfield Lock
Brimsdown
Ponders End
Chingford
Highams Park
Wood Street
Edmonton Green
Silver Street
White Hart Lane
Bruce Grove
Angel Road
Northumberland Park
Seven Sisters
Tottenham Hale
Blackhorse Road
Walthamstow Central
Theydon Bois
Debden
Loughton
Buckhurst Hill
Roding Valley
Woodford
South Woodford
Snaresbrook
Redbridge
Wanstead
Leytonstone
Stamford Hill
South Tottenham
St. James Street
Walthamstow Queen's Road
Leyton Midland Road
Stoke Newington
Rectory Road
Clapton
Hackney Downs
Stratford International
Leyton
Leytonstone High Road
Wanstead Park
Manor Park
Finchley Road & Frognal
Hampstead Heath
Gospel Oak
Kentish Town West
Upper Holloway
Kentish Town
West Hampstead
Belsize Park
Chalk Farm
Camden Town
Camden Road
Finchley Road
Swiss Cottage
Brondesbury Park
Brondesbury
Kensal Rise
Kensal Green
Queen's Park
Kilburn Park
Maida Vale
Kilburn High Road
South Hampstead
St. John's Wood
Mornington Crescent
Arsenal
Holloway Road
Caledonian Road
Finsbury Park
Drayton Park
Caledonian Road & Barnsbury
Highbury & Islington
Canonbury
Dalston Kingsland
Dalston Junction
Hackney Central
Hackney Wick
London Fields
Homerton
Cambridge Heath
Stratford
Maryland
Forest Gate
Woodgrange Park
Haggerston
Bethnal Green
Hoxton
St. Pancras International
King's Cross
Euston
Warwick Avenue
Edgware Road
Marylebone
Baker Street
Great Portland Street
Royal Oak
Paddington
Westbourne Park
Ladbroke Grove
Latimer Road
White City
Bayswater
Notting Hill Gate
Holland Park
Lancaster Gate
Bond Street
Oxford Circus
Regent's Park
Warren Street
Euston Square
Goodge Street
Russell Square
Farringdon
Barbican
Angel
Old Street
Essex Road
Liverpool Street
Moorgate
Shoreditch High Street
Chancery Lane
Holborn
Tottenham Court Road
Queensway
Marble Arch
St. Paul's
Covent Garden
City Thameslink
Stratford High Street
Abbey Road
Pudding Mill Lane
Bromley-by-Bow
Bow Road
Bow Church
Mile End
Stepney Green
Whitechapel
Aldgate East
Aldgate
Bank
Plaistow
Upton Park
East Ham
West Ham
Star Lane
Devons Road
Langdon Park
All Saints
Canning Town
Royal Victoria
Custom House for ExCeL
Prince Regent
Royal Albert
Beckton Park
Cyprus
West Ealing
Ealing Broadway
West Acton
North Acton
East Acton
Acton Main Line
Acton Central
South Acton
Acton Town
Wood Lane
Shepherd's Bush
Shepherd's Bush Market
Goldhawk Road
Kensington (Olympia)
Hammersmith
Barons Court
High Street Kensington
Green Park
Hyde Park Corner
Knightsbridge
Piccadilly Circus
Leicester Square
Charing Cross
Mansion House
Blackfriars
Temple
Cannon Street
Monument
Tower Hill
Tower Gateway
Fenchurch Street
Shadwell
Limehouse
Westferry
Poplar
Blackwall
East India
West India Quay
West Silvertown
Pontoon Dock
London City Airport
King George V
Chiswick Park
Turnham Green
Stamford Brook
Ravenscourt Park
West Kensington
Earl's Court
Gloucester Road
South Kensington
Sloane Square
Victoria
St. James's Park
Westminster
Embankment
River Thames
Wapping
Rotherhithe
Bermondsey
Canada Water
Canary Wharf
North Greenwich for The O2
Heron Quays
South Quay
Crossharbour
Mudchute
Island Gardens
Surrey Quays
West Brompton
Fulham Broadway
Imperial Wharf
Gunnersbury
Kew Bridge
Chiswick
Kew Gardens
Barnes Bridge
North Sheen
Barnes
Richmond
Mortlake
Parsons Green
Putney Bridge
Putney
East Putney
Southfields
Pimlico
Vauxhall
Battersea Park
Queenstown Road (Battersea)
Wandsworth Road
Clapham Junction
Wandsworth Town
Clapham High Street
Clapham North
Clapham Common
Earlsfield
Waterloo
Waterloo East
Southwark
Lambeth North
London Bridge
Borough
Elephant & Castle
Kennington
Oval
Stockwell
Loughborough Junction
Denmark Hill
Peckham Rye
Nunhead
South Bermondsey
Queen's Road Peckham
New Cross Gate
New Cross
Brockley
St. Johns
Deptford
Cutty Sark for Maritime Greenwich
Greenwich
Deptford Bridge
Elverson Road
Lewisham
Westcombe Park
Maze Hill
Blackheath
Kidbrooke
Charlton
Woolwich Dockyard
Woolwich Arsenal
Plumstead
Falconwood
Eltham
Welling



NUMBER OF PETROL STATIONS VS. POPULATION

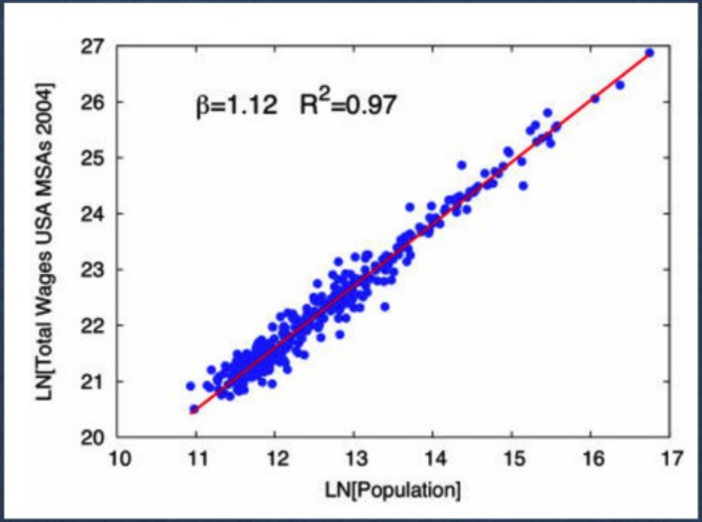


INFRASTRUCTURE

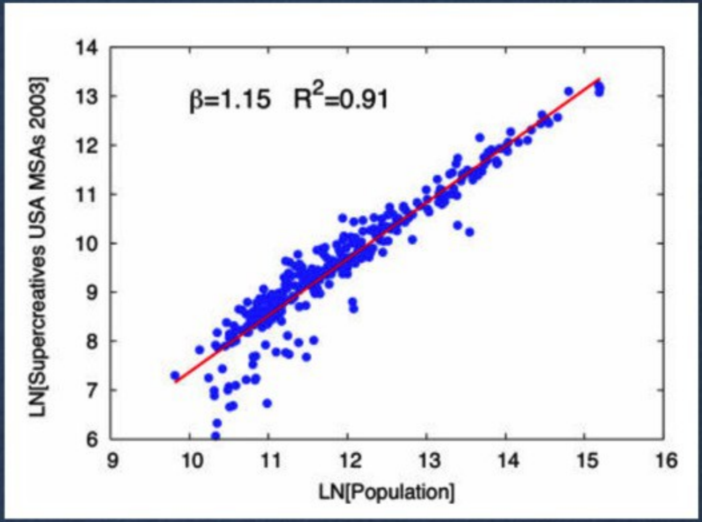
SUB-LINEAR SCALING

ECONOMY OF SCALE

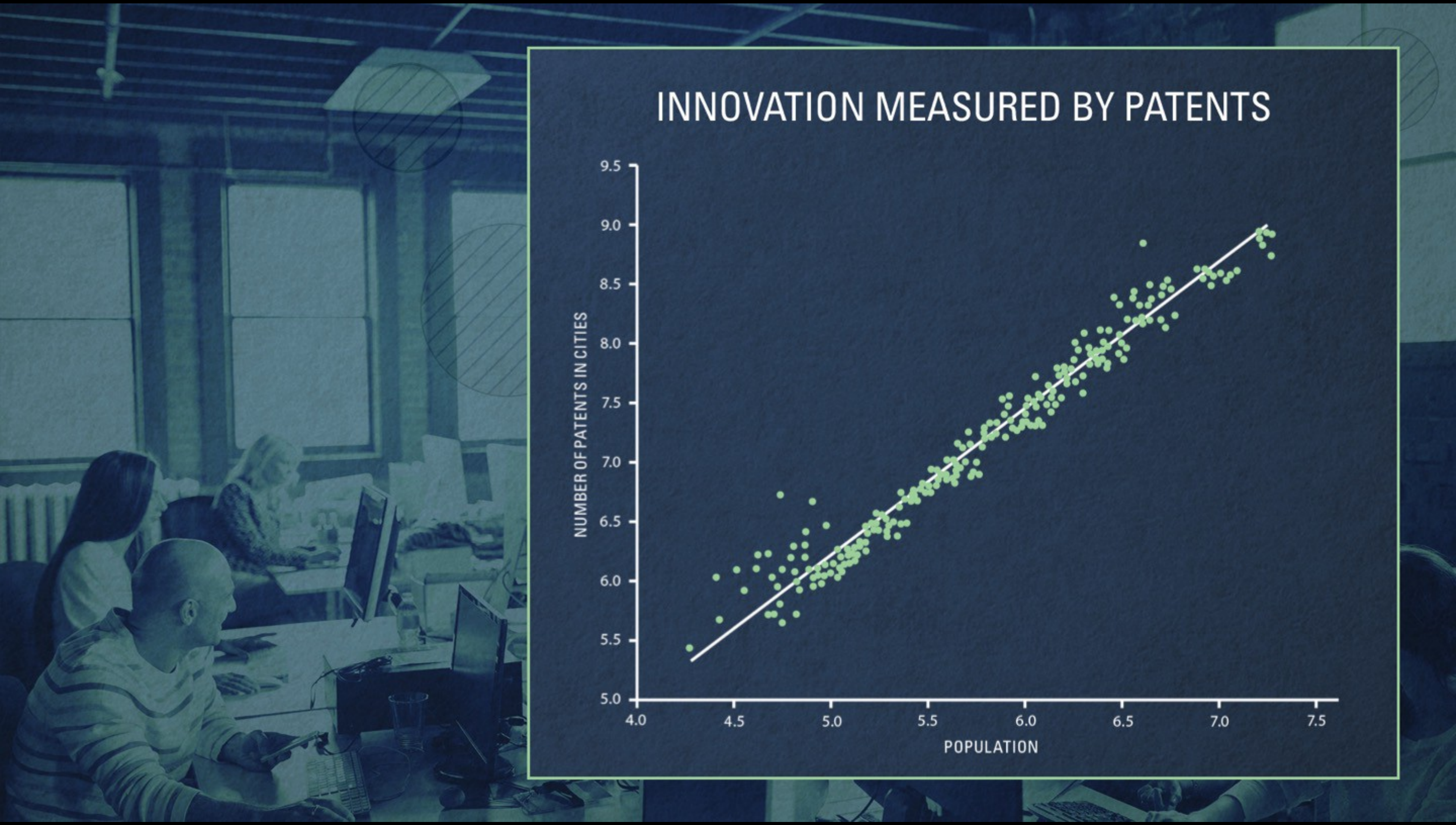
SUPER-LINEAR SCALING



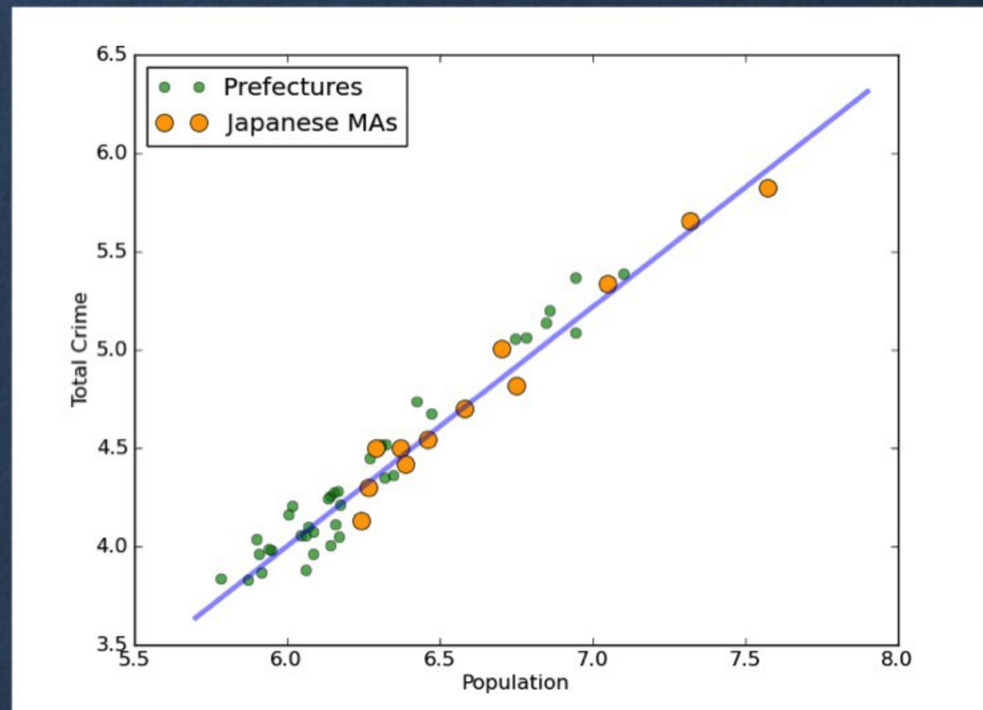
Total wages per MSA in 2004 for the USA vs. metropolitan population.



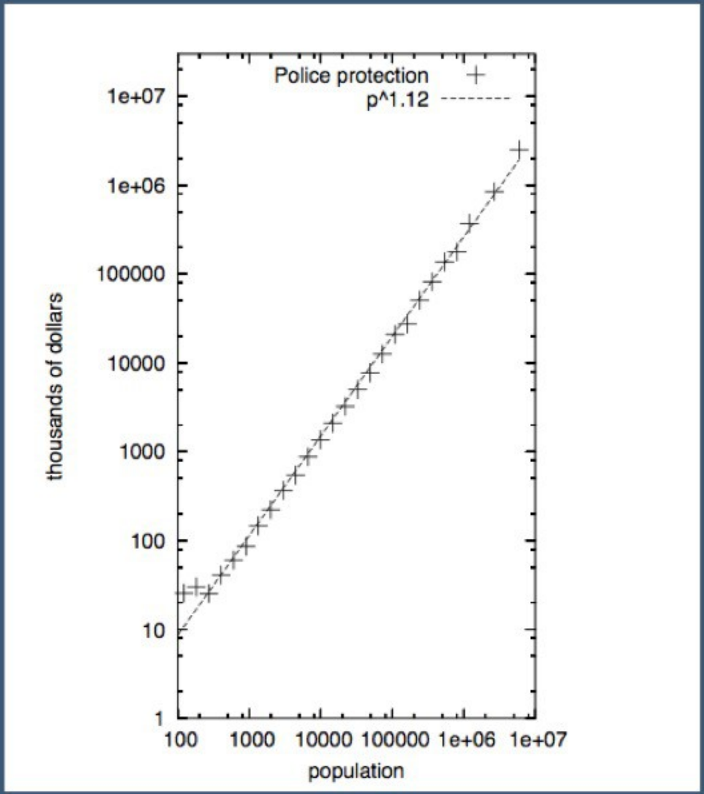
Supercreative employment per MSA in 2003, for the USA vs. metropolitan population.

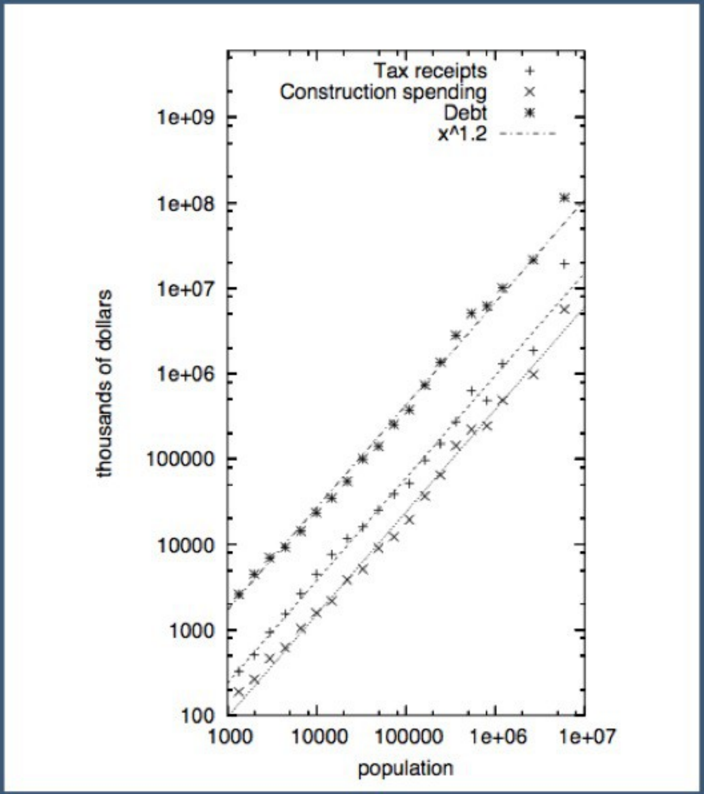

INNOVATION MEASURED BY PATENTS
NUMBER OF PATENTS IN CITIES
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
POPULATION

TOTAL CRIME (JAPAN)

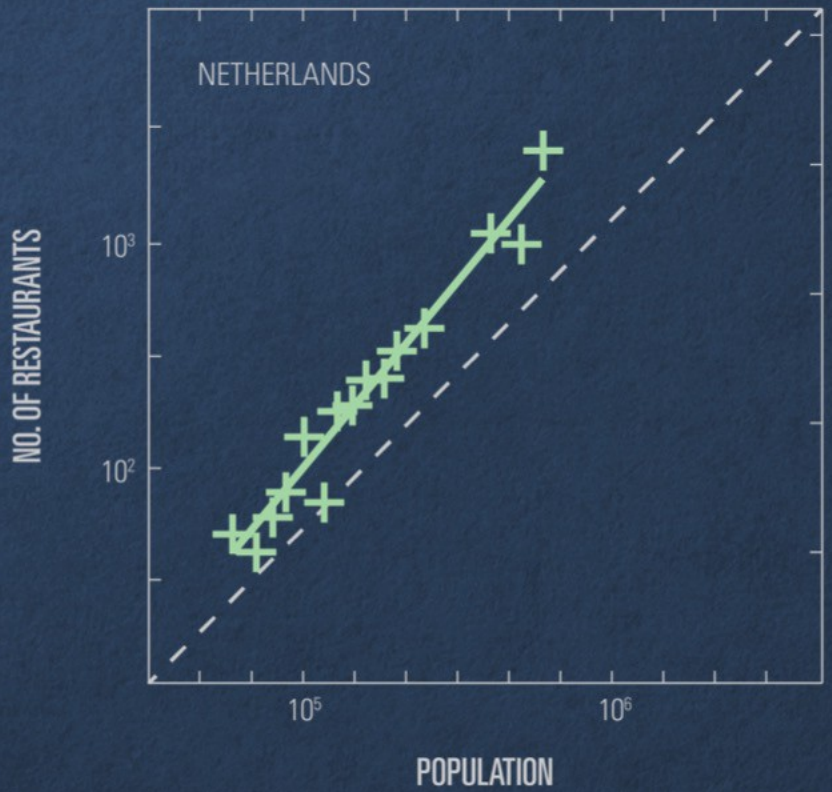


Slope = 1.21   [1.08, 1.35]

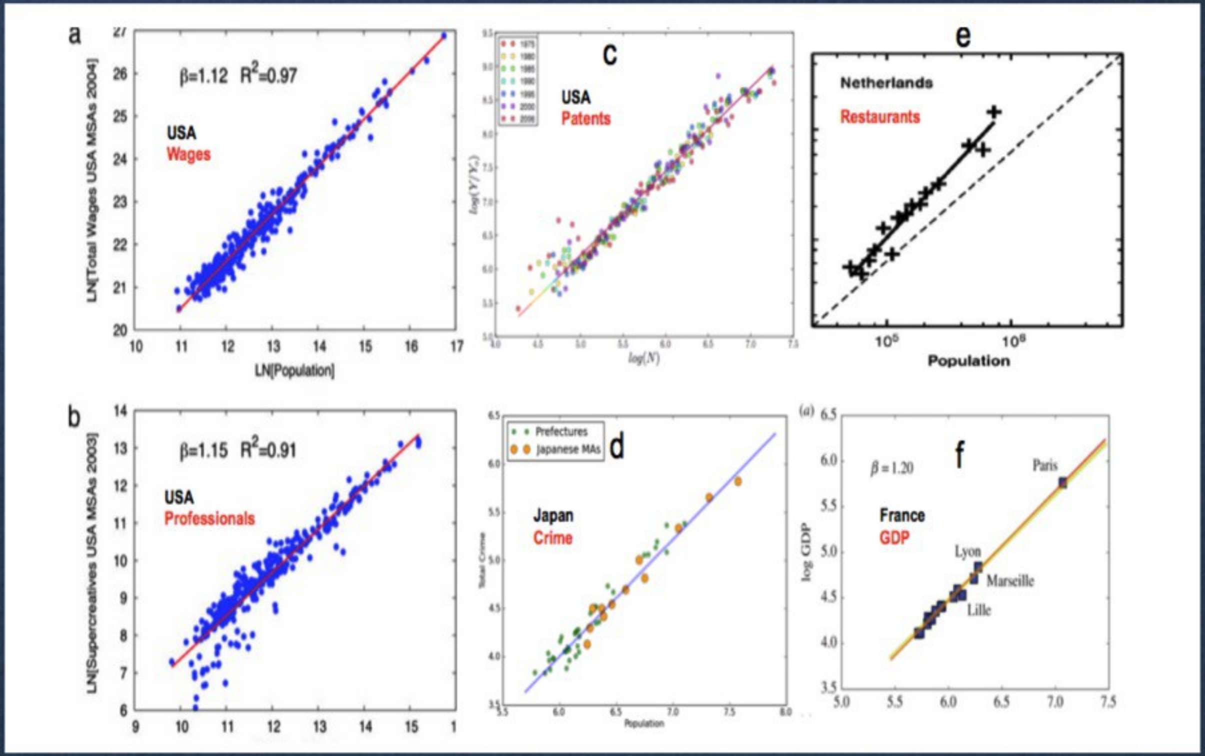

Police protection
p^1.12
thousands of dollars
population
1e+07
1e+06
100000
10000
1000
100
10
1
100
1000
10000
100000
1e+06
1e+07


Tax receipts
Construction spending
Debt
x^1.2
thousands of dollars
population
1e+09
1e+08
1e+07
1e+06
100000
10000
1000
100
1000
10000
100000
1e+06
1e+07

RESTAURANTS IN THE NETHERLANDS



UNIVERSALITY OF URBAN SCALING




THE GOOD,
THE BAD,
THE UGLY

ON AVERAGE DOUBLING THE SIZE OF A CITY

SYSTEMATICALLY INCREASES

ON AVERAGE DOUBLING THE SIZE OF A CITY

SYSTEMATICALLY INCREASES

INCOME, WEALTH, PATENTS, COLLEGES, CREATIVE PEOPLE, POLICE, AIDS & FLU, CRIME, SOCIAL INTERACTIONS,………..

