THE CONCEPTUAL FRAMEWORK OF (URBAN) SCALING

GEOFFREY WEST

SANTA FE INSTITUTE

GODZILLA
MAY 16
SEE IT IN realD 3D AND IMAX 3D
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GODZILLA SHOP
LEGAL

WE LIVE IN AN EXPONENTIALLY EXPANDING SOCIO-ECONOMIC UNIVERSE!!

1800 < 4% THE US POPULATION WAS URBAN

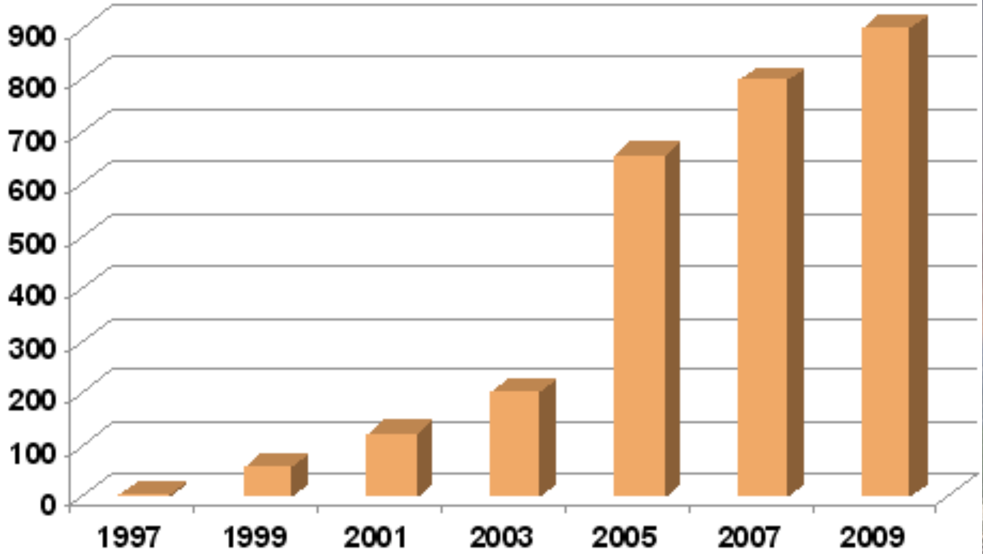
2014 > 80% URBANISED

2006 > 50% WORLD'S POPULATION URBANISED

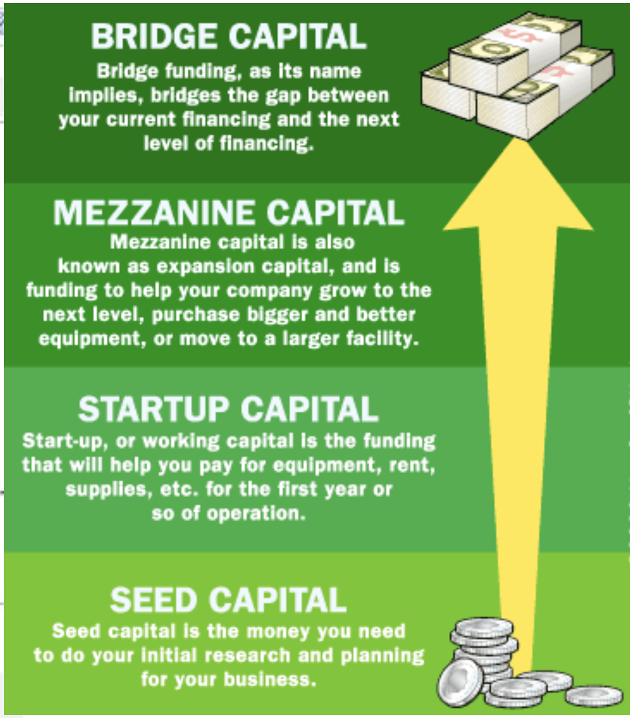
2050 > 75% URBANISED

EQUIVALENT TO URBANISING MORE THAN A MILLION PEOPLE EVERY WEEK FROM NOW TILL 2050

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



Growth rates of 100 software companies from IPO Dashboard




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

FATE OF THE PLANET

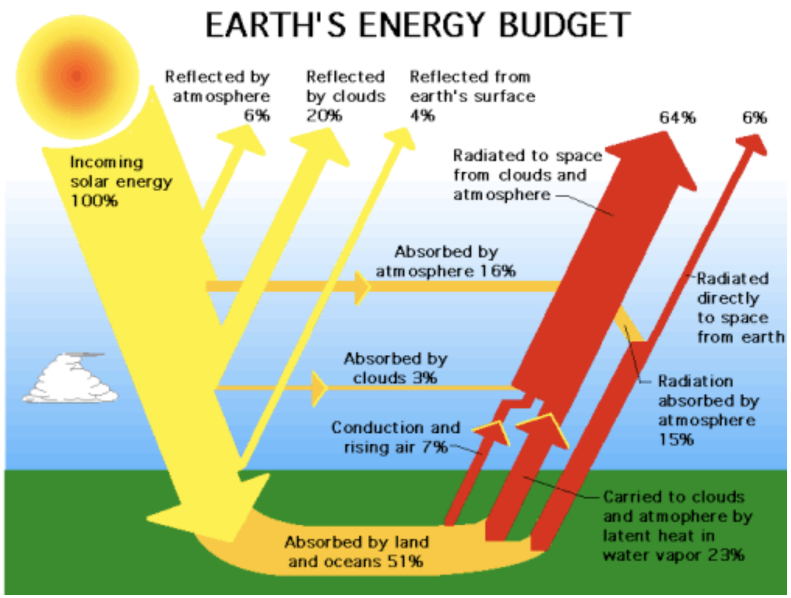
=

FATE OF OUR CITIES


lonelyplanetimages.com


THALDEN•BOYD ARCHITECTS
A Native American Firm


Missa Papæ Marcelli Cum


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 atmophere by latent heat in water vapor 23%
Absorbed by land and oceans 51%

SOCIO-ECONOMIC ENTROPY!!


南 口
9




Evening Standard
Classified
MASSIVE INCREASE IN KNIFE CRIME SURVEYS
Evening Standard

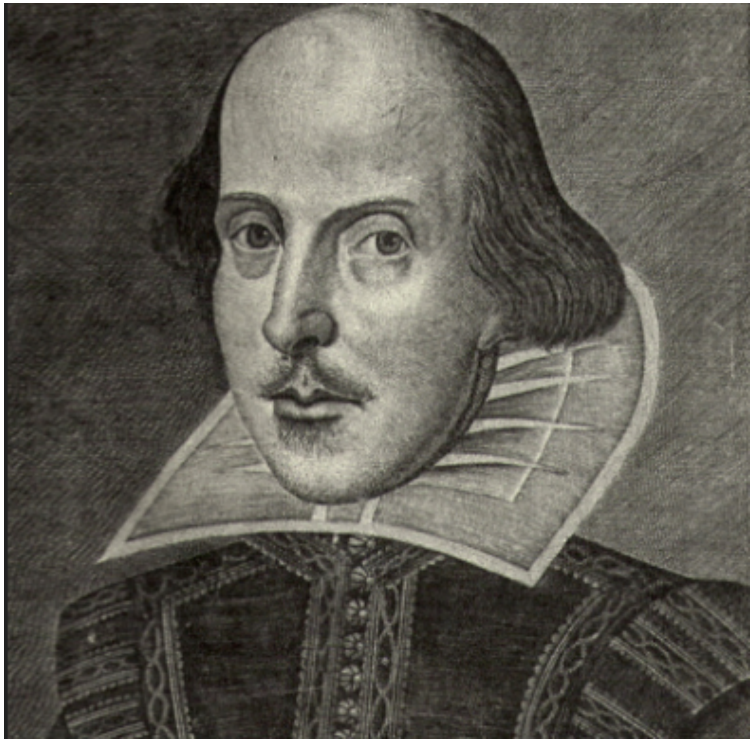

GETTY IMAGES




London After Climate Change?

"What is the city but the people?"

William Shakespeare



CITIES ARE THE PROBLEM;

CITIES ARE THE SOLUTION!!

URGENTLY NEED A QUANTITATIVE, PREDICTIVE SCIENCE OF CITIES

RESILIENCE

EVOLVABILITY

GROWTH

SCALABILITY

NEED A SCIENCE OF CITIES

COMPLEMENT TO TRADITIONAL (QUALITATIVE) THEORIES AND MODELS

WHAT CAN WE LEARN FROM BIOLOGY AND PHYSICS?

- **POPULATION, HEALTH, WELL-BEING,…….**

- **ENERGY, RESOURCES, FOOD,……**

THERMODYNAMICS, METABOLICS,……

- **SOCIAL, POLITICAL, CULTURAL,…….**

ORGANISATION, 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

ENERGY & RESOURCES
(METABOLISM, INFRASTRUCTURE)

vs.

INFORMATION
(GENOMICS, INNOVATION)

COARSE - GRAINED DESCRIPTION

WITH INCREASING RESOLUTION AND GRANULARITY

STATISTICAL/PROBABILISTIC

QUANTITATIVE, PREDICTIVE

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 MOLECULAR TIME-SCALES OF GENES AND RESPIRATORY ENZYMES?

WHY DO WE NEED TO SLEEP ABOUT EIGHT HOURS EACH NIGHT?

WHY DO MICE HAVE MANY MORE TUMOURS/ GRAM OF TISSUE THAN WE DO AND WHALES HAVE ALMOST NONE?

WHAT'S THE DIFFERENCE BETWEEN GROWING BABIES IN YOUR BODY AND GROWING TUMORS (OR ORGANS)?

ARE CITIES AND COMPANIES JUST VERY LARGE ORGANISMS SATISFYING THE LAWS OF BIOLOGY?

WHY DO ALL COMPANIES DIE WHEREAS ALMOST ALL CITIES SURVIVE?


TWA
TWA
TWA
TWA


GM


LEHMAN BROTHERS


© Alex Hinds
This Business
is now
CLOSED

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

GEOMETRIC SCALING

ISOMETRIC – KEEP THE SAME SHAPE

i) AREA ~ LENGTH x LENGTH

$$A \sim L^2$$

ii) VOLUME ~ LENGTH x LENGTH x LENGTH

$$V \sim L^3$$

VOLUME INCREASES MUCH FASTER THAN AREA

i) $V \sim A^{3/2}$ SUPER-LINEAR SCALING

ii) $A \sim V^{2/3}$ SUB-LINEAR SCALING

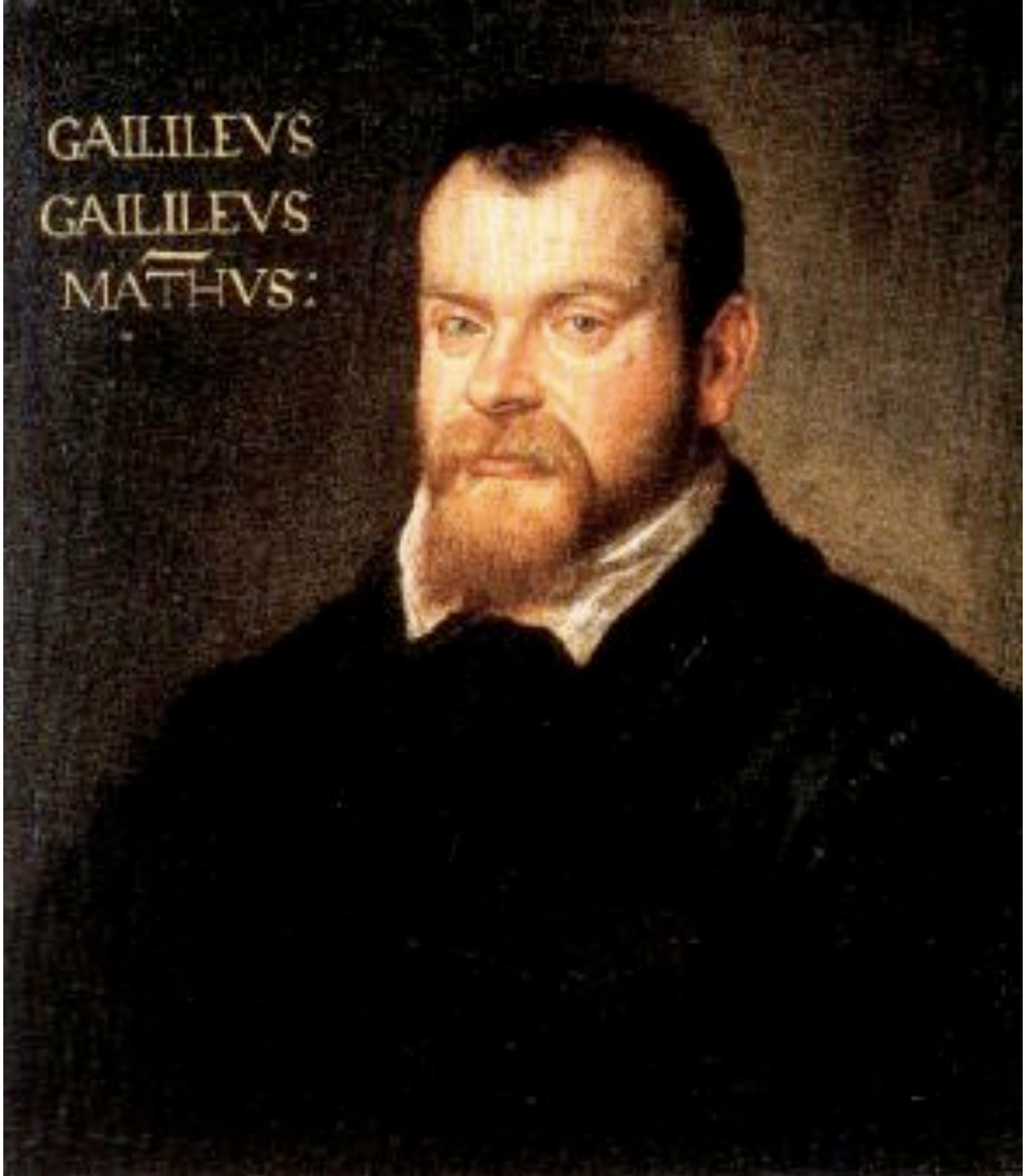
IF DENSITY IS FIXED, MASS ~ VOLUME:

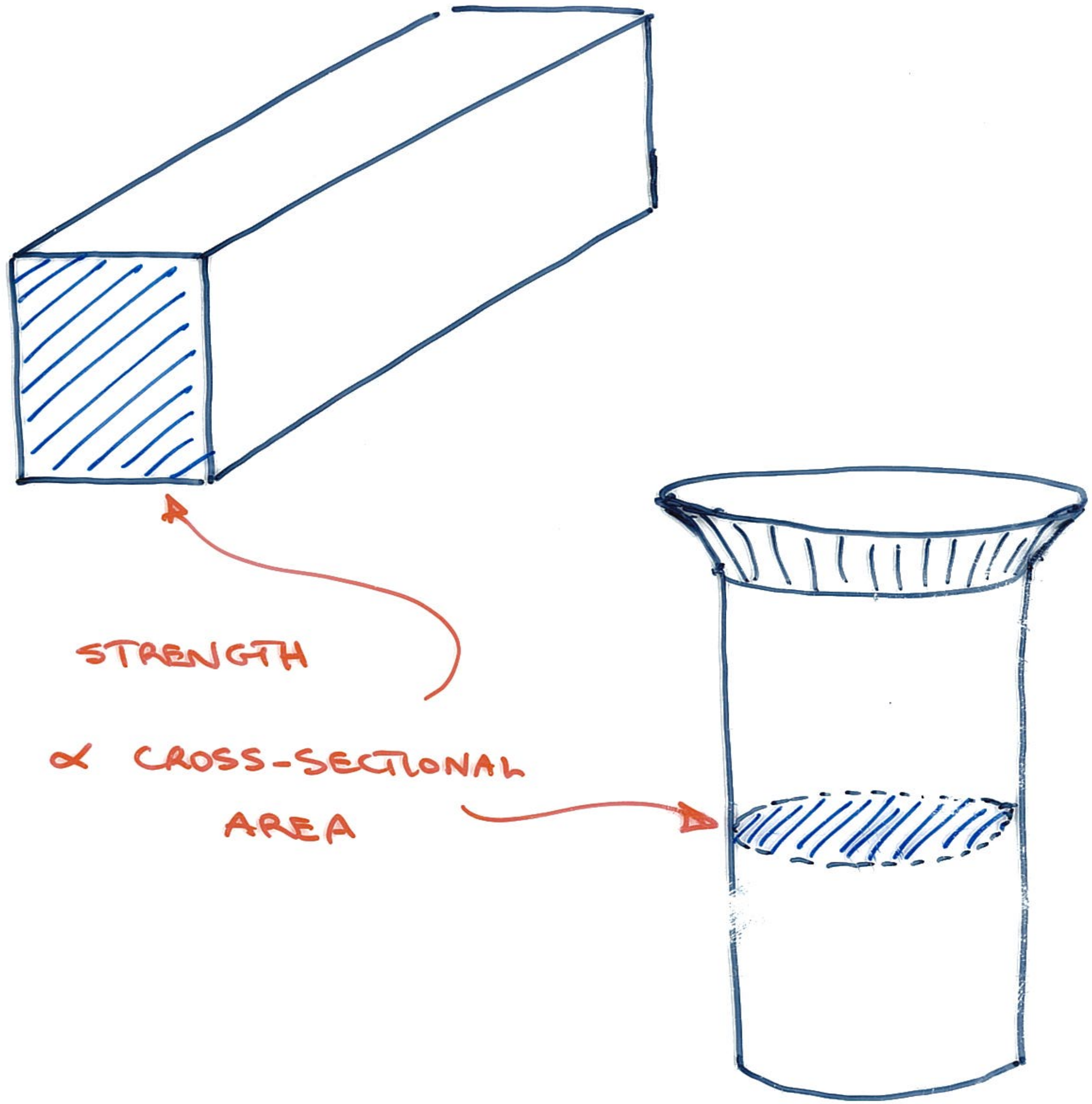
iii) $M \sim V$ LINEAR SCALING

SO $A \sim M^{2/3}$

NON-LINEAR

POWER LAWS EXPONENTS


GAILILEVS
GAILILEVS
MATHVS:


STRENGTH
∝ CROSS-SECTIONAL
AREA

GALILEO

i) **STRENGTH OF A LIMB OR BEAM**

~ CROSS-SECTIONAL AREA ~ L^2

ii) **WEIGHT SUPPORTED ~ L^3**

AS SIZE INCREASES WEIGHT WILL EVENTUALLY EXCEED STRENGTH LEADING TO

GALILEO

i) STRENGTH OF A LIMB OR BEAM

~ CROSS-SECTIONAL AREA ~ L^2

ii) WEIGHT SUPPORTED ~ L^3

AS SIZE INCREASES WEIGHT WILL EVENTUALLY EXCEED STRENGTH LEADING TO

COLLAPSE AND LIMITS TO GROWTH

TO AVOID NEED:

i)CHANGE DESIGN

ii)CHANGE MATERIALS

iii)OR BOTH

TO AVOID NEED:

i) CHANGE DESIGN

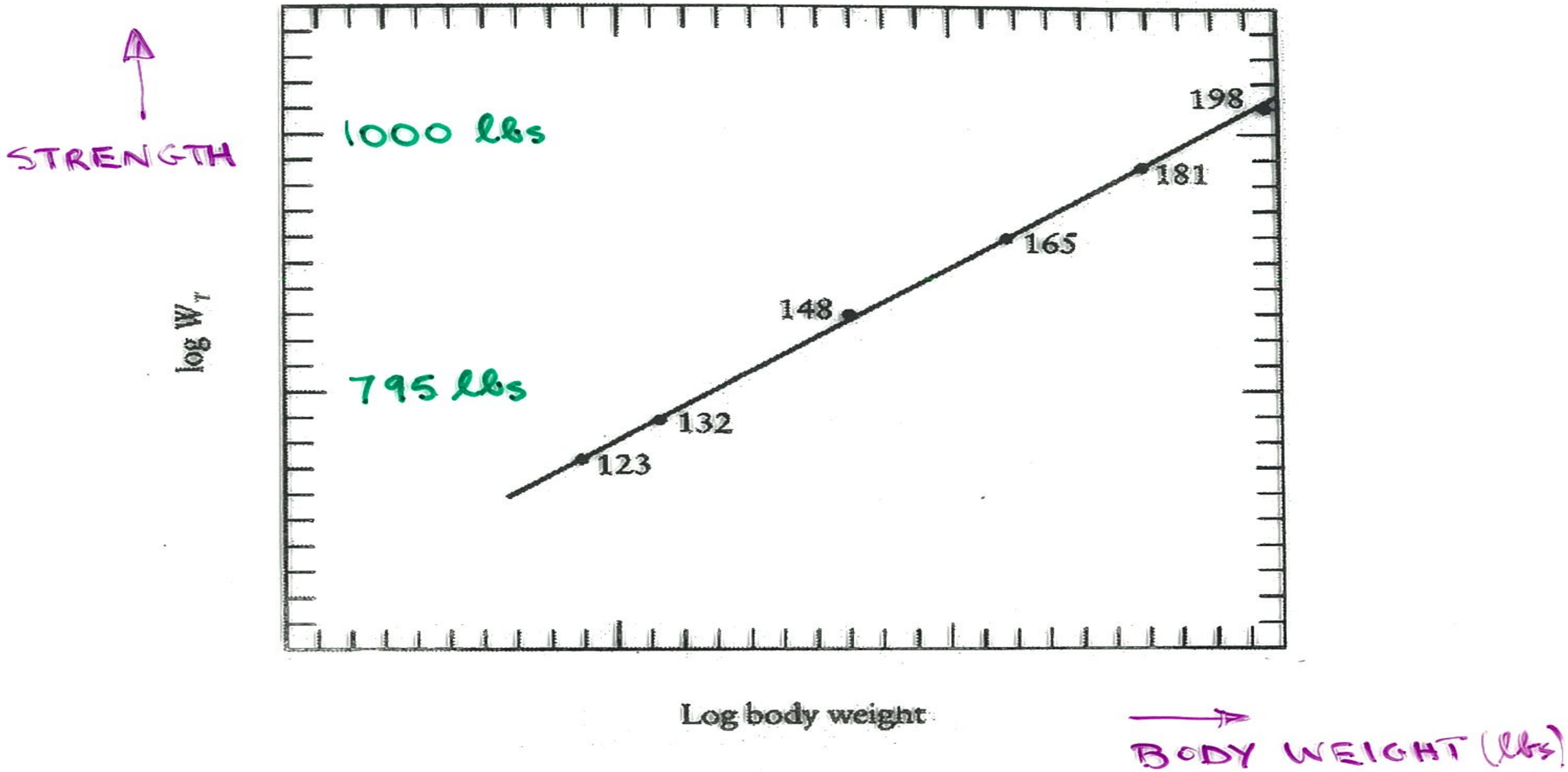
ii) CHANGE MATERIALS

iii) OR BOTH

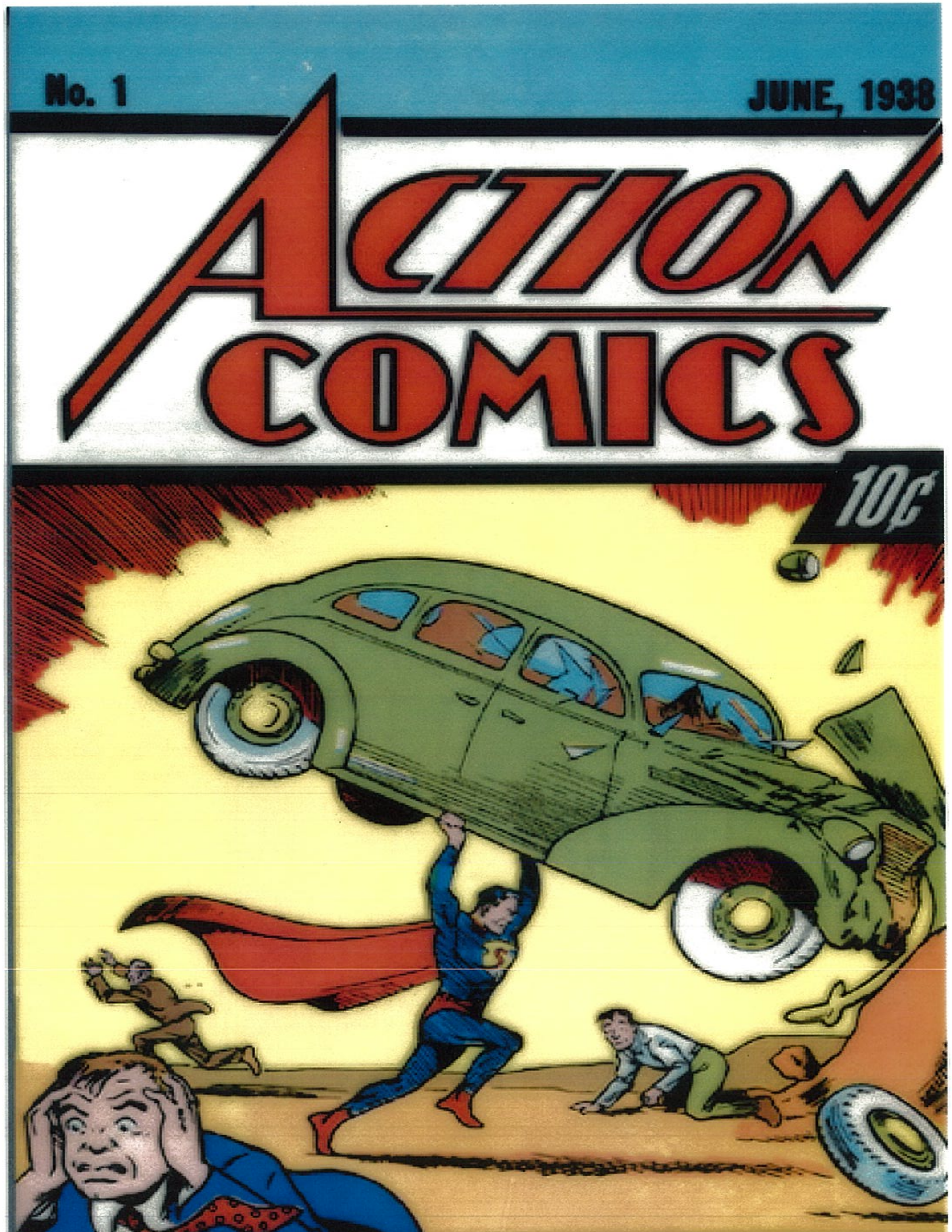
→ **INNOVATION**

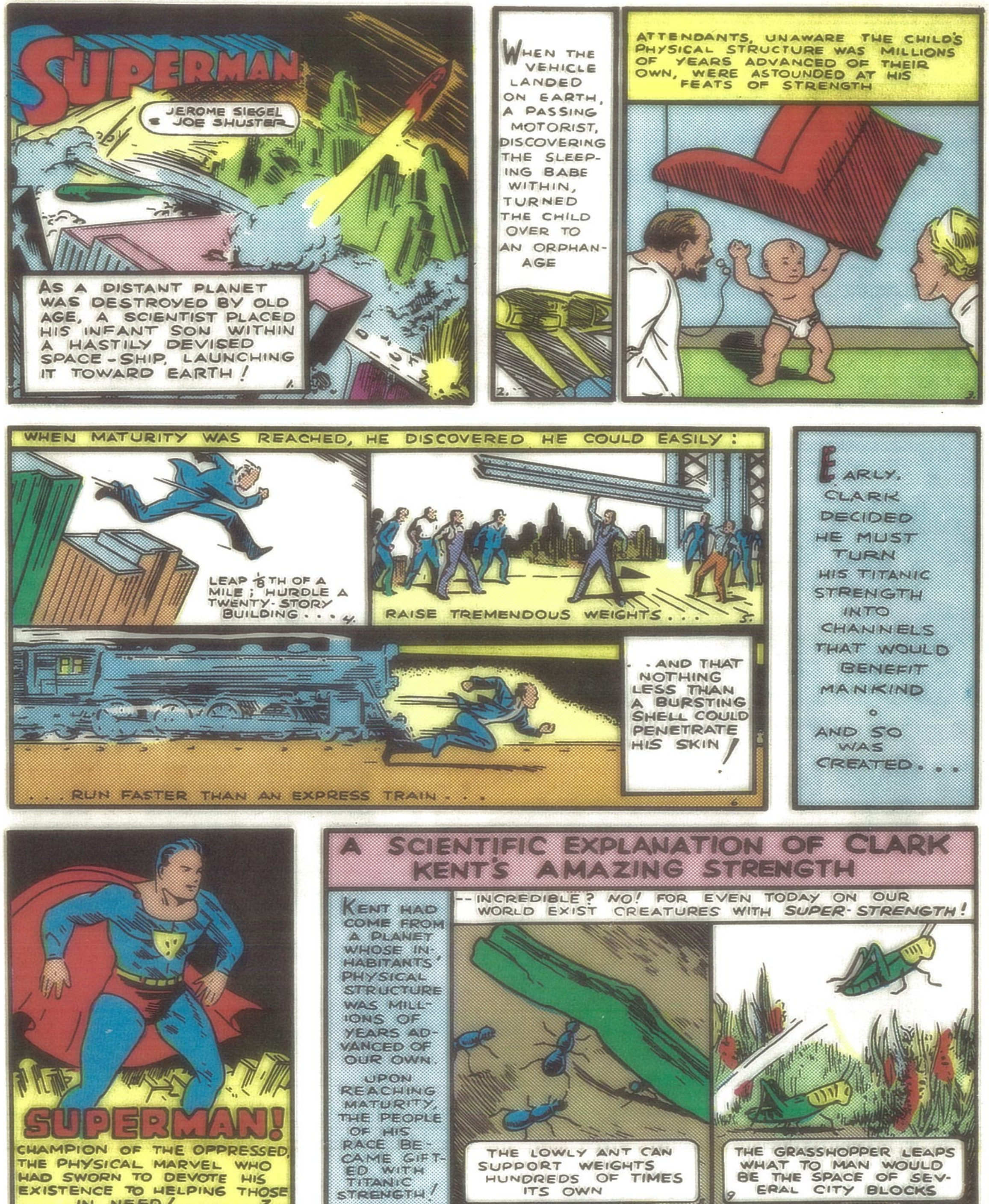
WEIGHT-LIFTING ("PUMPING IRON")

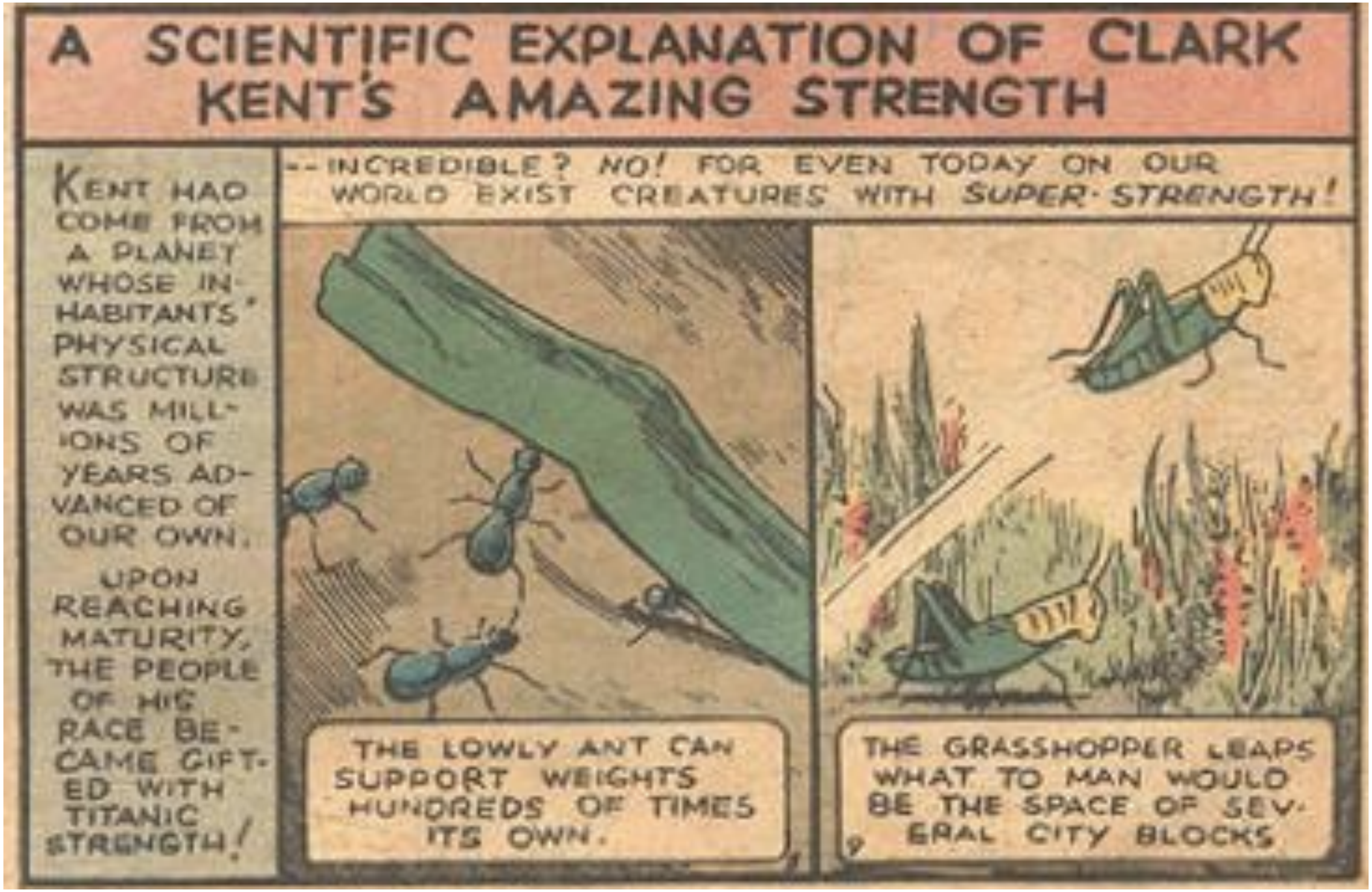
(PLOTTED LOGARITHMICALLY)