ON AVERAGE DOUBLING THE SIZE OF A CITY

SYSTEMATICALLY INCREASES

INCOME, WEALTH, PATENTS, COLLEGES, CREATIVE PEOPLE, POLICE, AIDS & FLU, CRIME, SOCIAL INTERACTIONS,………..

ALL BY APPROXIMATELY 15%

REGARDLESS OF CITY

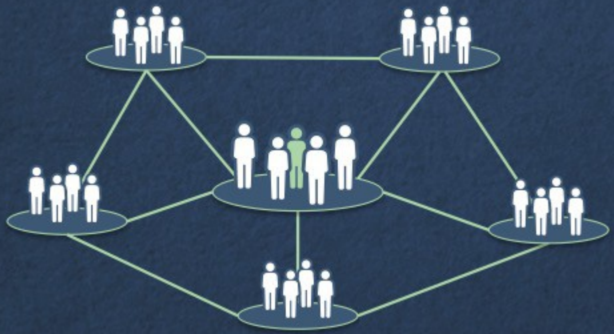
AND……………

AND……………

SAVES APPROXIMATELY 15% ON ALL INFRASTRUCTURE (ROADS, ELECTRICAL LINES, GAS STATIONS,…….)

Universality of Social Networks

(clustering hierarchies)

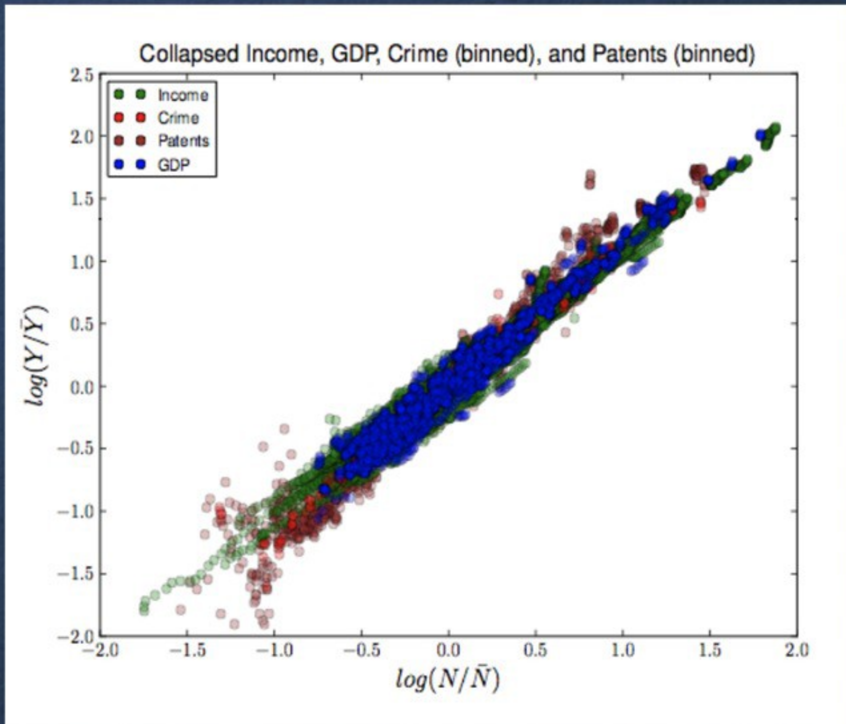


POSITIVE FEEDBACK MECHANISM IN SOCIAL NETWORKS

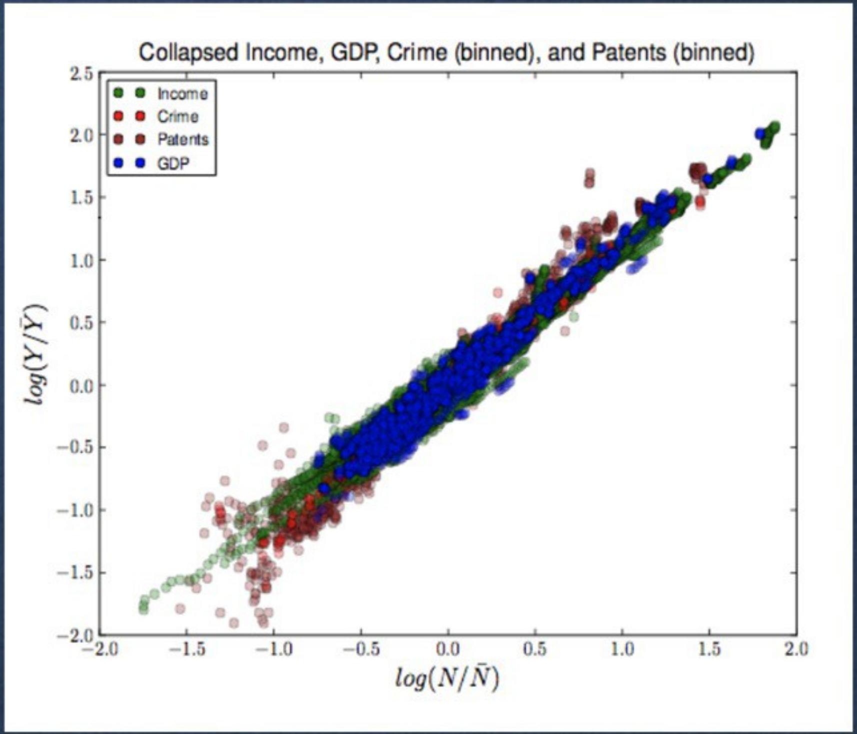
↓

SUPERLINEAR SCALING & INCREASING PACE OF LIFE

UNIVERSALITY

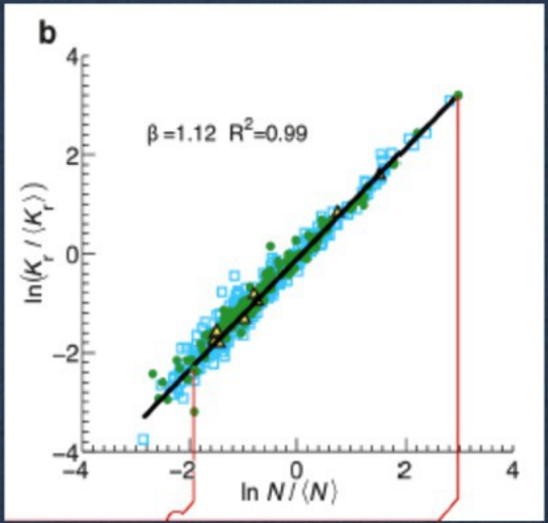


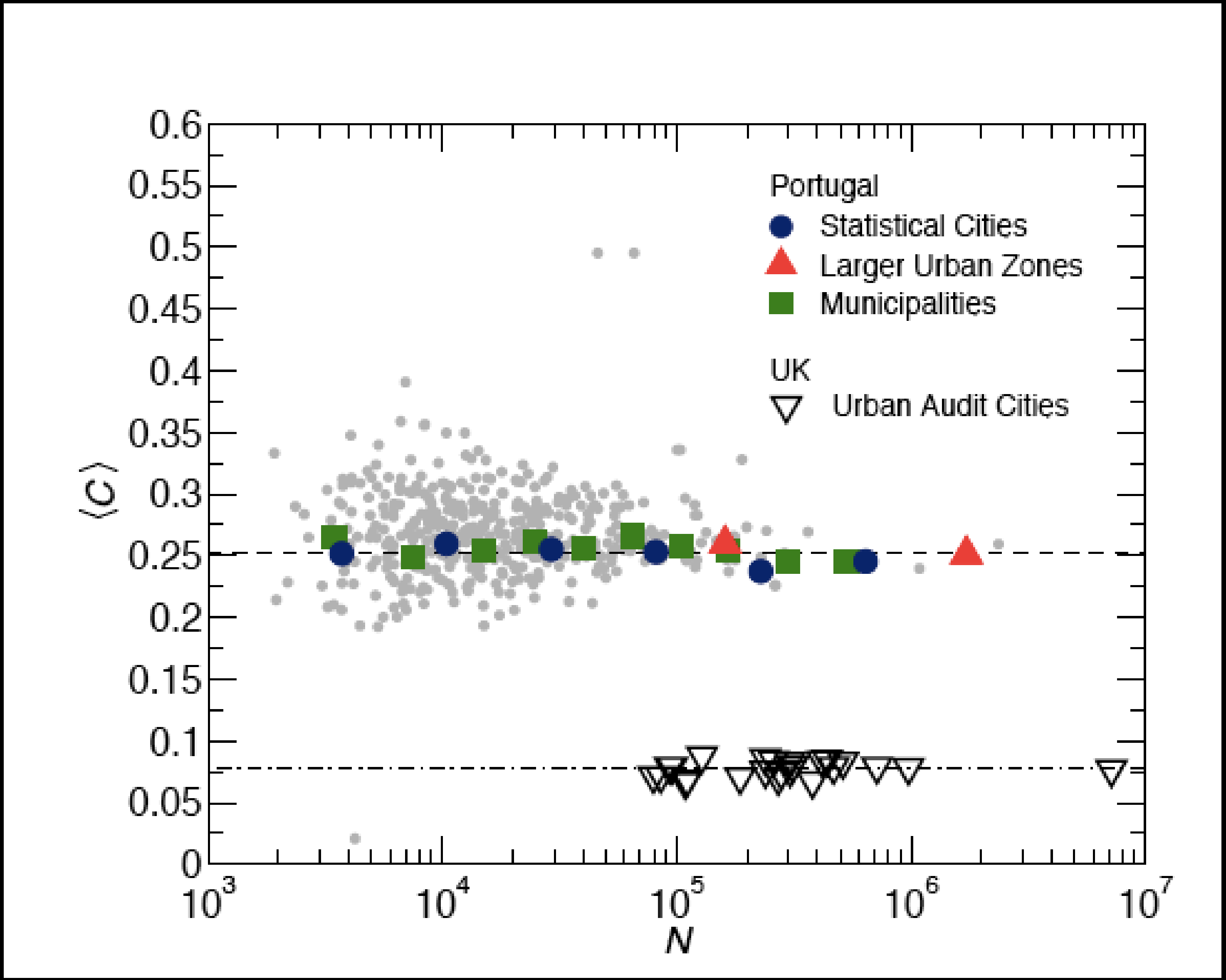
UNIVERSALITY



SOCIAL CONNECTIVITY

(Cell Phone Data)





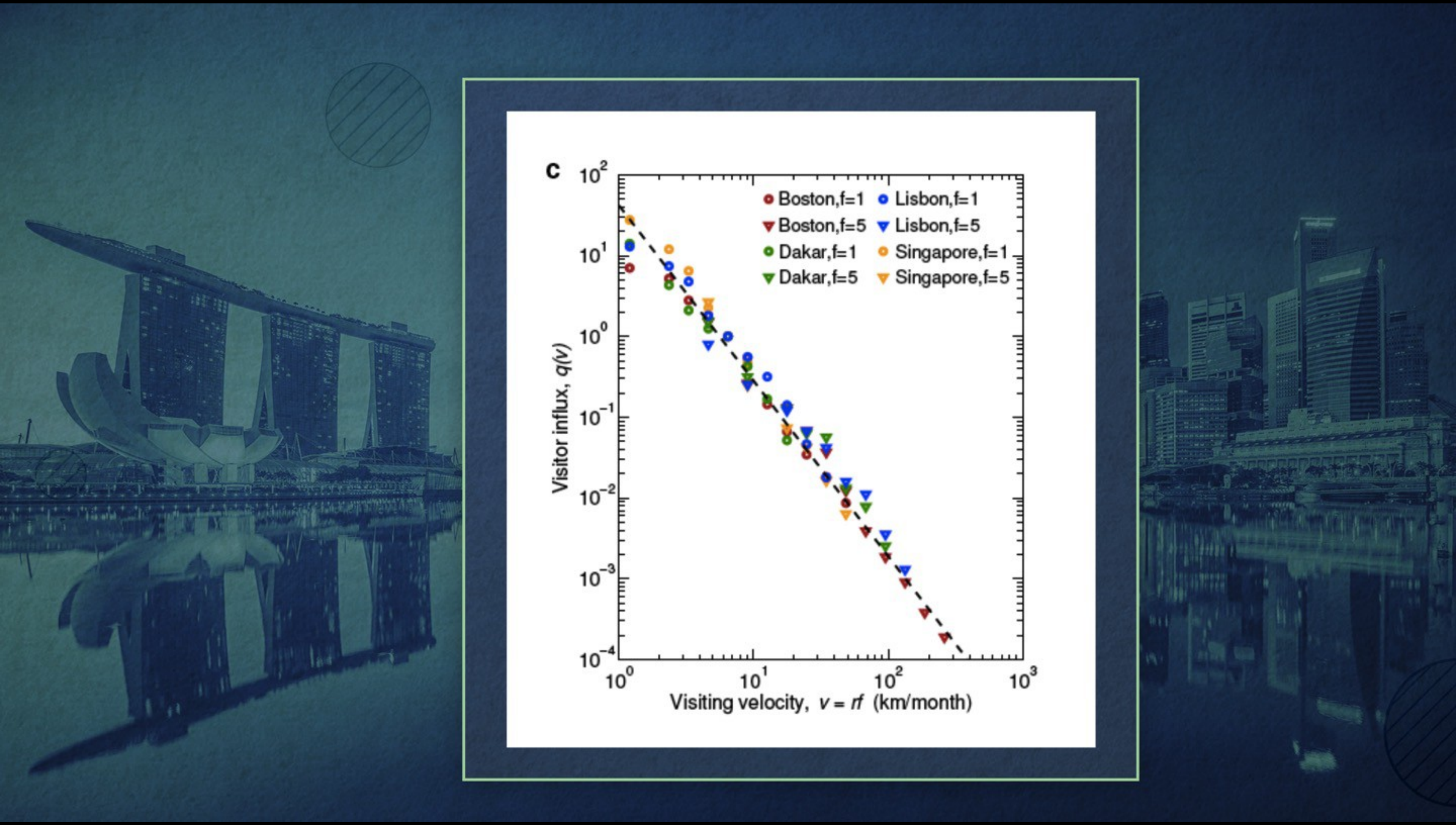
Portugal
Statistical Cities
Larger Urban Zones
Municipalities
UK
Urban Audit Cities
⟨C⟩
N
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
10^3
10^4
10^5
10^6
10^7

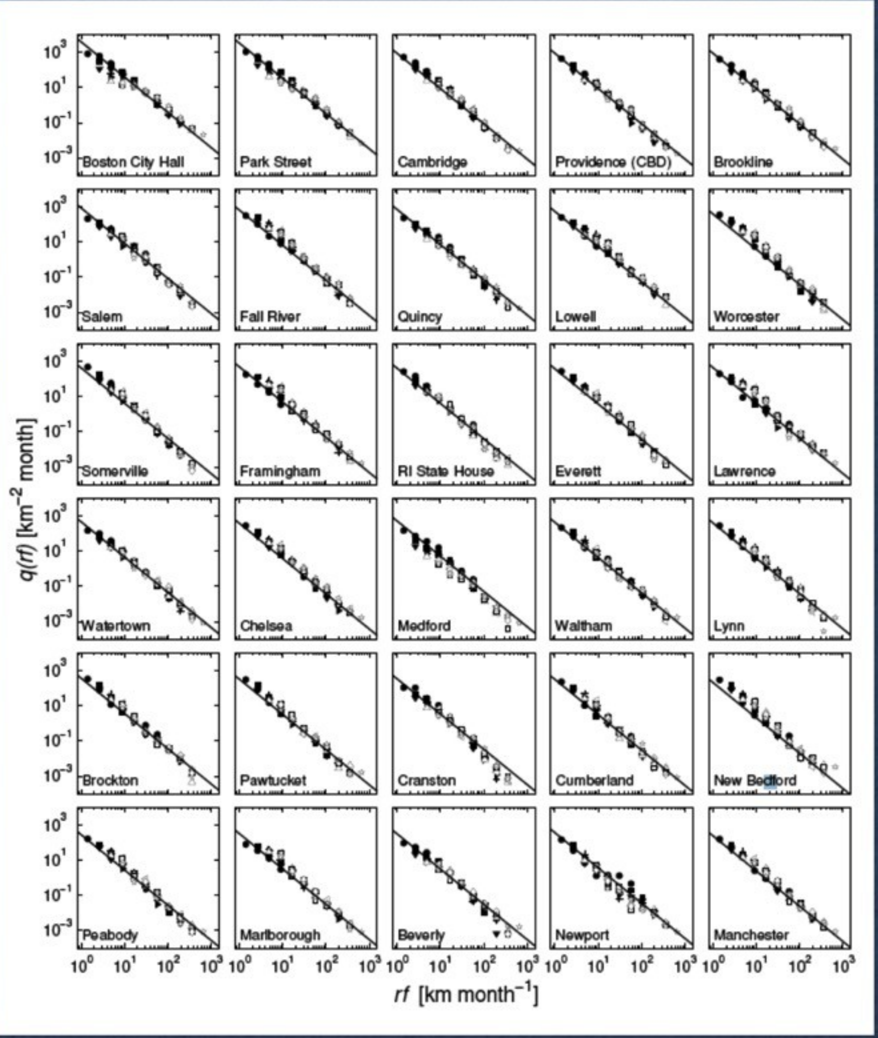
MOVEMENT IN CITIES

People on average minimize travel time and distance.