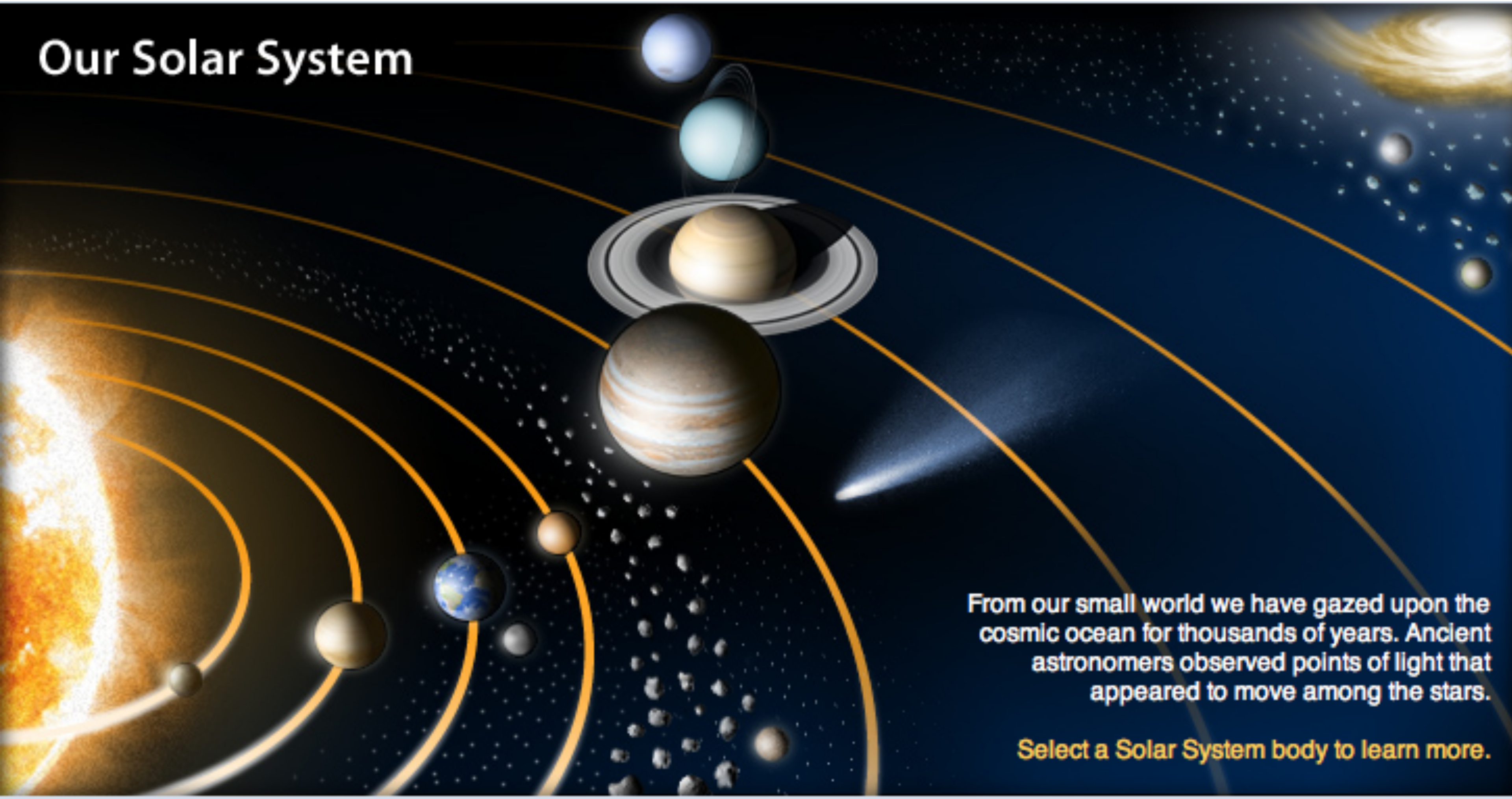
WHO IS THE STRONGEST AND WHO IS THE WEAKEST?

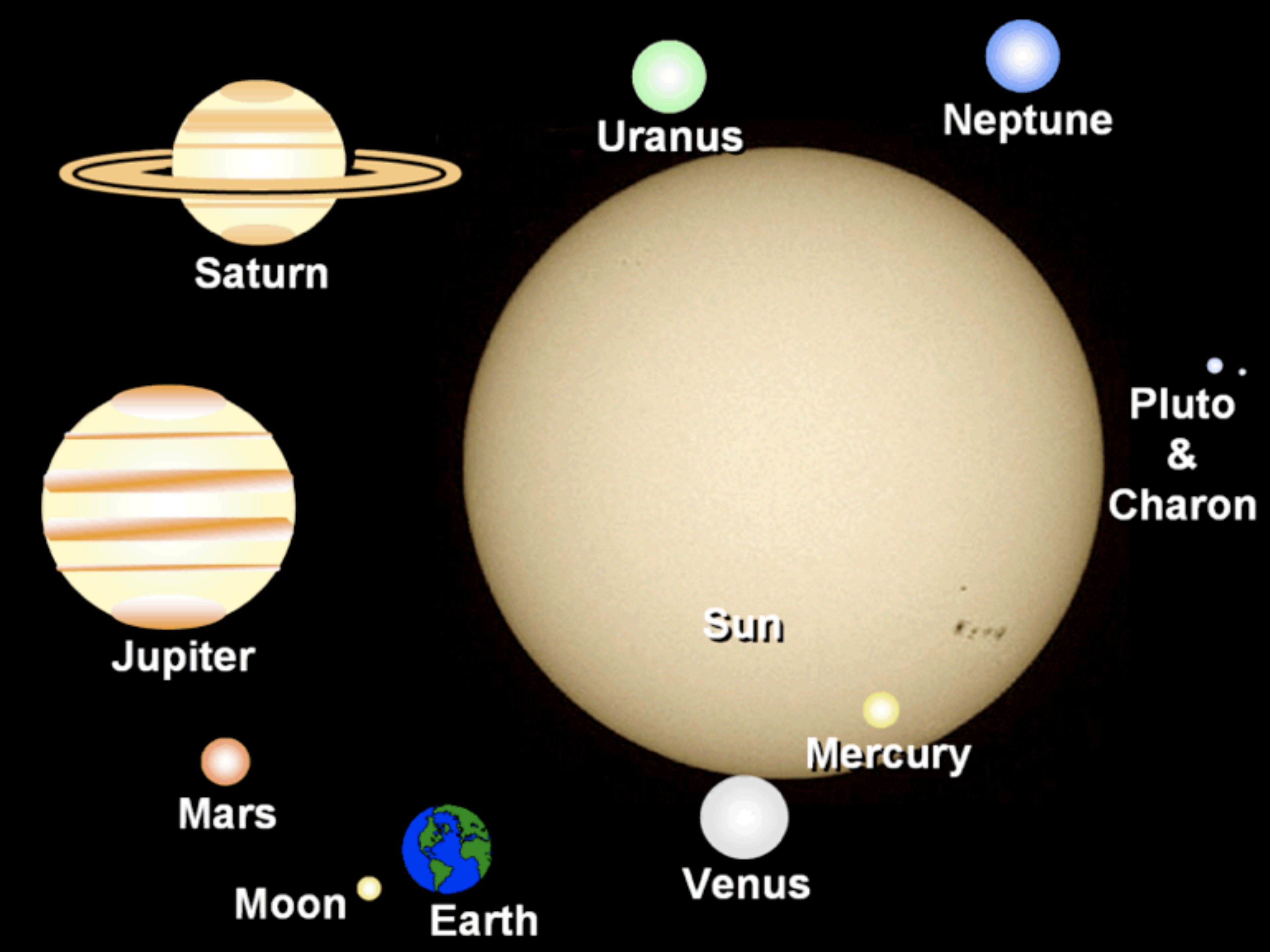

No. 1
JUNE, 1938
ACTION COMICS
10¢

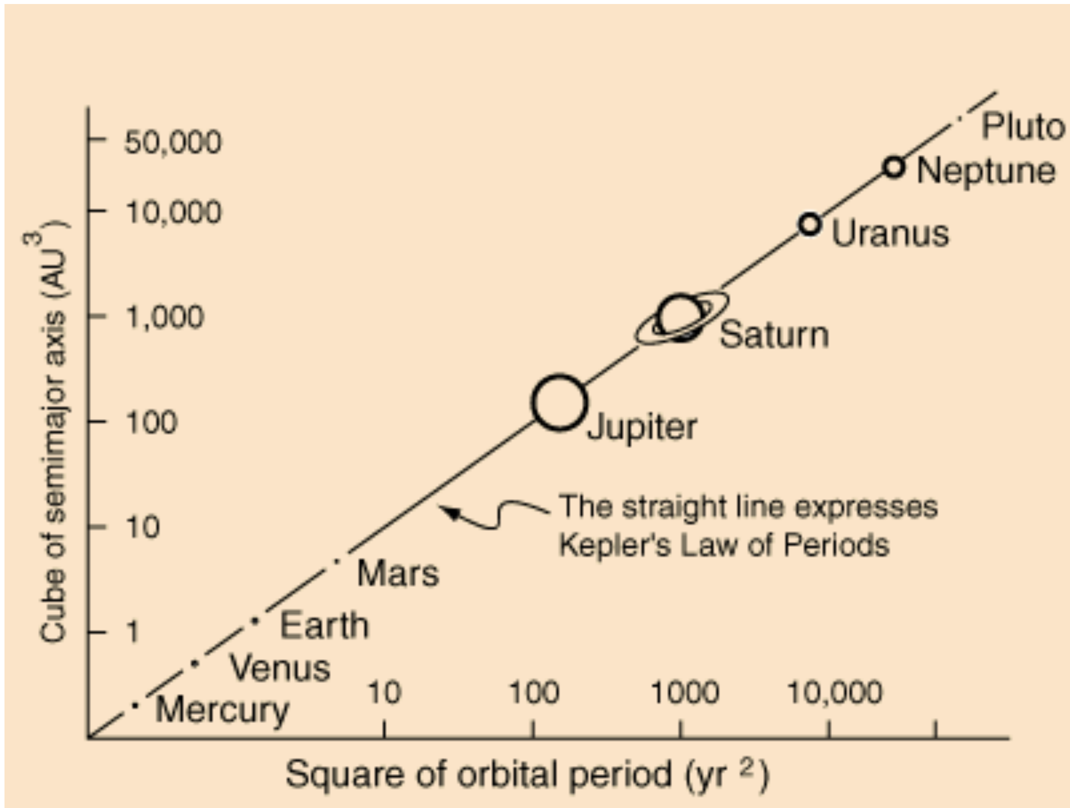

SUPERMAN
JEROME SIEGEL & JOE SHUSTER
AS A DISTANT PLANET WAS DESTROYED BY OLD AGE, A SCIENTIST PLACED HIS INFANT SON WITHIN A HASTILY DEVISED SPACE-SHIP, LAUNCHING IT TOWARD EARTH!
WHEN THE VEHICLE LANDED ON EARTH, A PASSING MOTORIST, DISCOVERING THE SLEEPING BABE WITHIN, TURNED THE CHILD OVER TO AN ORPHANAGE
ATTENDANTS, UNAWARE THE CHILD'S PHYSICAL STRUCTURE WAS MILLIONS OF YEARS ADVANCED OF THEIR OWN, WERE ASTOUNDED AT HIS FEATS OF STRENGTH
WHEN MATURITY WAS REACHED, HE DISCOVERED HE COULD EASILY:
LEAP 1/8TH OF A MILE; HURDLE A TWENTY-STORY BUILDING . . .
RAISE TREMENDOUS WEIGHTS . . .
. . . RUN FASTER THAN AN EXPRESS TRAIN . . .
. . AND THAT NOTHING LESS THAN A BURSTING SHELL COULD PENETRATE HIS SKIN!
EARLY, CLARK DECIDED HE MUST TURN HIS TITANIC STRENGTH INTO CHANNELS THAT WOULD BENEFIT MANKIND . AND SO WAS CREATED . . .
SUPERMAN!
CHAMPION OF THE OPPRESSED, THE PHYSICAL MARVEL WHO HAD SWORN TO DEVOTE HIS EXISTENCE TO HELPING THOSE IN NEED!
A SCIENTIFIC EXPLANATION OF CLARK KENT'S AMAZING STRENGTH
KENT HAD COME FROM A PLANET WHOSE INHABITANTS' PHYSICAL STRUCTURE WAS MILLIONS OF YEARS ADVANCED OF OUR OWN. UPON REACHING MATURITY, THE PEOPLE OF HIS RACE BECAME GIFTED WITH TITANIC STRENGTH!
--INCREDIBLE? NO! FOR EVEN TODAY ON OUR WORLD EXIST CREATURES WITH SUPER-STRENGTH!
THE LOWLY ANT CAN SUPPORT WEIGHTS HUNDREDS OF TIMES ITS OWN
THE GRASSHOPPER LEAPS WHAT TO MAN WOULD BE THE SPACE OF SEVERAL CITY BLOCKS



A SCIENTIFIC EXPLANATION OF CLARK KENT'S AMAZING STRENGTH
KENT HAD COME FROM A PLANET WHOSE IN-HABITANTS' PHYSICAL STRUCTURE WAS MILL-IONS OF YEARS AD-VANCED OF OUR OWN.
UPON REACHING MATURITY, THE PEOPLE OF HIS RACE BE-CAME GIFT-ED WITH TITANIC STRENGTH!
--INCREDIBLE? NO! FOR EVEN TODAY ON OUR WORLD EXIST CREATURES WITH SUPER-STRENGTH!
THE LOWLY ANT CAN SUPPORT WEIGHTS HUNDREDS OF TIMES ITS OWN.
THE GRASSHOPPER LEAPS WHAT TO MAN WOULD BE THE SPACE OF SEV-ERAL CITY BLOCKS


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.


Uranus
Neptune
Saturn
Pluto
&
Charon
Jupiter
Sun
Mercury
Mars
Venus
Moon
Earth


50,000
10,000
1,000
100
10
1
Cube of semimajor axis (AU^3)
Pluto
Neptune
Uranus
Saturn
Jupiter
The straight line expresses
Kepler's Law of Periods
Mars
Earth
Venus
Mercury
10
100
1000
10,000
Square of orbital period (yr ^{2})

$$T^2 \propto R^3$$

$$\frac{T^2}{R^3} = CONSTANT$$

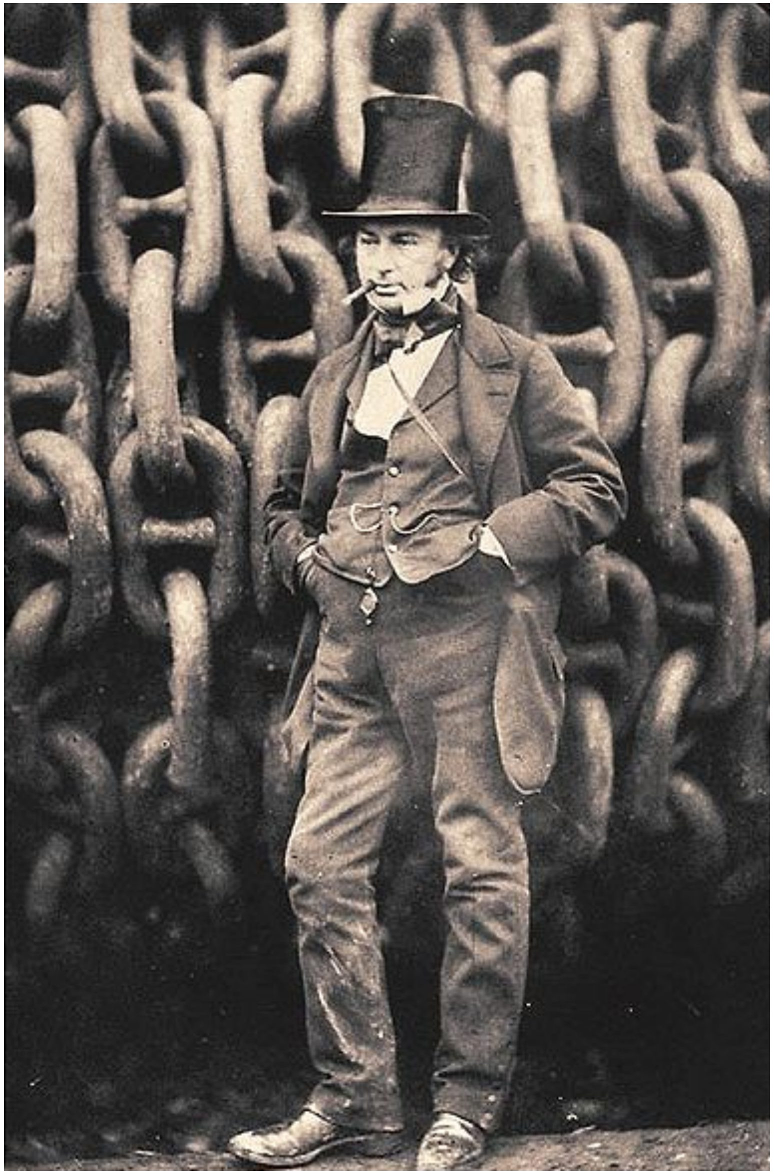
INVARIANT

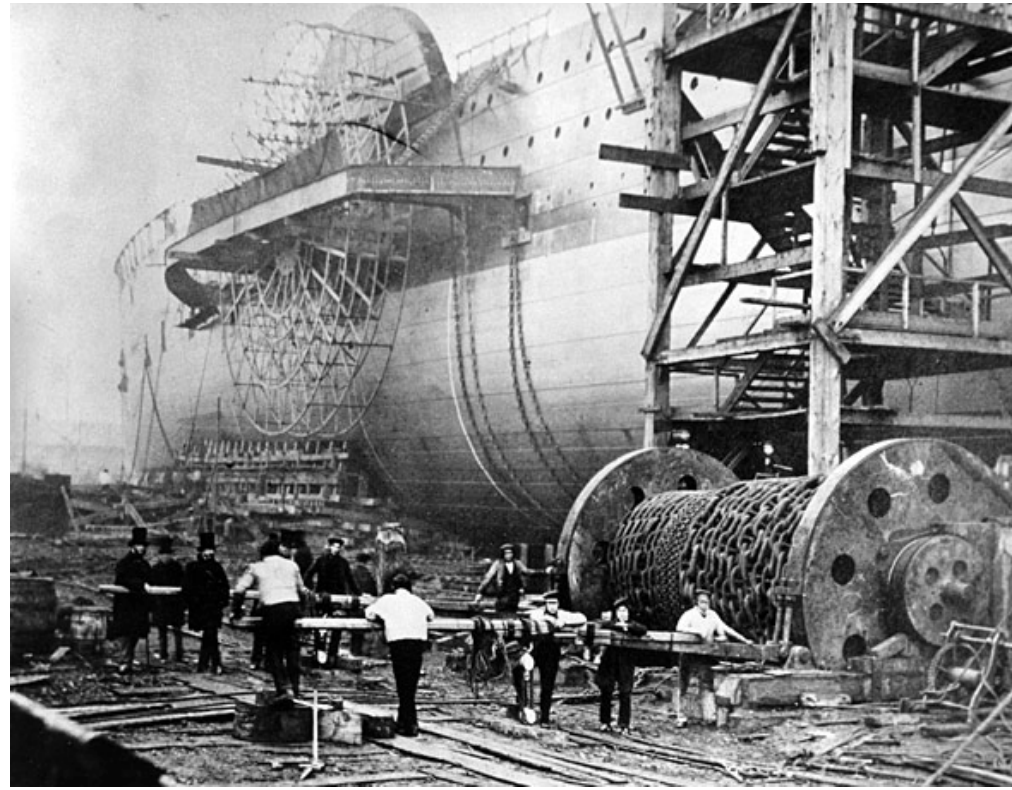
$$T \propto R^{3/2}$$

POWER LAW WITH EXPONENT b:

$$Y(X) = Y_0 X^b$$

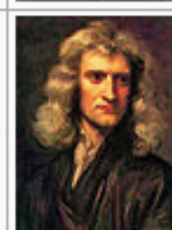
$$Y_0 = Y(1)$$





THE GREAT EASTERN (1858)

Isambard Kingdom Brunel

1	Sir Winston Churchill	(1874–1965)		Politician
2	Isambard Kingdom Brunel	(1806–1859)		Engineer
3	Diana, Princess of Wales	(1961–1997)		Member of the British Royal family. Philanthropist.
4	Charles Darwin	(1809–1882)		Naturalist
5	William Shakespeare	(1564–1616)		Poet and playwright
6	Sir Isaac Newton	(1642–1727)		Physicist, mathematician, astronomer, natural philosopher and biblical scholar

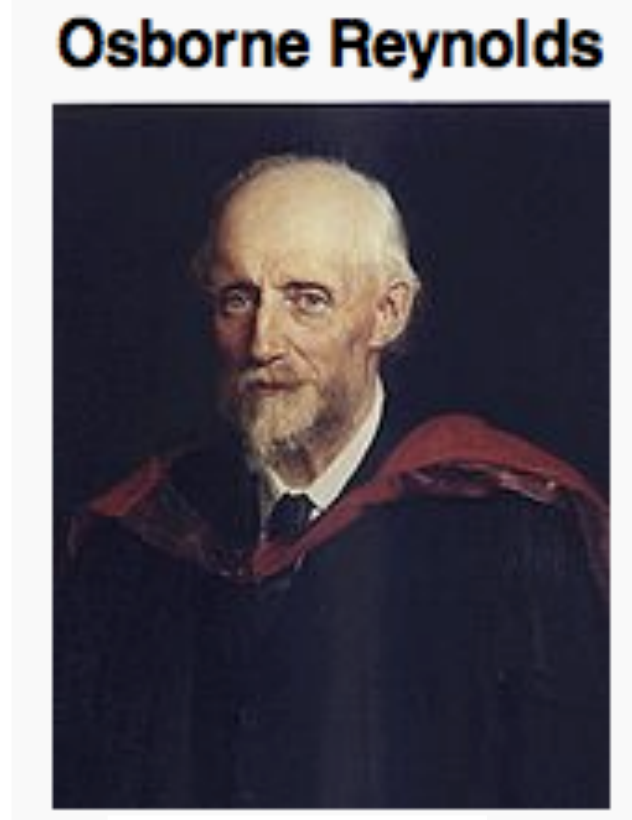
$$F \equiv \frac{v^2}{gL}$$

William Froude

MODELLING, SCALE-INVARIANCE

……by which the results of small-scale tests could be used to predict the behaviour of full-sized hulls.

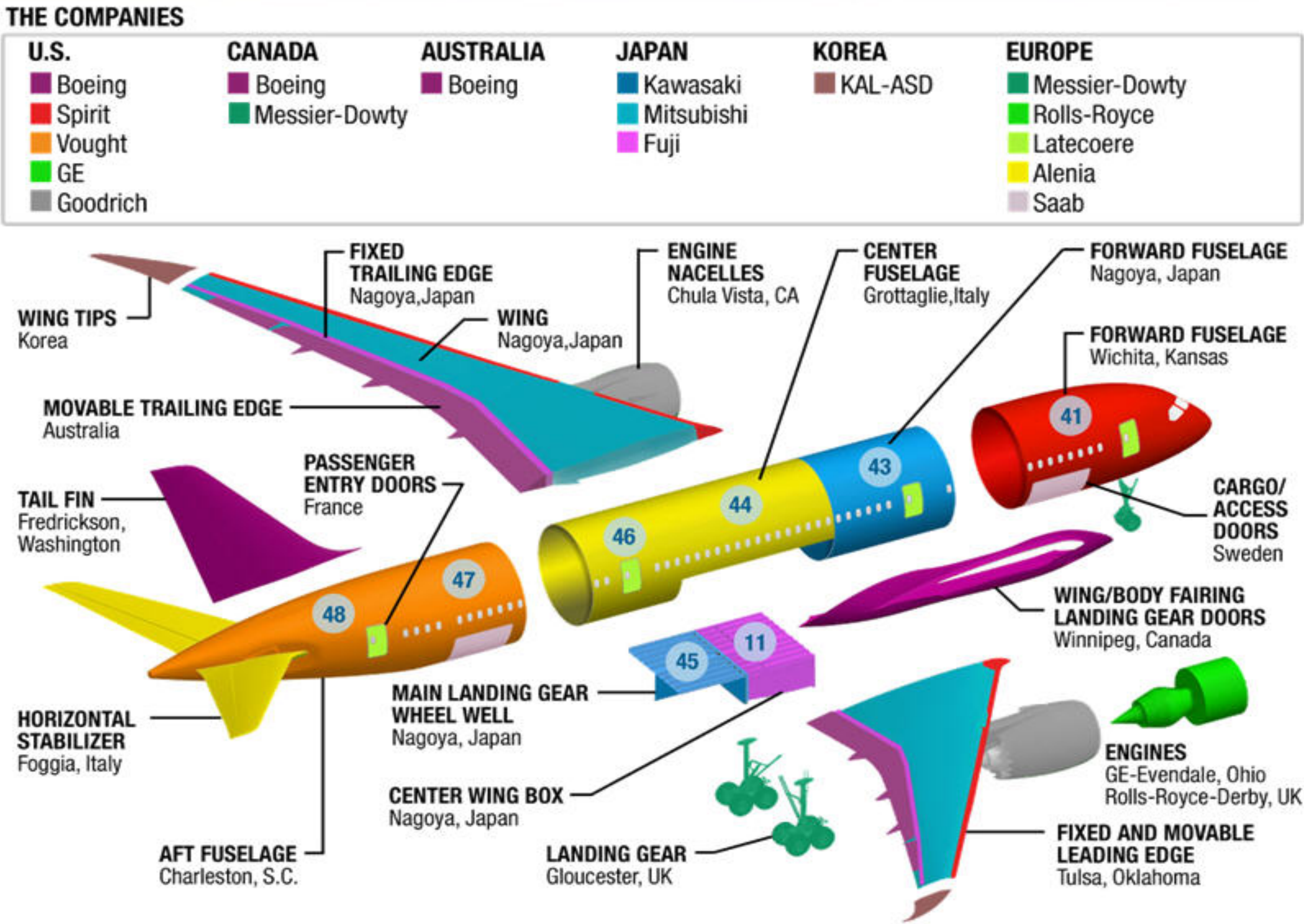
Lord Rayleigh (John Strutt)
(1842-1919)



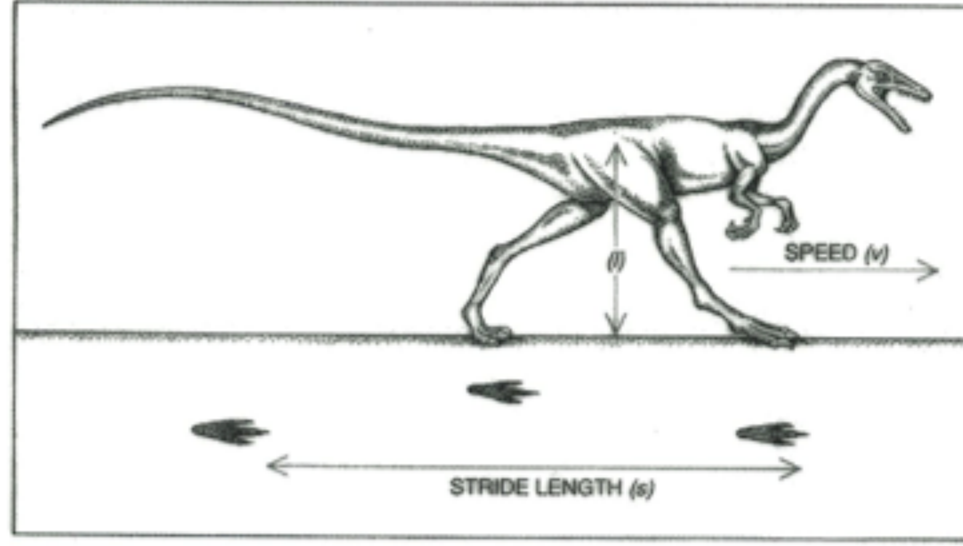
$$R = \frac{\rho v L}{\mu}$$

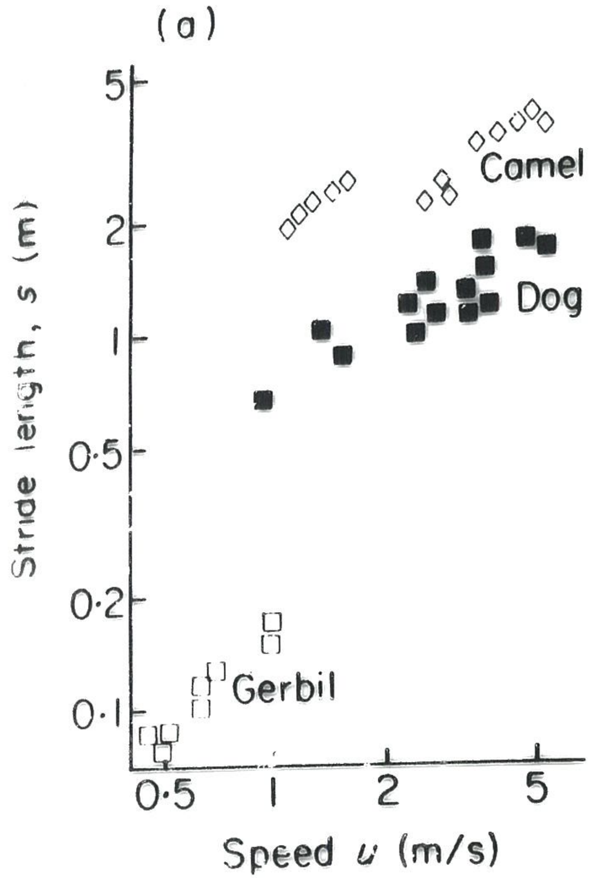
MODELLING, SCALE-INVARIANCE


WE HAVE THEM!
$150 Bicycle for $150
$150 " " $130
$150 " " $110
$150 " " $85
$135 " " $70
BARGAINS IN CHEAP WHEELS.
Do not forget "Dunlap" and "Warwick" detachable tires and hollow rims! Most $150 wheels do not have them, ours do. Come and see them.
WRIGHT CYCLE EXCHANGE,
1015 WEST THIRD ST.,
Between Williams and Baxter.