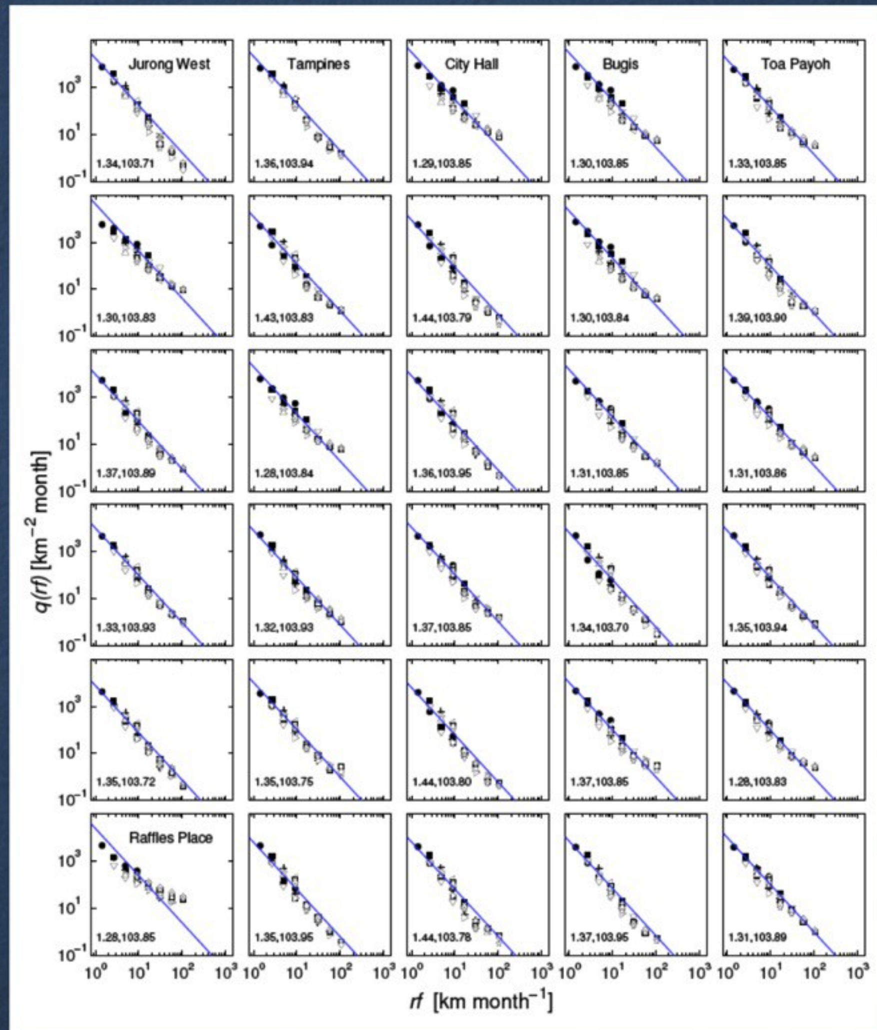
"Theorem": the number traveling to any location in any city from a distance r away f times a month is:

$$q(r,f) = \frac{A}{(rf)^2}$$


c
Boston,f=1
Lisbon,f=1
Boston,f=5
Lisbon,f=5
Dakar,f=1
Singapore,f=1
Dakar,f=5
Singapore,f=5
Visitor influx, q(v)
Visiting velocity, v = rf (km/month)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}



Boston City Hall
Park Street
Cambridge
Providence (CBD)
Brookline
Salem
Fall River
Quincy
Lowell
Worcester
Somerville
Framingham
RI State House
Everett
Lawrence
Watertown
Chelsea
Medford
Waltham
Lynn
Brockton
Pawtucket
Cranston
Cumberland
New Bedford
Peabody
Marlborough
Beverly
Newport
Manchester
q(rf) [km^-2 month]
rf [km month^-1]

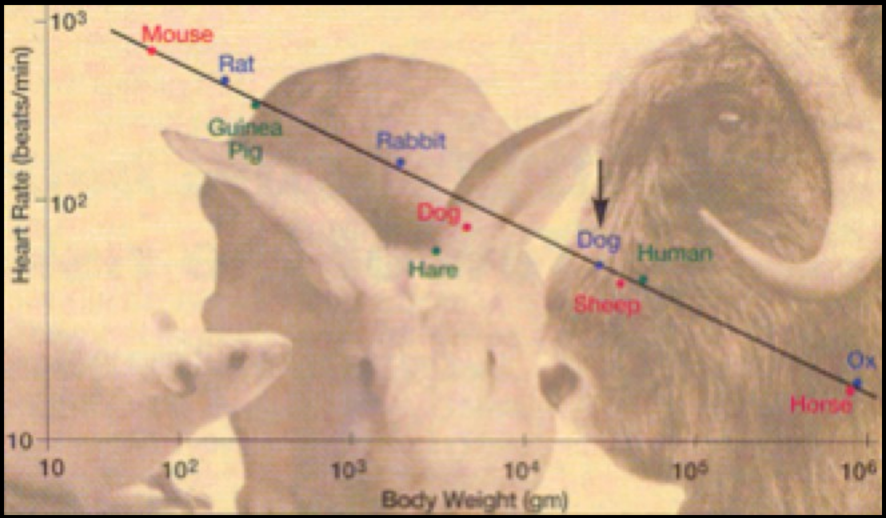

Jurong West
Tampines
City Hall
Bugis
Toa Payoh
1.34,103.71
1.36,103.94
1.29,103.85
1.30,103.85
1.33,103.85
1.30,103.83
1.43,103.83
1.44,103.79
1.30,103.84
1.39,103.90
1.37,103.89
1.28,103.84
1.36,103.95
1.31,103.85
1.31,103.86
1.33,103.93
1.32,103.93
1.37,103.85
1.34,103.70
1.35,103.94
1.35,103.72
1.35,103.75
1.44,103.80
1.37,103.85
1.28,103.83
Raffles Place
1.28,103.85
1.35,103.95
1.44,103.78
1.37,103.95
1.31,103.89
q(rf) [km^-2 month]
rf [km month^-1]

NETWORK DYNAMICS DETERMINES THE PACE OF LIFE

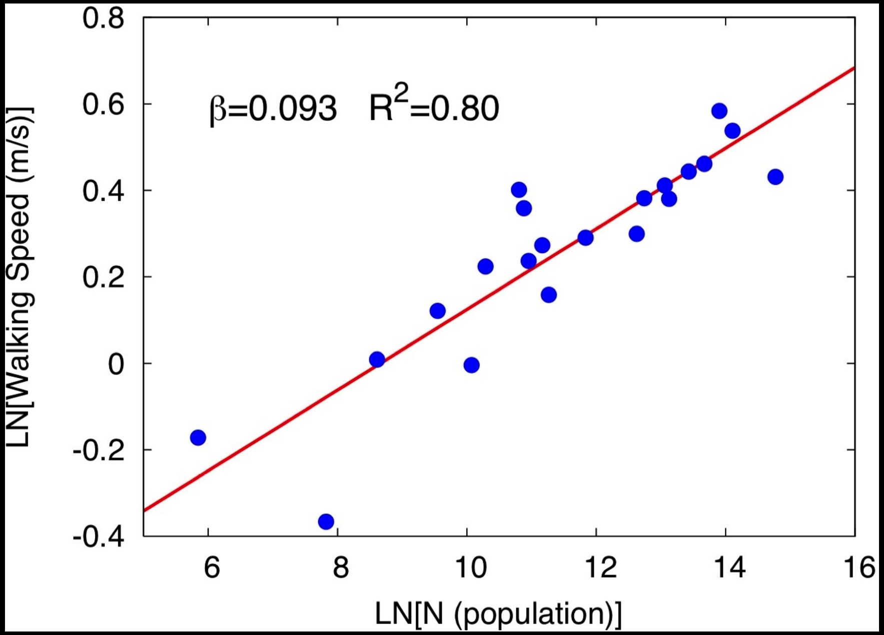
IF THE SLOPE IS < 1 PACE OF LIFE SLOWS DOWN

IF THE SLOPE IS > 1 PACE OF LIFE SPEEDS UP

Pace of biological life vs. Pace of social life



Heart Rate vs Body Weight



Walking Speed vs. Population Size

Research revealed almost half the nation found the slow pace of high streets to be their biggest shopping bugbear. Photo: Mercury Press

GROWTH EQUATION

Total Incoming Rate

(resources, products, patents, . . . “energy” or “dollar” equivalent)

≈ Maintenance

(repair, replacement, sustenance, . . .)

\+

Growth

$$R = \sum_{i=1}^{n} Y_i(N) = \sum_{j=1}^{N} r_j + \frac{d}{dt}\sum_{j=1}^{N} c_j$$

n **= NUMBER OF "DRIVERS"** Y_i **CONTRIBUTING TO THE CITY "METABOLISM"**

r_J **= RATE AT WHICH THESE RESOURCES ARE USED BY THE** j^{th} **INDIVIDUAL (MAINTAIN HIS/ HER/ITS LIFE-STYLE, ETC)**

c_j **= COST OF ADDING A NEW INDIVIDUAL TO THE CITY POPULATION**

SCALING LAWS TELL US THAT EACH i SCALES AS $Y_i(N) = Y_i(1)N^{\cap_i}$

WITH $\cap_i \lfloor \cap \lfloor 1.15$

APPROXIMATELY THE SAME FOR ALL i, SO

$$R(N) = R(1)N^{\cap}$$

INTRODUCE AVERAGE COSTS:

$$R_0 \vartheta \frac{1}{N} \varsigma_{j=1}^{N} r_j$$

$$E_0 \vartheta \frac{1}{N} \varsigma_{j=1}^{N} c_j$$

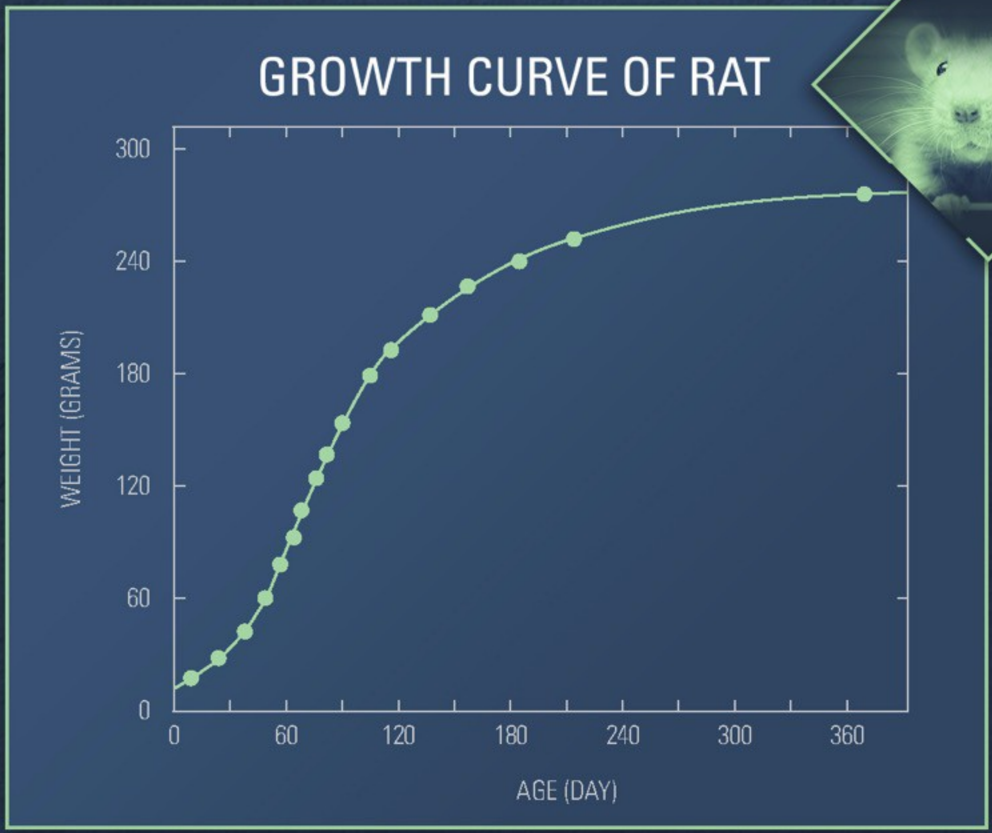
$$R \lfloor NR_{O} + E_{O}\frac{dN}{dt}$$

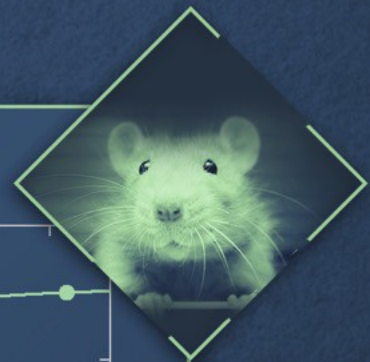
$$\frac{dN}{dt} = \varphi\tau\phi\frac{R_1}{E_0}\propto\div\varepsilon\;\upsilon\chi\psi N^{\cap}\,2\,\varphi\tau\phi\frac{R_0}{R_1}\propto\div\varepsilon\, N$$

SOLUTION:

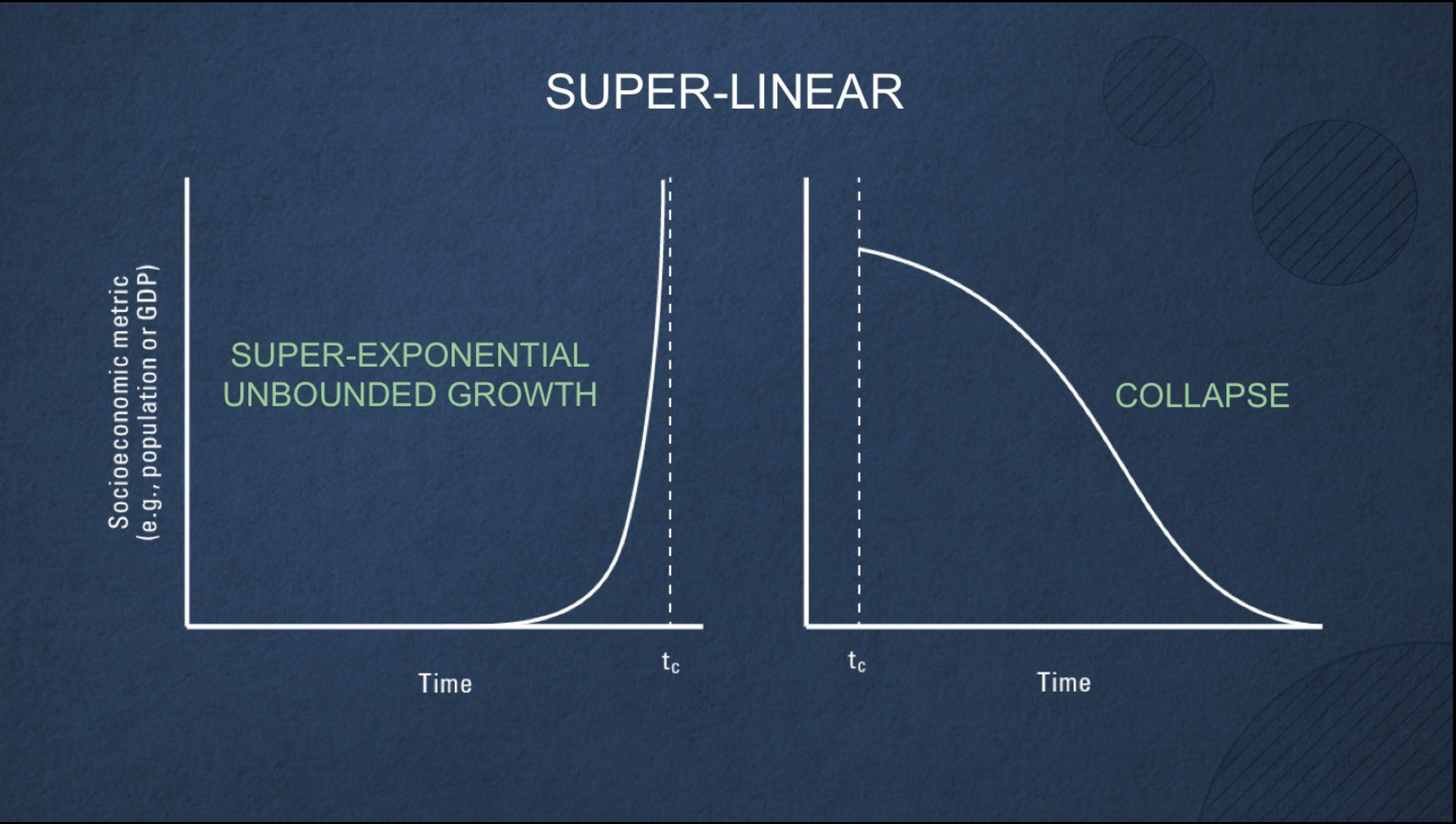
$$N^{12\cap} = \frac{R_1}{R_0} + \upsilon\chi\psi\, N^{12\cap}(0)\,2\,\frac{R_1}{R_0}\oplus\ni\otimes\, e^{2\frac{R_0}{E_0}(12\cap)t}$$

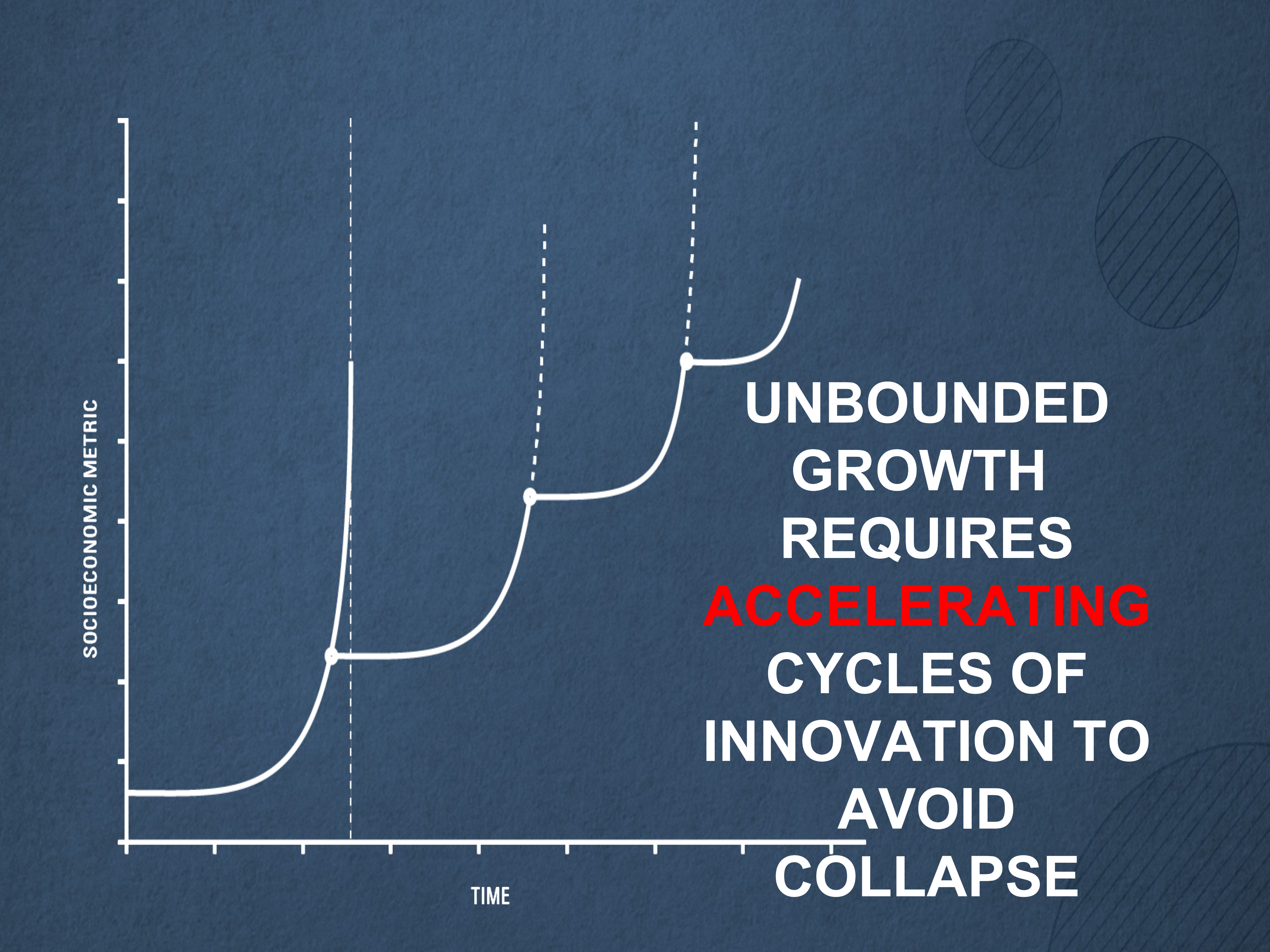
CHARACTER OF SOLUTION SENSITIVE TO $\cap >, =, < 1$



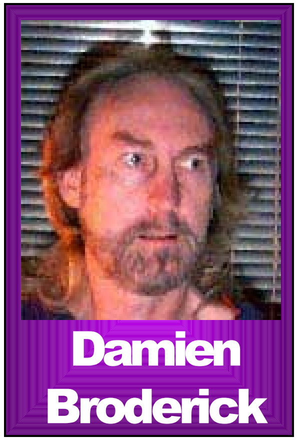


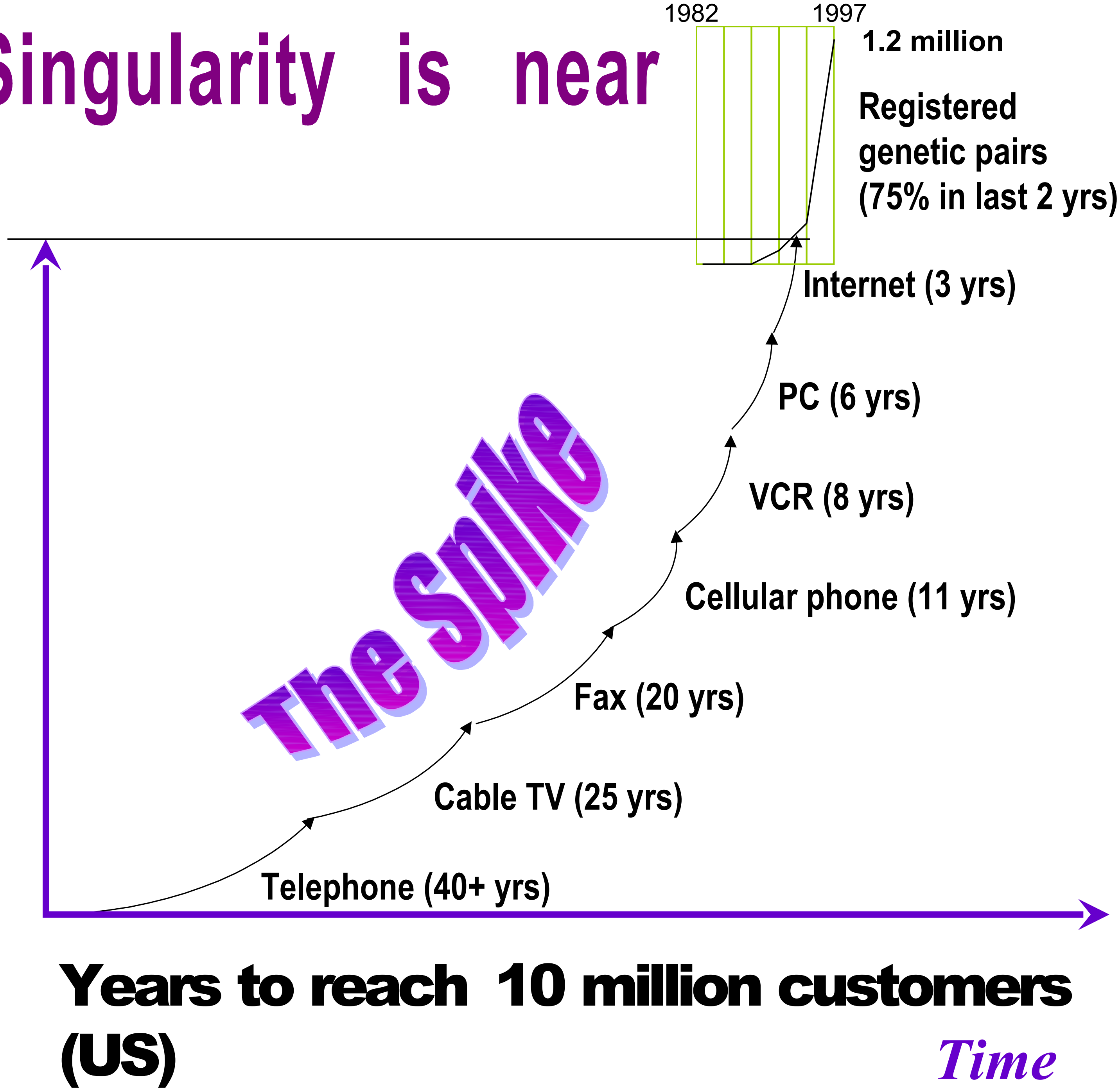
SUB-LINEAR SCALING LEADS TO BOUNDED GROWTH


SUPER-LINEAR
Socioeconomic metric
(e.g., population or GDP)
SUPER-EXPONENTIAL
UNBOUNDED GROWTH
Time
tc
tc
COLLAPSE
Time

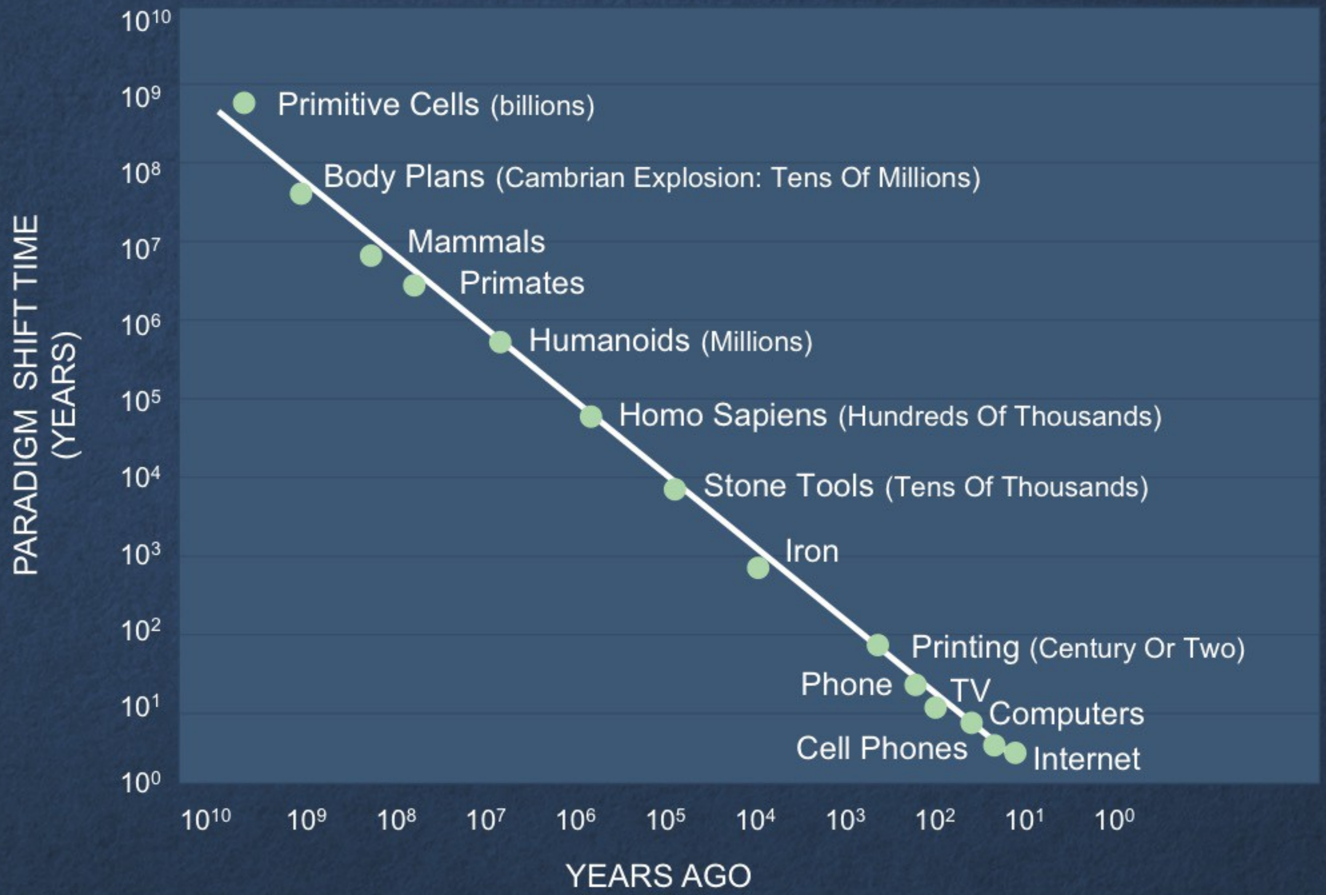

SOCIOECONOMIC METRIC
TIME
UNBOUNDED GROWTH REQUIRES ACCELERATING CYCLES OF INNOVATION TO AVOID COLLAPSE

Singularity is near





SEQUENCE OF SINGULARITIES



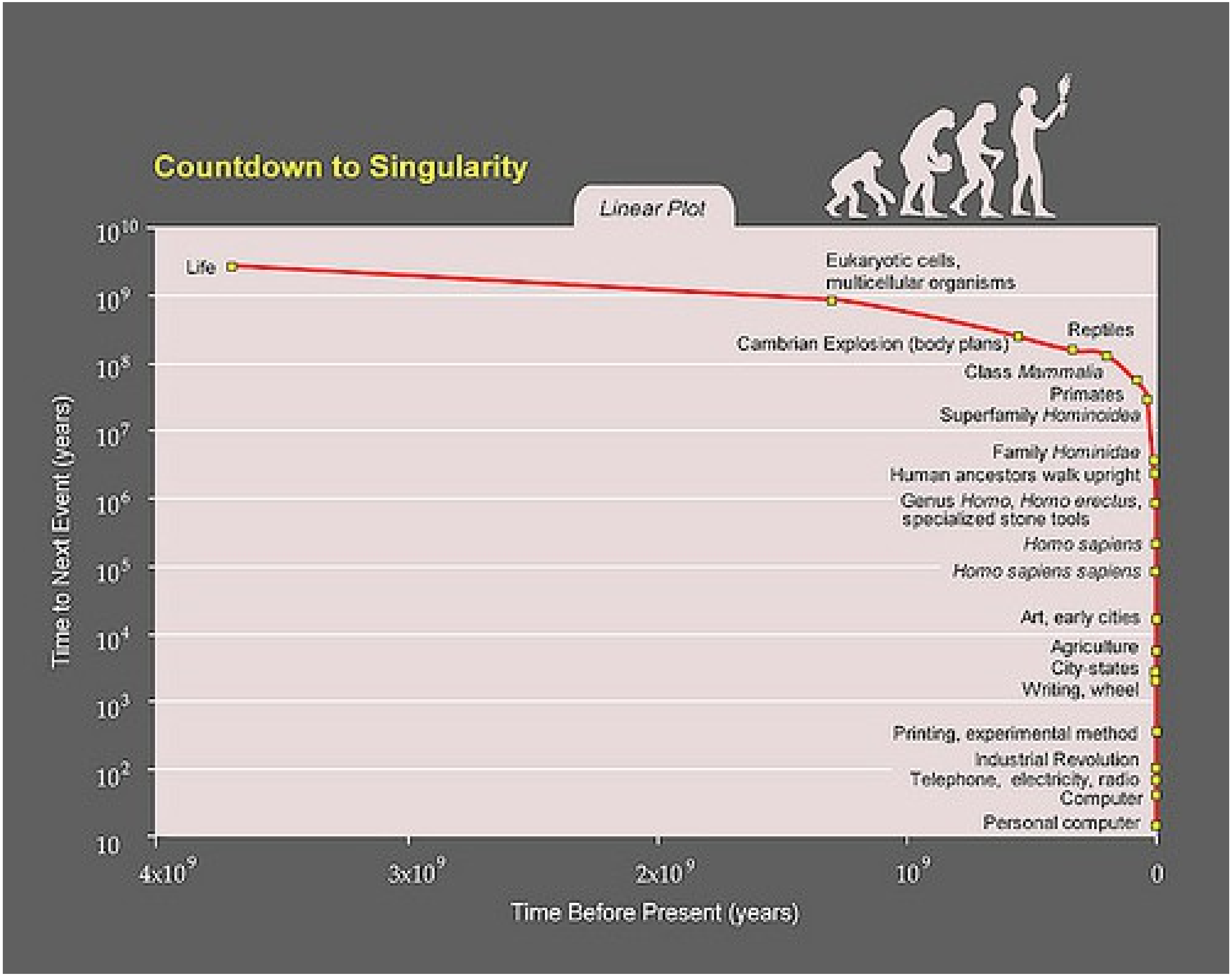
UNBOUNDED GROWTH LEADING TO “FINITE-TIME SINGULARITY” & COLLAPSE

UNLESS INNOVATIONS (SYSTEMATICALLY) OCCCUR FASTER AND FASTER

CONTINUOUS TENSION BETWEEN:

INNOVATION & WEALTH CREATION vs ECONOMIES OF SCALE

SUSTAINABLE????



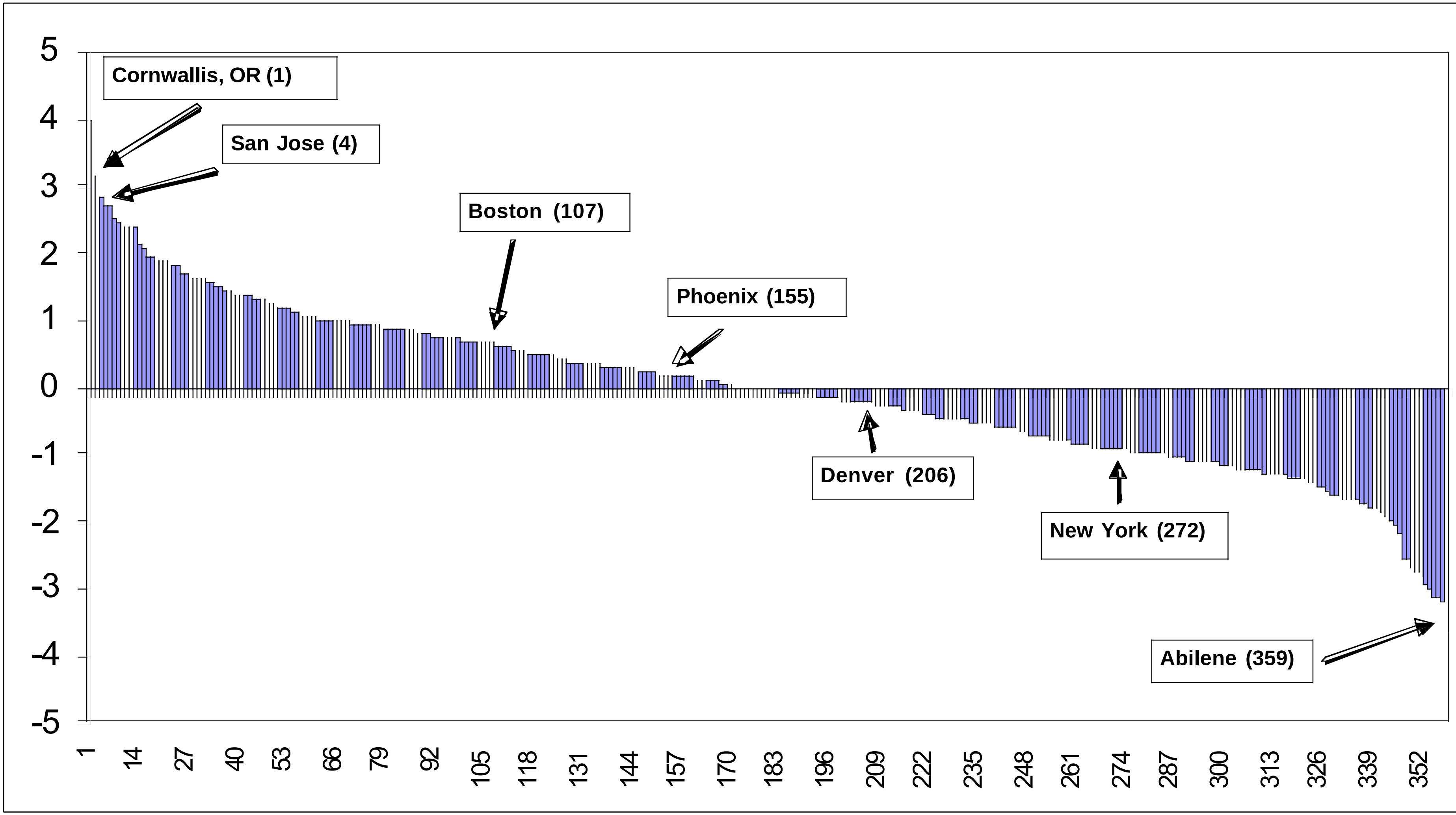
Countdown to Singularity
Linear Plot
Life
Eukaryotic cells, multicellular organisms
Cambrian Explosion (body plans)
Reptiles
Class Mammalia
Primates
Superfamily Hominoidea
Family Hominidae
Human ancestors walk upright
Genus Homo, Homo erectus, specialized stone tools
Homo sapiens
Homo sapiens sapiens
Art, early cities
Agriculture
City-states
Writing, wheel
Printing, experimental method
Industrial Revolution
Telephone, electricity, radio
Computer
Personal computer
Time to Next Event (years)
Time Before Present (years)

Average "idealised, universal" characteristics of cities and companies of a given size (constrained by underlying principles and dynamics of network structures) as manifested in scaling laws

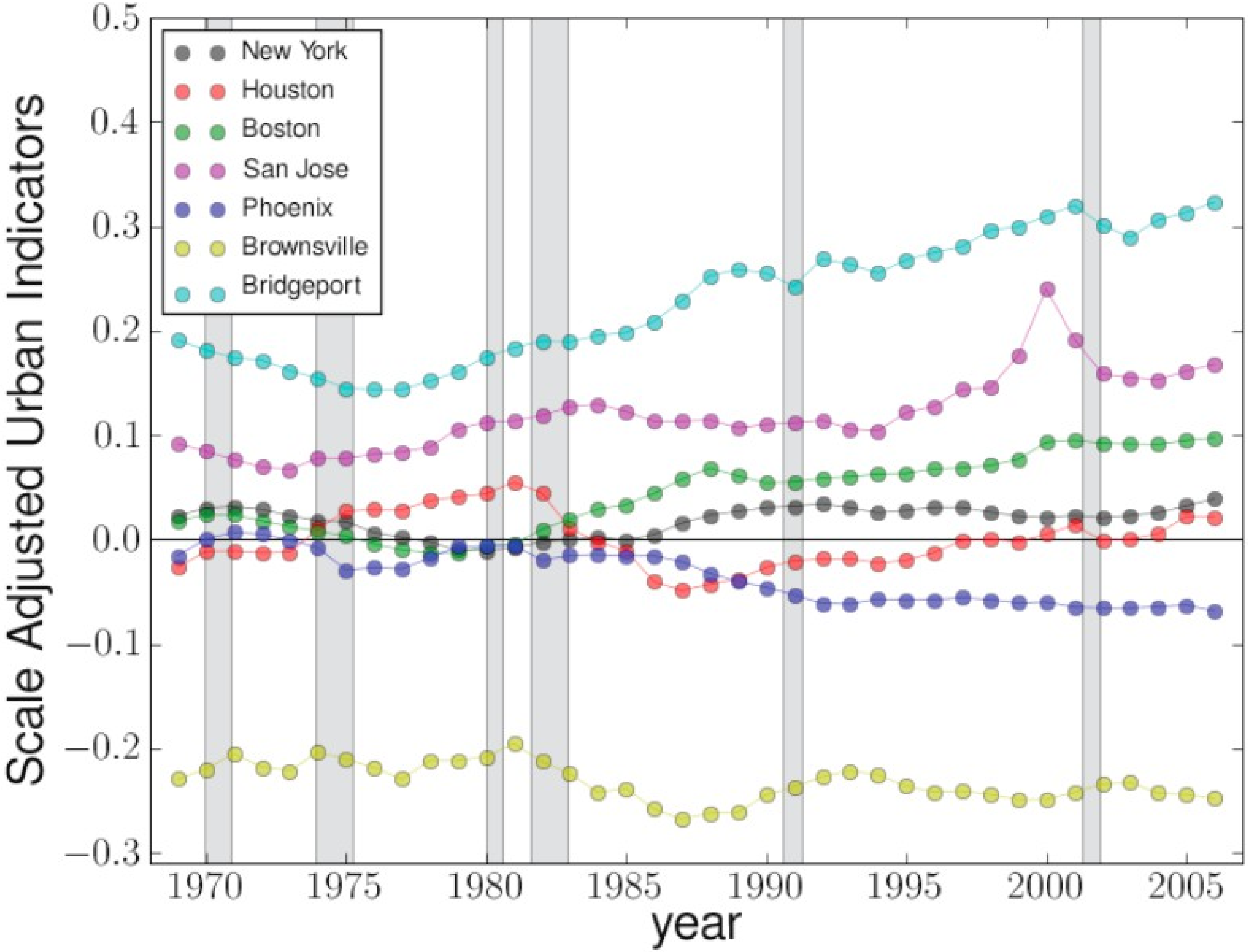
vs.