THE COMPANIES
U.S.
Boeing
Spirit
Vought
GE
Goodrich
CANADA
Boeing
Messier-Dowty
AUSTRALIA
Boeing
JAPAN
Kawasaki
Mitsubishi
Fuji
KOREA
KAL-ASD
EUROPE
Messier-Dowty
Rolls-Royce
Latecoere
Alenia
Saab
WING TIPS
Korea
FIXED TRAILING EDGE
Nagoya,Japan
WING
Nagoya,Japan
ENGINE NACELLES
Chula Vista, CA
CENTER FUSELAGE
Grottaglie,Italy
FORWARD FUSELAGE
Nagoya, Japan
FORWARD FUSELAGE
Wichita, Kansas
MOVABLE TRAILING EDGE
Australia
41
43
44
46
47
48
45
11
TAIL FIN
Fredrickson, Washington
PASSENGER ENTRY DOORS
France
CARGO/ ACCESS DOORS
Sweden
WING/BODY FAIRING LANDING GEAR DOORS
Winnipeg, Canada
MAIN LANDING GEAR WHEEL WELL
Nagoya, Japan
HORIZONTAL STABILIZER
Foggia, Italy
CENTER WING BOX
Nagoya, Japan
ENGINES
GE-Evendale, Ohio
Rolls-Royce-Derby, UK
AFT FUSELAGE
Charleston, S.C.
LANDING GEAR
Gloucester, UK
FIXED AND MOVABLE LEADING EDGE
Tulsa, Oklahoma





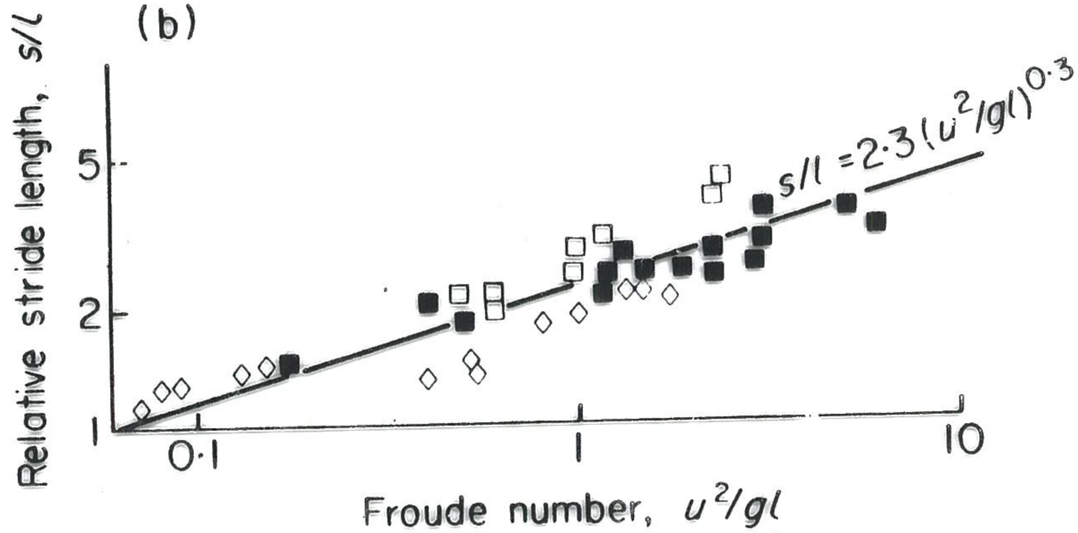


Fig. 1.17(a) Graphs of stride length (s) against speed (u) for several mammals. (b) Graphs of relative stride length (s/l) against Froude number (u^2/gl), based on the same data (l is leg length). The data are from films taken by the author and his associates.

DINOSAUR TRACKS provide a record of stride length and speed. A small, three-toed carnivore may have pursued a larger sauropod along this Texan trail. This pair of footprints was discovered by Ronald T. Bird at Paluxy Creek in 1944.

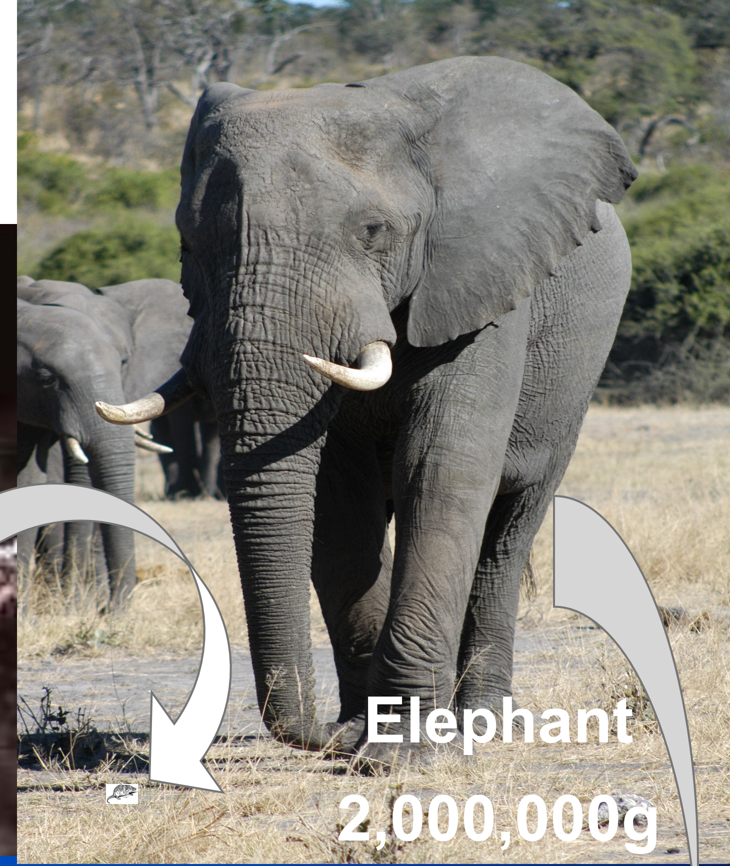
SCALABILITY

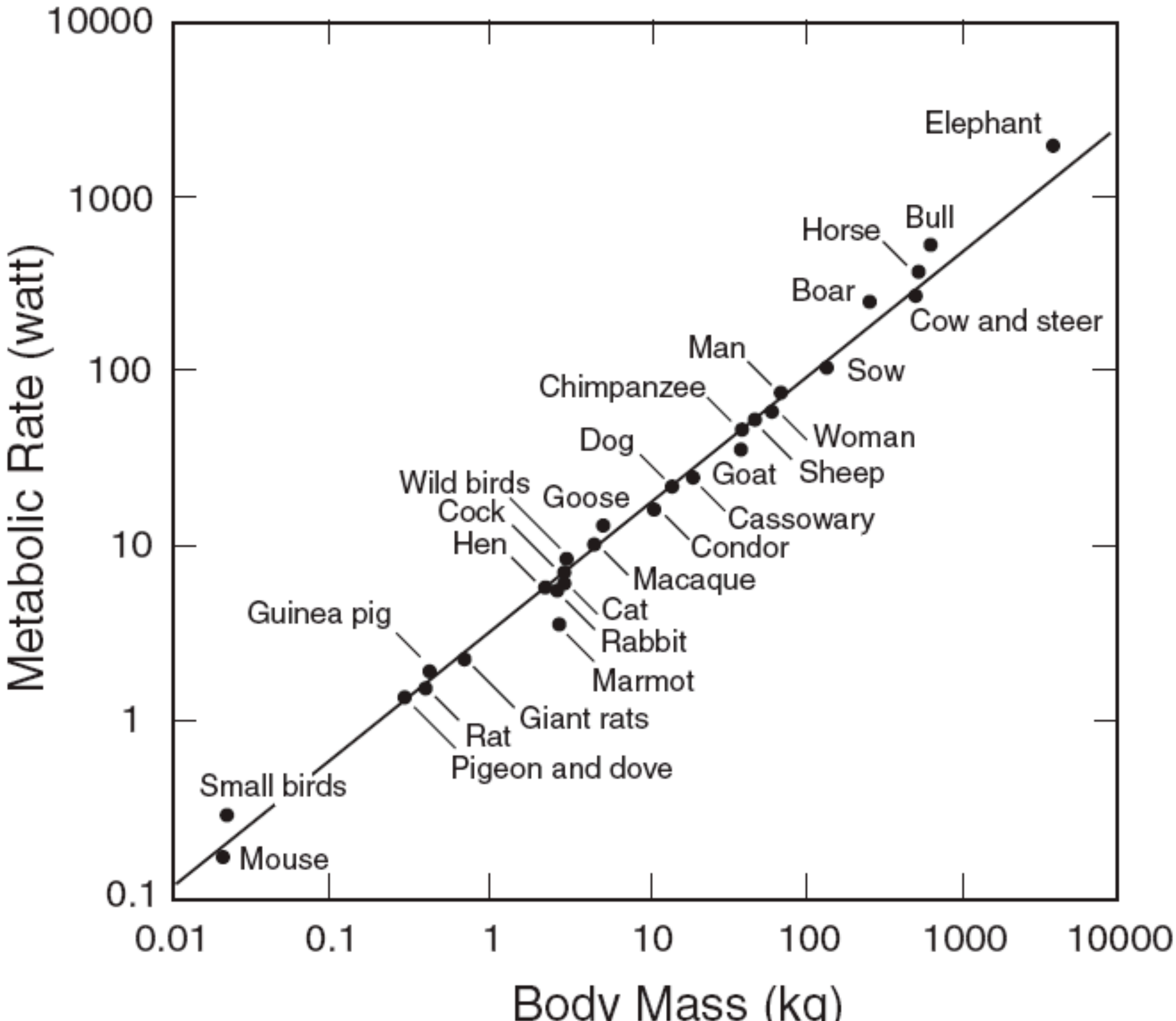
RESILIENCE

EVOLVABILITY

GROWTH

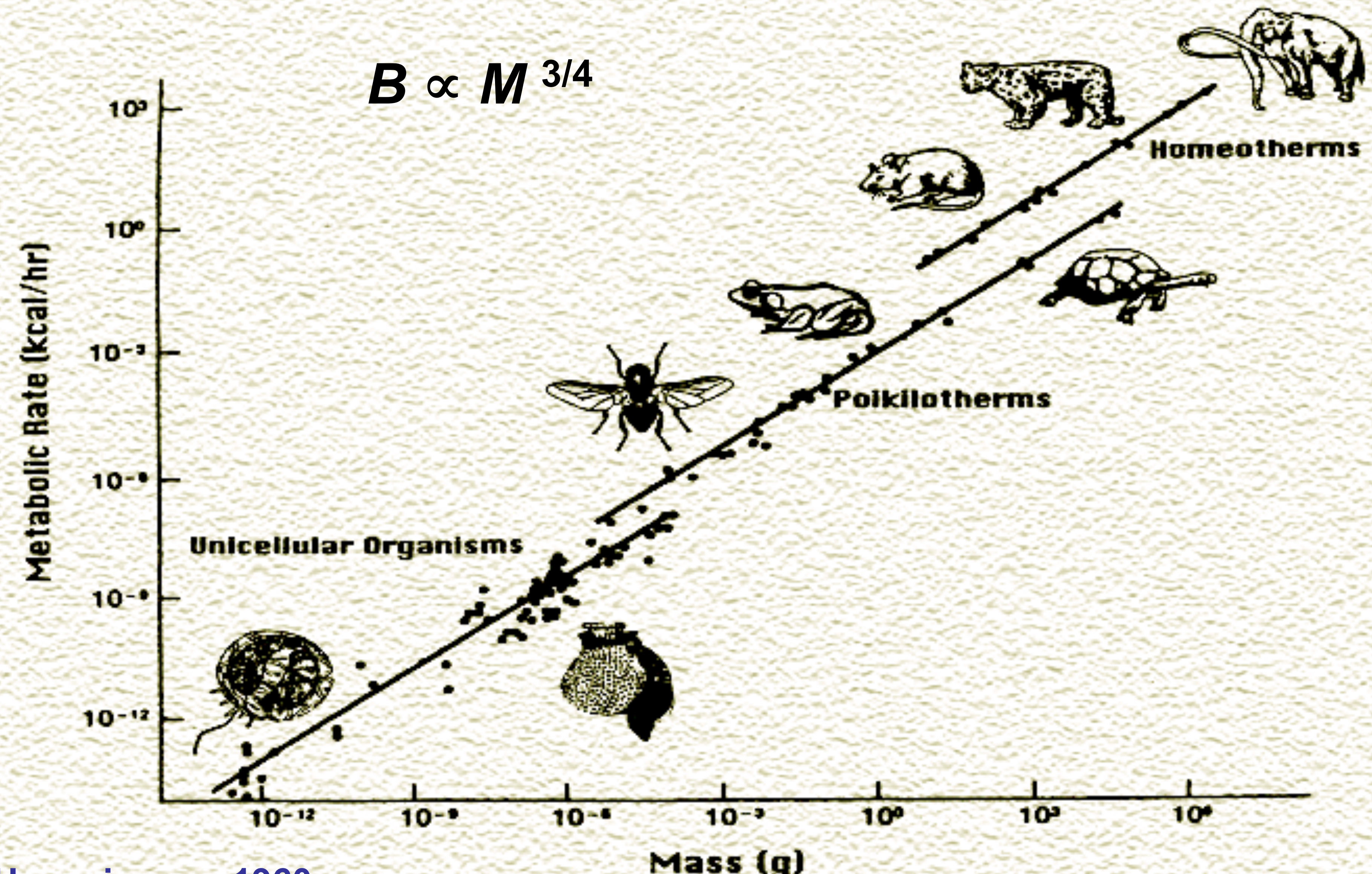
Mammals vary in size by 8 orders of magnitude





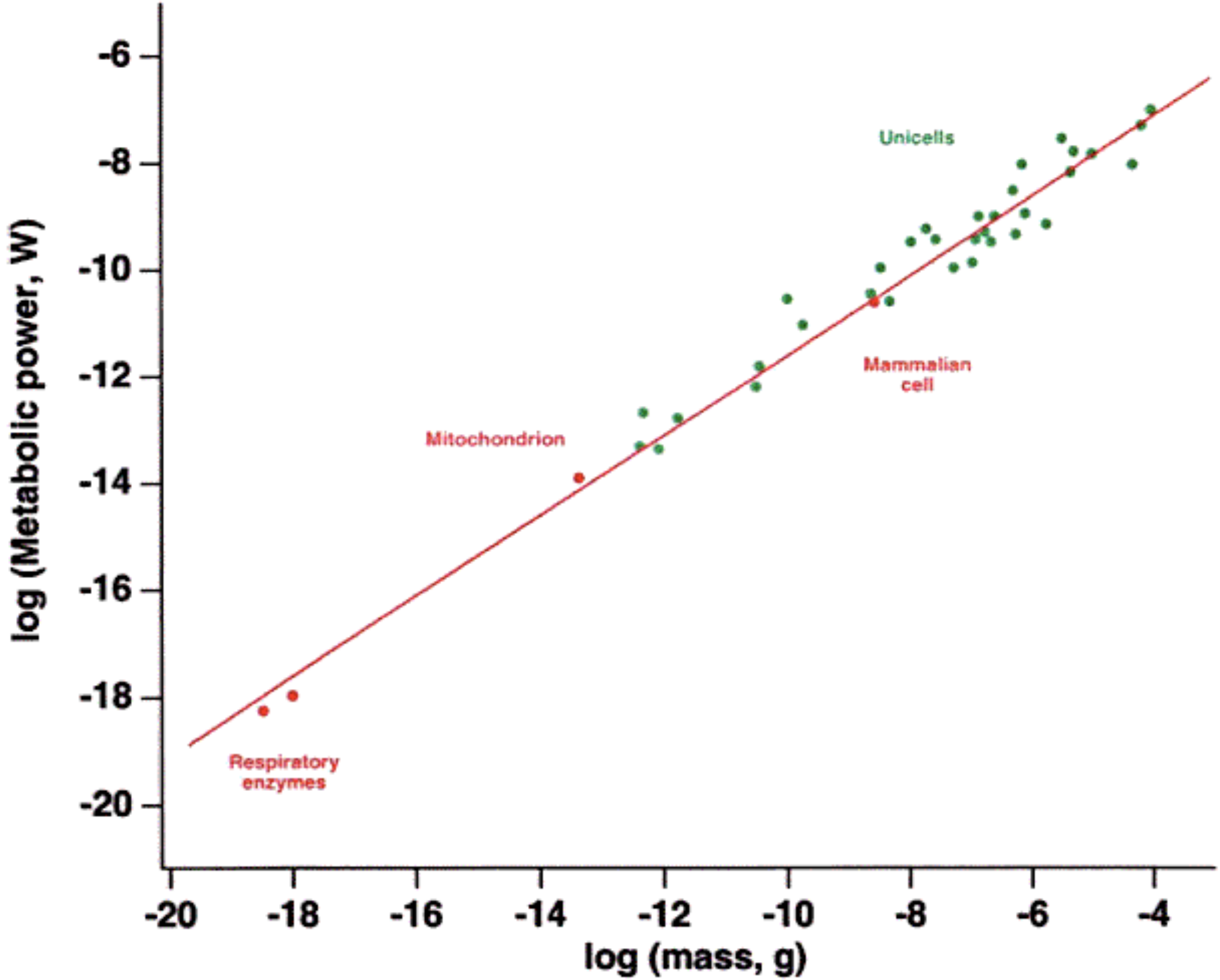
SLOPE = ¾ < 1; SUB-LINEAR; ECONOMY OF SCALE

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

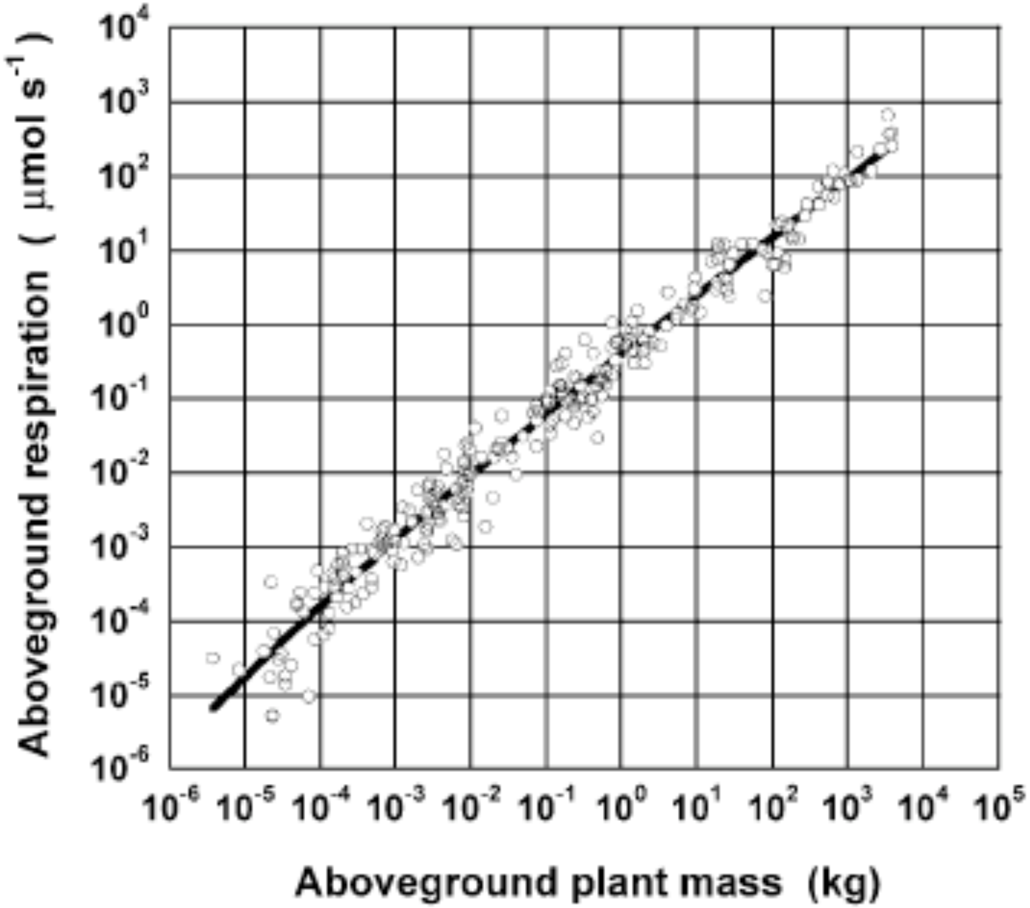


Hemmingson 1960

WEST, BROWN & WOODRUFF, PNAS 2001



PLANTS/TREES



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

SINCE $N_{cells} \sim M$ NAIVELY MIGHT EXPECT $B \sim M$

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

OVER 27 ORDERS OF MAGNITUDE

SPECIFIC METABOLIC RATE (PER UNIT MASS)

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

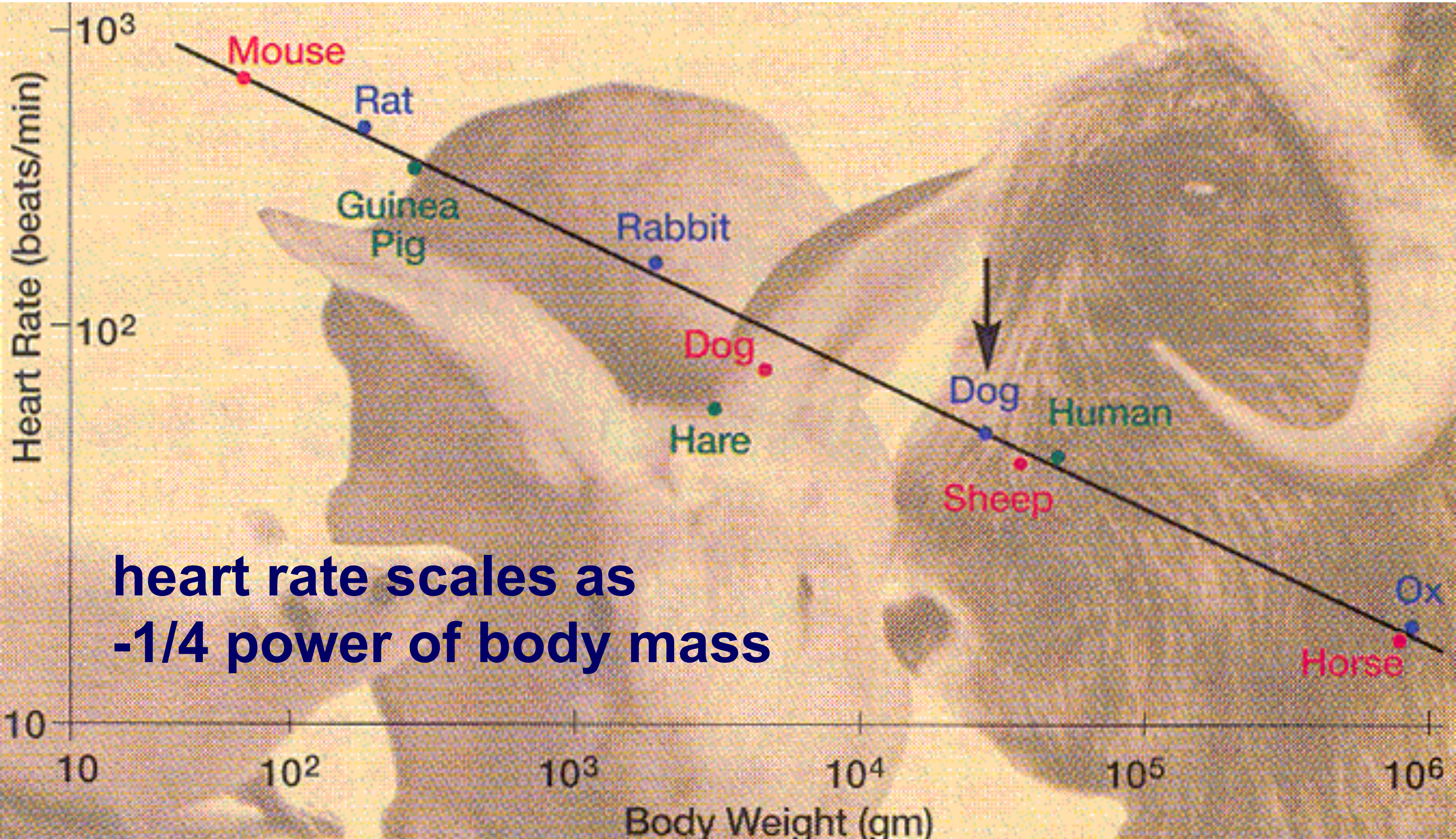
SO METABOLIC RATE OF AVERAGE CELL

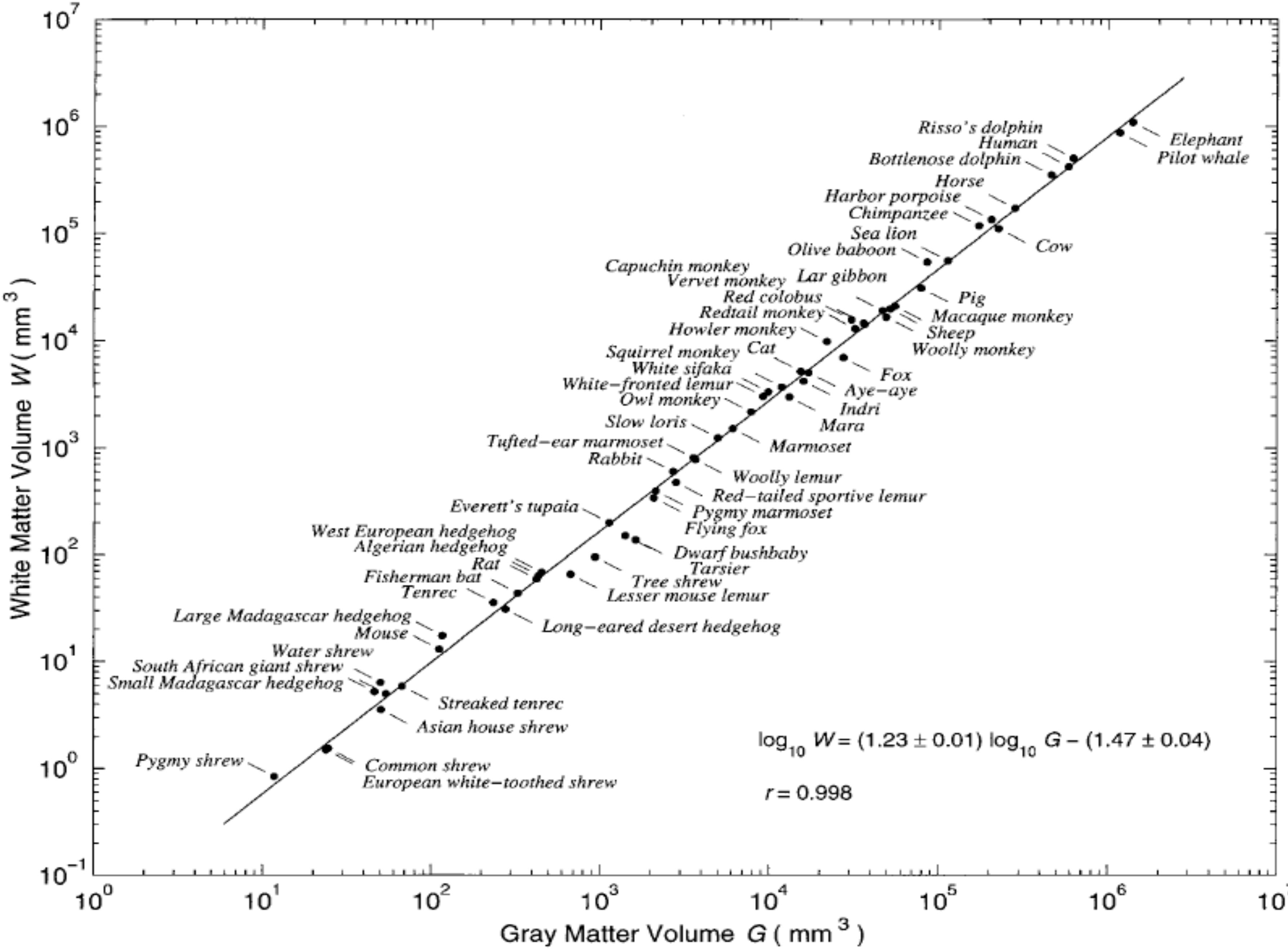
$$B_{cell} \propto M^{-1/4}$$

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

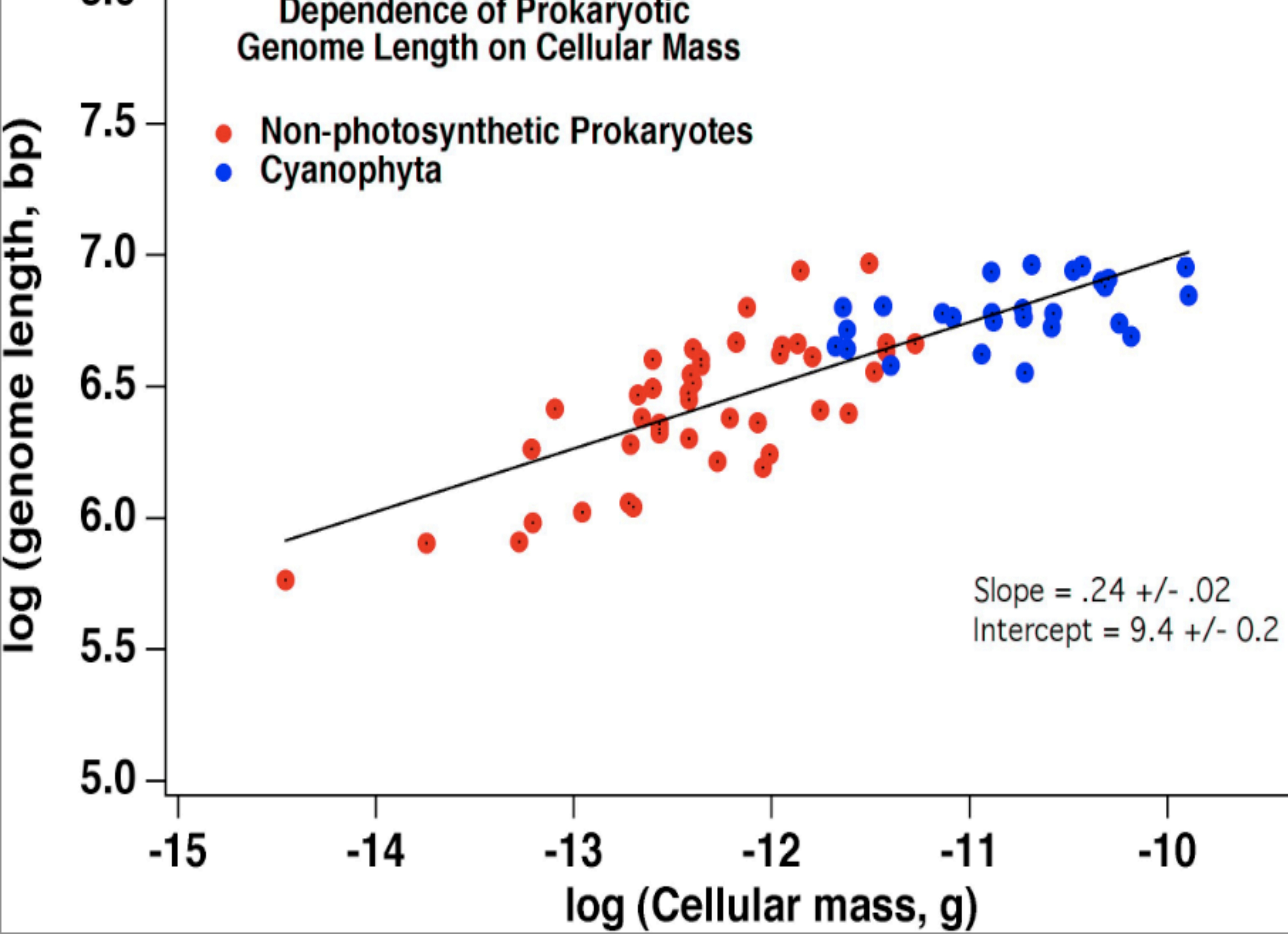
SIMILAR SCALING HOLDS TRUE FOR ALL PHYSIOLOGICAL PROCESSES AND LIFE HISTORY EVENTS OVER THE ENTIRE SPECTRUM OF LIFE

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





White Matter Volume W (mm^3)
Gray Matter Volume G (mm^3)
Risso's dolphin
Human
Bottlenose dolphin
Elephant
Pilot whale
Horse
Harbor porpoise
Chimpanzee
Sea lion
Cow
Olive baboon
Capuchin monkey
Vervet monkey
Lar gibbon
Pig
Red colobus
Redtail monkey
Macaque monkey
Sheep
Howler monkey
Woolly monkey
Squirrel monkey
Cat
Fox
White sifaka
White−fronted lemur
Aye−aye
Owl monkey
Indri
Slow loris
Mara
Marmoset
Tufted−ear marmoset
Rabbit
Woolly lemur
Red−tailed sportive lemur
Everett's tupaia
Pygmy marmoset
Flying fox
West European hedgehog
Algerian hedgehog
Dwarf bushbaby
Rat
Tarsier
Fisherman bat
Tree shrew
Tenrec
Lesser mouse lemur
Large Madagascar hedgehog
Long−eared desert hedgehog
Mouse
Water shrew
South African giant shrew
Small Madagascar hedgehog
Streaked tenrec
Asian house shrew
Pygmy shrew
Common shrew
European white−toothed shrew
$\log_{10} W = (1.23 \pm 0.01)\log_{10} G - (1.47 \pm 0.04)$
$r = 0.998$


Dependence of Prokaryotic
Genome Length on Cellular Mass
Non-photosynthetic Prokaryotes
Cyanophyta
Slope = .24 +/- .02
Intercept = 9.4 +/- 0.2
log (genome length, bp)
7.5
7.0
6.5
6.0
5.5
5.0
-15
-14
-13
-12
-11
-10
log (Cellular mass, g)