Characteristics of specific cities and companies as measured by their deviations from scaling laws representing their individuality and local environment and conditions

2003 Patenting Rankings

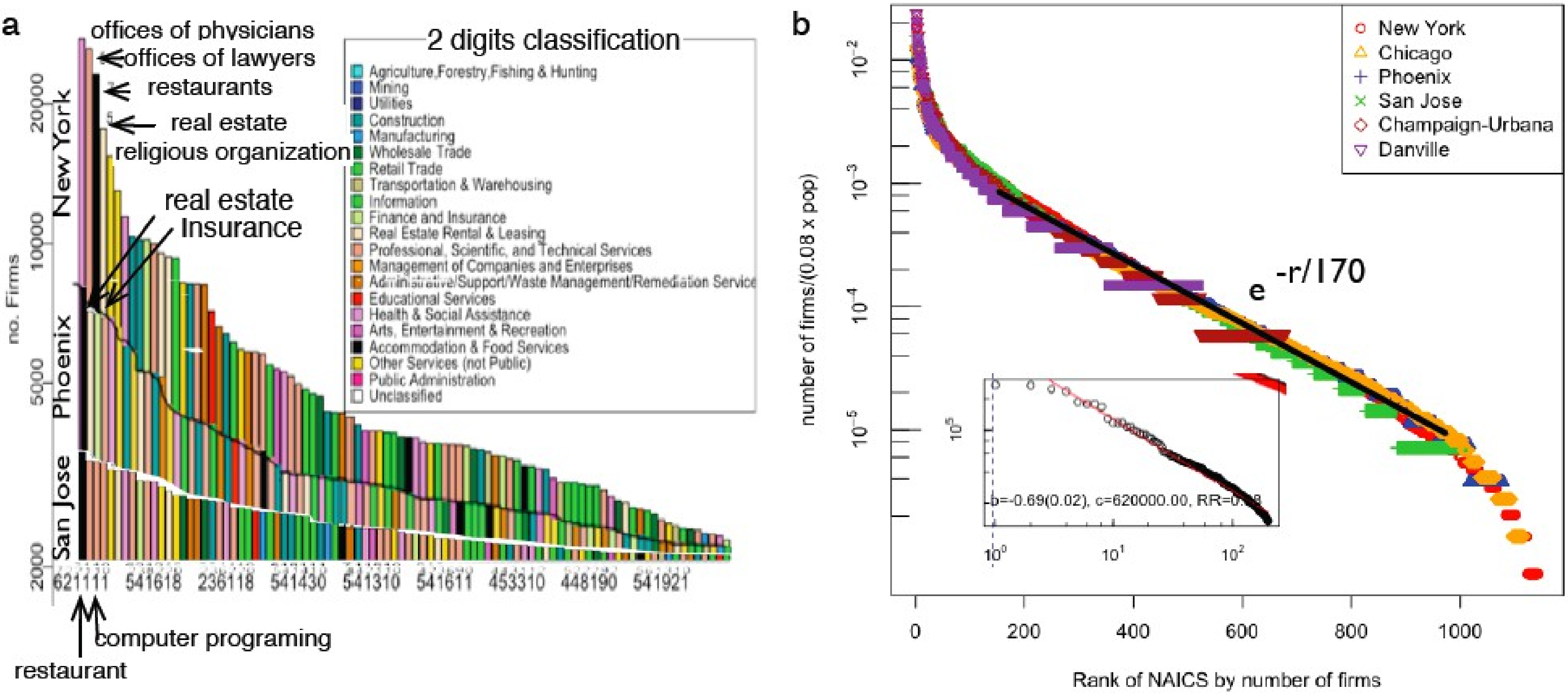


L. M. A. Bettencourt, J. Lobo, D. Strumsky and G. B.West (2010) PLoS ONE 5(11): e13541



New York
Houston
Boston
San Jose
Phoenix
Brownsville
Bridgeport
Scale Adjusted Urban Indicators
year
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
1970
1975
1980
1985
1990
1995
2000
2005

DIVERSITY OF FIRMS AND OCCUPATIONS



H. Youn, L. M. A. Bettencourt, J. Lobo, D. Strumsky, H. Samaniego, and G. B. West (2013) PNAS submitted

GDP INCREASES EXPONENTIALLY WITH DIVERSITY

AND

AS A POWER LAW WITH POPULATION SIZE

SINCE GDP SCALES WITH SIZE AS

$$G(N) = G_0 N^b \qquad (b \sim 1.15)$$

THEN:

$$G(N) = G_1 e^{D/x} \qquad (X_0 \sim 211)$$

WHERE $G_1 = G_0 N_0^b$

IF NUMBER OF ESTABLISHMENTS OF TYPE j SCALES AS

$$n_j \sim N^{\beta_j}$$

THEN ITS RANKING SCALES AS

$$x_j \sim N^{(1-\beta_j)/B}$$

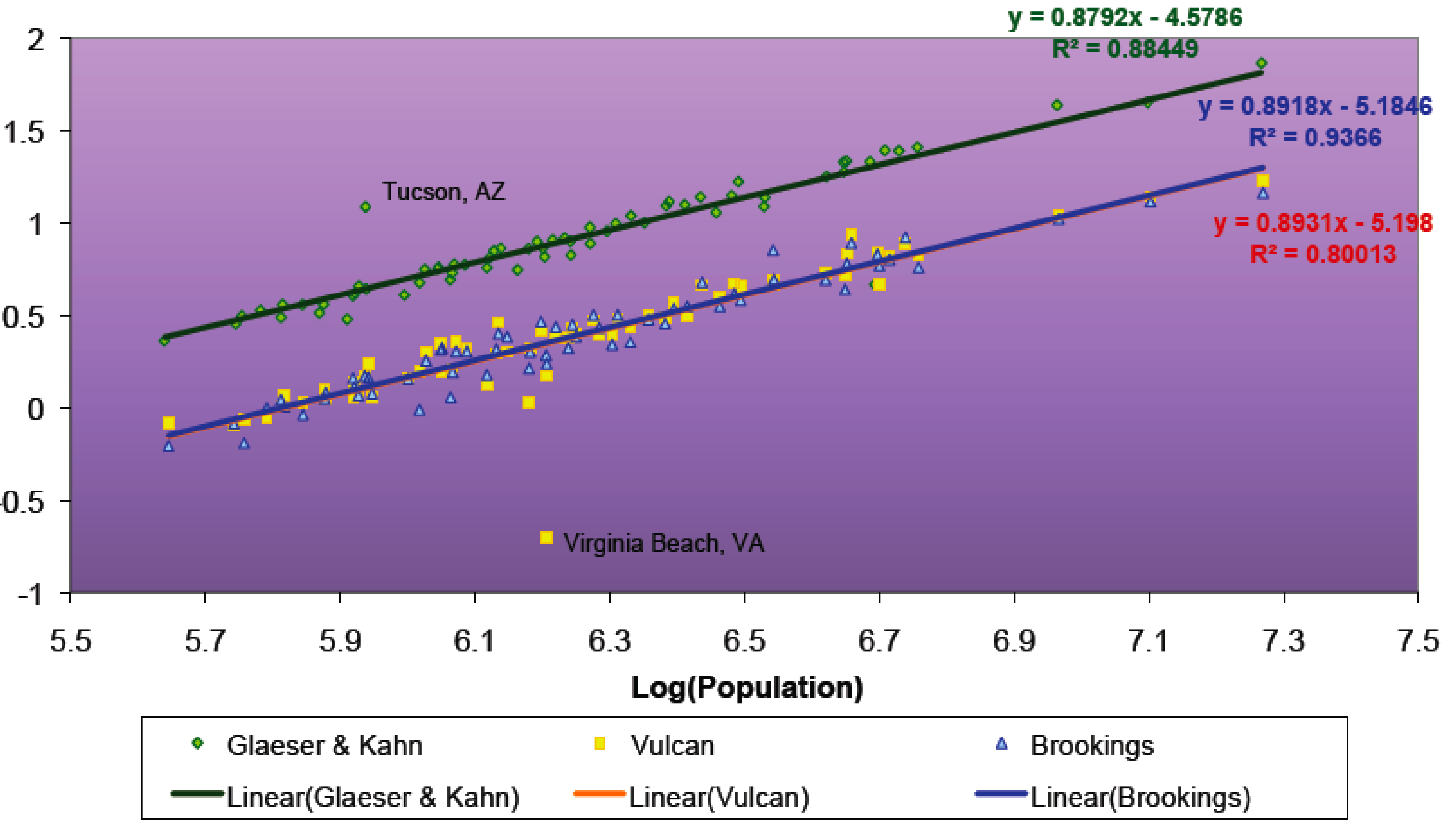
$x_j < x_0$

$$x_j \sim (1-\beta)\ln N$$

$x_j >$

x_0

SO BUSINESS TYPES WHOSE ABUNDANCES SCALE SUPER-LINEARLY (PROFESSIONAL, SERVICE,…..e.g. LAWYERS, DOCTORS) INCREASE IN RANK WITH INCREASING CITY SIZE WHEREAS THOSE THAT SCALE SUB-LINEARLY (PRIMARY



y = 0.8792x - 4.5786
R² = 0.88449
y = 0.8918x - 5.1846
R² = 0.9366
y = 0.8931x - 5.198
R² = 0.80013
Tucson, AZ
Virginia Beach, VA
2
1.5
1
0.5
0
-0.5
-1
5.5
5.7
5.9
6.1
6.3
6.5
6.7
6.9
7.1
7.3
7.5
Log(Population)
Glaeser & Kahn
Vulcan
Brookings
Linear(Glaeser & Kahn)
Linear(Vulcan)
Linear(Brookings)

SOCIO-ECONOMIC QUANTITIES DEPEND ON "TWO-BODY" INTERACTIONS (INFORMATION EXCHANGE) AND THEREFORE NUMBER AND DENSITY OF SOCIAL INTERACTIONS:

$$Y(N) \propto N_{\text{int}}$$

[UNLIKE BIOLOGY WHERE Y(N) ~ N]

IF EVERYONE INTERACTED WITH EVERYONE ELSE, THEN

$$Y(N) \propto N_{\text{int}} \sim N^2$$

EFFECTIVE INTERACTION SPATIAL AREA FOR AVERAGE INDIVIDUAL = ε^2

EACH INDIVIDUAL INTERACTS WITH ΔN OTHERS:

$$\Delta N \approx \rho\, \varepsilon^2$$

TOTAL NUMBER OF INTERACTIONS $\approx N\Delta N \approx N\rho\, \varepsilon^2$

SOCIO-ECONOMIC METRICS

$$Y(N) \propto (N\Delta N)Y_0 \sim (N\rho\varepsilon^2)Y_0 \sim \frac{N^2}{A}(\varepsilon^2 Y_0)$$

$$Y(N) \sim \left(\frac{\varepsilon^2}{A}\right) N^2 Y_0$$

IF ROADS, CABLES, ETC ARE SPACE-FILLING (THEY SERVICE EVERYONE) WITH TOTAL LENGTH L, THEN

AREA $A \sim L\varepsilon$

$$\left(\frac{L}{N}\right) \Big/ \left(\frac{Y}{N}\right) = l/Y_0$$

INVARIANT!

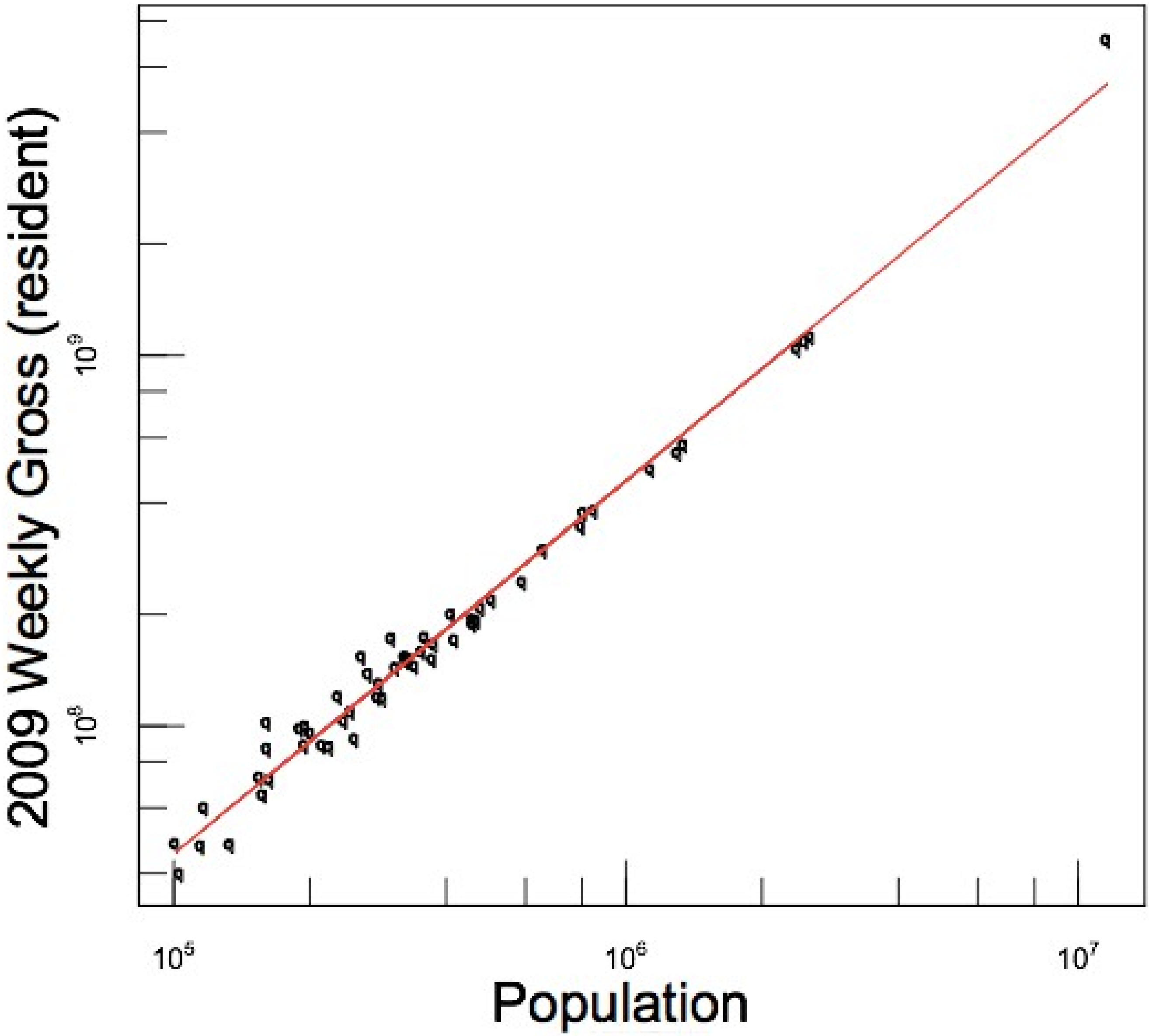
IF

$$L = L_0 N^{\beta_I} \qquad\qquad R = R_0 N^{\beta_{SE}}$$

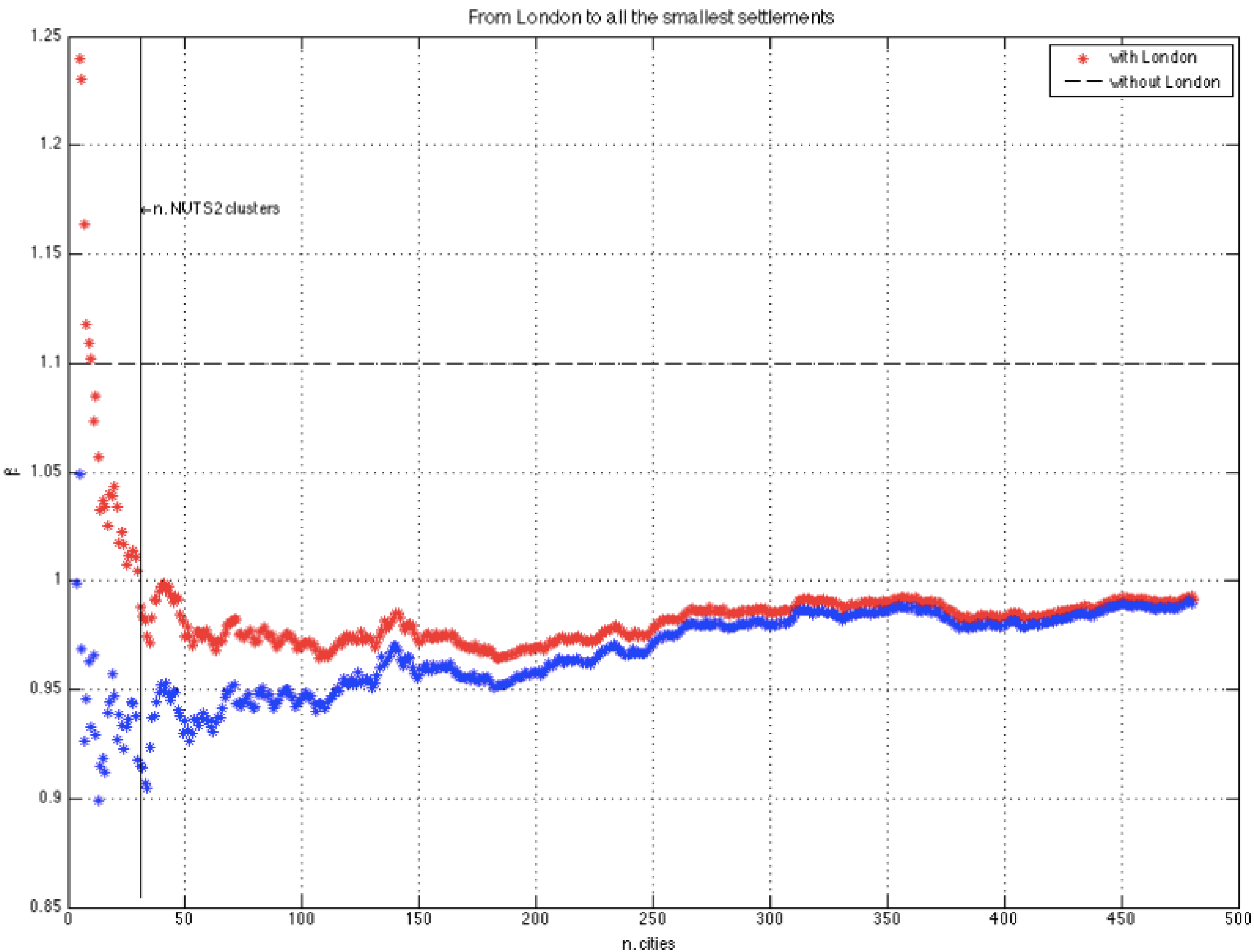
WITH $\beta_I = 1 + \varepsilon_I$ $\beta_{SE} = 1 + \varepsilon_{SE}$

THEN $\varepsilon_I = \varepsilon_{SE}$ (~ 0.15)

➔ *CAN DETERMINE THE SOCIAL INFORMATIONAL NETWORK SCALING FROM*



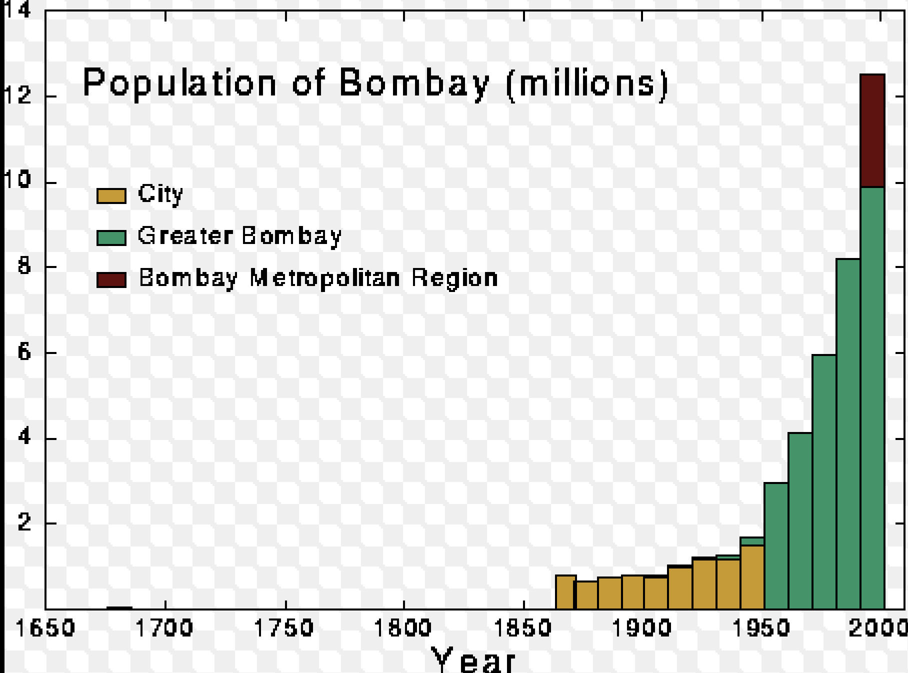
E. Arcaute, E. Hatna, P. Ferguson, H. Youn, A. Joahnason & M. Batty

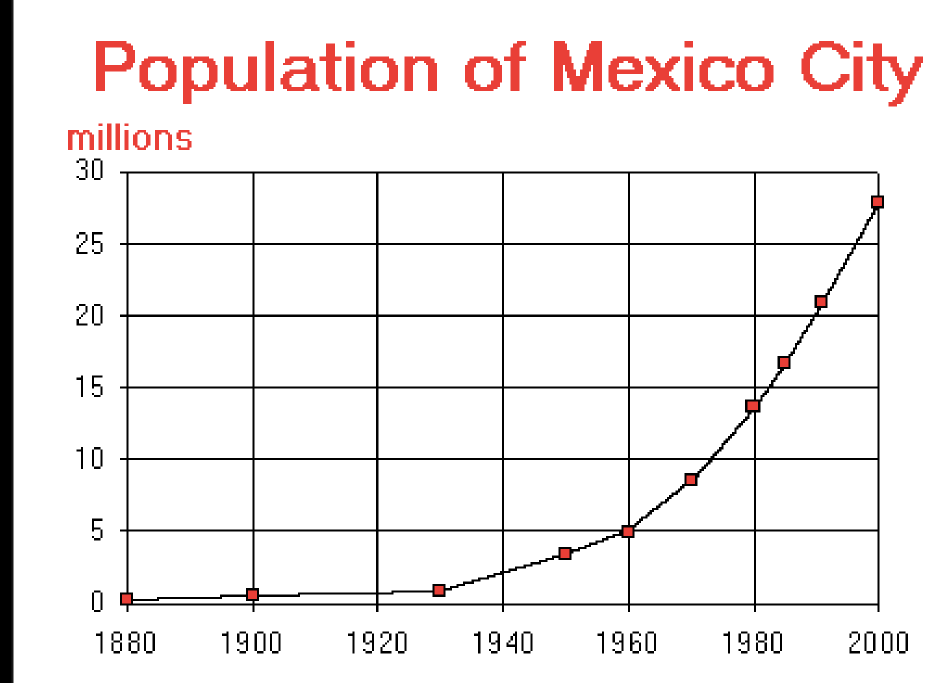

From London to all the smallest settlements
with London
without London
←n. NUTS2 clusters
β
n. cities
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0
50
100
150
200
250
300
350
400
450
500

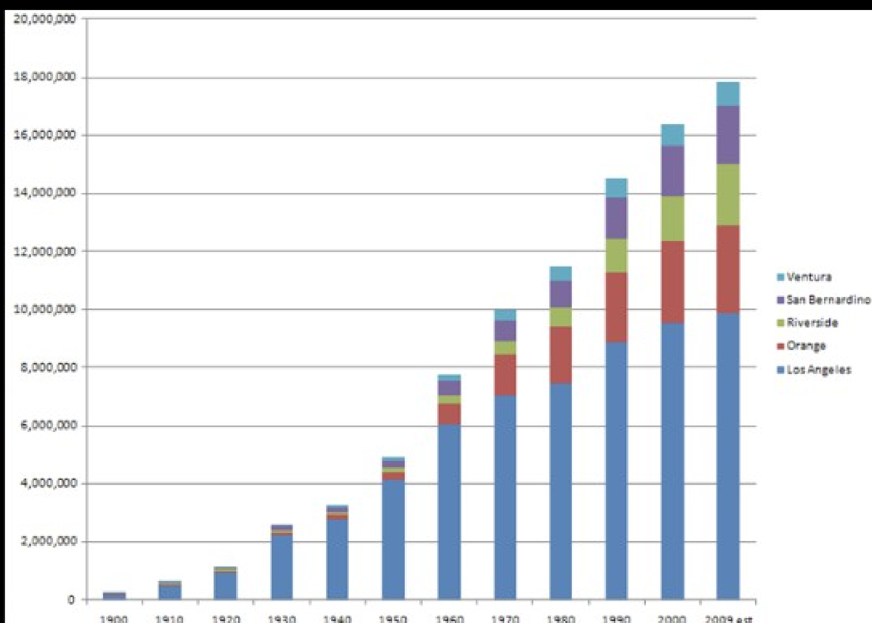
The Editors: Is London's success causing the UK a problem?

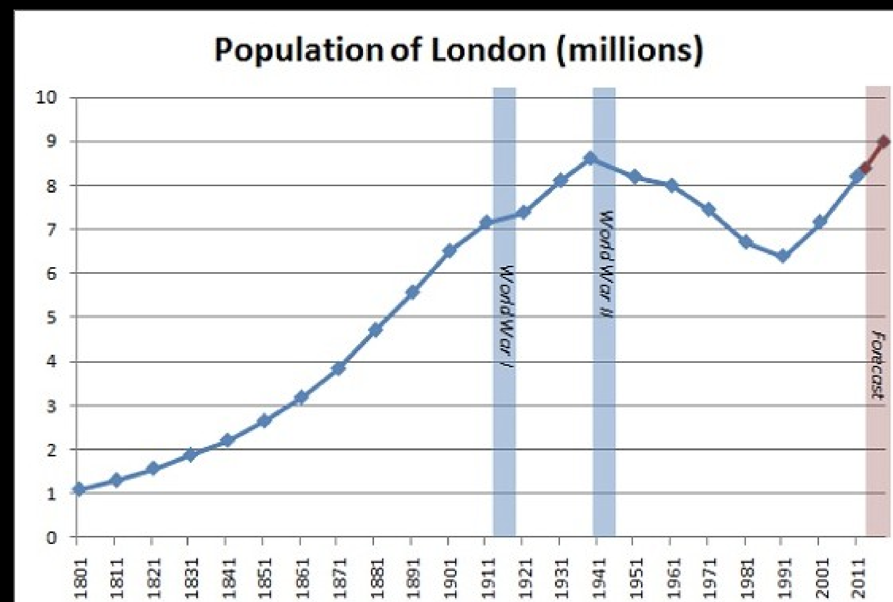
The BBC's Economics Editor, Stephanie Flanders, visits London, Birmingham and Manchester and discovers wide discrepancies between the capital's economy and the rest of the country.

She says London's ebullient economy is subsidising other parts of the country but there is a lot of resentment in other big provincial cities.

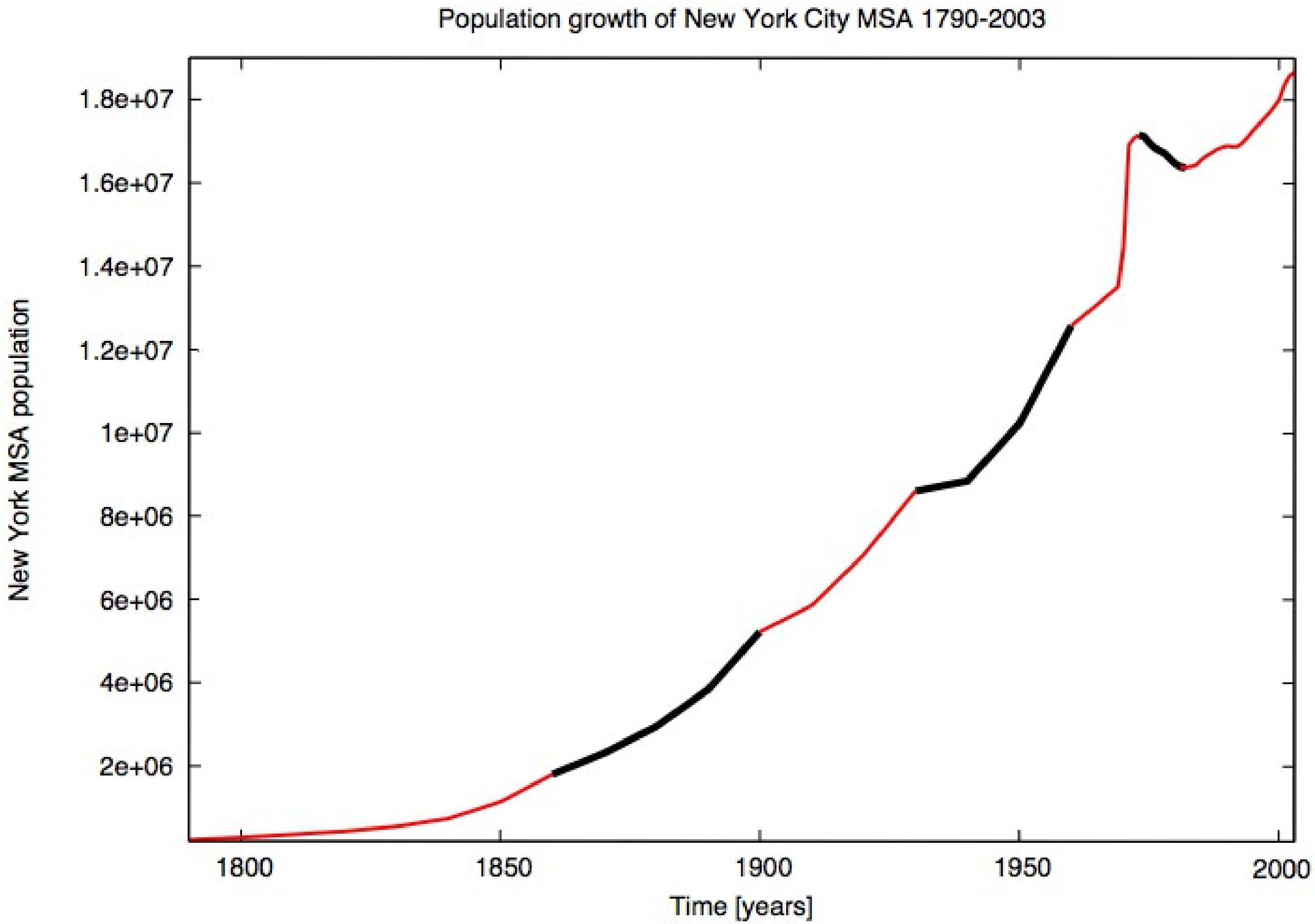

Population of Bombay (millions)
City
Greater Bombay
Bombay Metropolitan Region
Year


Population of Mexico City
millions

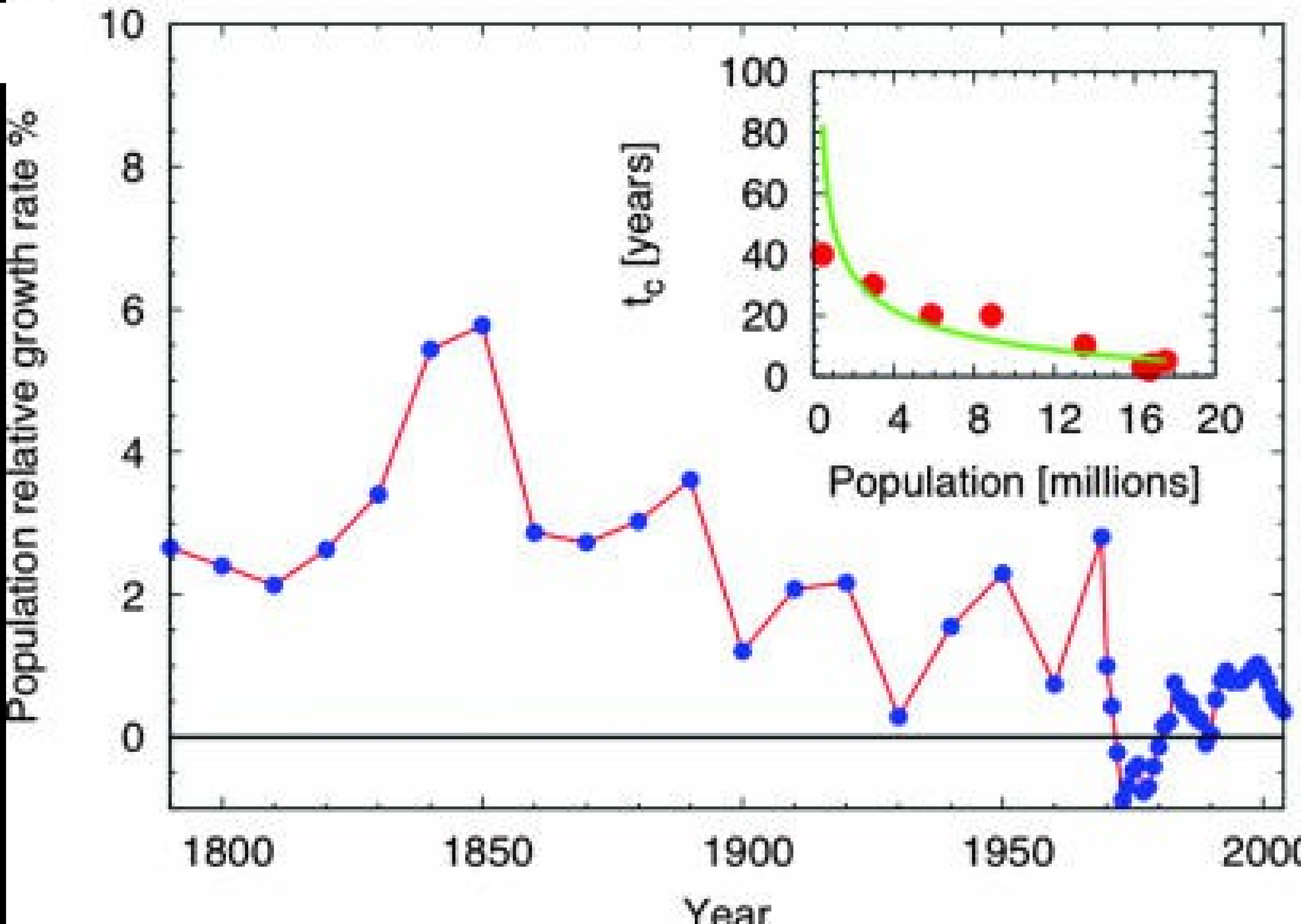

Ventura
San Bernardino
Riverside
Orange
Los Angeles


Population of London (millions)
World War I
World War II
Forecast

1790 - 2003

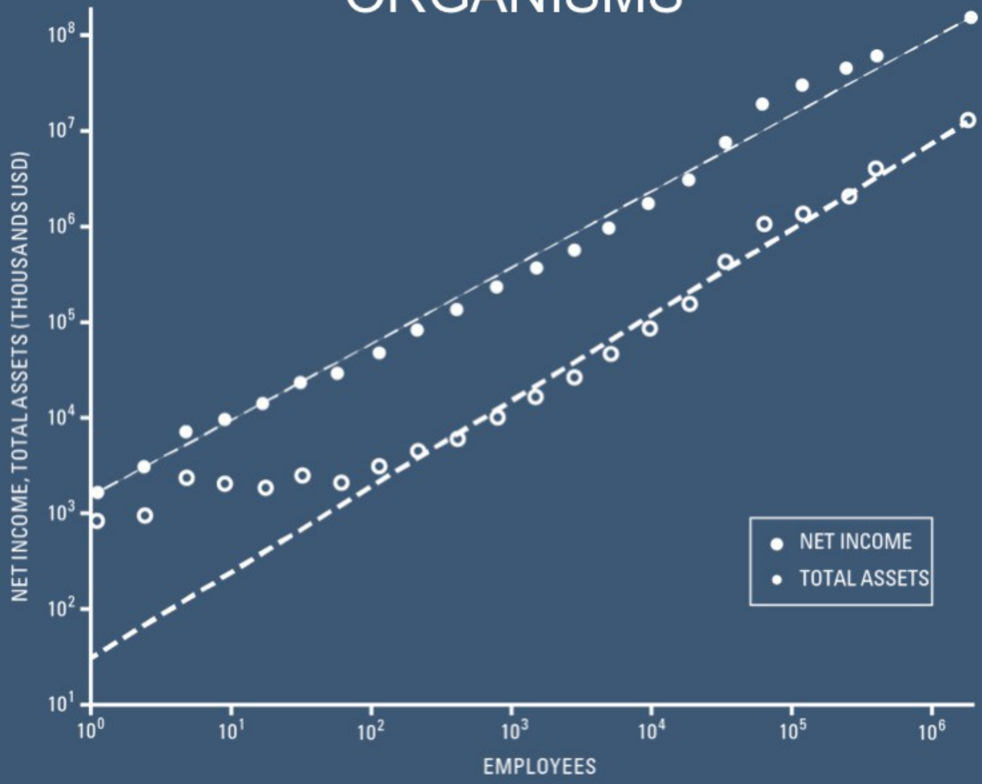


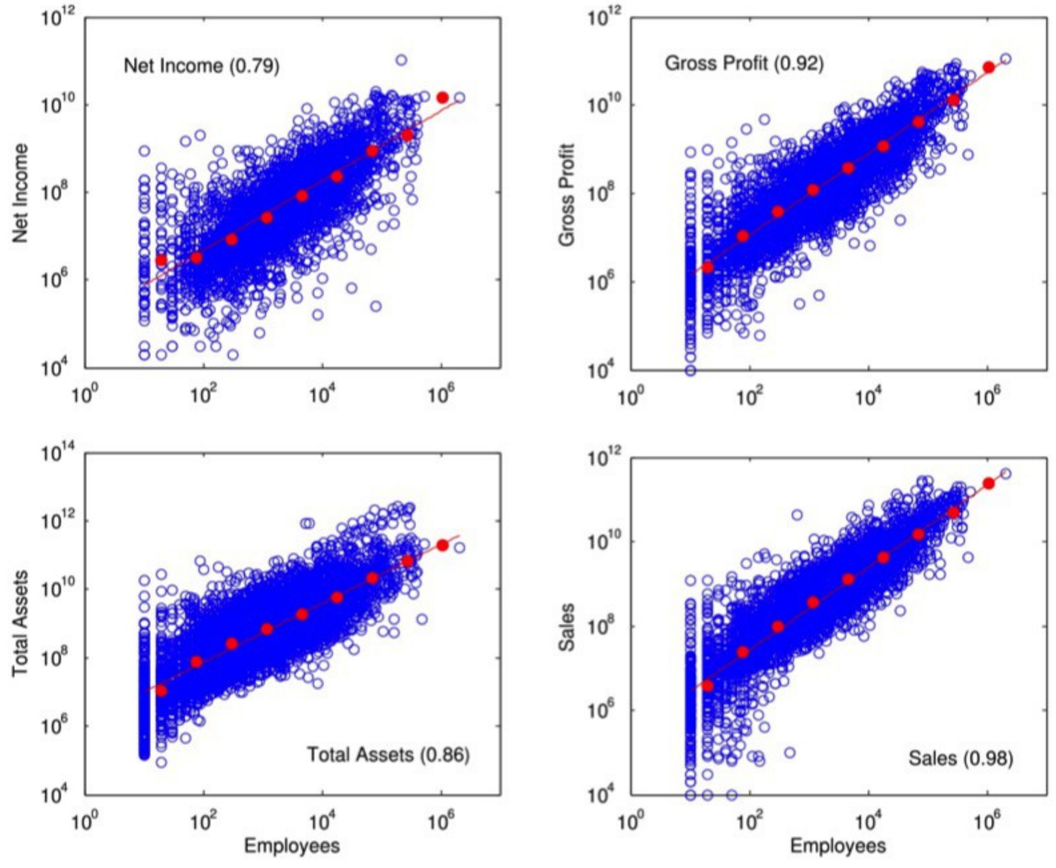
Population growth of New York City MSA 1790-2003
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
New York MSA population
1800
1850
1900
1950
2000
Time [years]



Successive cycles of superlinear innovation reset the singularity and postpone instability and subsequent collapse. The relative population growth rate of New York City over time reveals periods of accelerated (super-exponential) growth. Successive shorter periods of super exponential growth appear, separated by brief periods of deceleration. (Inset) t_c for each of these periods vs. population at the onset of the cycle. Observations are well fit with $\beta = 1.09$ (green line).