LIFESPAN

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

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

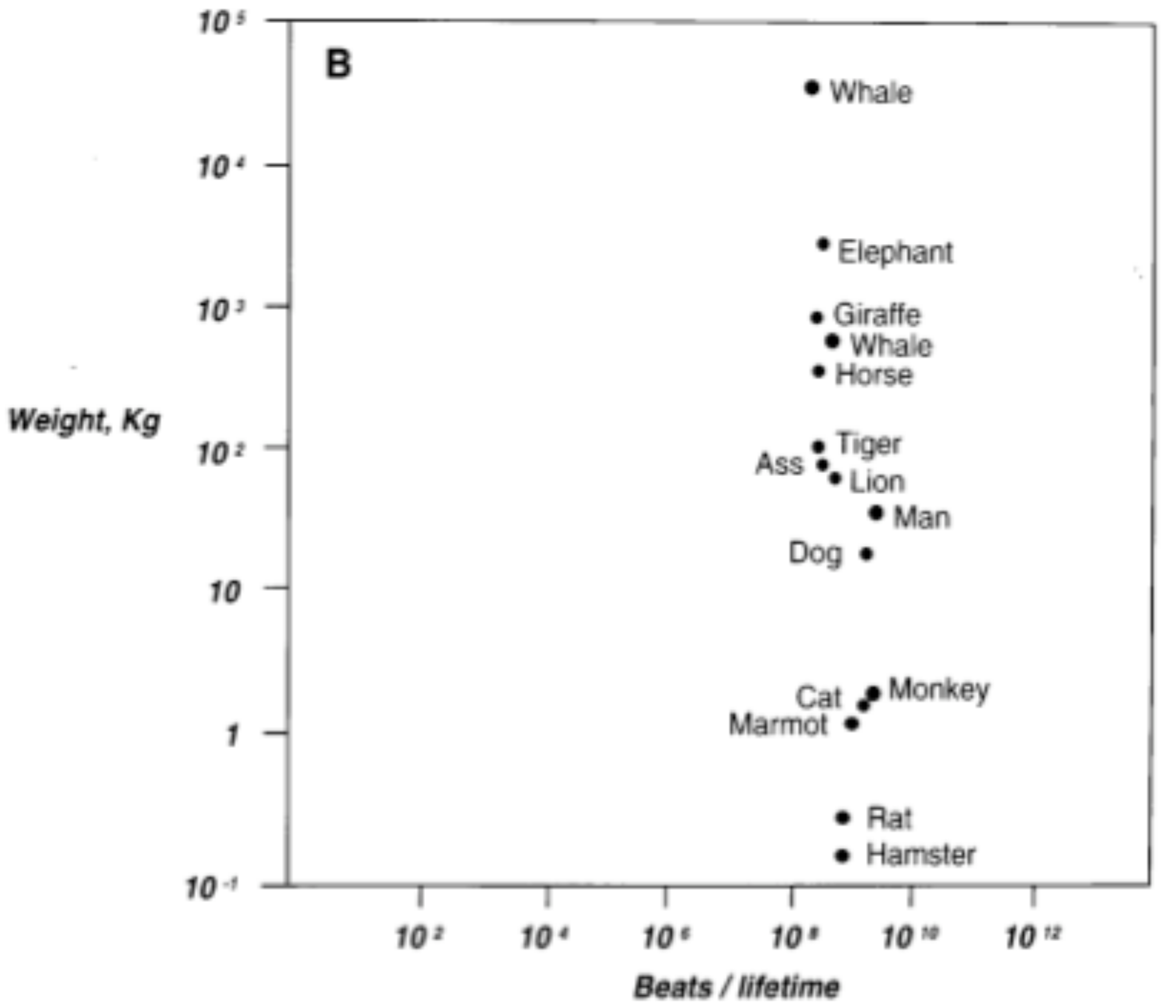
$$\sim M^{-1/4}$$

$\Rightarrow$ 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)

MORE FUNDAMENTALLY, ACROSS AEROBIC METABOLISM: THE NUMBER OF TURNOVERS IN A LIFETIME OF CytO ENZYMES (RESPIRATORY COMPLEX) IS AN APPROXIMATE INVARIANT (~ 10^{16})



LIFE IS THE MOST COMPLEX SYSTEM

SCALING LAWS ARE REMARKABLE BECAUSE

i) THEY EXIST

ii) THEY ARE VERY SIMPLE

iii) THEY ARE UNIVERSAL

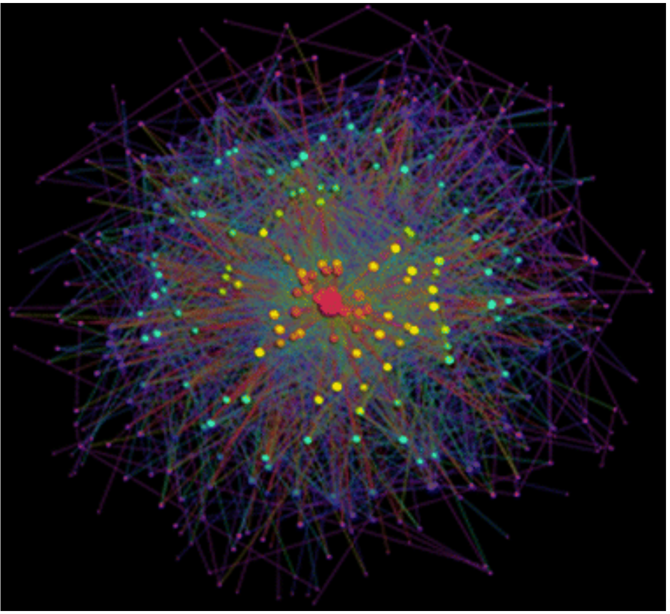
DOMINANCE OF 1/4 POWER

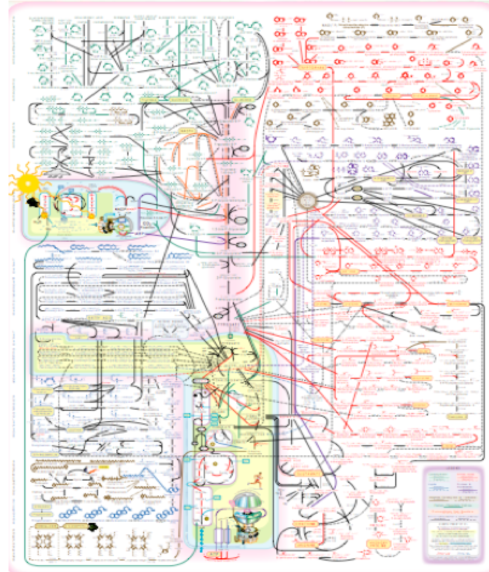
iv) ⇒ BIGGER IS MORE EFFICIENT

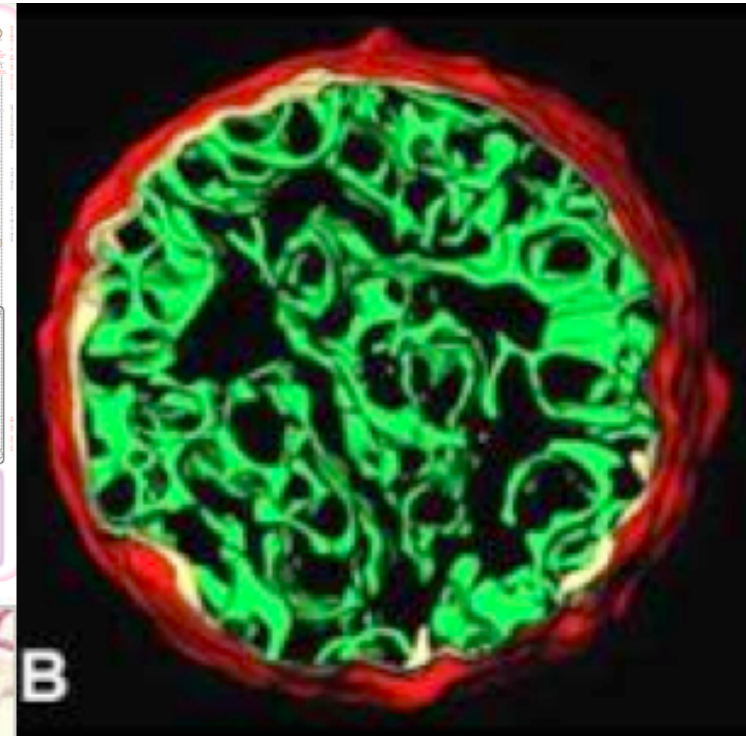
v) FEW QUANTITATIVE "LAWS" IN BIOLOGY

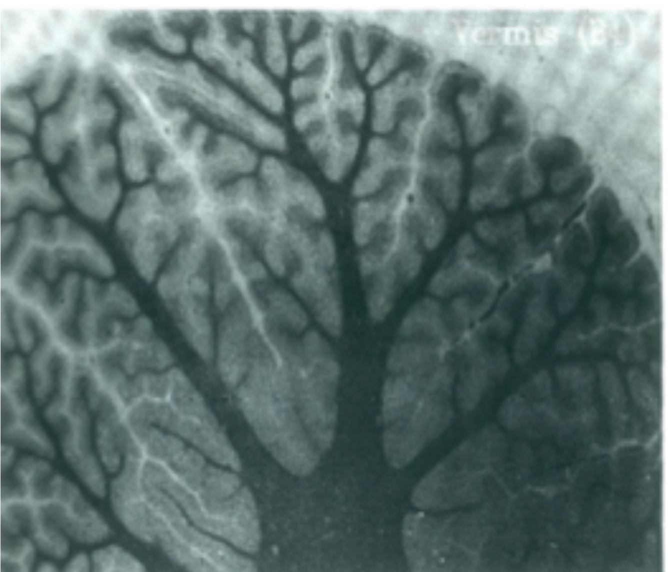
NETWORKS!!!

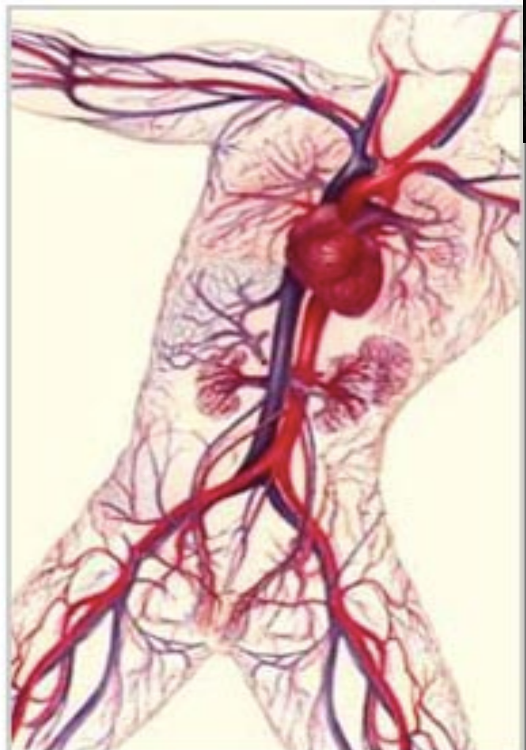
(FRACTAL - LIKE)

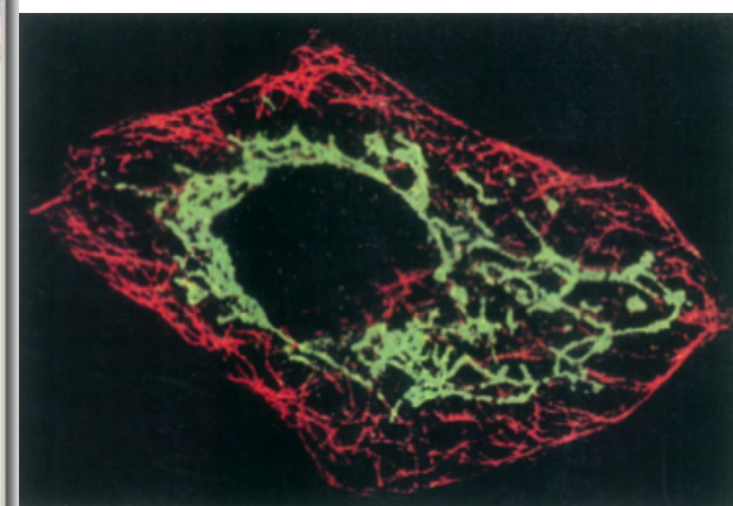





B


Vermis (E)





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

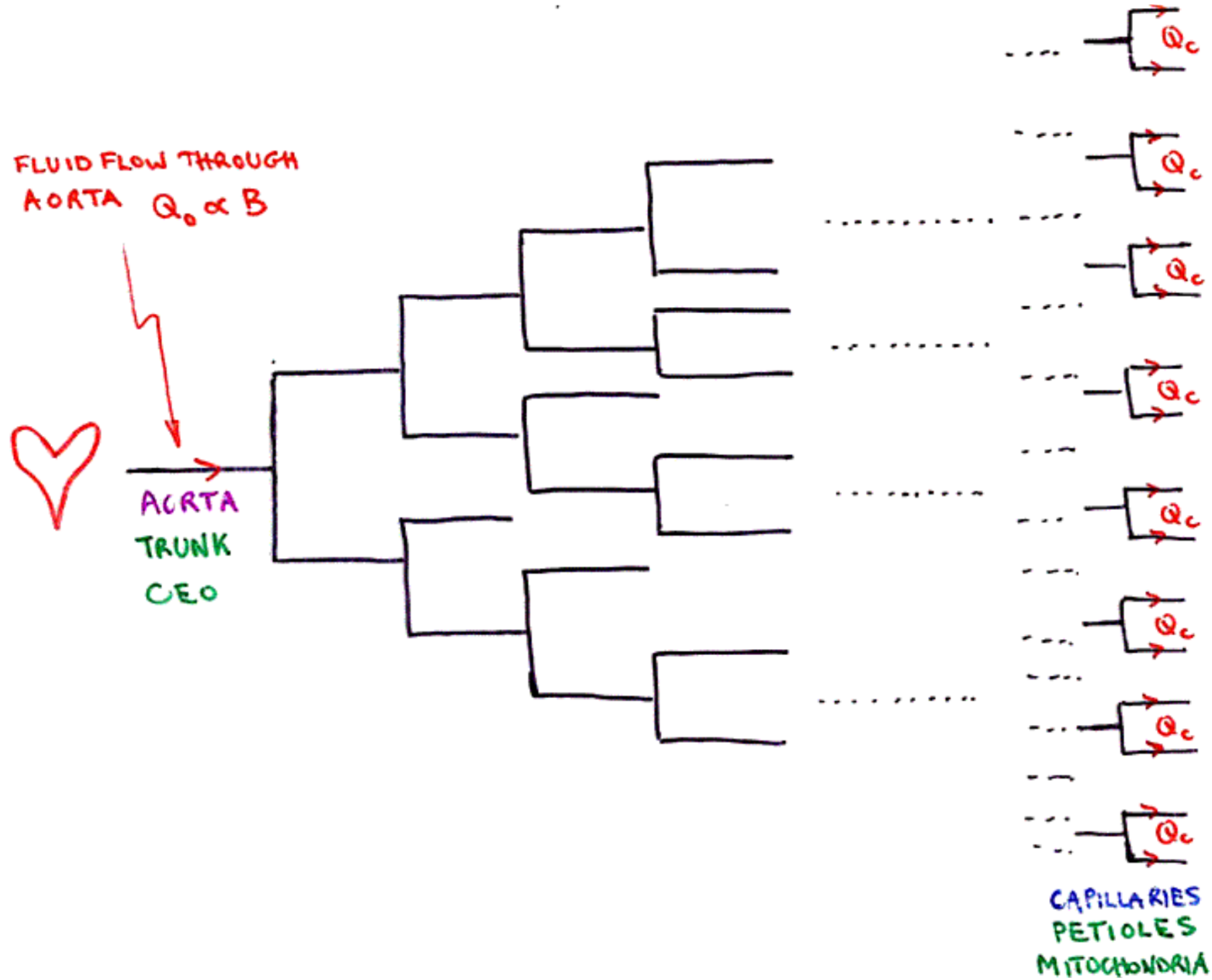
III. THE TERMINAL BRANCHES OF THE NETWORK ARE INVARIANT UNITS

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,……..



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)

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

TOTAL NUMBER OF CAPILLARIES

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

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

TOTAL NUMBER OF CELLS

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

TOTAL NUMBER OF CAPILLARIES

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

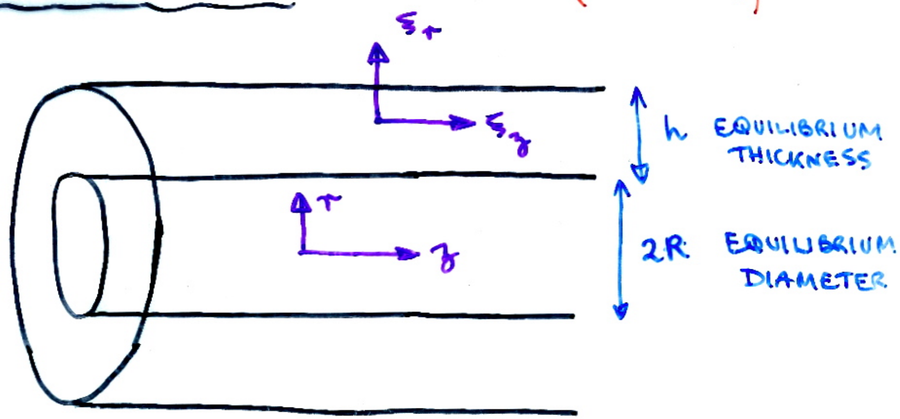
MISMATCH!

$\Rightarrow$ 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 : $\rho \dfrac{Dv_i}{Dt} = \partial_j \theta_{ij}$ NAVIER-STOKES EQ^{N}.

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

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

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 $\displaystyle\int_{\text{SURFACE}} \theta_{ij}\, dS_j$ 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 $c = \dfrac{\omega}{k}$ PHASE VELOCITY

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

YOUNG'S MODULUS

POISSON RATIO

[KORTEWEG - MOENS VELOCITY, FIRST DERIVED BY YOUNG]

TYPICALLY $kR = \dfrac{2\pi R}{\lambda} << 1$ 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$^{\text{NS}}$

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

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

$$F(r_k, l_k, n, M) = \underbrace{\dot{E}(M)}_{\sim M^a} + \lambda\Big[\sum_{k=0}^{N} \pi r_k^2 l_k n^k - \underbrace{V_b(M)}_{\sim M^b}\Big]$$

$$+ \sum_{k=0}^{N} \lambda_k \big[n^k l_k^3 - \underbrace{V_N(M)}_{N_c l_c^3 \sim M^a}\big] + \lambda_M M$$

FOR FIXED M, AS ABOVE ;

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

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

IE, $\underline{V_b \sim M}$

IN d DIMENSIONS

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

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

$\Rightarrow$ "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

AREA

NON-FRACTAL : $M^{2/3}$ 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		Branch radius		
	Exponent predicted	Symbol	Symbol	Exponent	
				Predicted	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

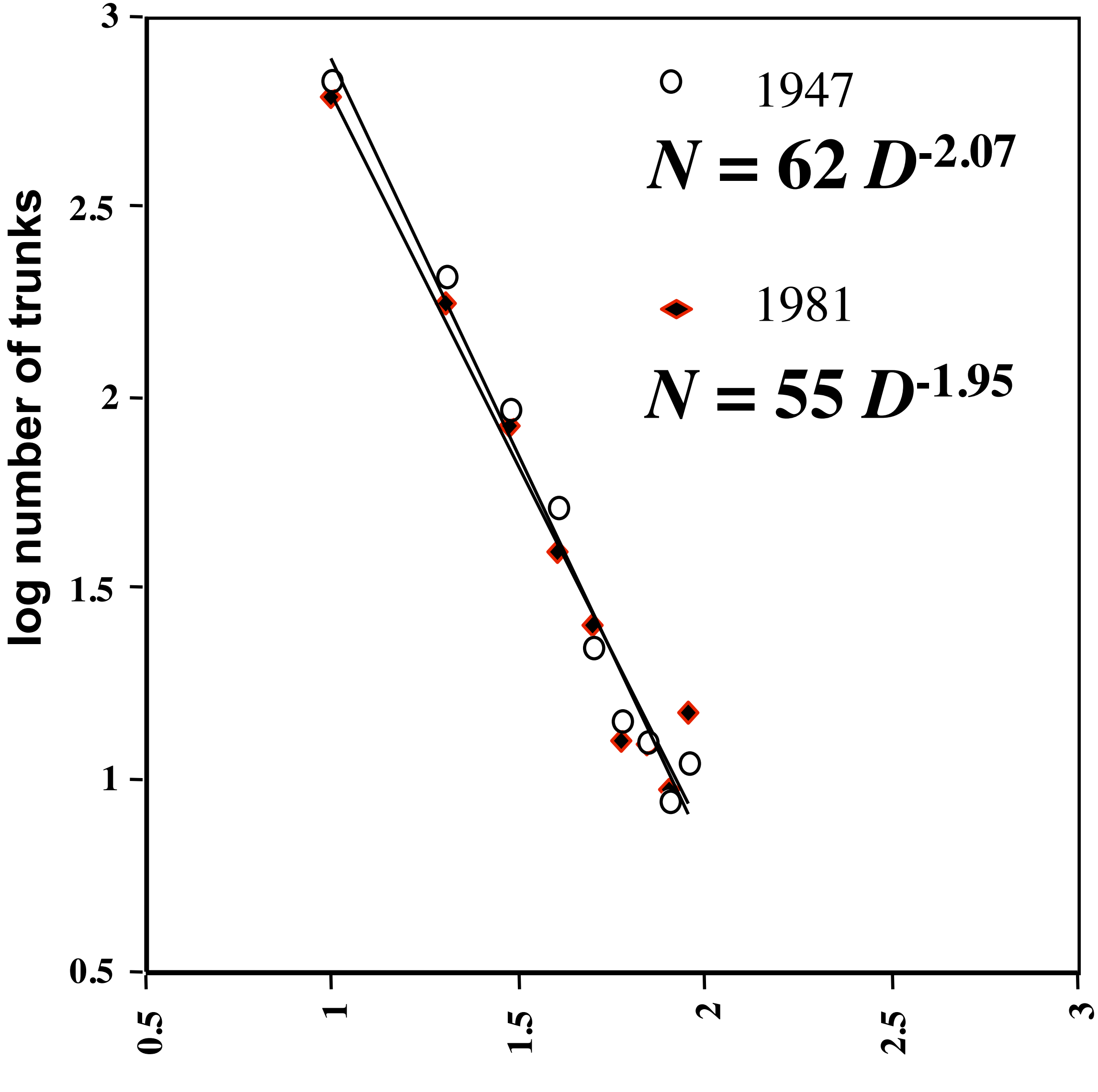
VERY DIFFERENT EVOLVED ENGINEERING DESIGN (NON-PULSATILE FIBRE BUNDLES) BUT SAME NETWORK PRINCIPLES

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*)*

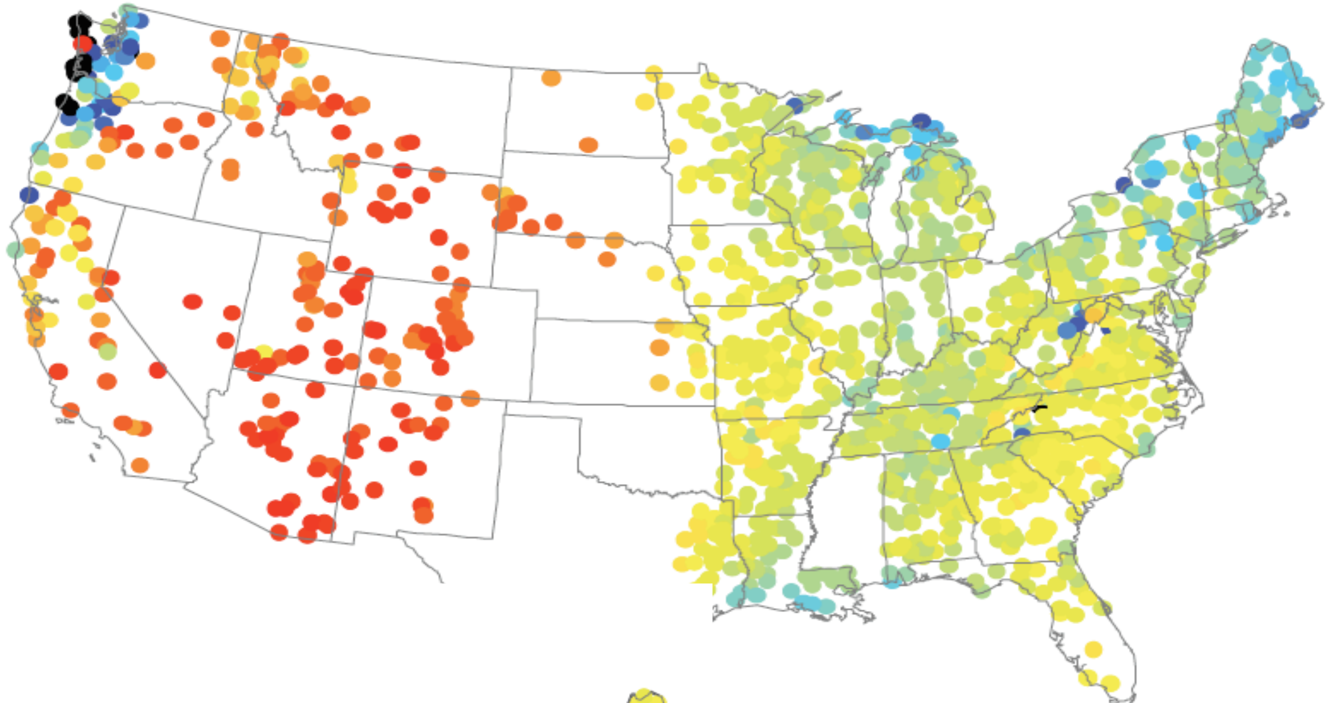
Scaling quantity	Individual tree	Entire forest
Area preserving	$\frac{R_{i+1}}{R_i} = \frac{1}{n^{1/2}}$	$\frac{r_{k+1}}{r_k} = \frac{1}{\lambda^{1/2}}$
Space filling	$\frac{L_{i+1}}{L_i} = \frac{1}{n^{1/3}}$	$\frac{l_{k+1}}{l_k} = \frac{1}{\lambda^{1/3}}$
Biomechanics	$R_i^2 = L_i^3$	$r_k^2 = l_k^3$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

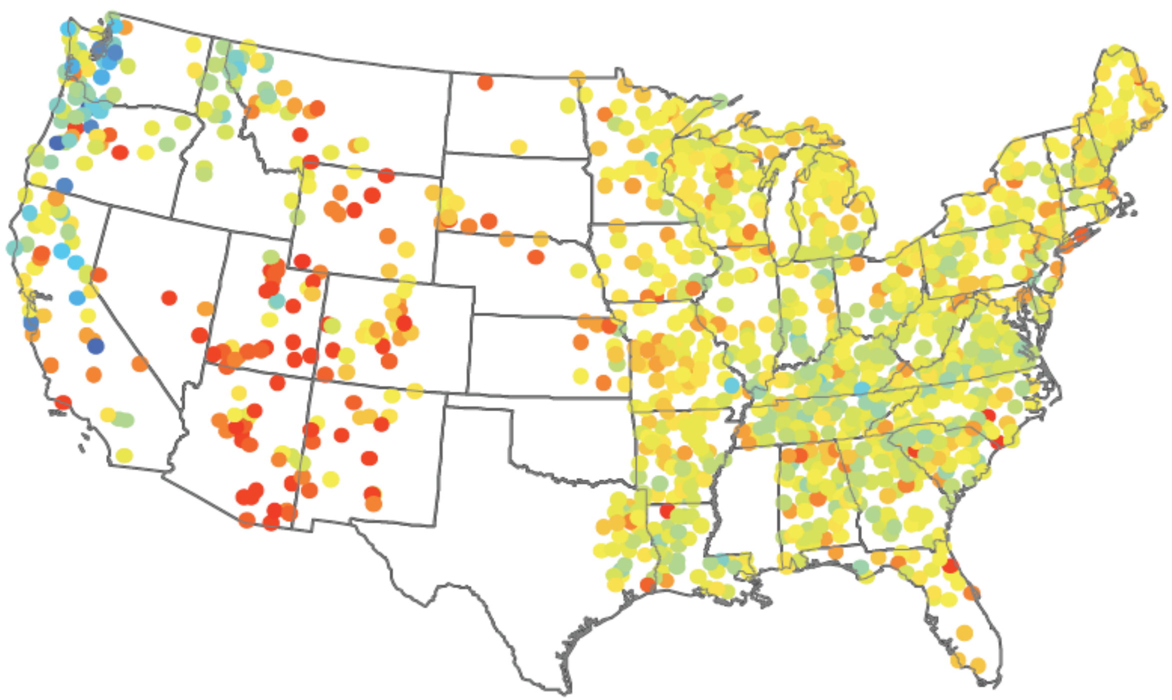
Stand property	Predicted stem radius, r_k, based scaling function
Size class neighbor separation	$d_k \propto r_k$
Canopy scaling	$r_k^{\mathrm{can}} \propto r_k^{2/3}$
Canopy spacing	$d_k^{\mathrm{can}} = c_1 r_k \left[1 - \left(\frac{r_{\bar{k}}}{r_k} \right)^{1/3} \right]$
Energy Equivalence	$\Delta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

$$\left.\begin{array}{l}\text{BLOOD PRESSURE} \sim M^0 \\ \text{AORTA BLOOD VELOCITY} \sim M^0\end{array}\right\}\ \text{INVARIANT !}$$

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

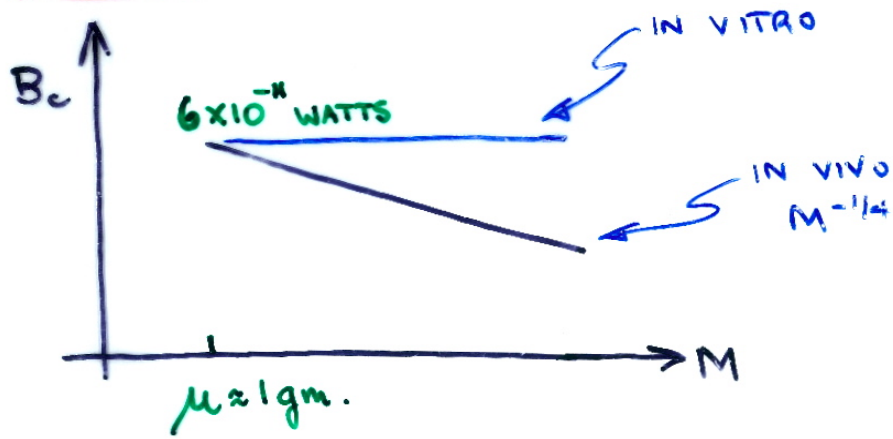
(CONTROLS FUNDAMENTAL BIOCHEMICAL RATES)