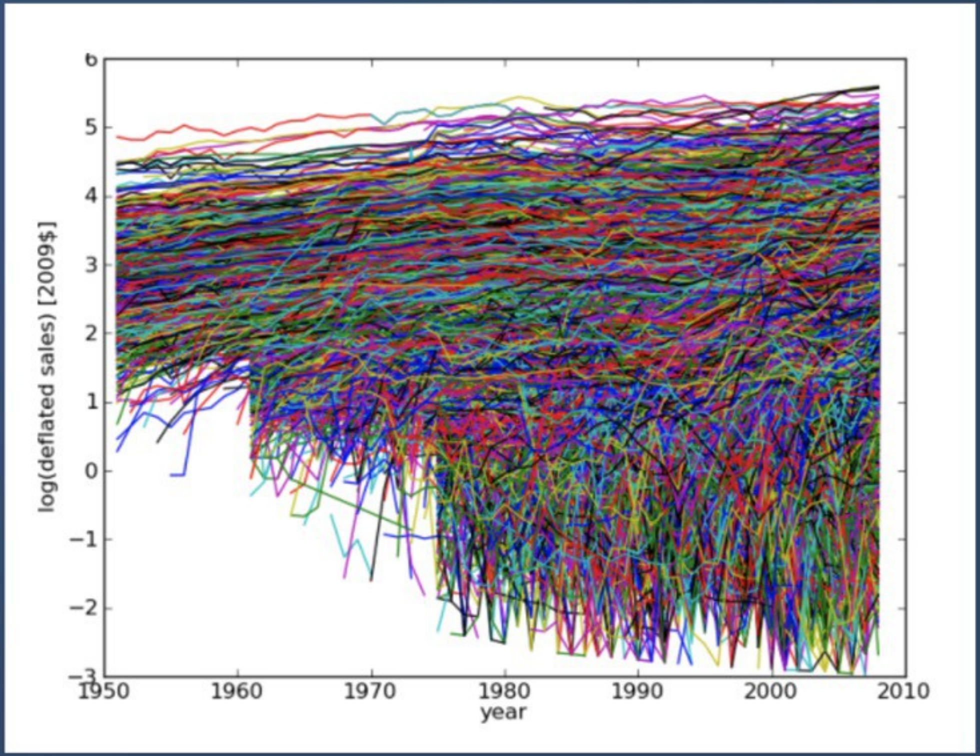
COMPANIES SCALE SUB-LINEARLY ANALOGOUS TO ORGANISMS

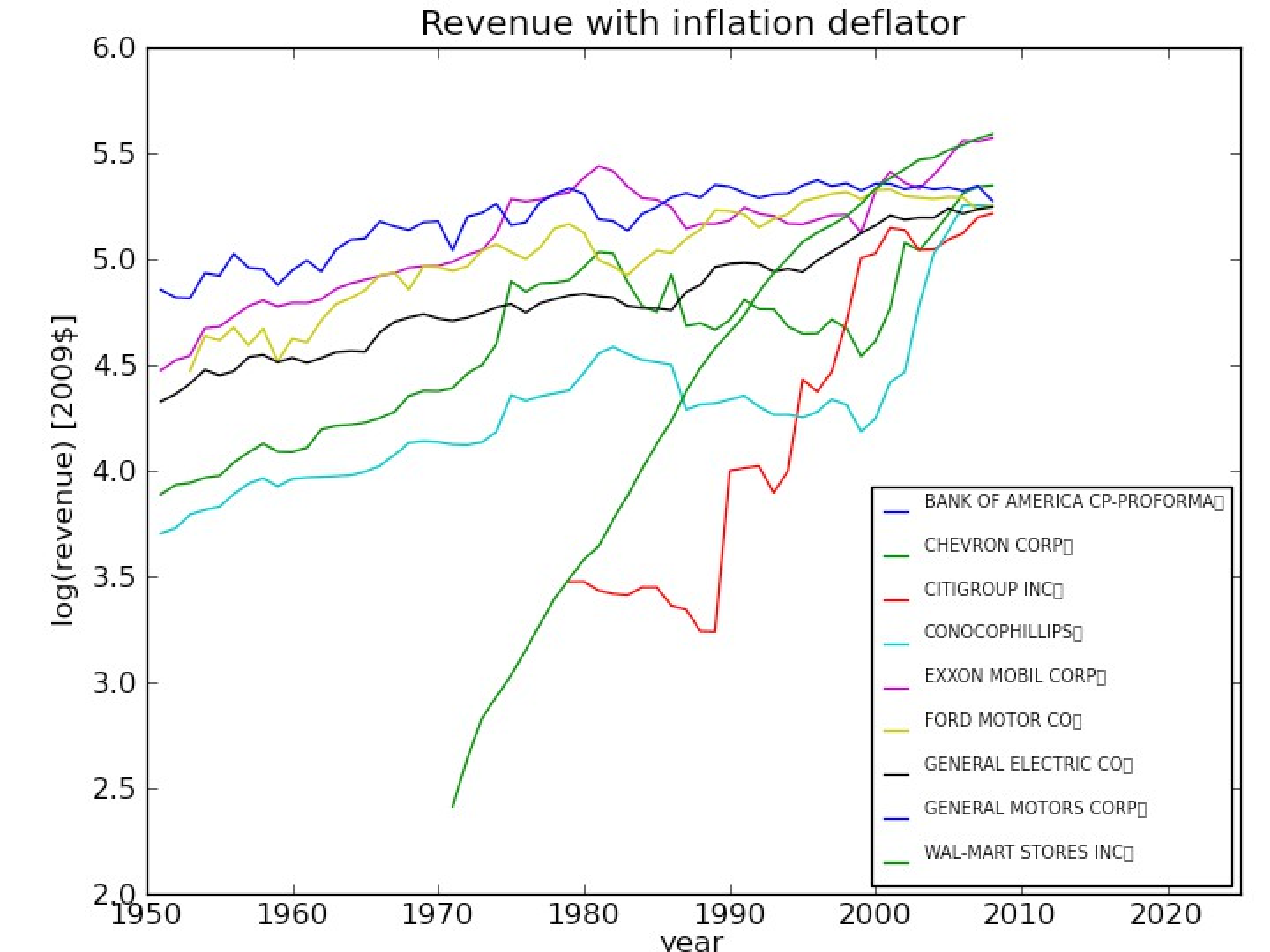




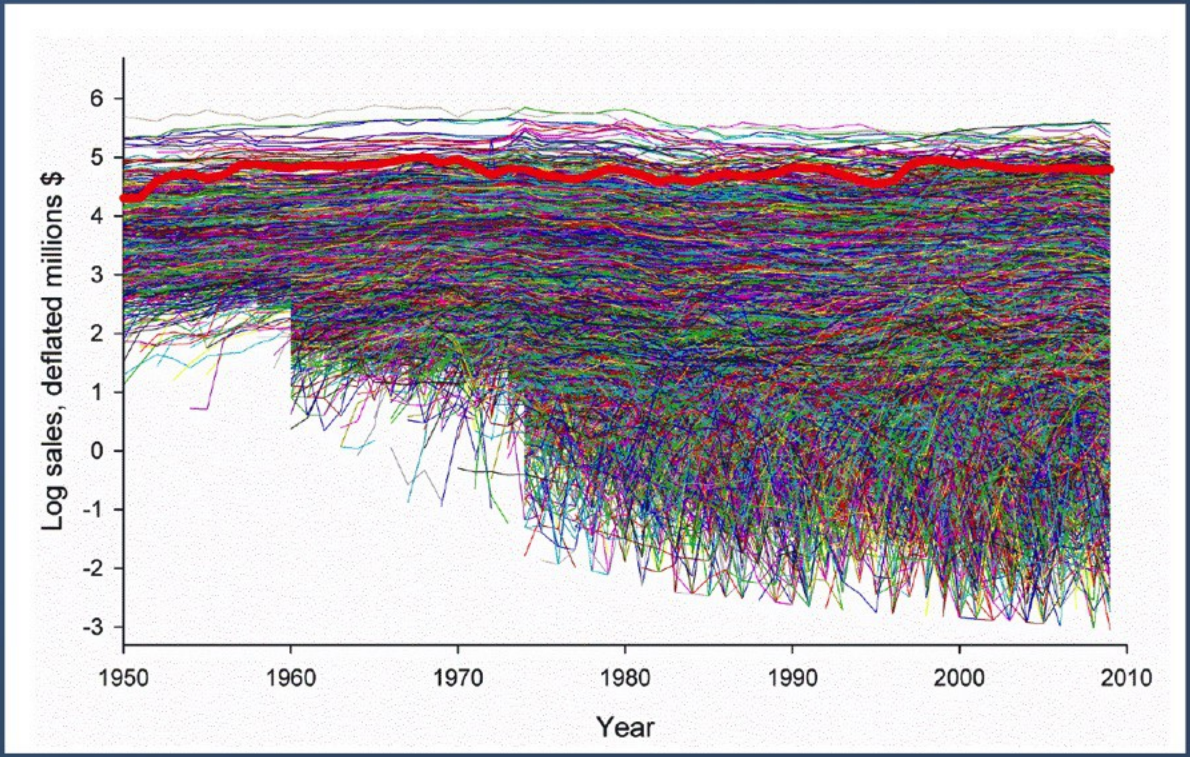
Net Income (0.79)
Net Income
Gross Profit (0.92)
Gross Profit
Total Assets (0.86)
Total Assets
Sales (0.98)
Sales
Employees
Employees

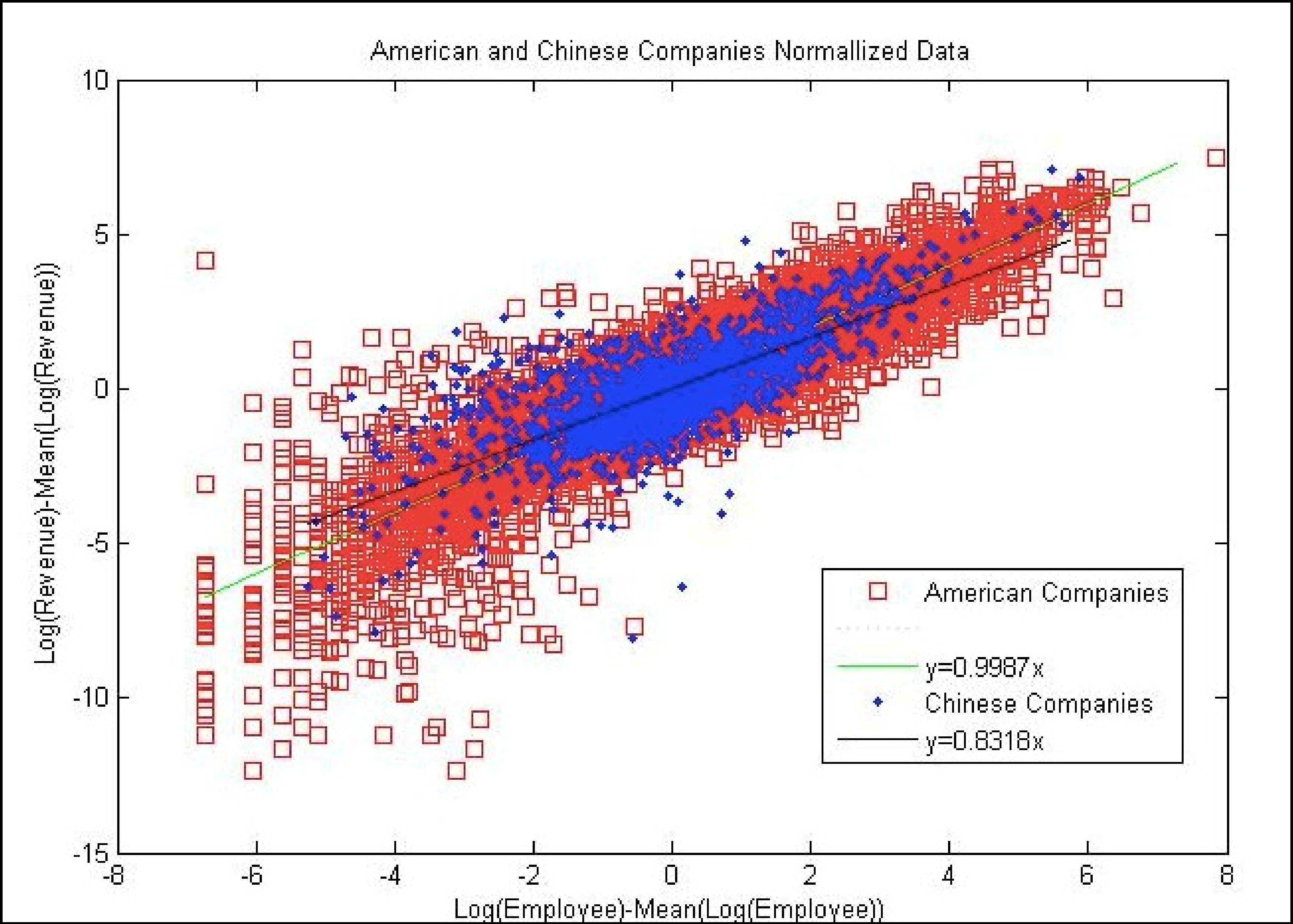
GROWTH OF FIRMS




Revenue with inflation deflator
log(revenue) [2009$]
year
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1950
1960
1970
1980
1990
2000
2010
2020
BANK OF AMERICA CP-PROFORMA
CHEVRON CORP
CITIGROUP INC
CONOCOPHILLIPS
EXXON MOBIL CORP
FORD MOTOR CO
GENERAL ELECTRIC CO
GENERAL MOTORS CORP
WAL-MART STORES INC

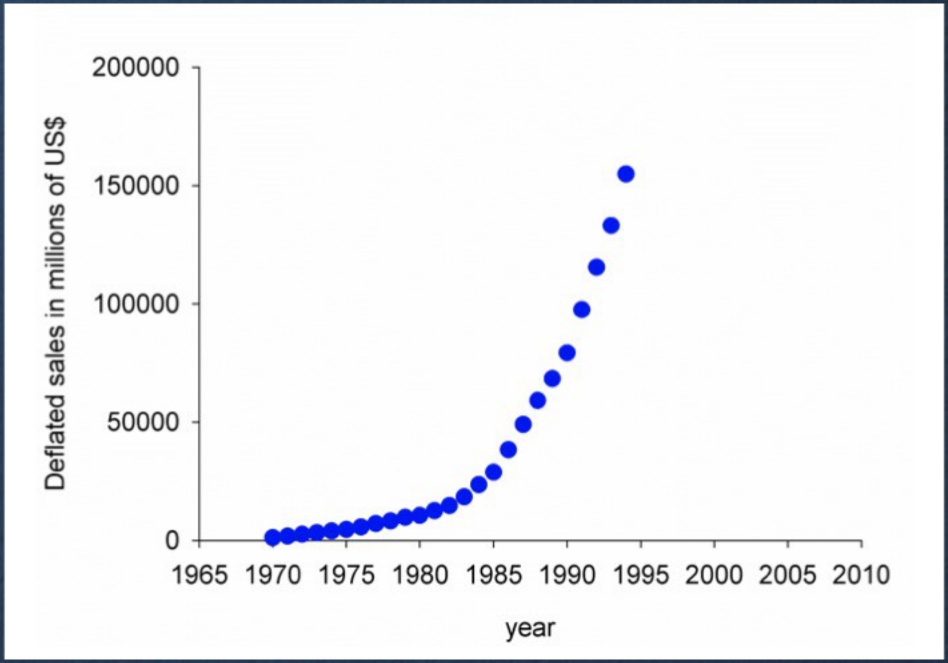
GROWTH OF FIRMS RELATIVE TO GDP



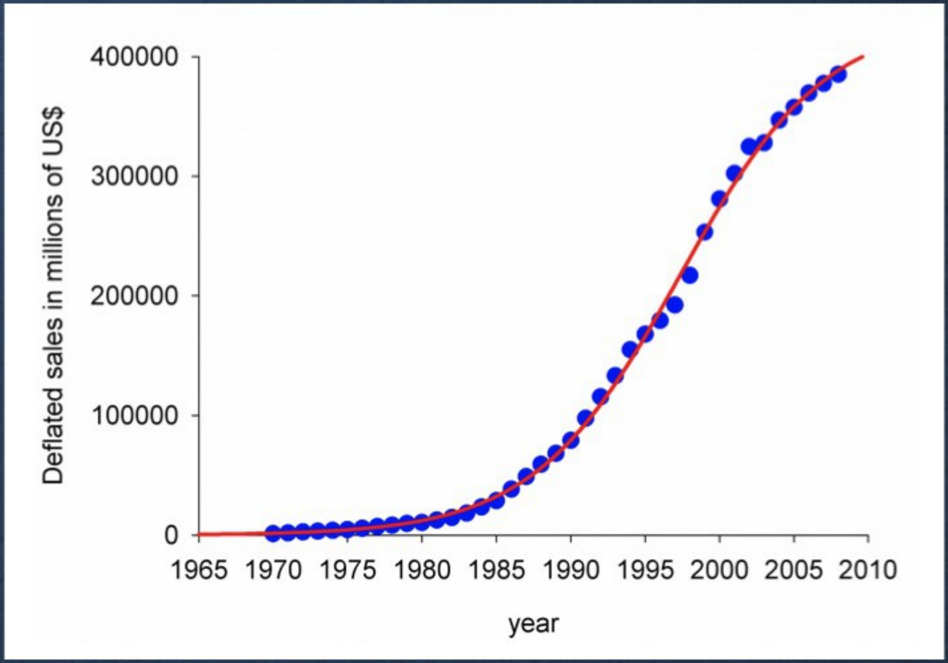


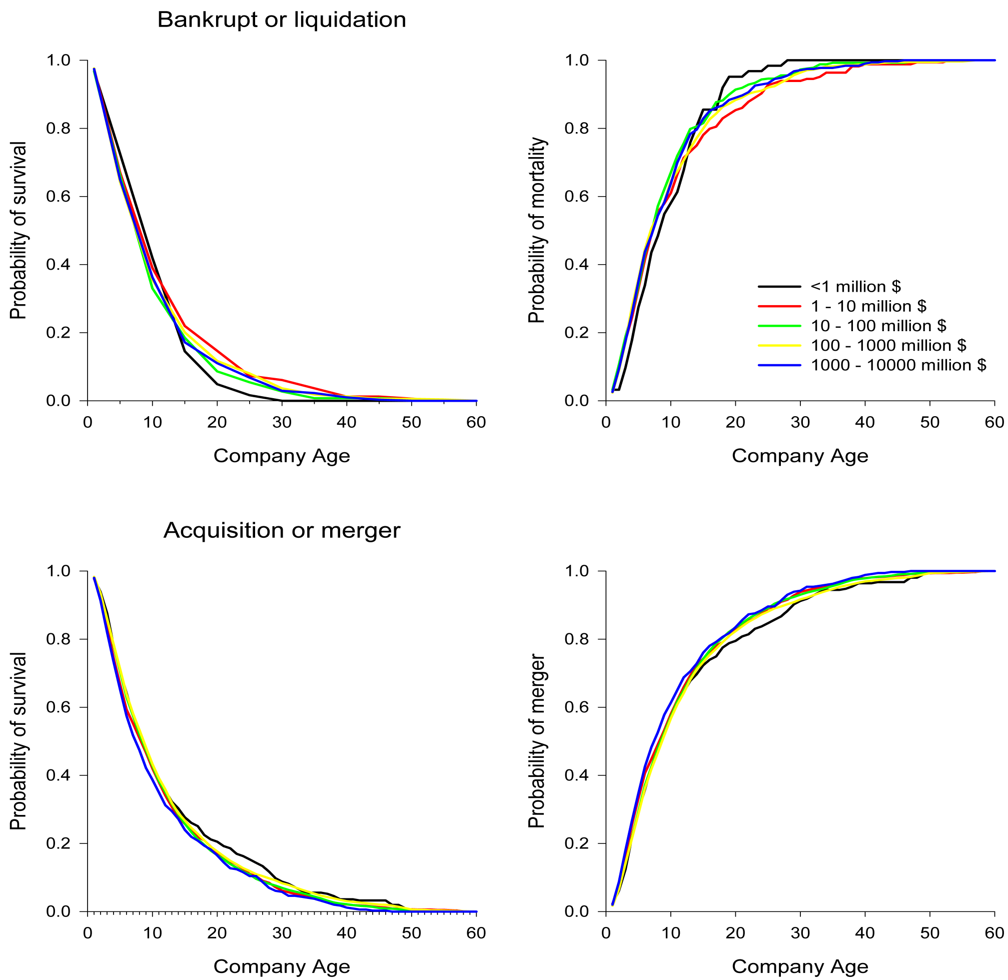
American and Chinese Companies Normallized Data
Log(Revenue)-Mean(Log(Revenue))
Log(Employee)-Mean(Log(Employee))
10
5
0
-5
-10
-15
-8
-6
-4
-2
0
2
4
6
8
American Companies
y=0.9987x
Chinese Companies
y=0.8318x