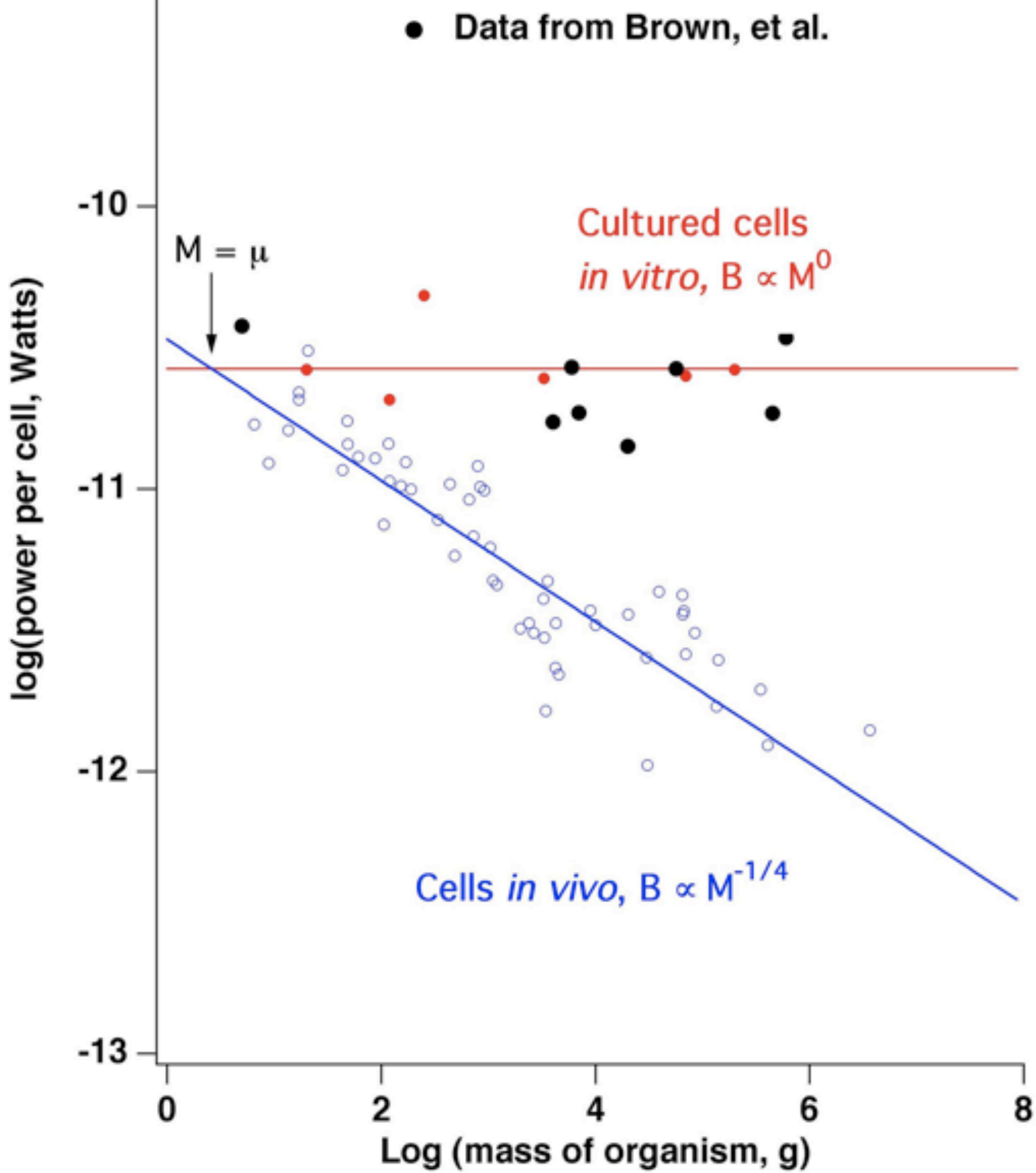
⇒ IF THE NETWORK WERE REMOVED SO CELLS

BECOME FREE (IN VITRO) B_c SHOULD BECOME

INDEPENDENT OF WHAT MAMMAL THEY ORIGINATED

IN: <u>PREDICT</u>



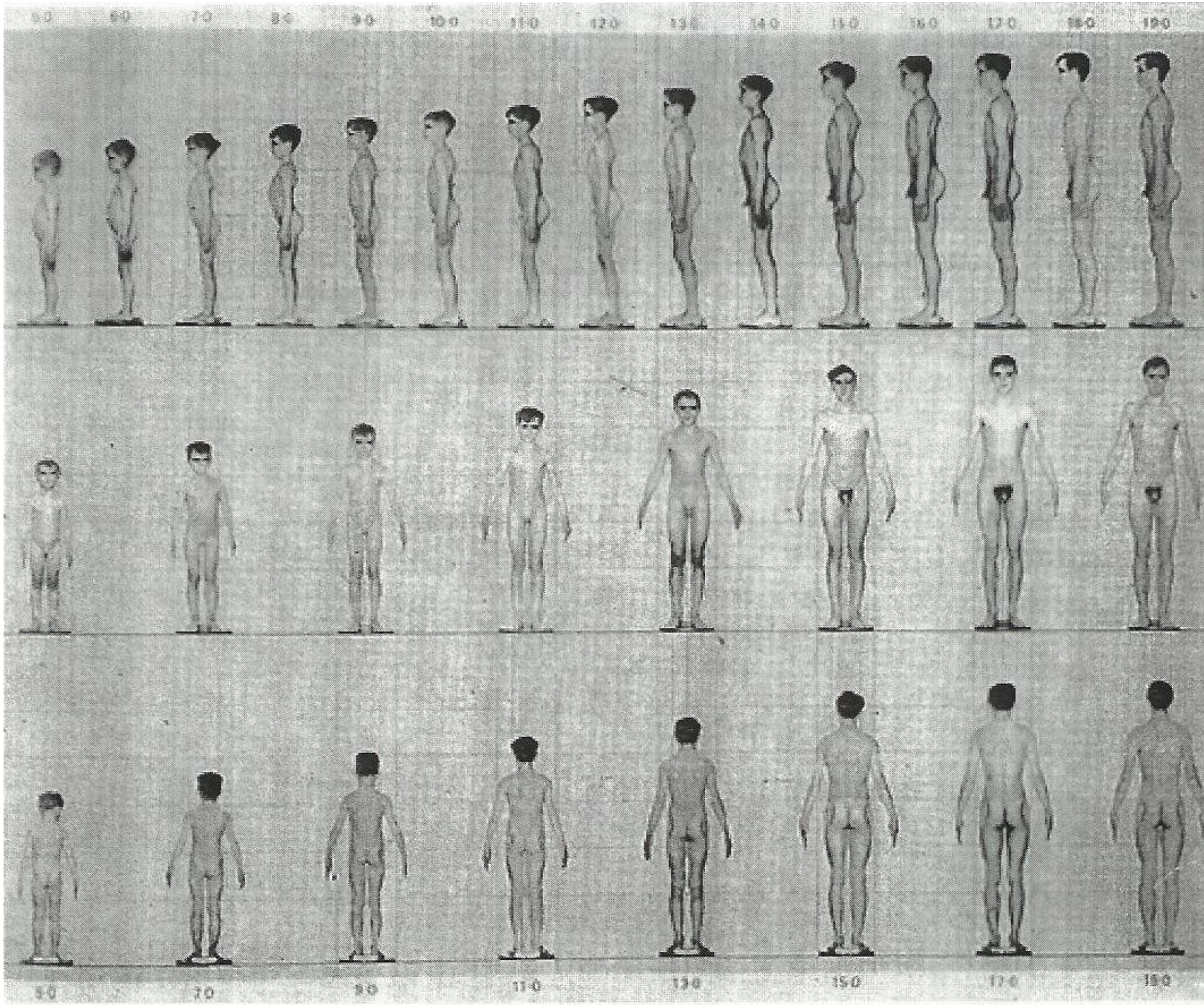


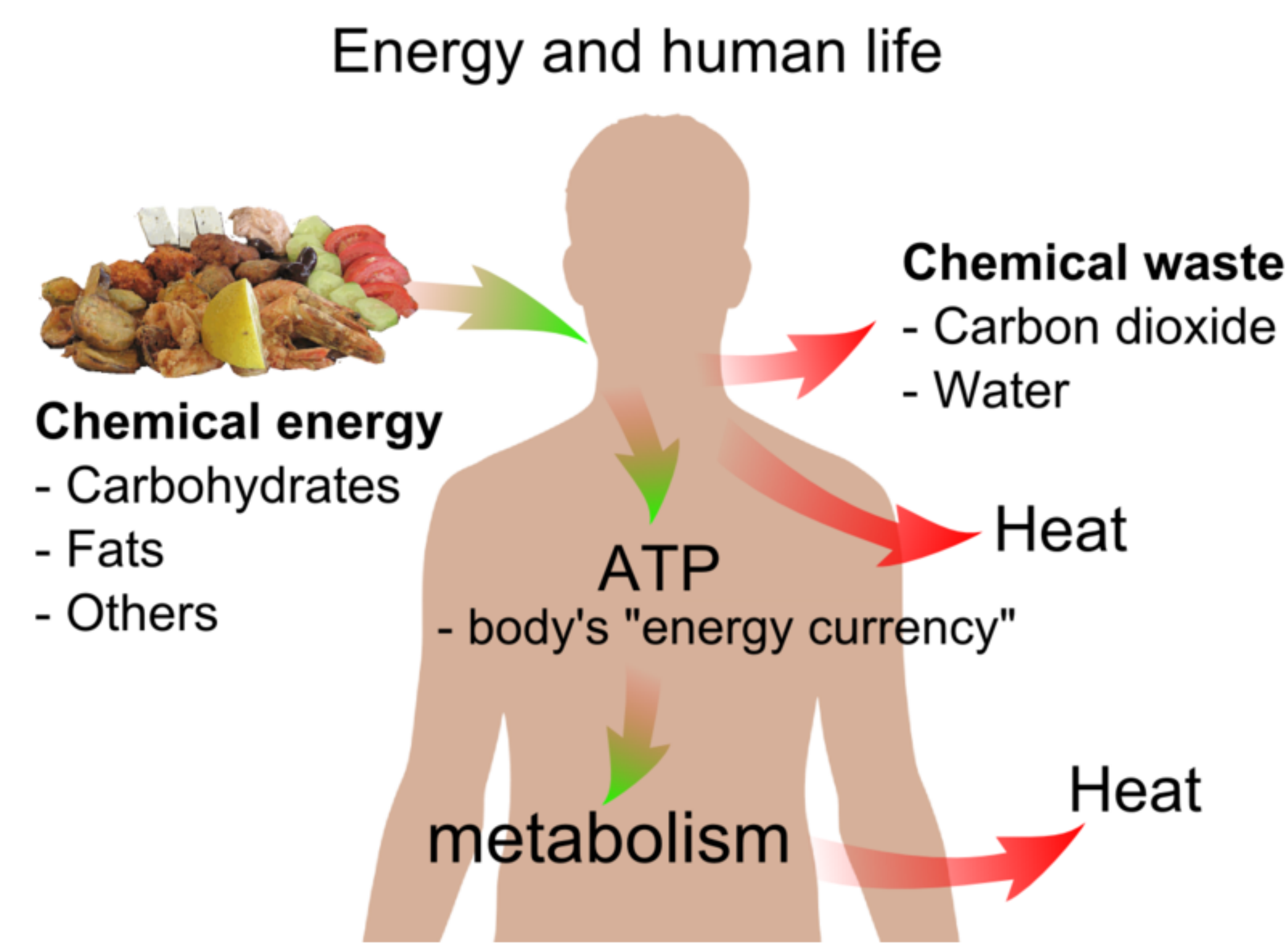
Data from Brown, et al.
-10
-11
-12
-13
M = μ
Cultured cells
in vitro, B ∝ M^0
Cells in vivo, B ∝ M^-1/4
log(power per cell, Watts)
0
2
4
6
8
Log (mass of organism, g)

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

$$B_{cell} \propto \frac{B}{M} = B_0 M^{-1/4}$$

THE PACE OF LIFE SYSTEMATICALLY SLOWS WITH INCREASING SIZE





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

INCOMING METABOLISED ENERGY

↓

MAINTENANCE
(of existing cells)

+

GROWTH
(of new cells)

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

IN TERMS OF MASS AT AGE t

$$\Rightarrow \frac{dm}{dt} = am^{3/4} - bm$$

where

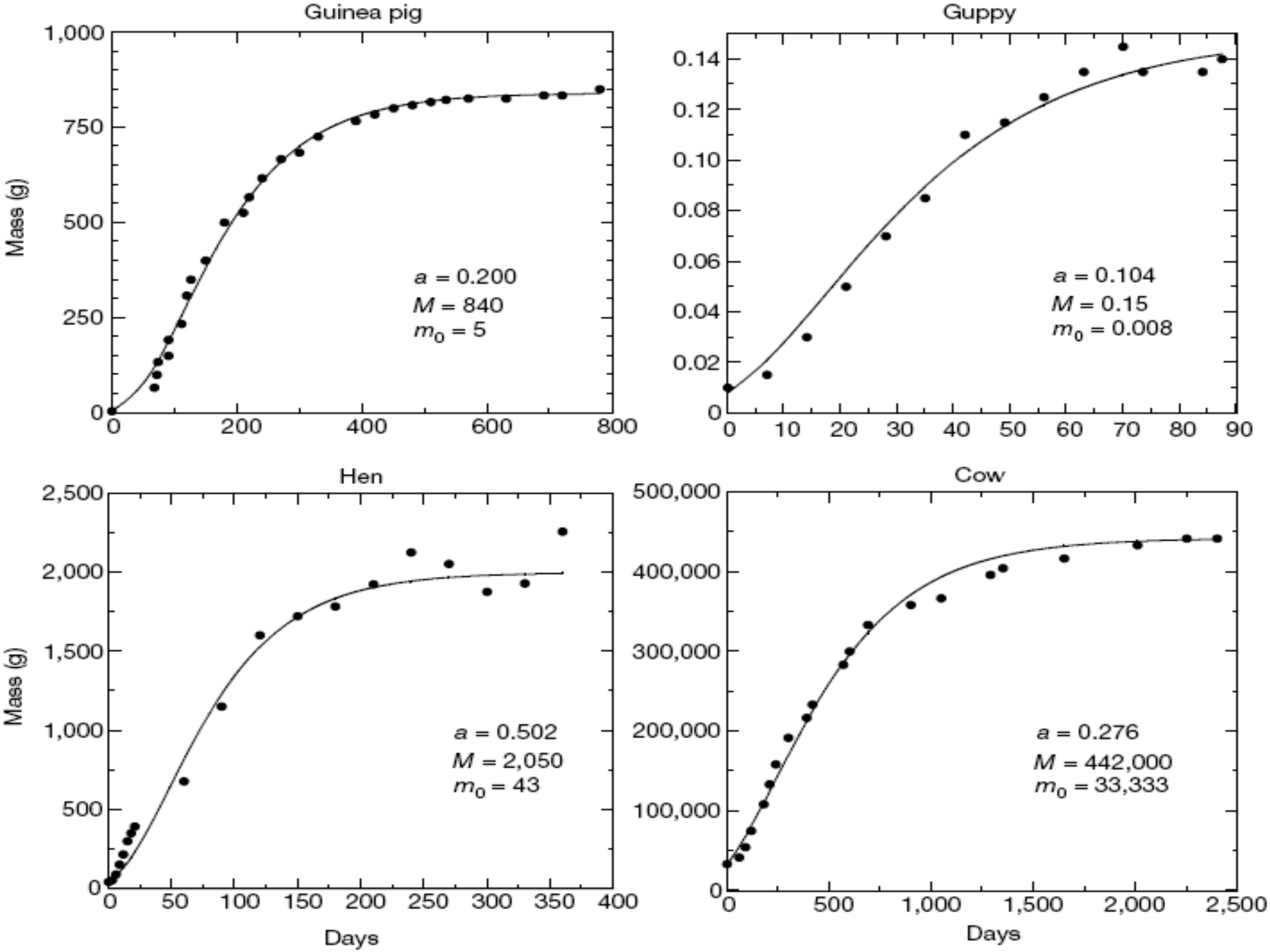
$$a \equiv \frac{B_0 m_c}{E_c}$$

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

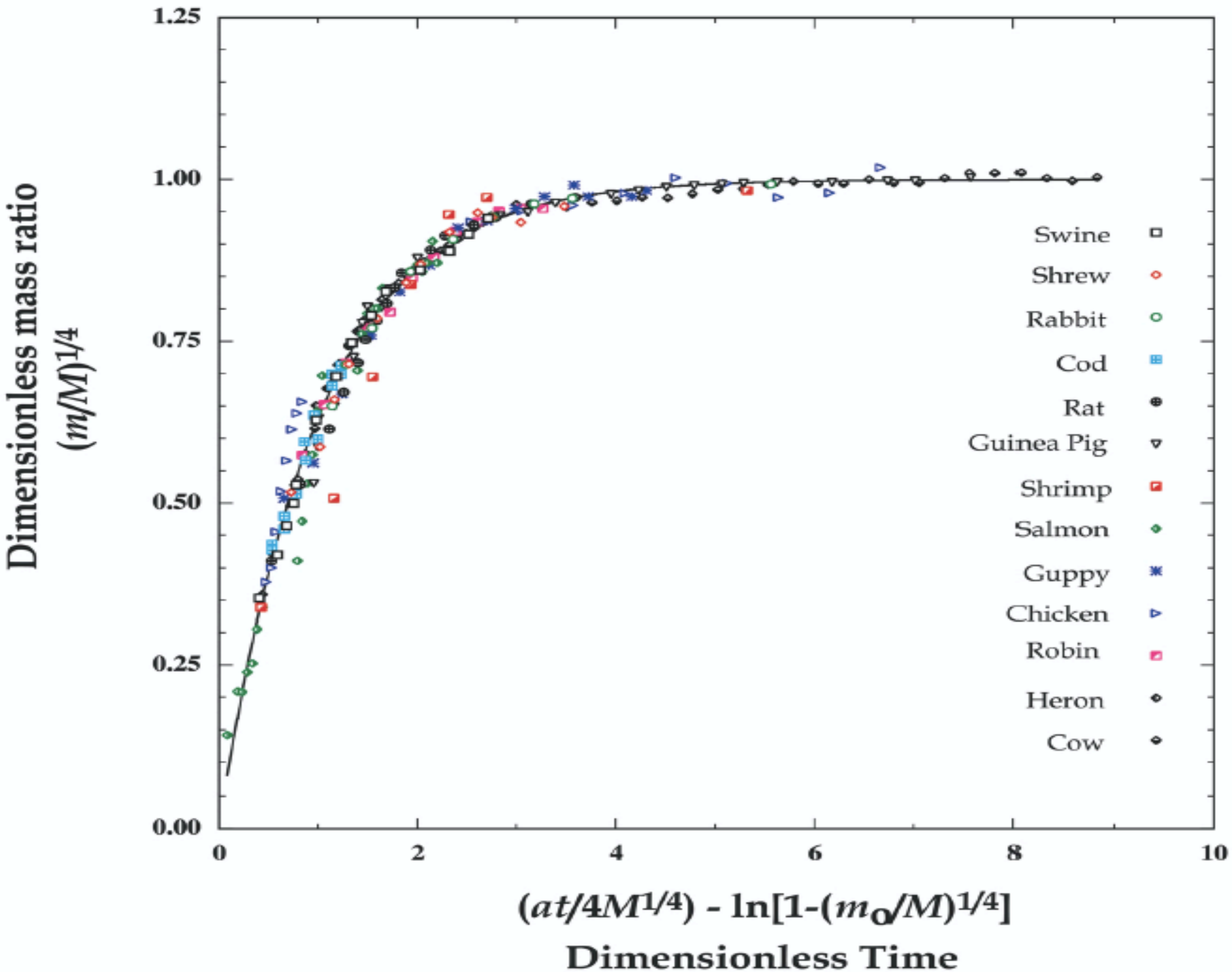
SOLUTION:

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

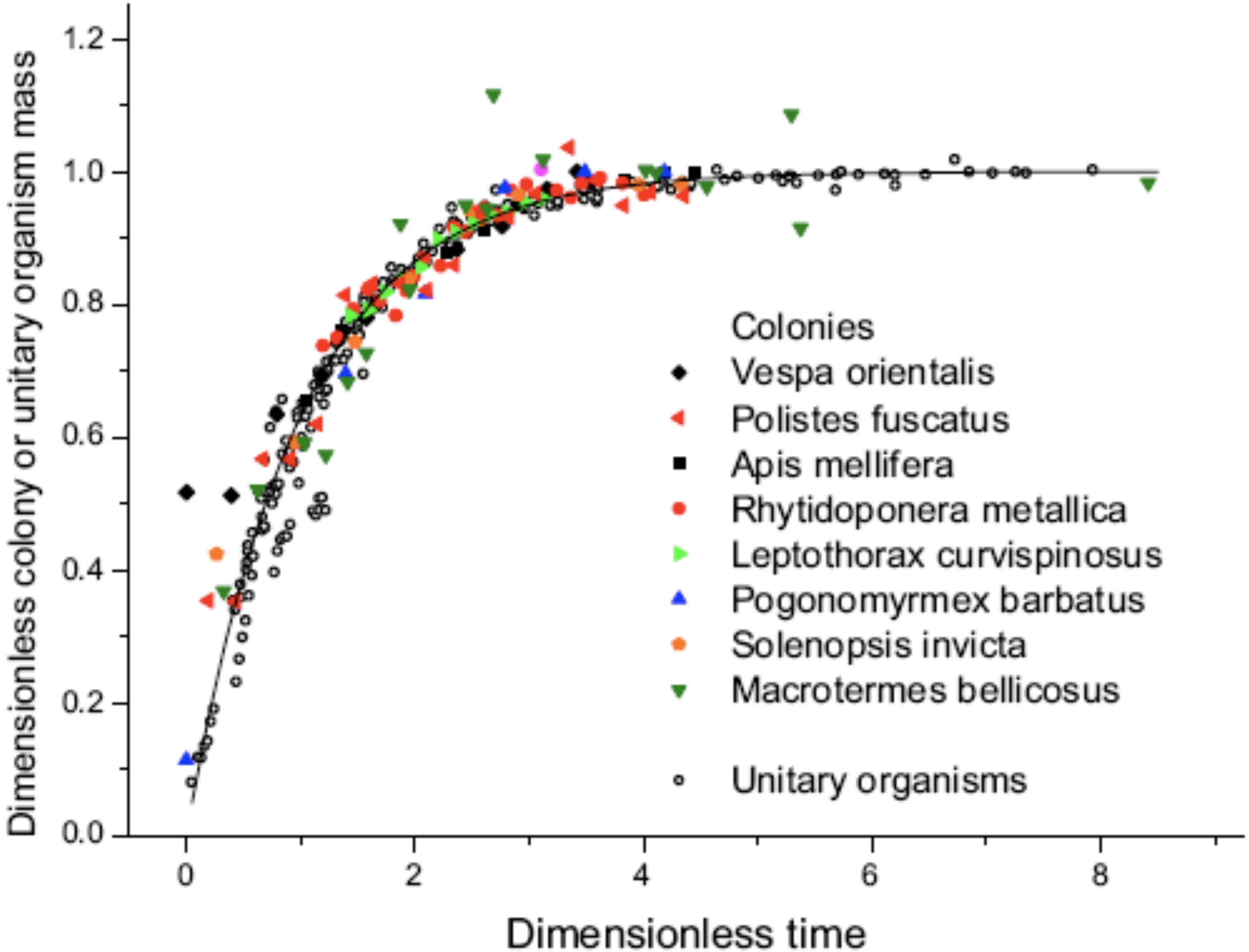
WHERE m_0 = MASS AT BIRTH ($m = m_0$ WHEN $t = 0$)



Guinea pig
Mass (g)
a = 0.200
M = 840
m0 = 5
Guppy
a = 0.104
M = 0.15
m0 = 0.008
Hen
Mass (g)
Days
a = 0.502
M = 2,050
m0 = 43
Cow
Days
a = 0.276
M = 442,000
m0 = 33,333



Dimensionless mass ratio
$(m/M)^{1/4}$
1.25
1.00
0.75
0.50
0.25
0.00
0
2
4
6
8
10
$(at/4M^{1/4}) - \ln[1-(m_o/M)^{1/4}]$
Dimensionless Time
Swine
Shrew
Rabbit
Cod
Rat
Guinea Pig
Shrimp
Salmon
Guppy
Chicken
Robin
Heron
Cow



C. Hou, M.Kaspari, M.H. vander Zanden, J.F. Giloolly, PNAS (2010)

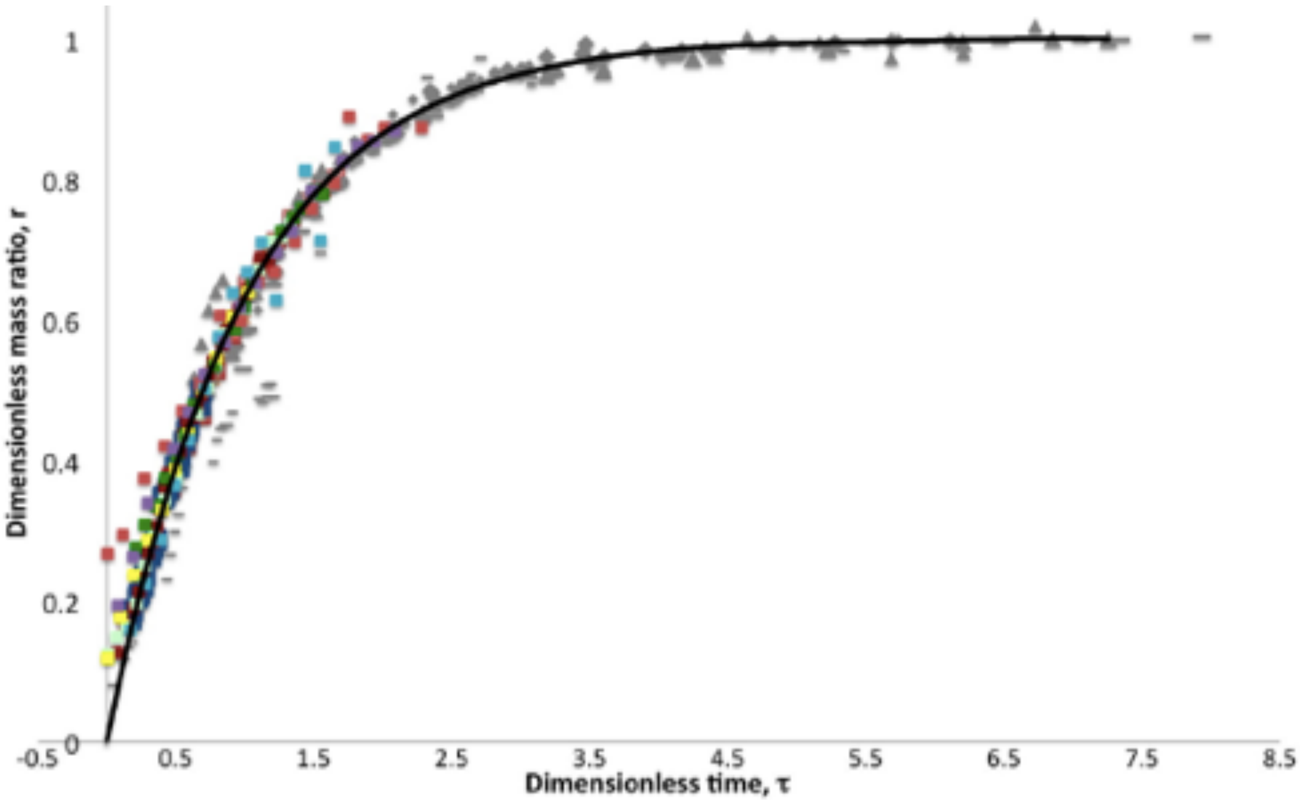
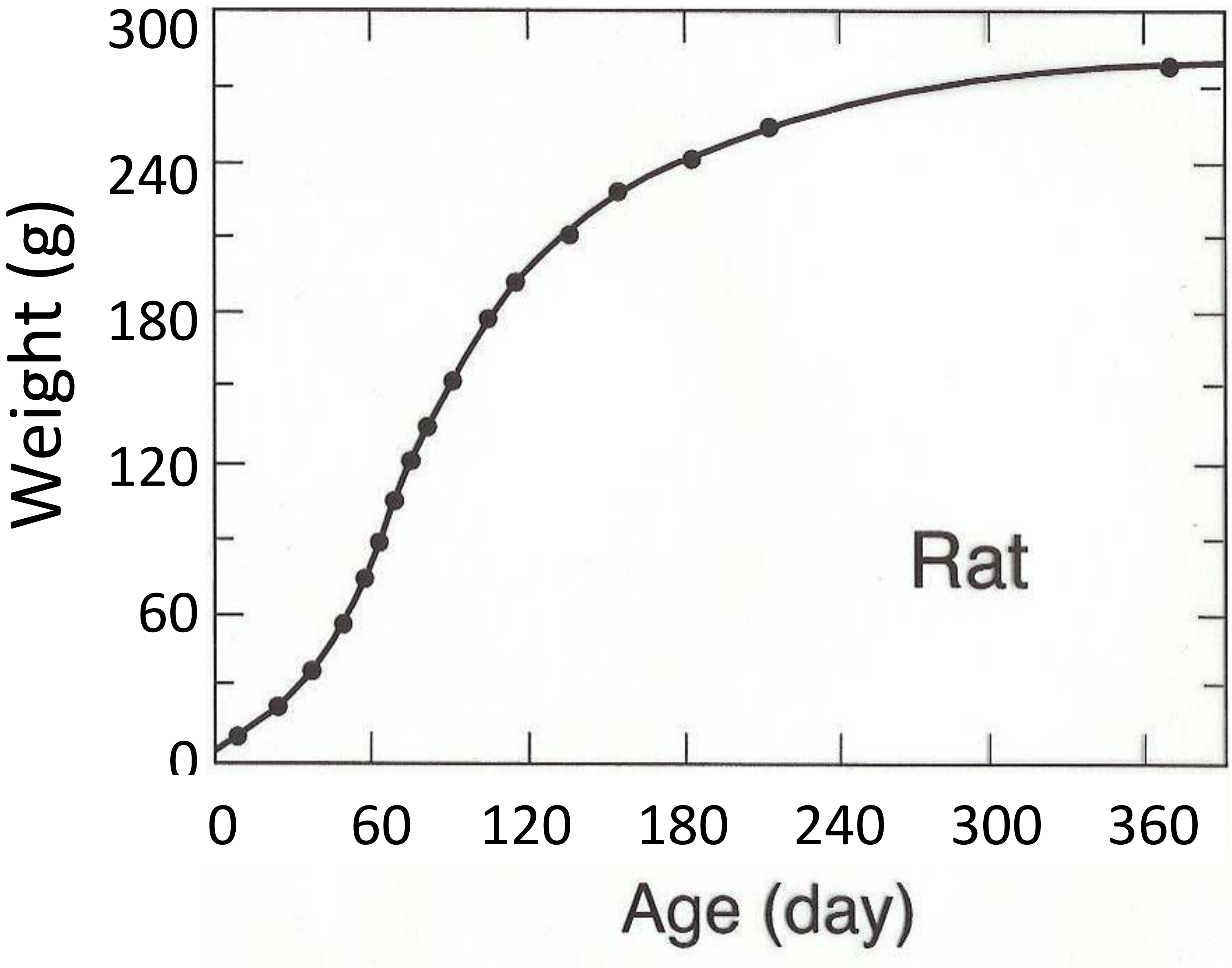


FIGURE 5. Plots of dimensionless ratio versus dimensionless time as defined by Eqs. (29)-(30). Data in grey are for ontogenetic growth from 13 species of animals (see [90] for original data sources), ranging from guppy to cod to guinea pig, and data in color with square symbols are for tumor growth trajectories 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



SUB-LINEAR SCALING (SLOPE < 1) LEADS TO BOUNDED GROWTH


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 $= 1.7 \times 10^4$ 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

JAMES BROWN (UNM/SFI)
BRIAN ENQUIST (U. ARIZONA)
WOODY WOODRUFF (LANL)
VAN SAVAGE (HARVARD)
JAMIE GILOOLLY (U. FLORIDA)
DREW ALLEN (UCSB)
MICHELLE GIRVAN (U. MARYLAND)
ALEX HERMAN (UCSF)
CHRIS KEMPES (MIT)

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

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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

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

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

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

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

WHERE

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

(FIXED POINTS)

LUIS BETTENCOURT (SFI - PHYSICS)
JOSE LOBO (ASU - URBAN ECONOMICS)
DEBORAH STRUMSKY (UNC - ECONOMICS)
HYEJIN YOUN (OXFORD - PHYSICS)
MARCUS HAMILTON (SFI/UNM - ANTHROPOLOGY)
NATHANIEL RODRIGUEZ (SFI – COMPUTER SCIENCE)
CLIO ANDRIS (SFI – GEOGRAPHY)

MARKUS SCHLAPFER (MIT – ENGINEERING)
CARLO RATTI (MIT – ARCHITECTURE)

DIRK HELBING (ETH ZURICH - TRANSPORT/PHYSICS)
ERICH RAUCH (PHYSICS/BIOLOGY - MIT/PRINCETON)

DAVID LANE (U. REGGIO - STATISTICS/ECONOMICS)
SANDER van der LEEUW (ASU - ANTHROPOLOGY)
DENISE PUMAIN (PARIS - URBAN GEOGRAPHY)
SPYROS SKOURAS (ECONOMICS - U. ATHENS)

SUPPORT:

NATIONAL SCIENCE FOUNDATION

GENE & CLARE THAW CHARITABLE TRUST

BRYAN & JUNE ZWAN FOUNDATION

ROCKEFELLER FOUNDATION

McDONNELL FOUNDATION

TEMPLETON FOUNDATION

WE LIVE IN AN EXPONENTIALLY EXPANDING SOCIO-ECONOMIC UNIVERSE!!

1800 < 4% OF THE US POPULATION WAS URBAN

2011 > 80%

2006 > 50% WORLD'S POPULATION URBANISED

2050 > 75%

EVERY WEEK FROM NOW TILL 2050 OVER ONE MILLION PEOPLE ARE BEING ADDED TO OUR CITIES

URGENTLY NEED A QUANTITATIVE, PREDICTIVE SCIENCE OF CITIES

RESILIENCE

EVOLVABILITY

GROWTH

SCALABILITY

NEED A SCIENCE OF CITIES

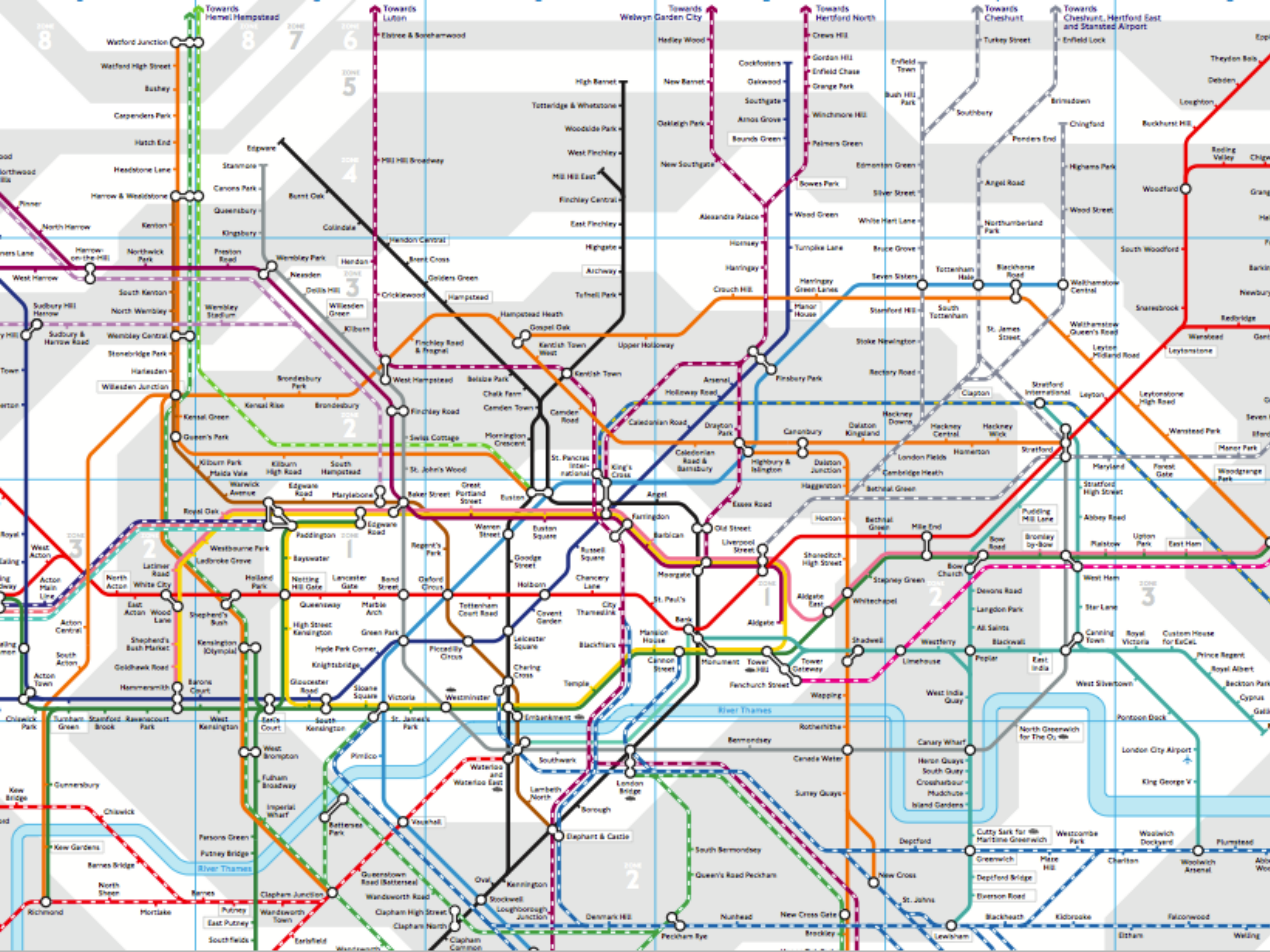
COMPLEMENT TO TRADITIONAL (QUALITATIVE) THEORIES AND MODELS

WHAT CAN WE LEARN FROM BIOLOGY AND PHYSICS?

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

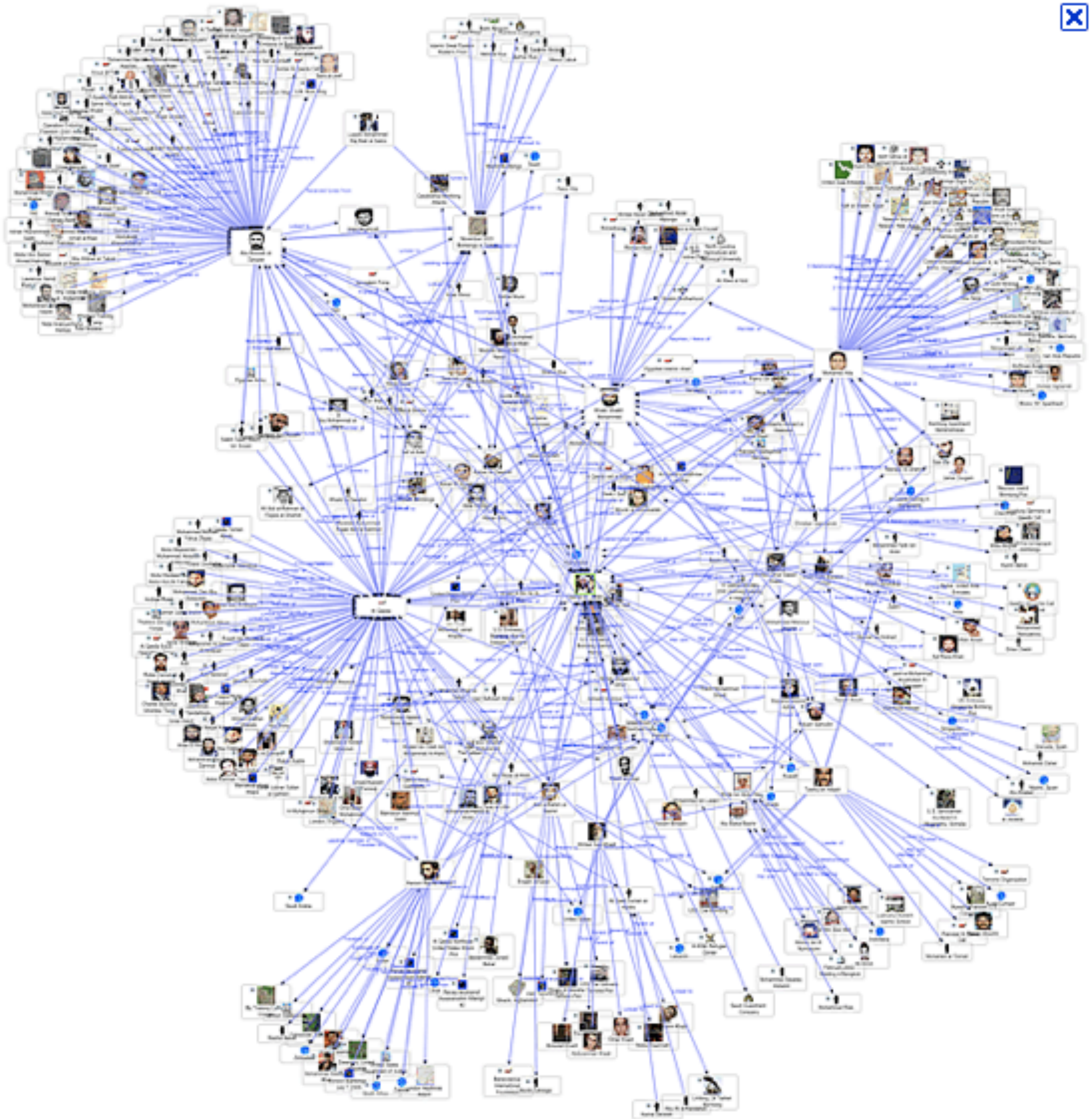
DO THEY MANIFEST "UNIVERSALITY"?

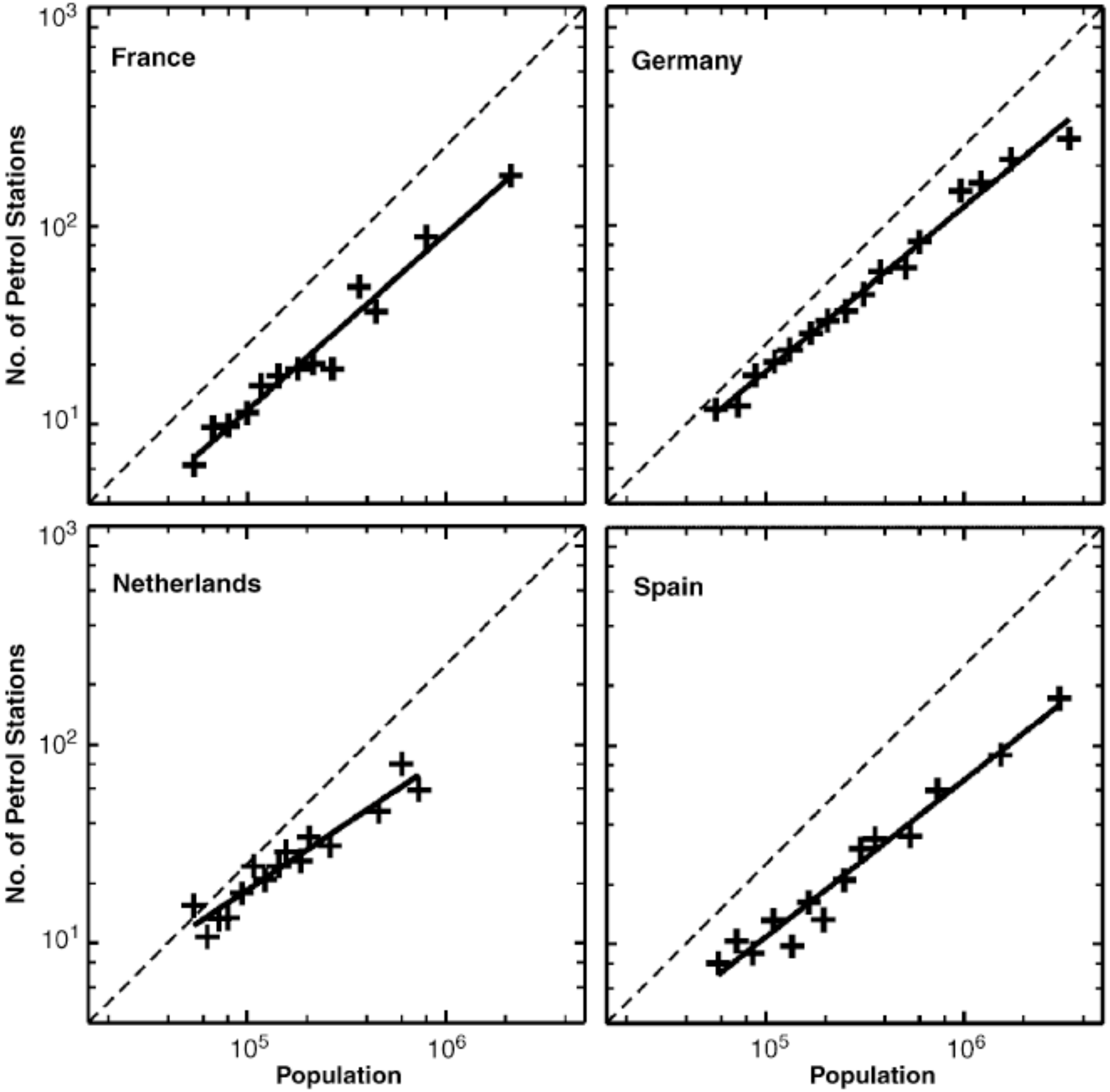

Satellite Imaging Corporation
12777 Jones Road, Suite 370
Houston, Texas 77070-4647 USA
Tel: 1.832.237.2900


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

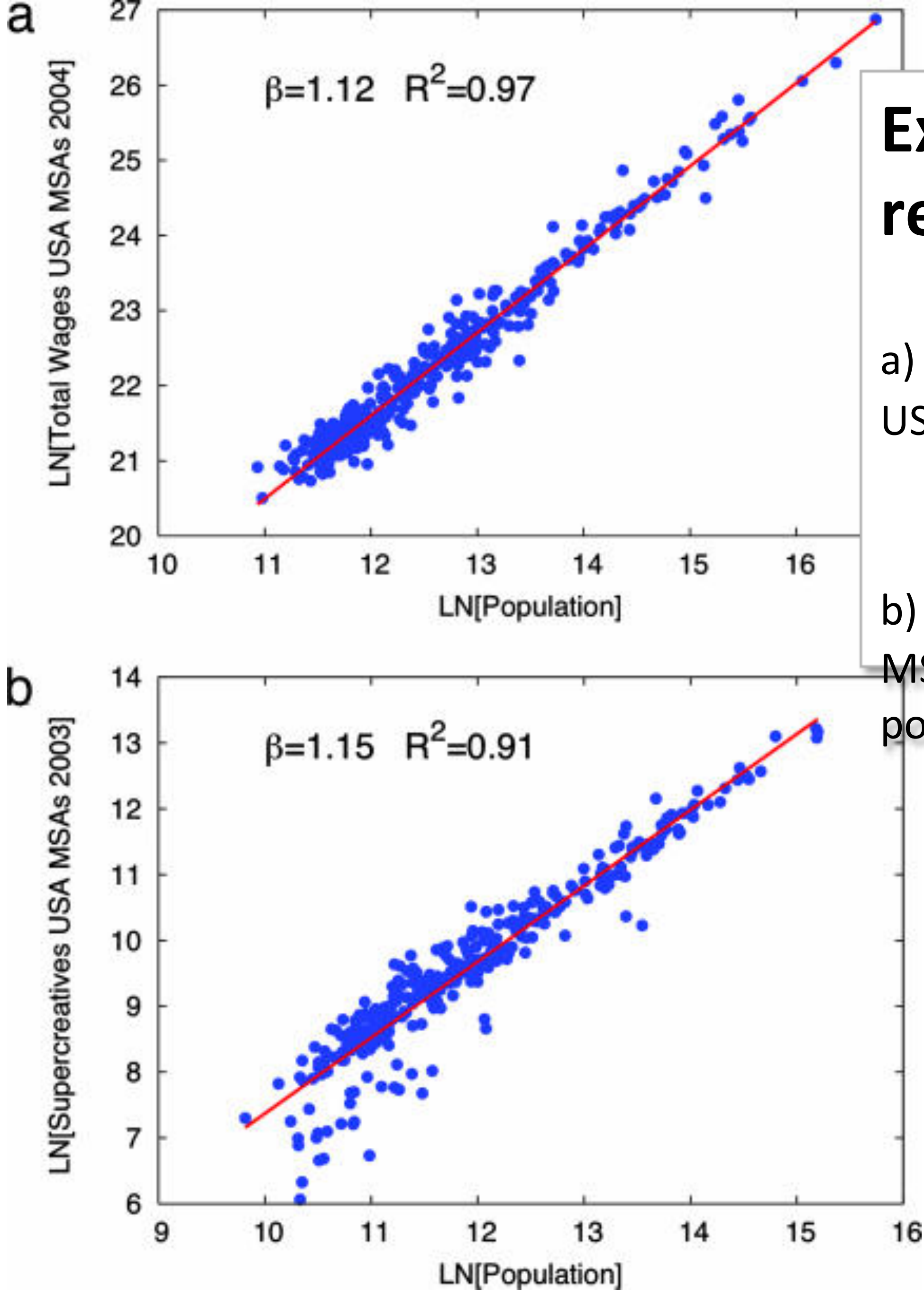
“What is the city but the people?”

William Shakespeare





C. Kühner, D. Helbing, G.B.West Physica A 363 (1) 96-103



Example of scaling relationships

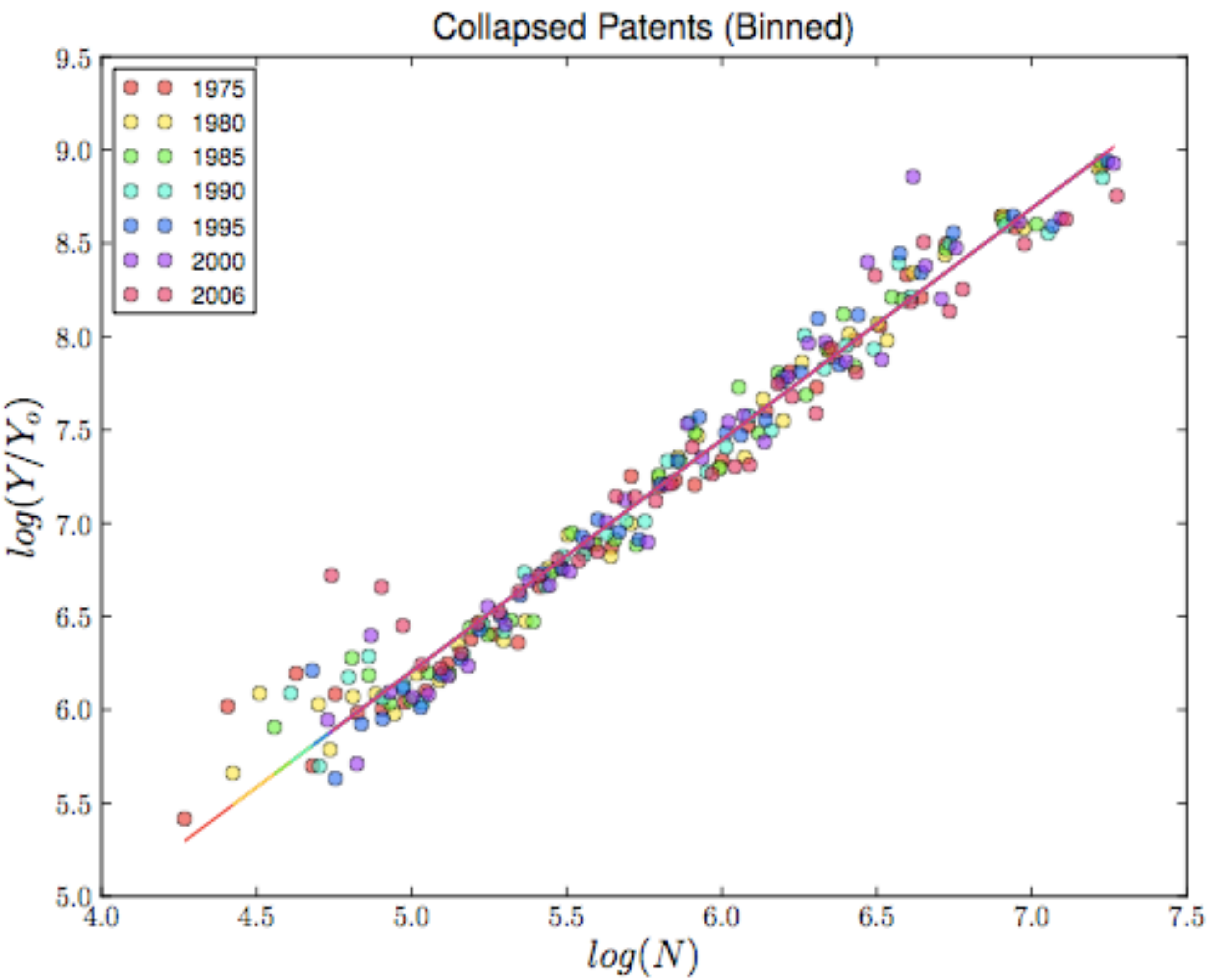
a) Total **WAGES** per MSA in 2004 for the USA vs. metropolitan population.

b) **SUPERCREATIVE** employment per MSA in 2003, for the USA vs. metropolitan population.

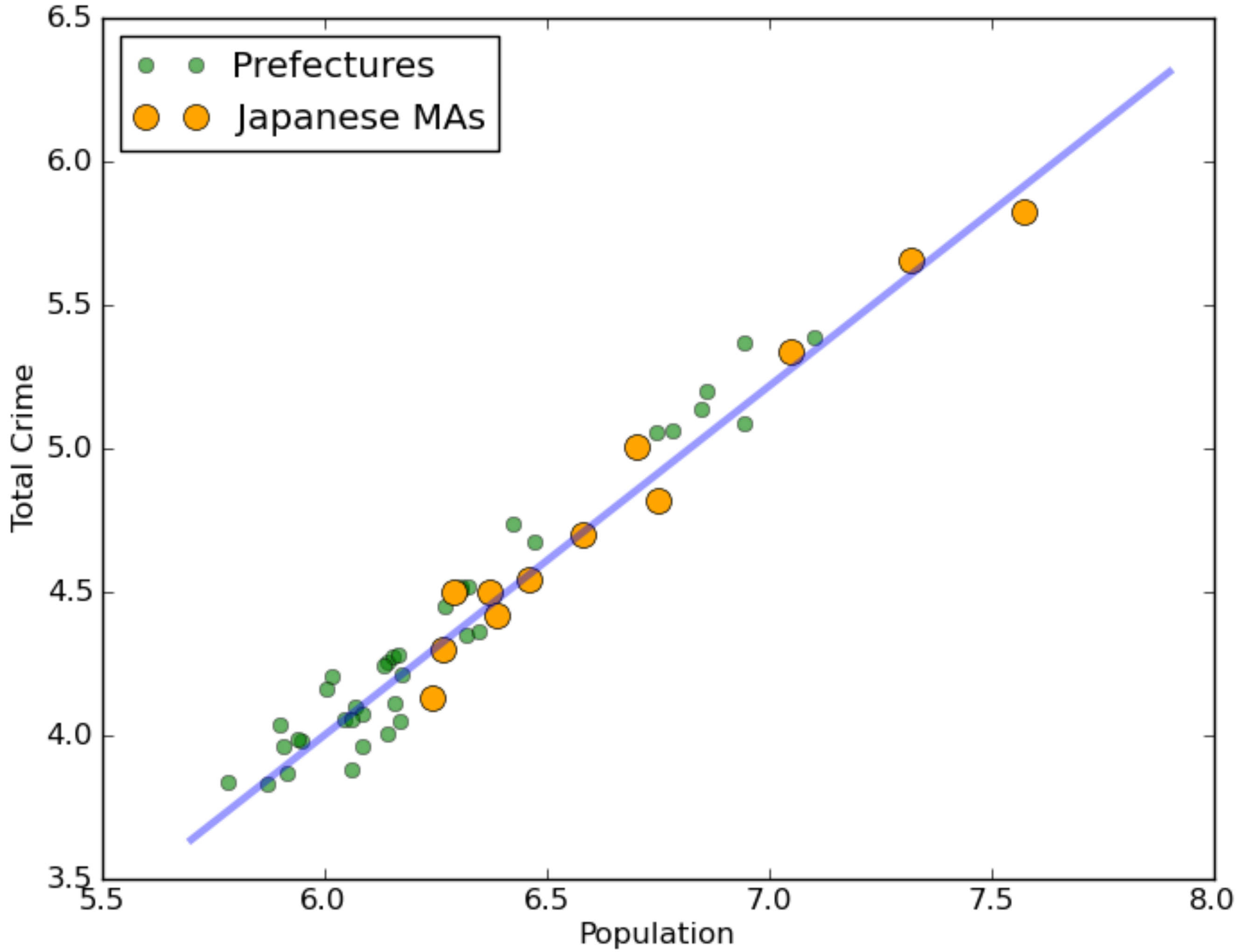
SUPER-LINEAR SCALING

L. M. A. Bettencourt, J. Lobo, D. Helbing, C. Kühnert, and G. B.West **104**, 7301–7306 (2007)

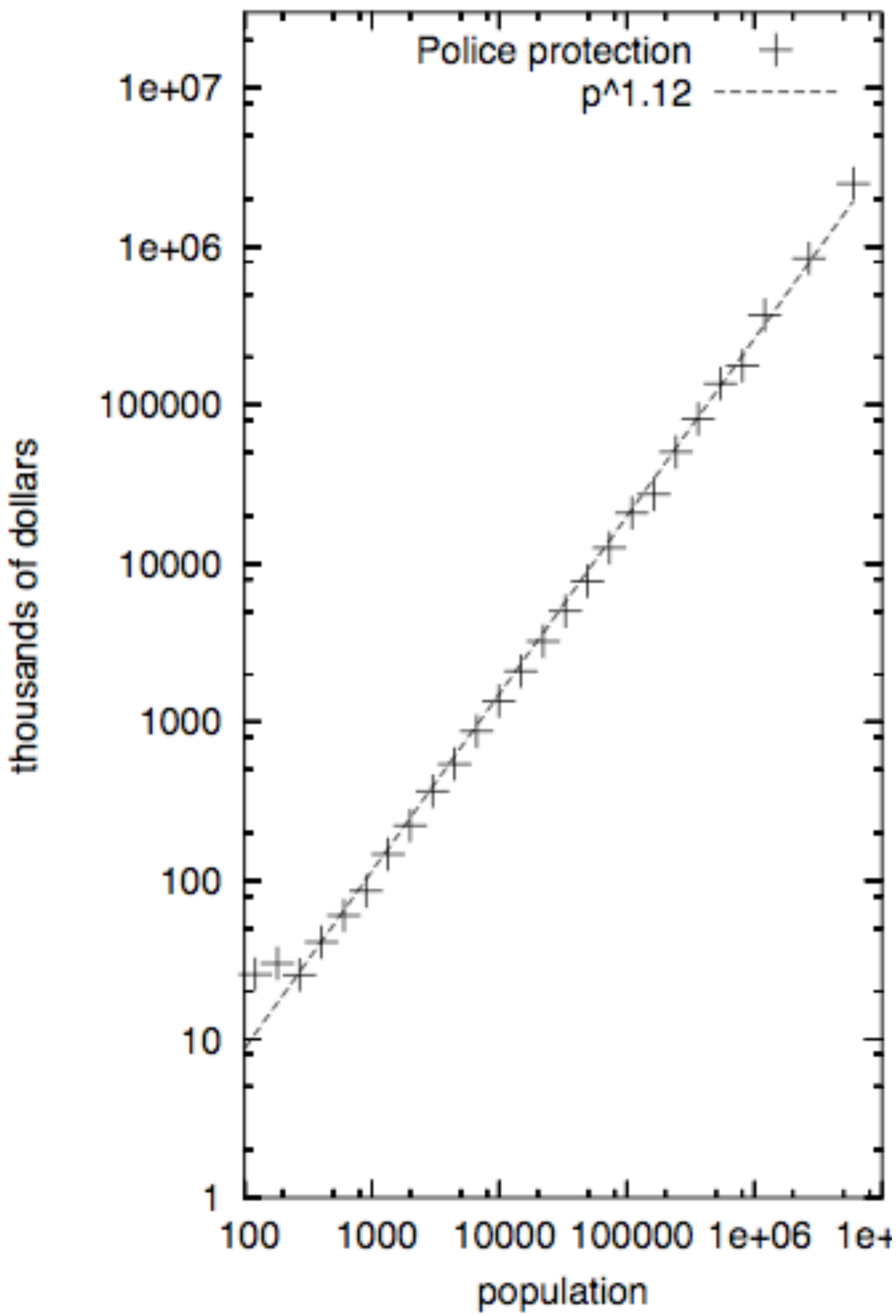
Innovation measured by Patents

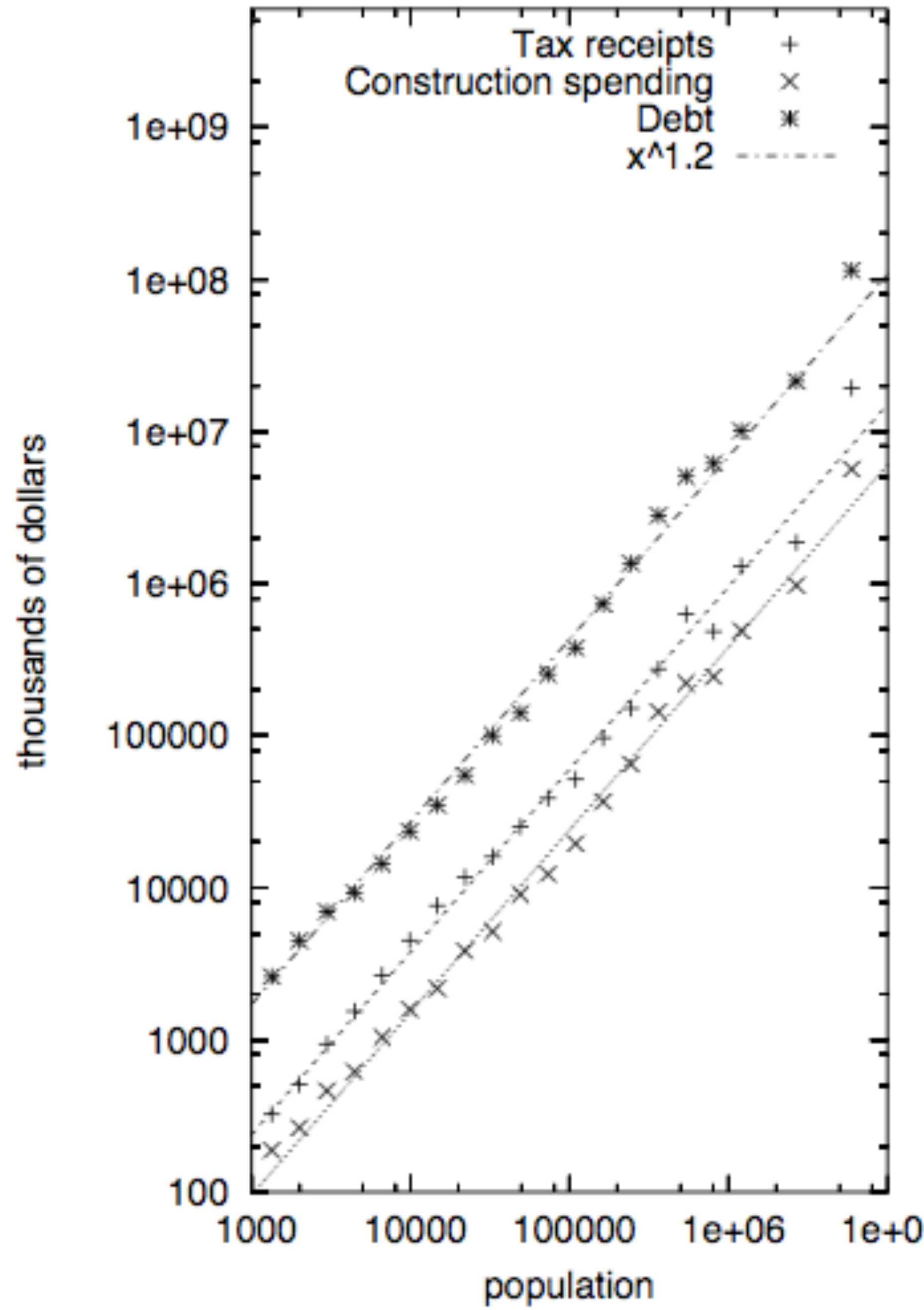


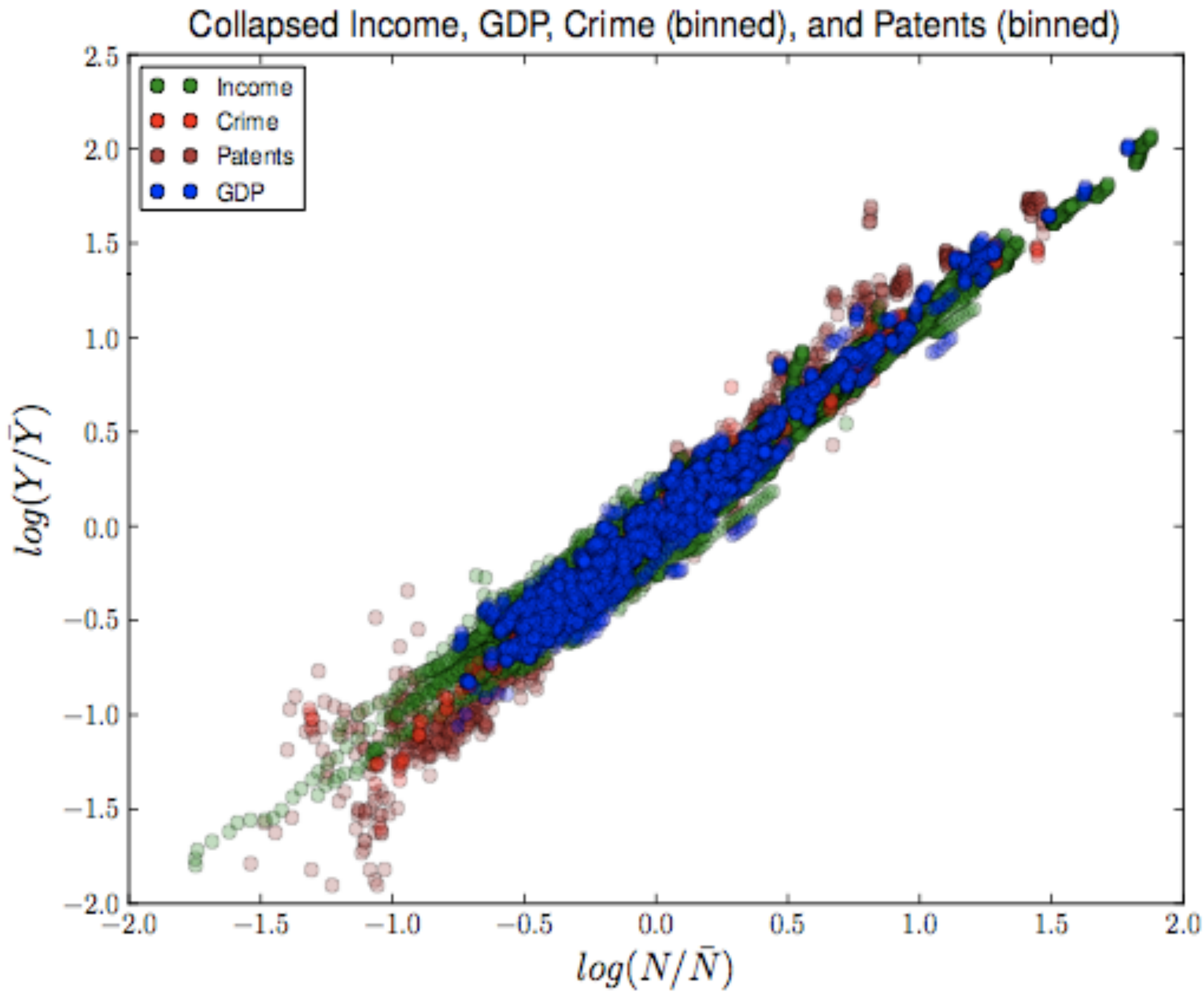
TOTAL CRIME (JAPAN)