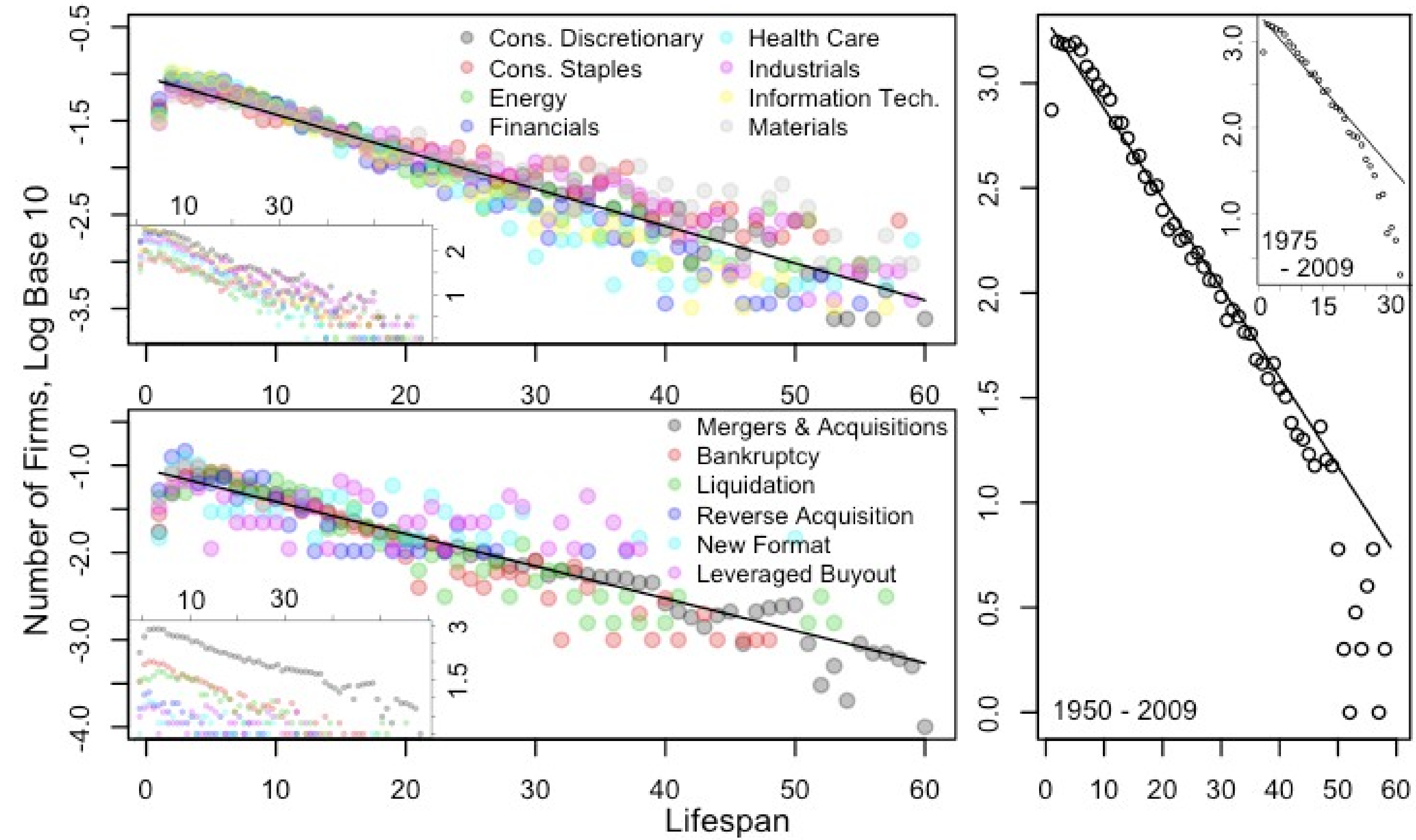
WALMART, 1970-1994



WALMART, 1970-2008

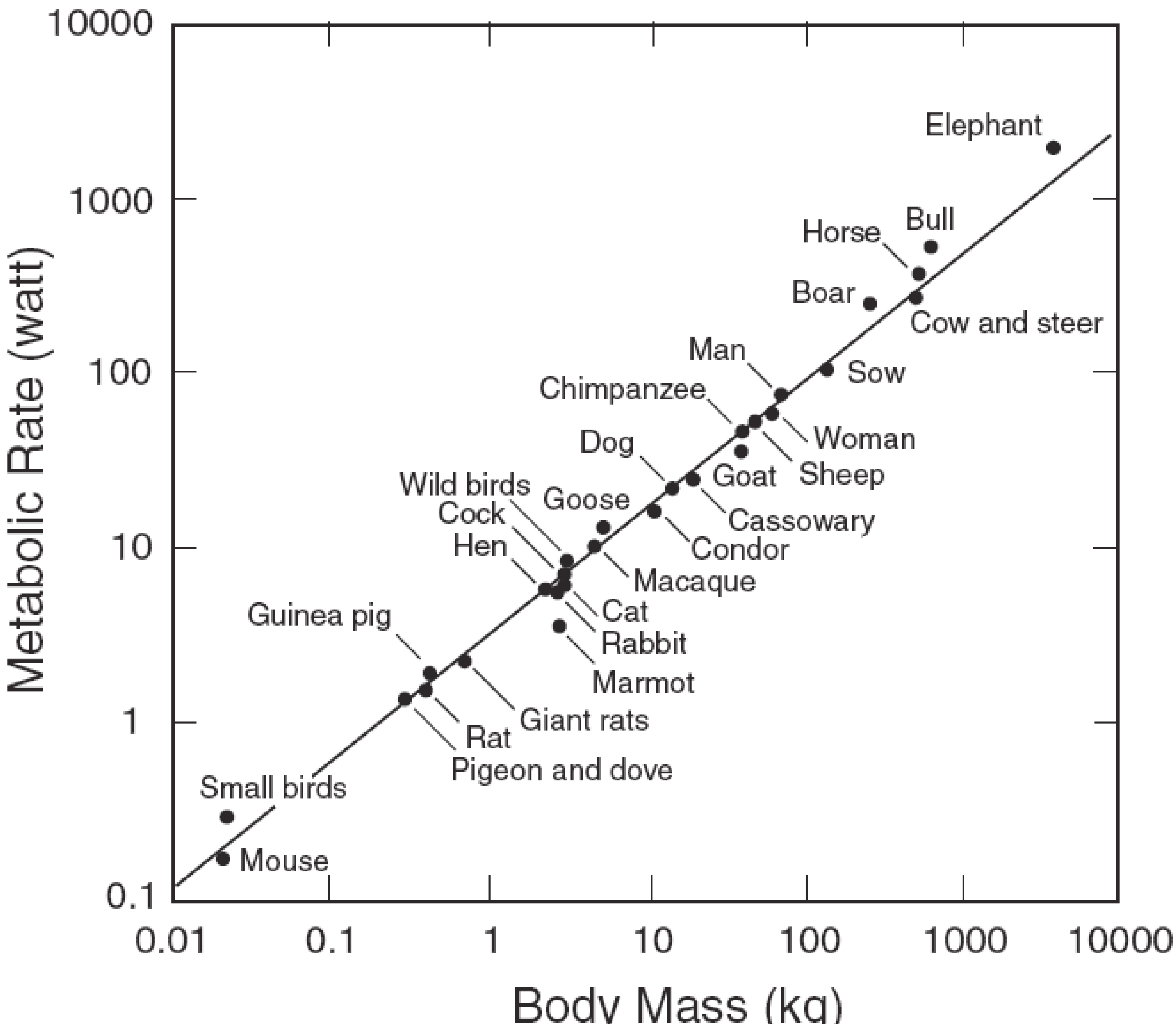



Bankrupt or liquidation
Probability of survival
Company Age
Probability of mortality
Company Age
<1 million $
1 - 10 million $
10 - 100 million $
100 - 1000 million $
1000 - 10000 million $
Acquisition or merger
Probability of survival
Company Age
Probability of merger
Company Age
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50
60

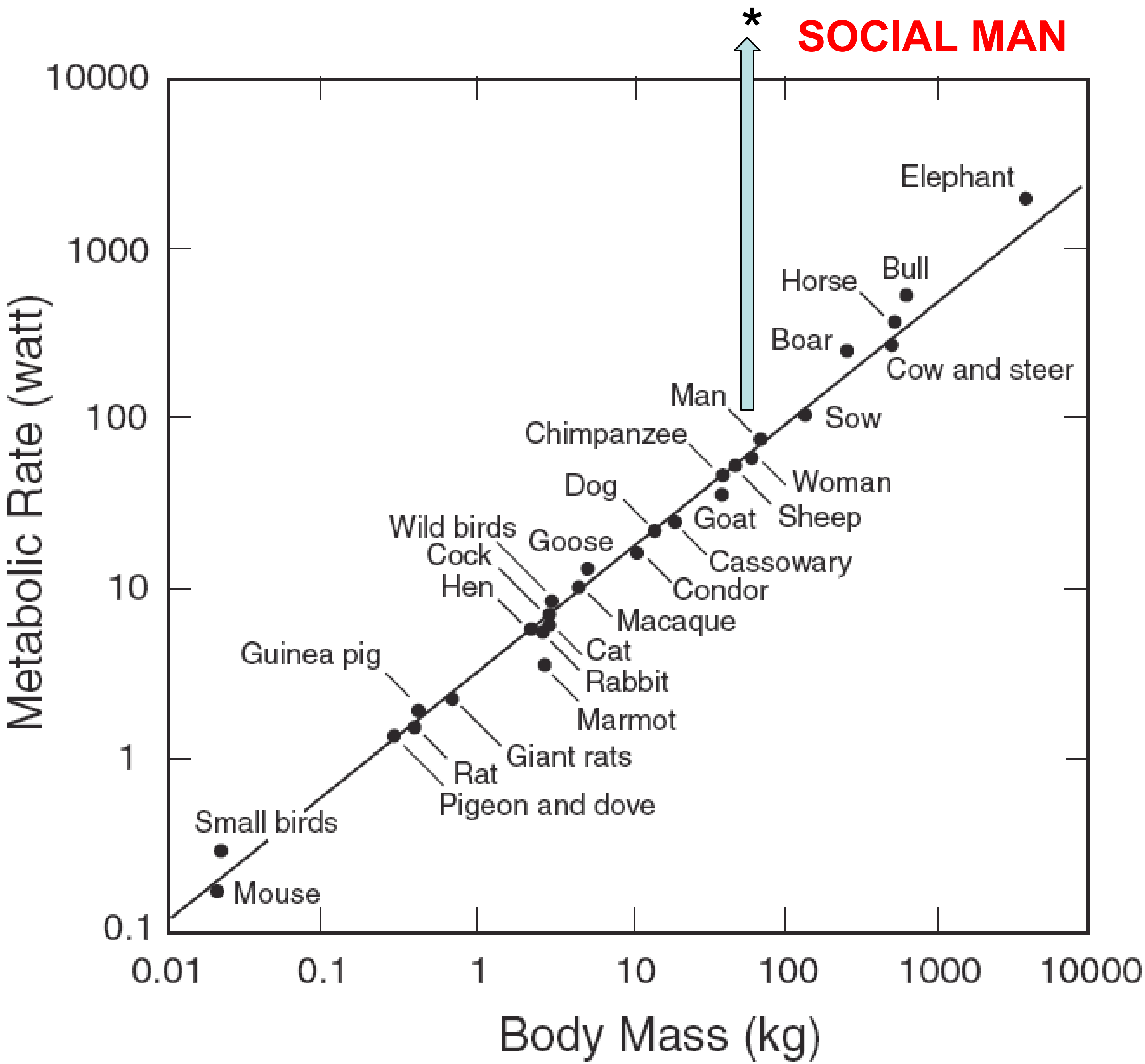

Cons. Discretionary
Cons. Staples
Energy
Financials
Health Care
Industrials
Information Tech.
Materials
Mergers & Acquisitions
Bankruptcy
Liquidation
Reverse Acquisition
New Format
Leveraged Buyout
Number of Firms, Log Base 10
Lifespan
1950 - 2009
1975 - 2009

Our “natural” metabolic rate *~90 watts*

Our social metabolic rate *~11,000 watts*



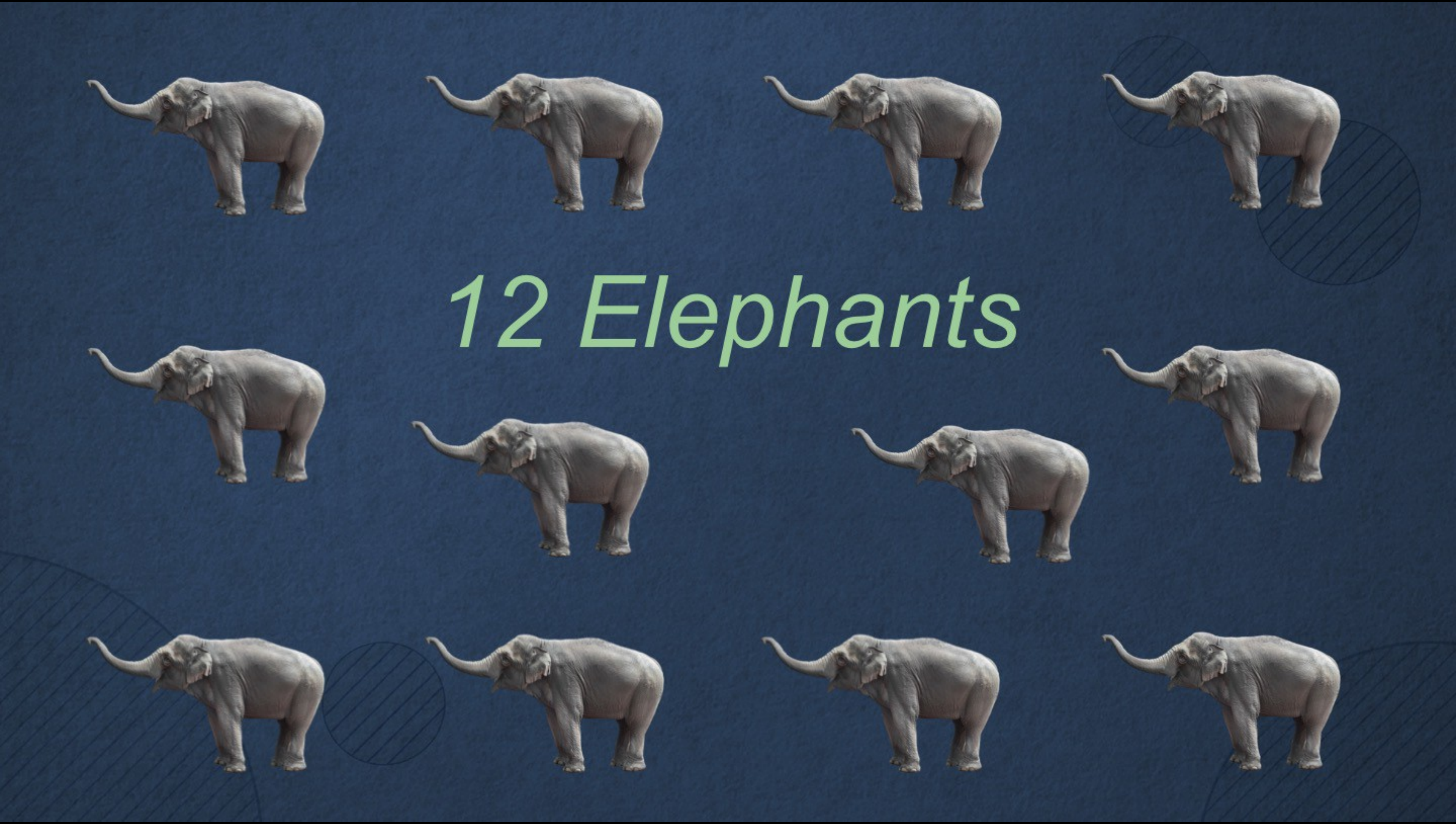
SLOPE = ¾ < 1; SUB-LINEAR; ECONOMY OF SCALE

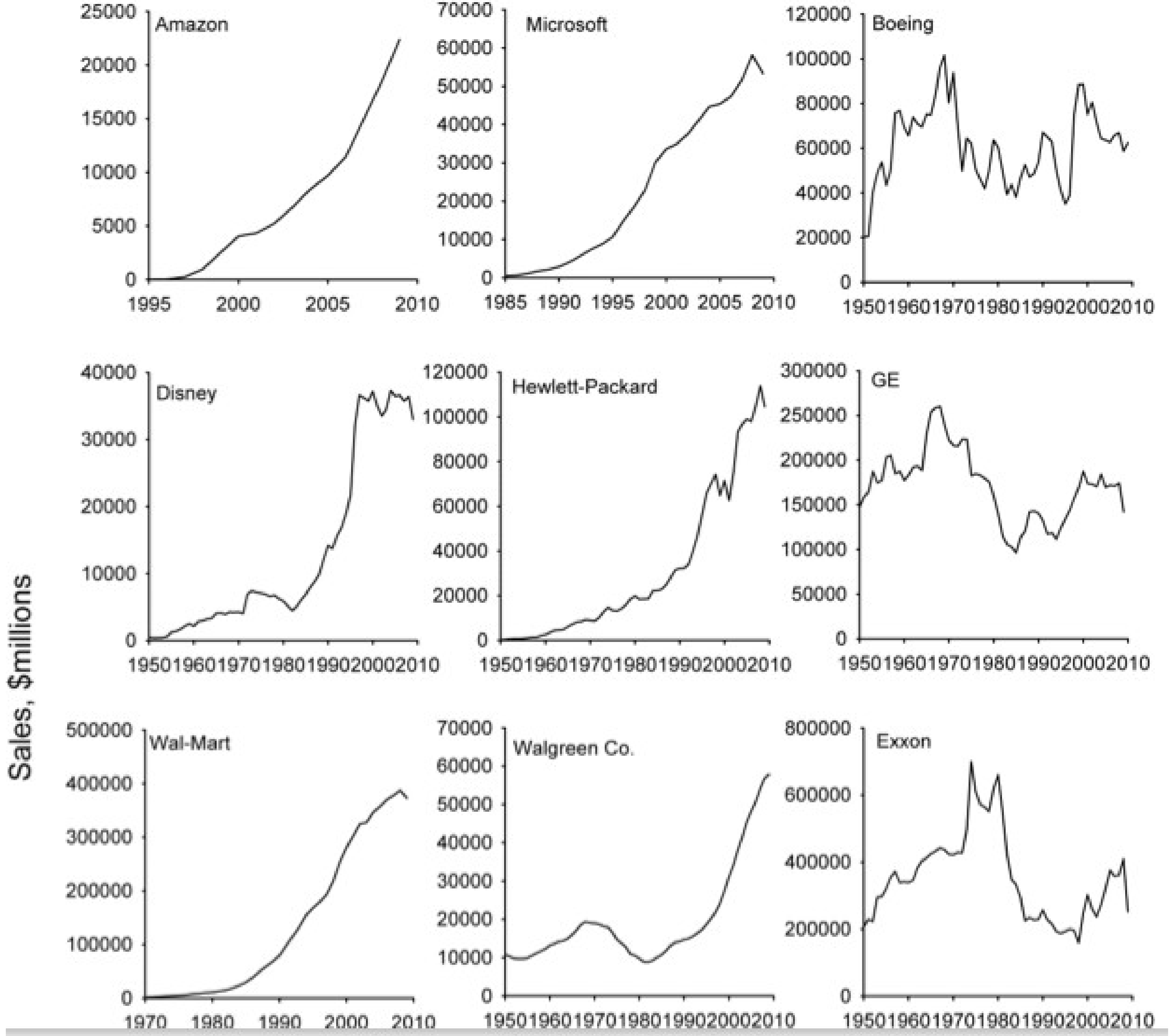


SLOPE = ¾ < 1; SUB-LINEAR; ECONOMY OF SCALE

We are equivalent to a

30,000 kg Gorilla


12 Elephants



Sales, $millions
Amazon
Microsoft
Boeing
Disney
Hewlett-Packard
GE
Wal-Mart
Walgreen Co.
Exxon

NEED A NEW PARADIGM, A NEW INTEGRATED CONCEPTUAL FRAMEWORK:

SYSTEMIC, HOLISTIC, QUANTITATIVE, MECHANISTIC, COMPUTATIONAL, PREDICTIVE

COUPLED WITH, INSPIRED BY, MOTIVATED BY, INSPIRING AND MOTIVATING,

"BIG DATA"

BUT MINDLESS BIG DATA IS (PROBABLY) BAD AND EVEN DANGEROUS

WITHOUT SOME CONCEPTUAL CONCEPTUAL FRAMEWORK

HOW MUCH, WHERE, WHEN, WHAT, WHY?

……..AND THERE IS NO VIRGIN DATA

Big Data Needs a Big Theory to Go with It

Just as the industrial age produced the laws of thermodynamics, we need universal laws of complexity to solve our seemingly intractable problems

By Geoffrey West

As the world becomes increasingly complex and interconnected, some of our biggest challenges have begun to seem intractable. What should we do about uncertainty in the financial markets? How can we predict energy supply and demand? How will climate change play out? How do we cope with rapid urbanization? Our traditional approaches to these problems are often qualitative and disjointed and lead to unintended consequences. To bring scientific rigor to the challenges of our time, we need to develop a deeper understanding of complexity itself.

Image: Eva Vazquez

Creative destruction is the essential fact about Capitalism

Joseph Schumpeter

Creative destruction is the essential fact about Capitalism

All successful people are standing on ground that is crumbling beneath their feet

Joseph Schumpeter

THE SINGULARITY IS NEAR!

The ever accelerating progress of technology….gives the appearance of approaching some essential singularity in the history of the race beyond which human affairs, as we know them, could not continue.

John von Neumann (1903 - 1957)

Jim Brown (UNM)

Brian Enquist (U of Arizona)

Woody Woodruff (LANL)

Van Savage (UCLA)

Jamie Gillooly (U of Florida)

Drew Allen (MacQuarie U)

Chen Hou (MissouriTech)

Melanie Moses (UNM)

Alex Herman (UCSF)

Ric Charnov (UNM)

Chris Kempes (SFI)

Wenyun Zhuo (UNM)

Luis Bettencourt (Chicago)

Jose Lobo (U of Arizona)

Debbie Strumsky (U of Arizona)

Hyejin Youn (Oxford U)

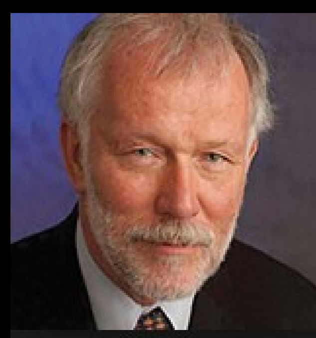
Marcus Hamilton (U of Missouri)

Madeleine Daepp (MIT)

Markus Schlapfer (ETH Zurich)

Carlo Ratti (MIT)

David Lane (U of Reggio)



Sander van der Leeuw (U of Arizona)

Denise Pumain (U of Paris)

Dirk Helbing (ETH Zurich)