Slope = 1.21 [1.08, 1.35]


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


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



UNIVERSALITY

L. M. A. Bettencourt & G. B. West (2010) *Nature* 467: 912; (N. Rodriguez)

THE GOOD, THE BAD & THE UGLY

DOUBLING THE SIZE OF A CITY

ON AVERAGE SYSTEMATICALLY INCREASES

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

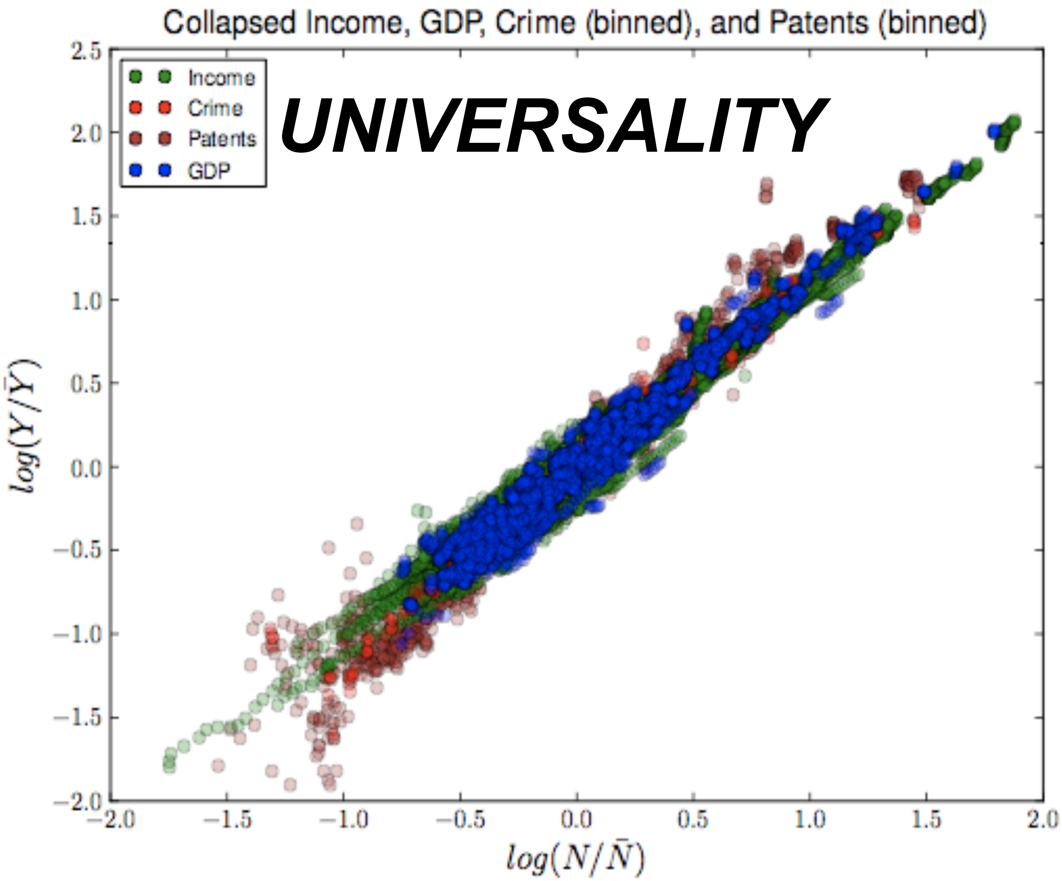
ALL BY APPROXIMATELY 15%

REGARDLESS OF CITY

AND...............

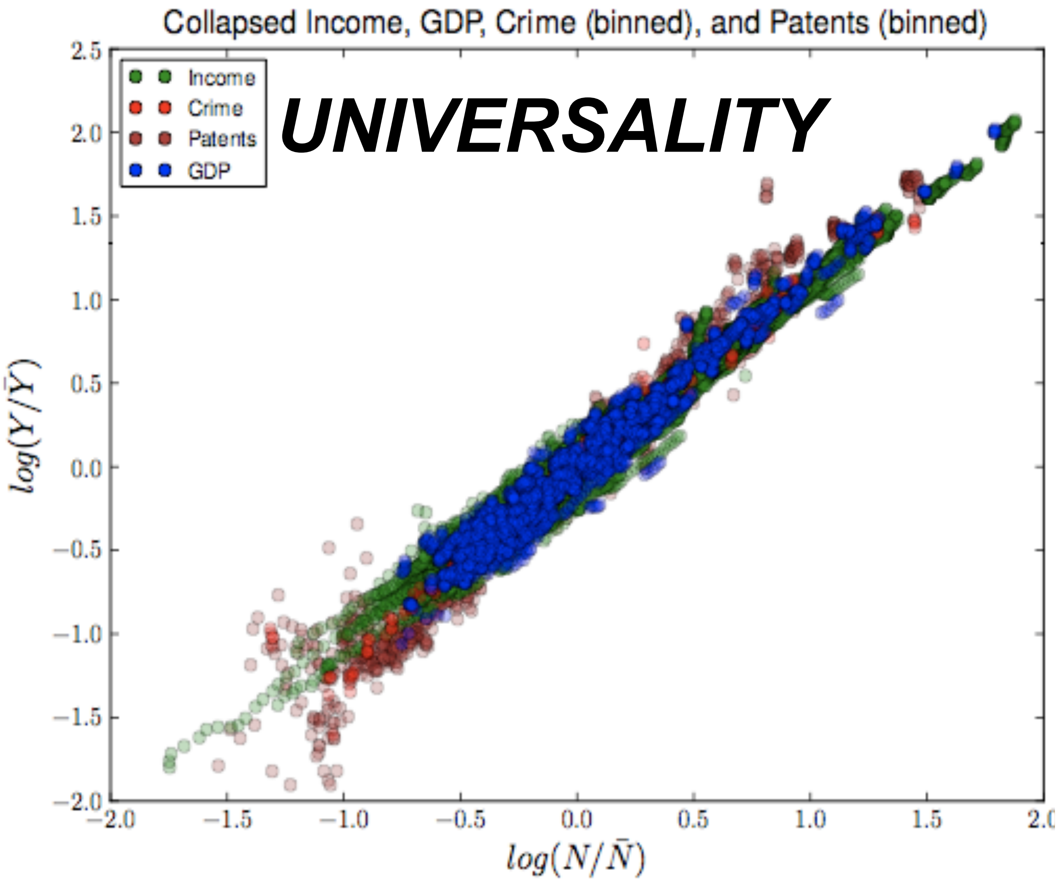
SAVES APPROXIMATELY 15% ON ALL INFRASTRUCTURE (ROADS, ELECTRICAL LINES, GAS STATIONS,........)

UNIVERSALITY OF SOCIAL NETWORKS (CLUSTERING HIERARCHIES)



SUPER-LINEAR SCALING

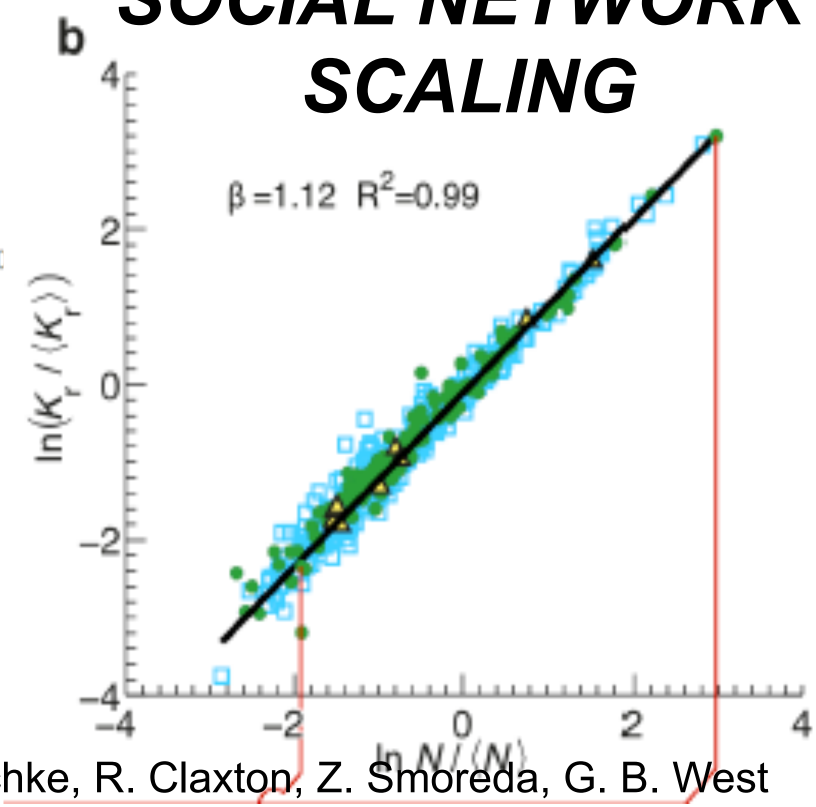
SLOPE ~ 1.15 > 1



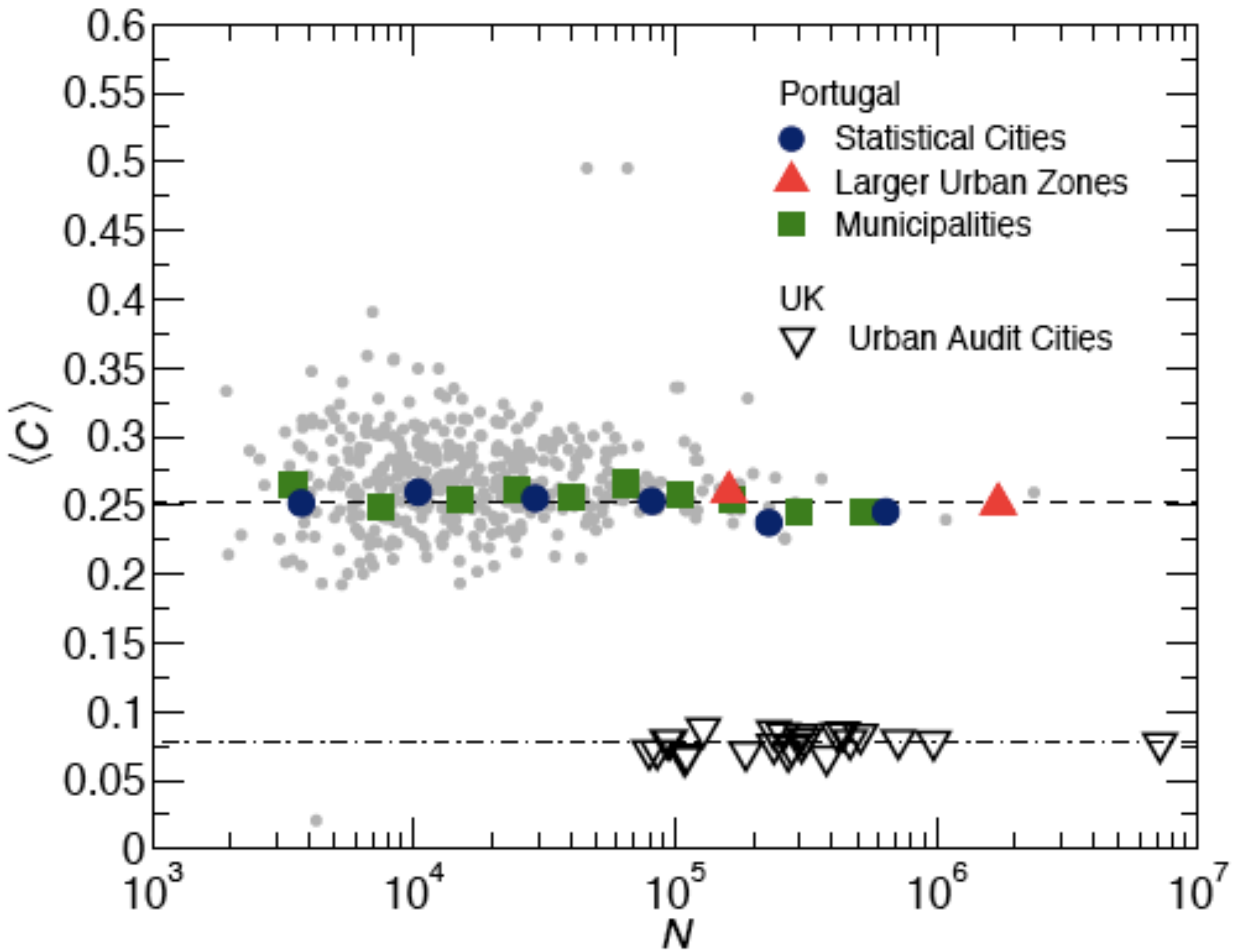
SUPER-LINEAR SCALING

SLOPE ~ 1.15 > 1

SOCIAL NETWORK SCALING



M. Schläpfer, L. M. A. Bettencourt, S. Grauwin, M. Raschke, R. Claxton, Z. Smoreda, G. B. West and C. Ratti. P. Roy. Soc (tbp)



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

FINANCIAL MARKETS,
ECONOMIES,
GLOBAL WARMING,
ENVIRONMENT,
URBANISATION,
HEALTH,
CRIME,
POLLUTION,……….

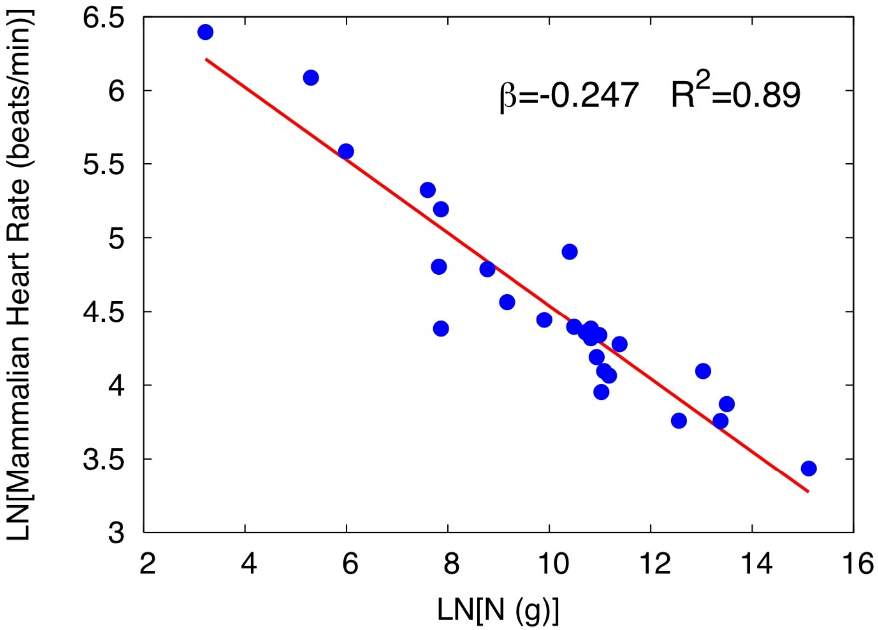
ARE NOT INDEPENDENT

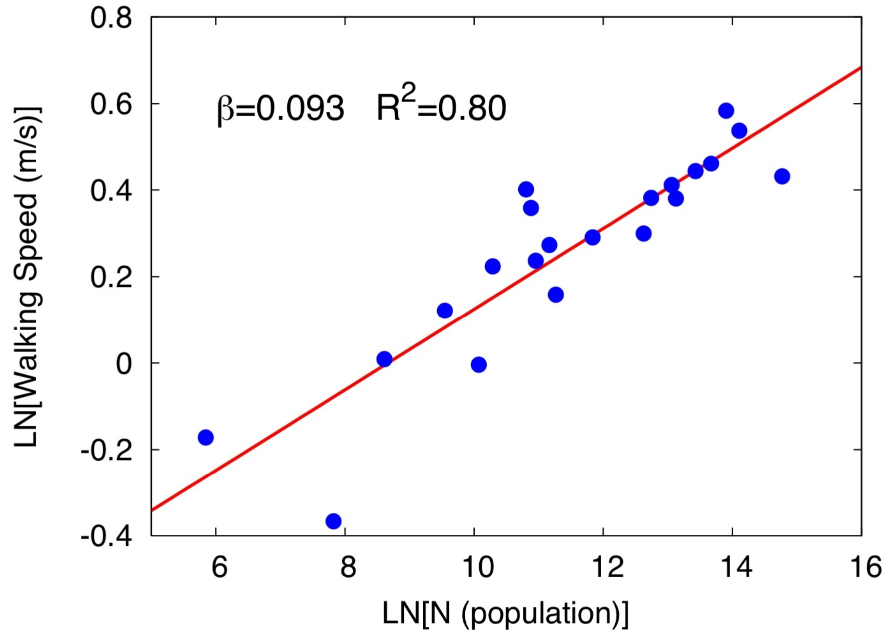
THEY ARE ALL HIGHLY COUPLED, INTER-RELATED COMPLEX ADAPTIVE SYSTEMS

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

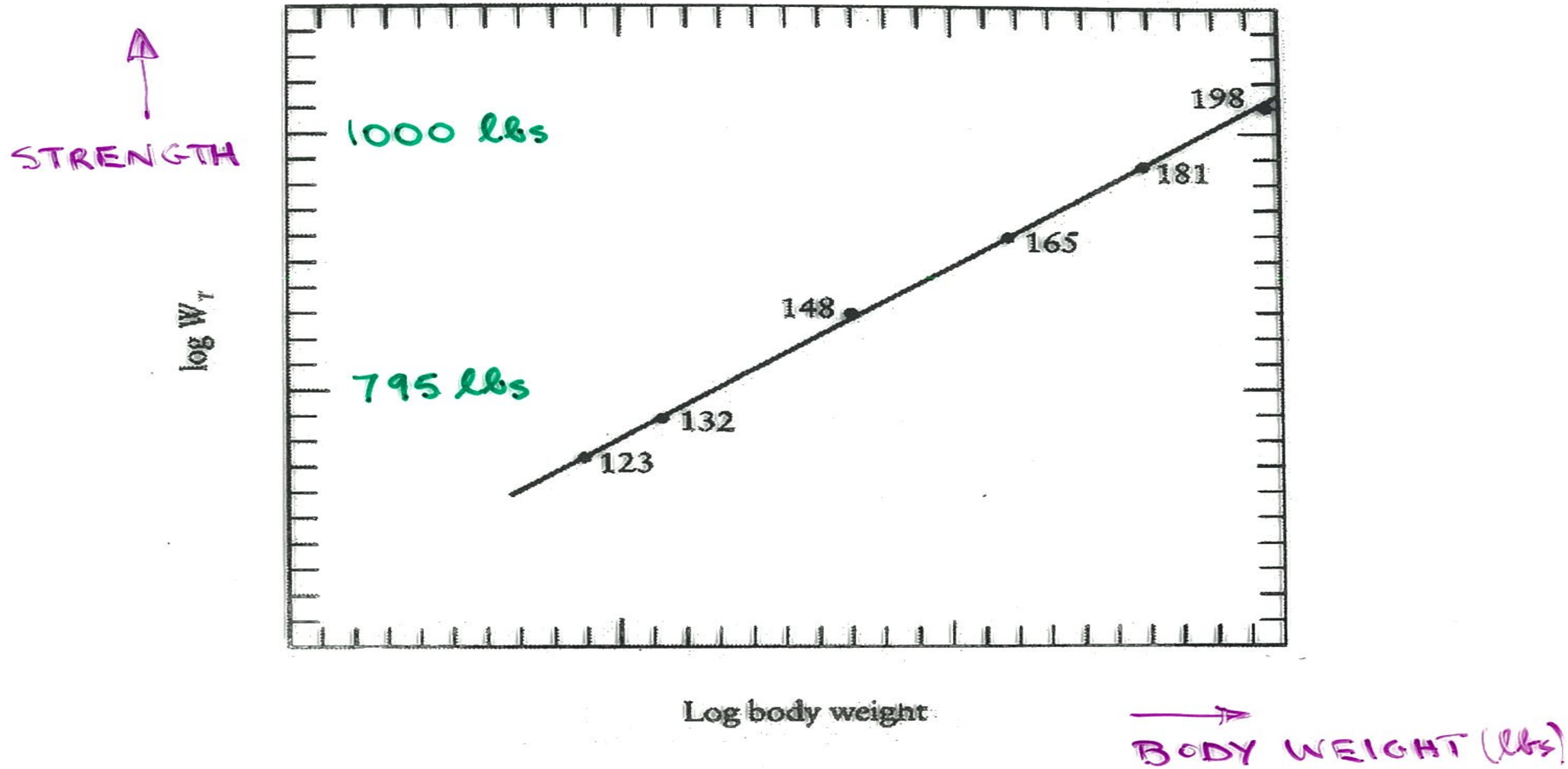




Heart Rate vs. Body Size Walking Speed vs. Population S

WEIGHT-LIFTING ("PUMPING IRON")

(PLOTTED LOGARITHMICALLY)



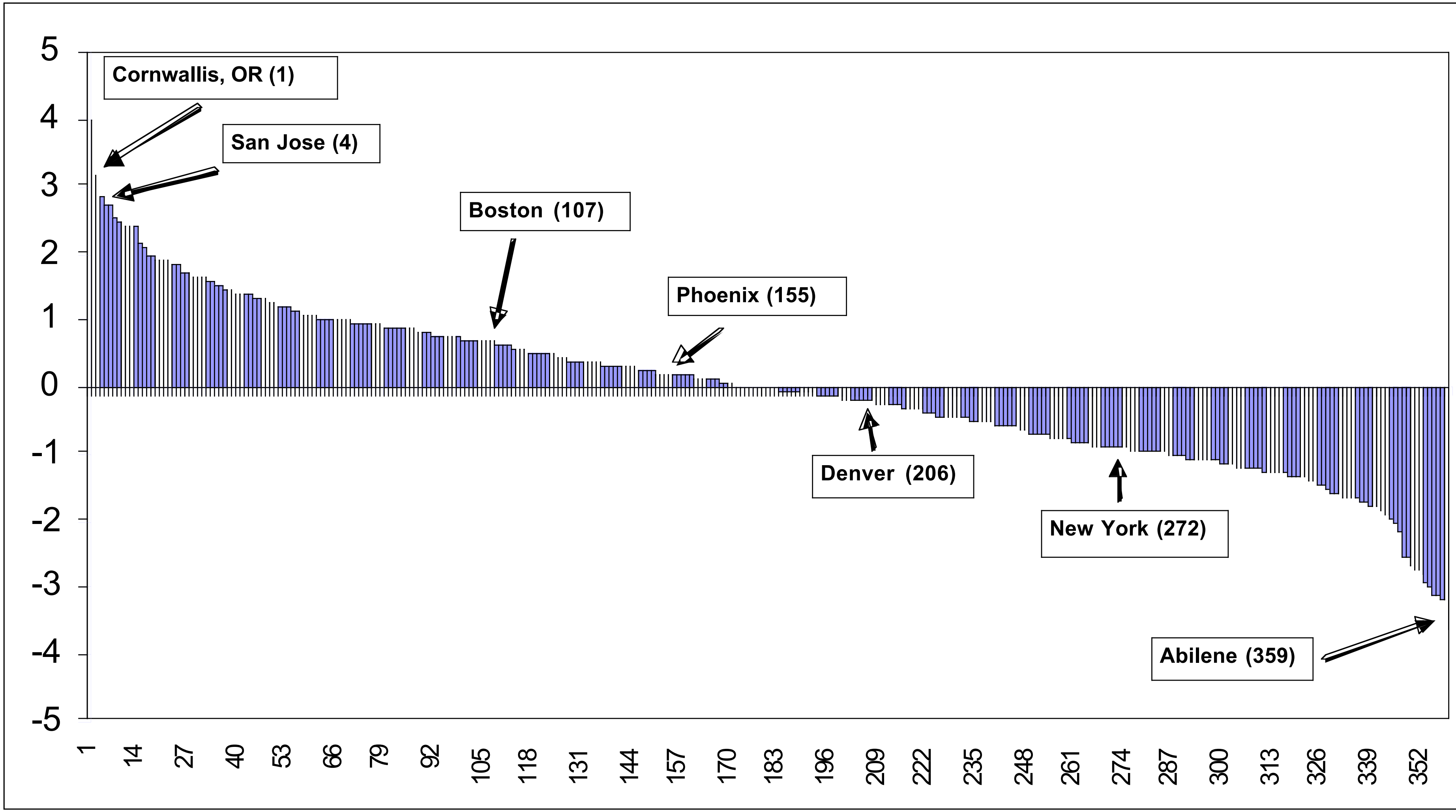
WHO IS THE STRONGEST AND WHO IS THE WEAKEST?

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

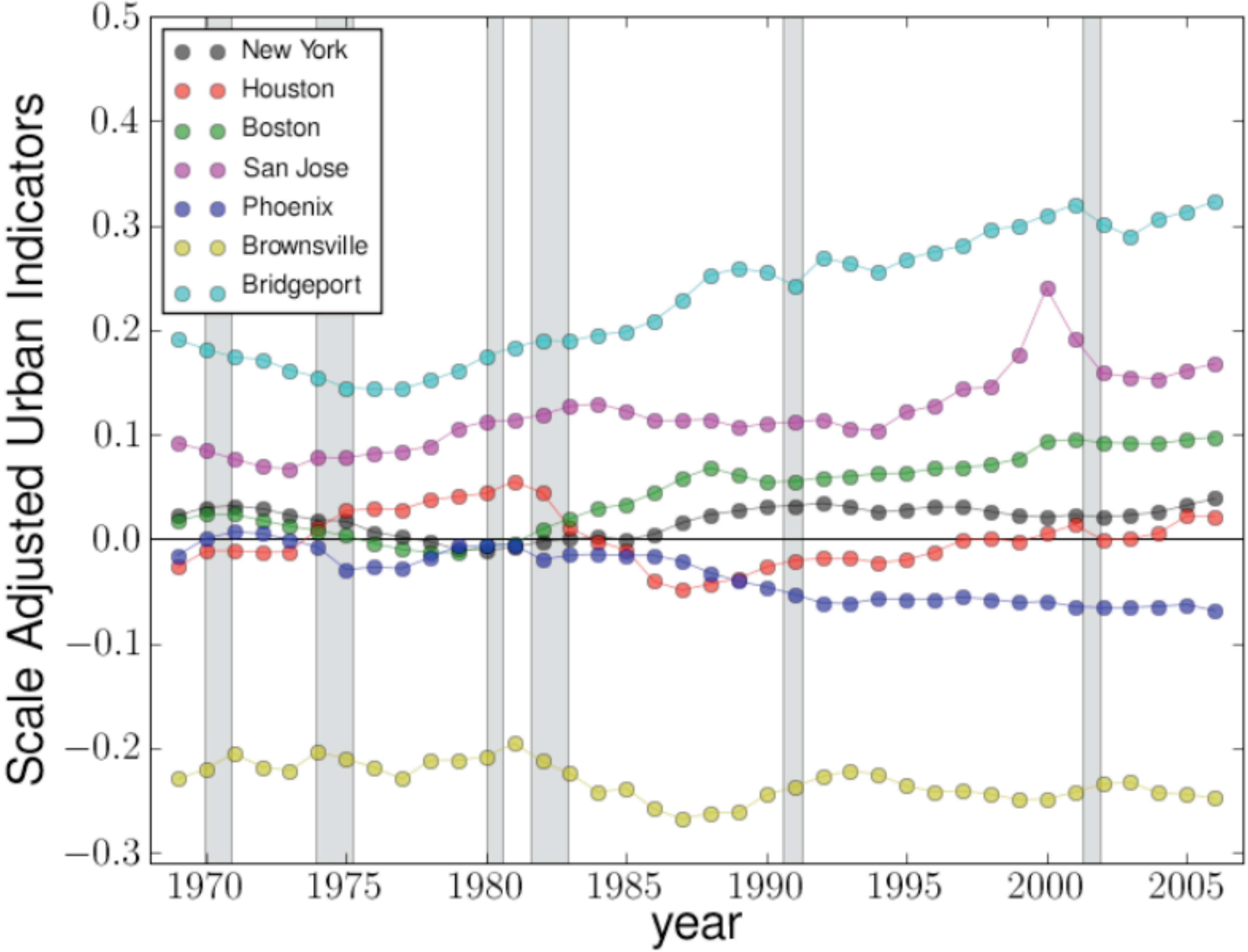
vs.

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

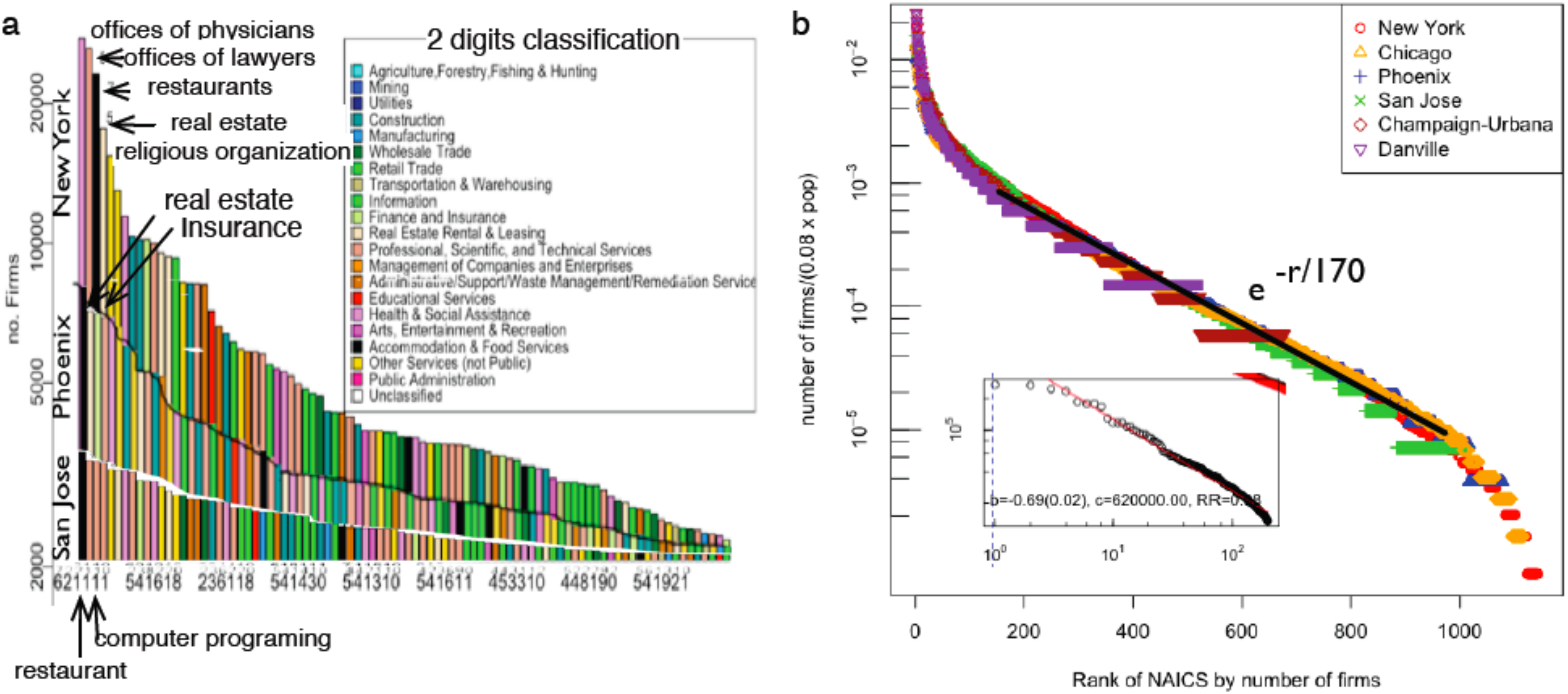


L. M. A. Bettencourt, J. Lobo, D. Strumsky and G. B.West (2010) PLoS ONE 5(11): e13541



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

IF NUMBER OF ESTABLISHMENTS OF TYPE j SCALES AS

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

THEN ITS RANKING SCALES AS

$$x_j \propto N^{(1-\beta_j)/\gamma} \qquad x_j < x_0$$

$$x_j \propto (1-\beta)\ln N \qquad x_j > x_0$$

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 (e.g. AGRICULTURE, MINING, FISHING, …..) DECREASE IN RANK

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

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

[UNLIKE BIOLOGY WHERE Y(N) ~ N]

IF EVERYONE INTERACTED WITH EVERYONE ELSE, THEN

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

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

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 $A \sim L\varepsilon$

$$\Rightarrow \left(\frac{L}{N}\right)\left(\frac{Y}{N}\right) \approx \varepsilon Y_0$$ **INVARIANT!**

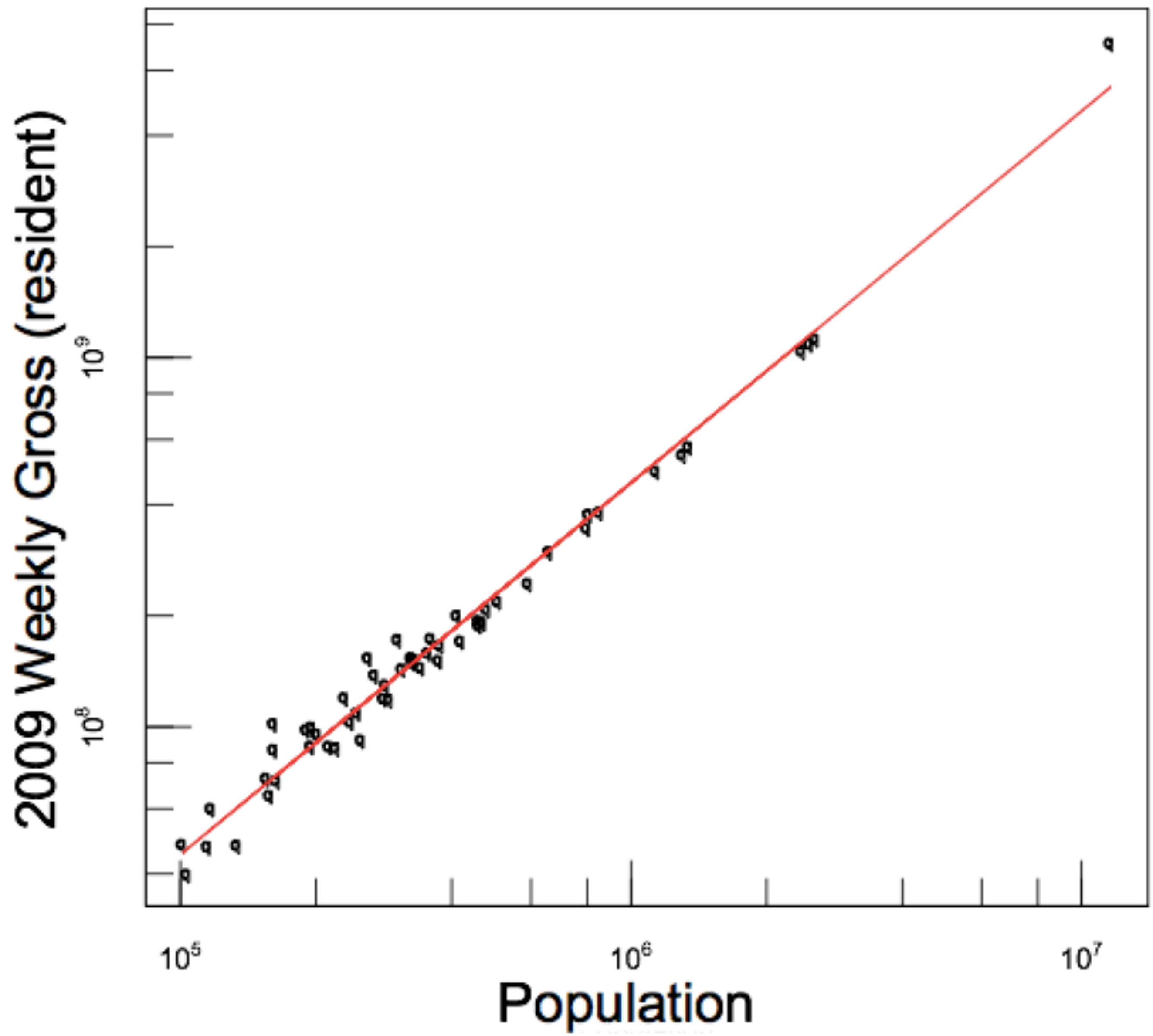
IF

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

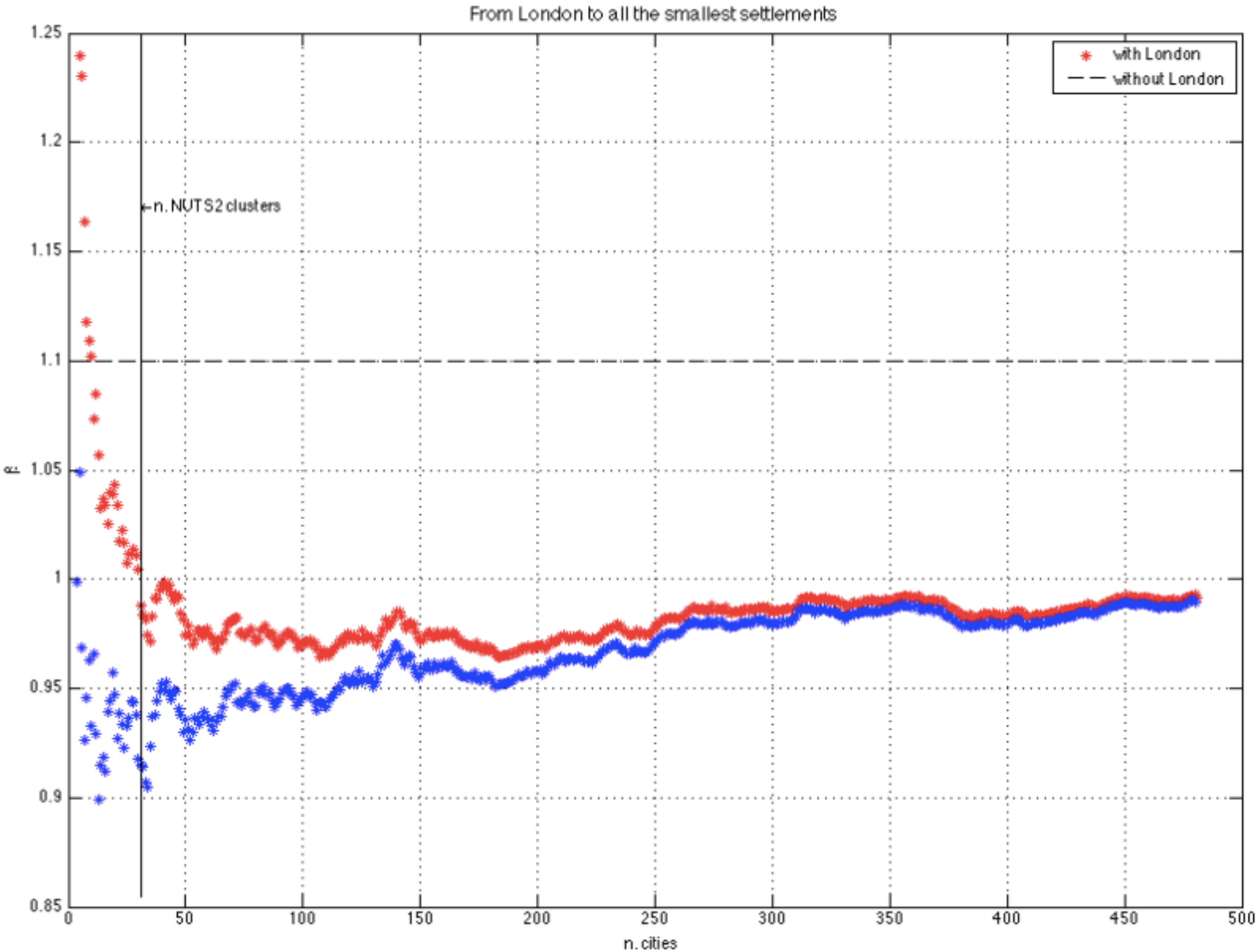
WITH $\beta_I = 1 + \varepsilon_I$ $\beta_{SE} = 1 + \varepsilon_{SE}$

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

➔ CAN DETERMINE THE SOCIAL INFORMATIONAL NETWORK SCALING FROM THE "METABOLIC" NETWORK SCALING



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


From London to all the smallest settlements
with London
without London
n. NUTS2 clusters
ρ
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

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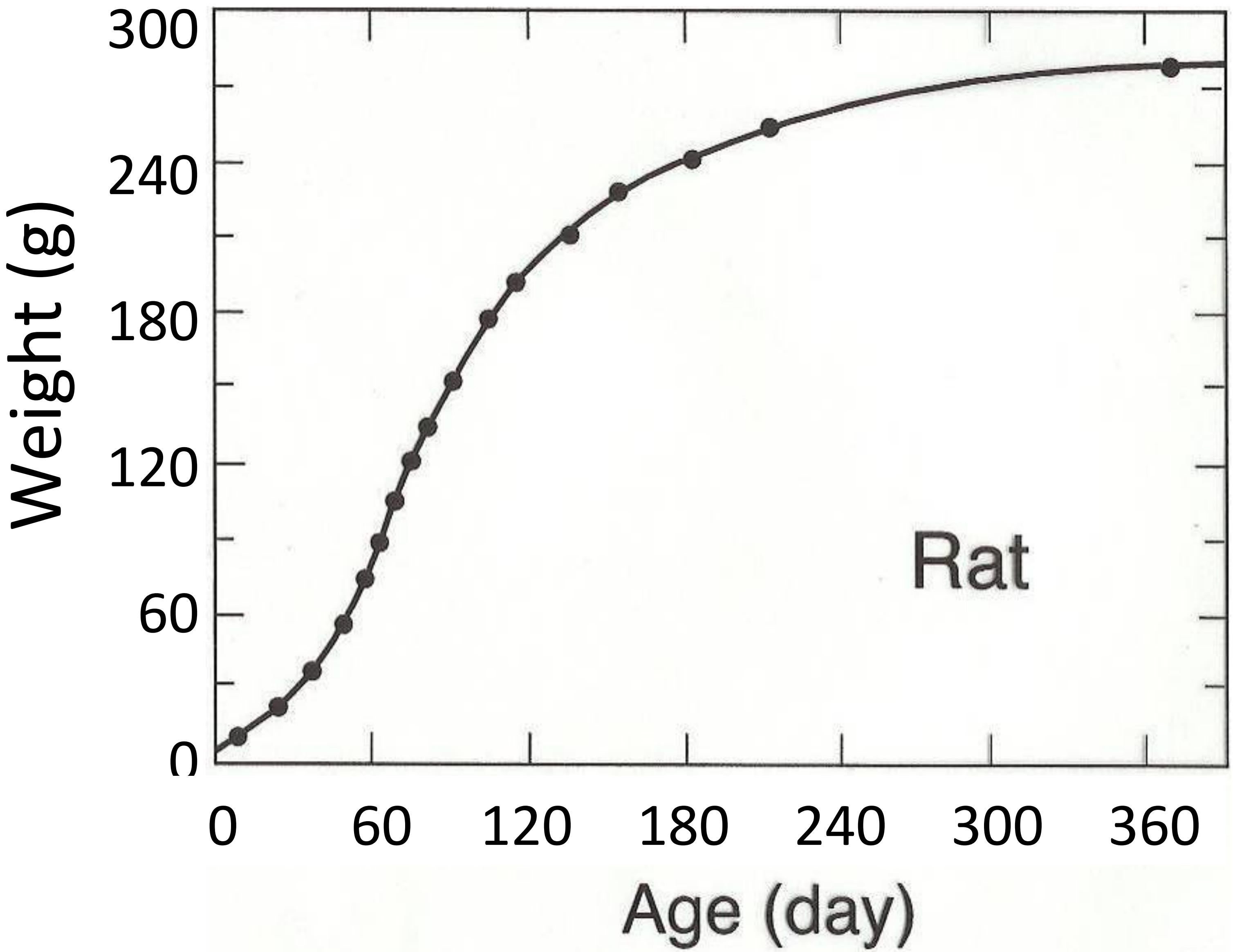
The Editors: Is London's success causing the UK a problem?

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.



SUB-LINEAR SCALING (b < 1) LEADS TO BOUNDED GROWTH

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 $Y_i(N) = Y_i(1)N^{\beta_i}$

WITH $\beta_i \approx \beta \approx 1.15$ ***APPROXIMATELY THE SAME FOR ALL i, SO***

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

INTRODUCE AVERAGE COSTS:

$$R_0 \equiv \frac{1}{N}\sum_{j=1}^{N} r_j$$

$$E_0 \equiv \frac{1}{N}\sum_{j=1}^{N} c_j$$

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

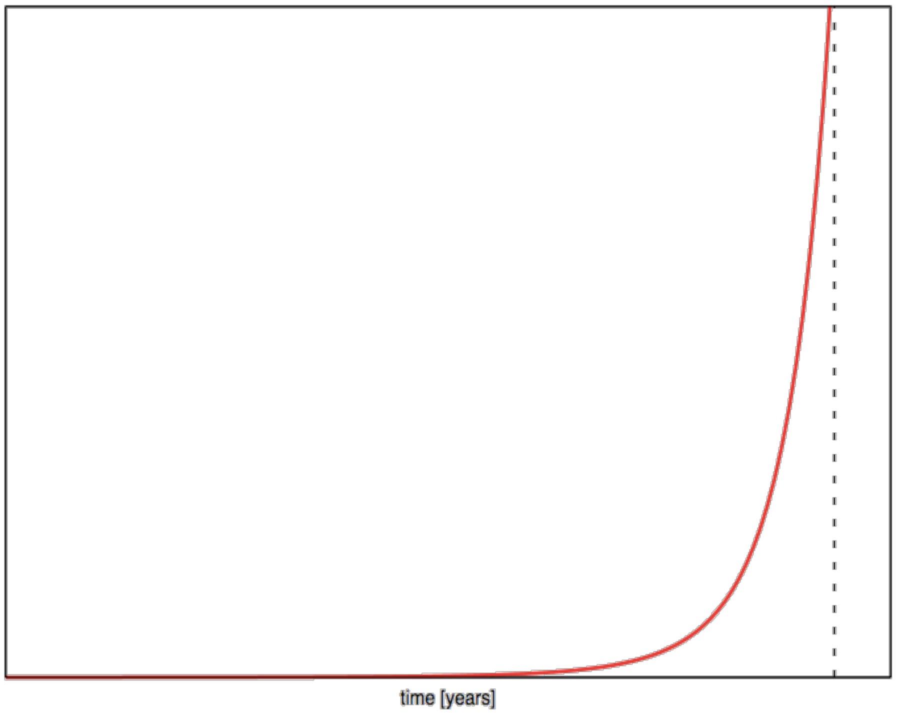
$$\frac{dN}{dt} = \left(\frac{R_1}{E_0}\right)\left[N^{\beta} - \left(\frac{R_0}{R_1}\right)N\right]$$

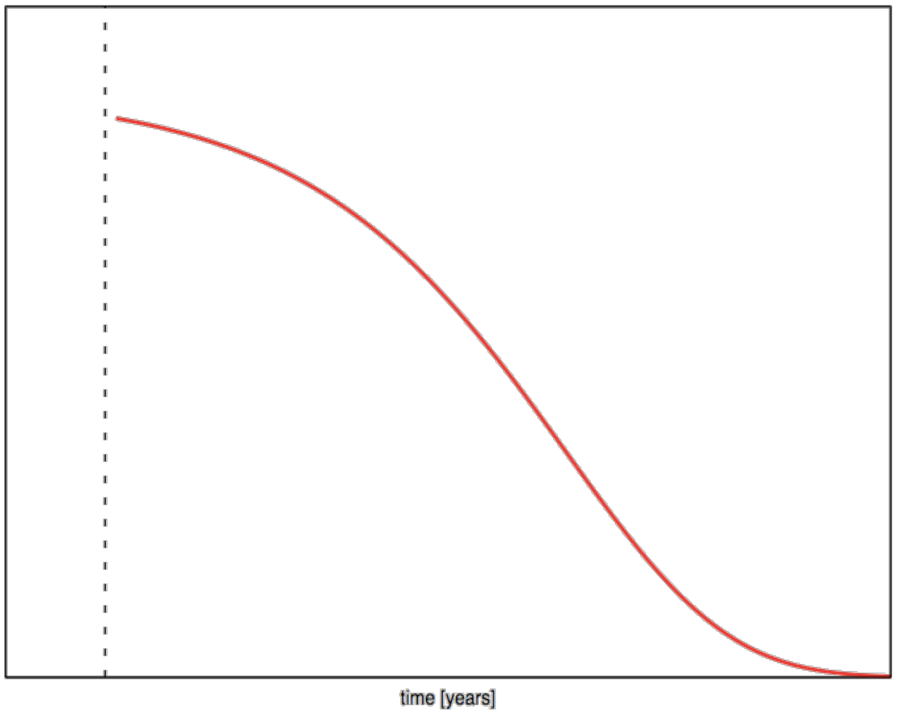
SOLUTION:

$$N^{1-\beta} = \frac{R_1}{R_0} + \left[N^{1-\beta}(0) - \frac{R_1}{R_0}\right]e^{-\frac{R_0}{E_0}(1-\beta)t}$$

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

b >1 (SUPER-LINEAR)

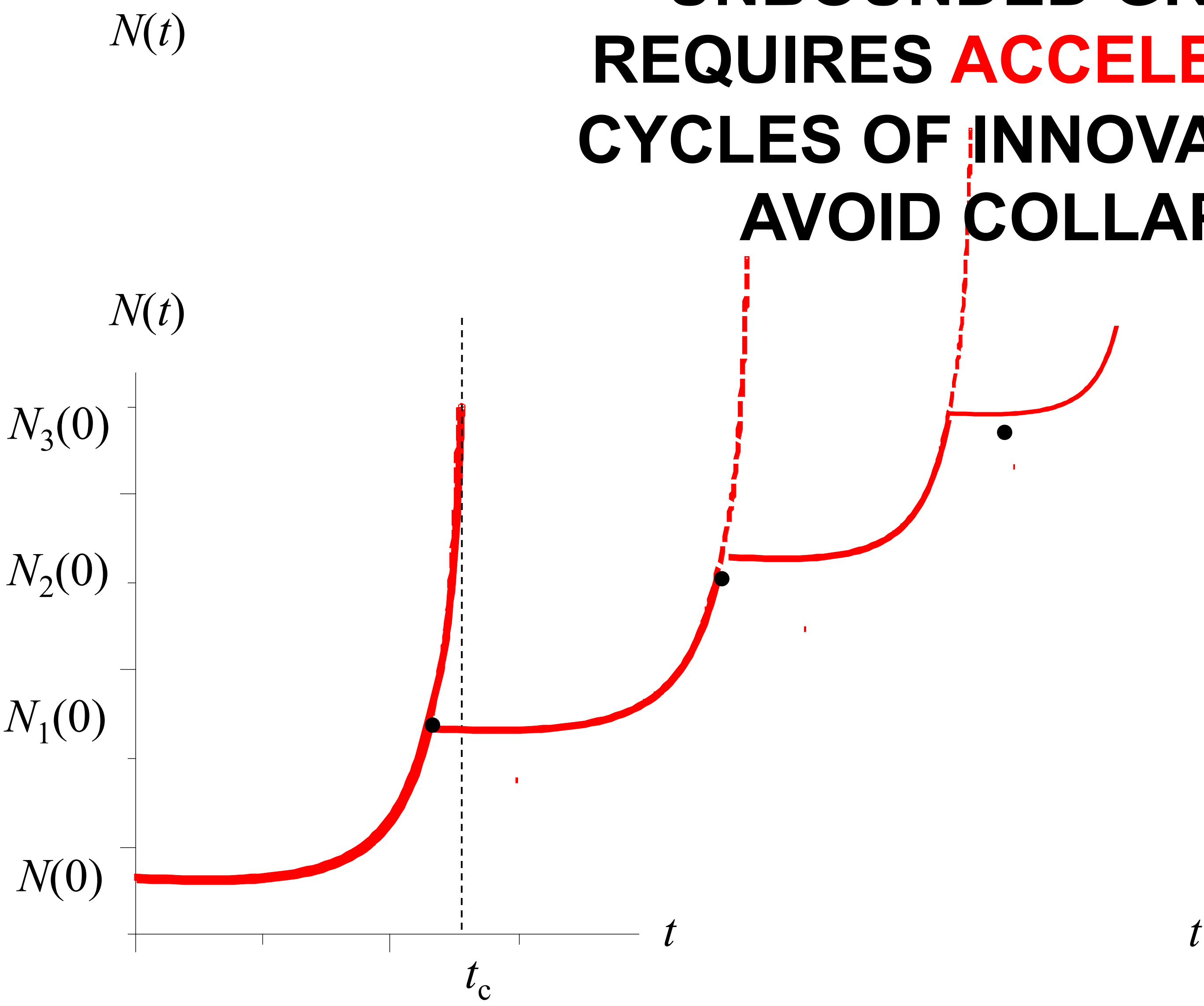




SUPER-EXPONENTIAL UNBOUNDED GROWTH

COLLAPSE

UNBOUNDED GROWTH REQUIRES ACCELERATING CYCLES OF INNOVATION TO AVOID COLLAPSE

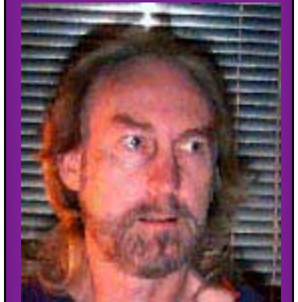


UNBOUNDED GROWTH LEADING TO "FINITE-TIME SINGULARITY" & COLLAPSE

UNLESS INNOVATIONS (SYSTEMATICALLY) OCCCUR FASTER AND FASTER

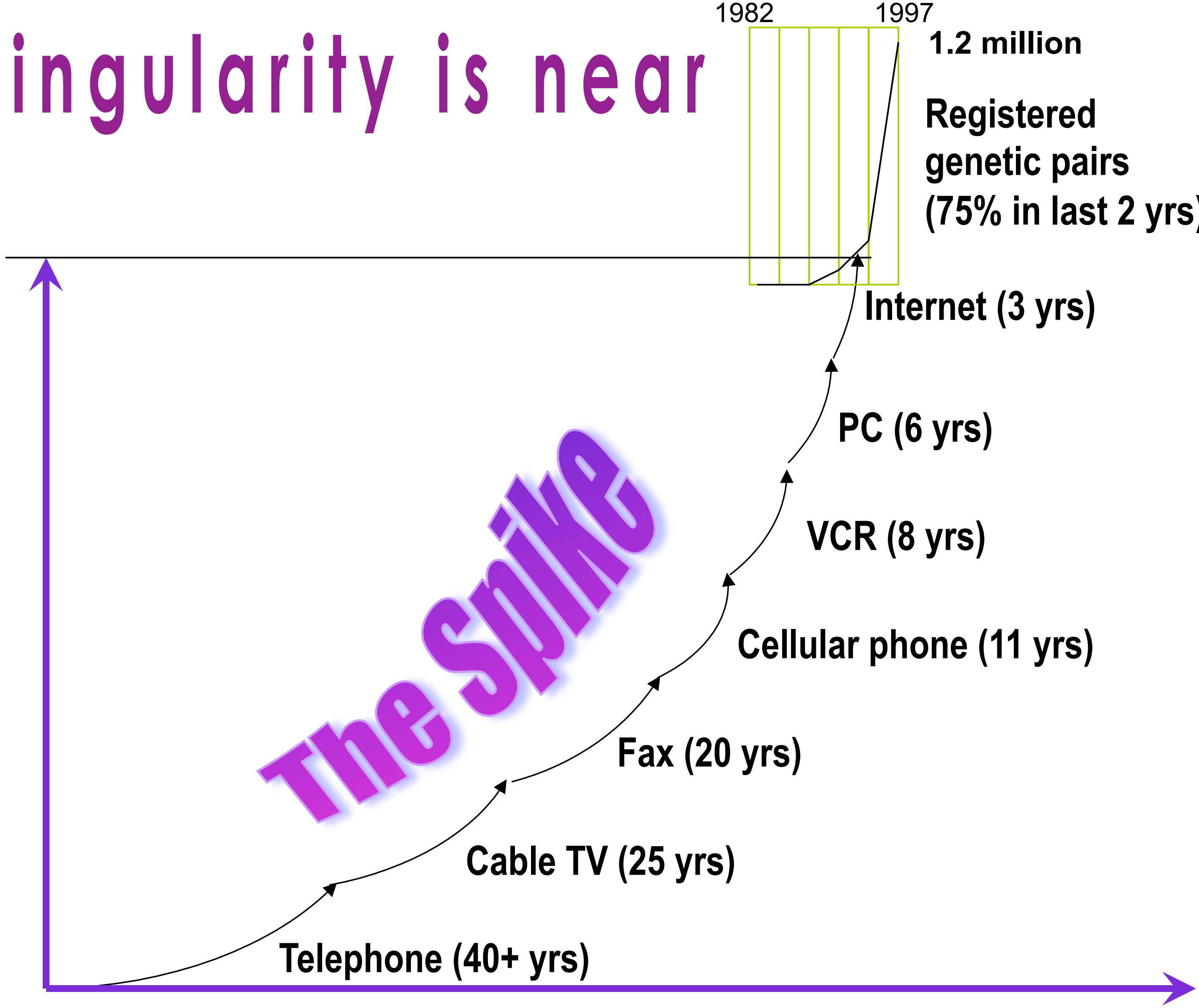
CONTINUOUS TENSION BETWEEN:

INNOVATION & WEALTH CREATION vs ECONOMIES OF SCALE



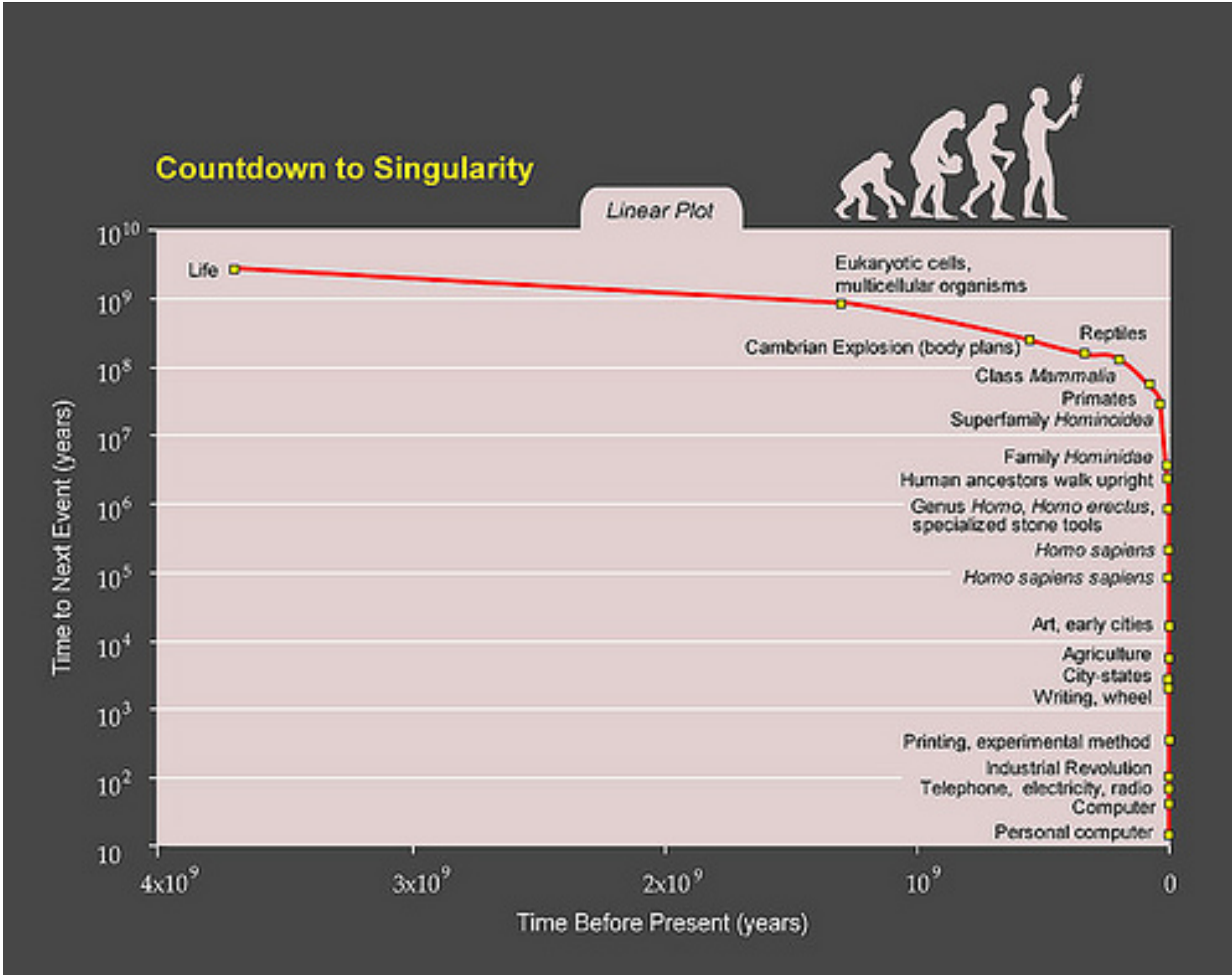
Damien Broderick

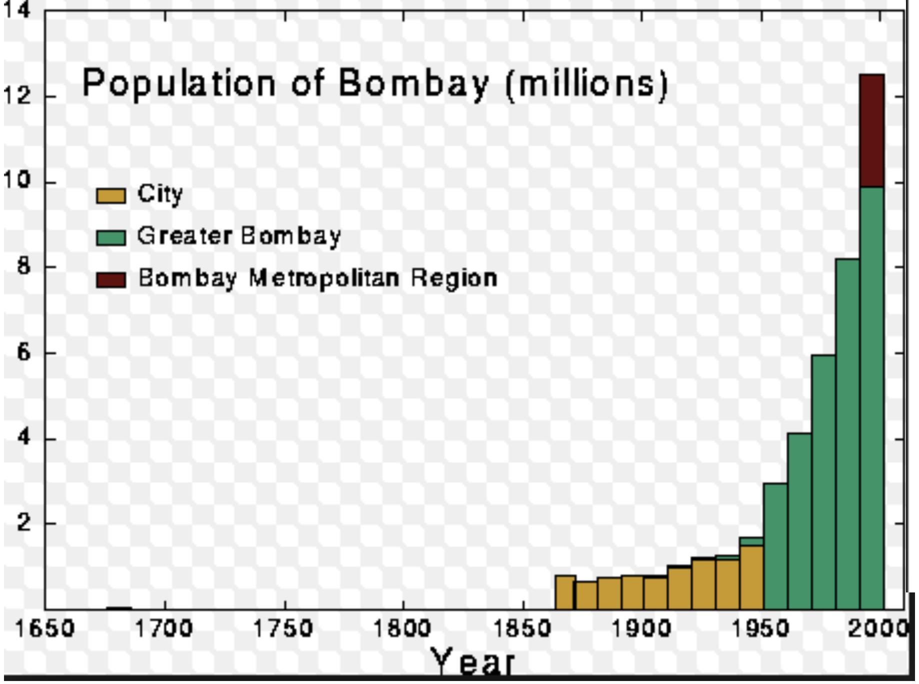
Singularity is near

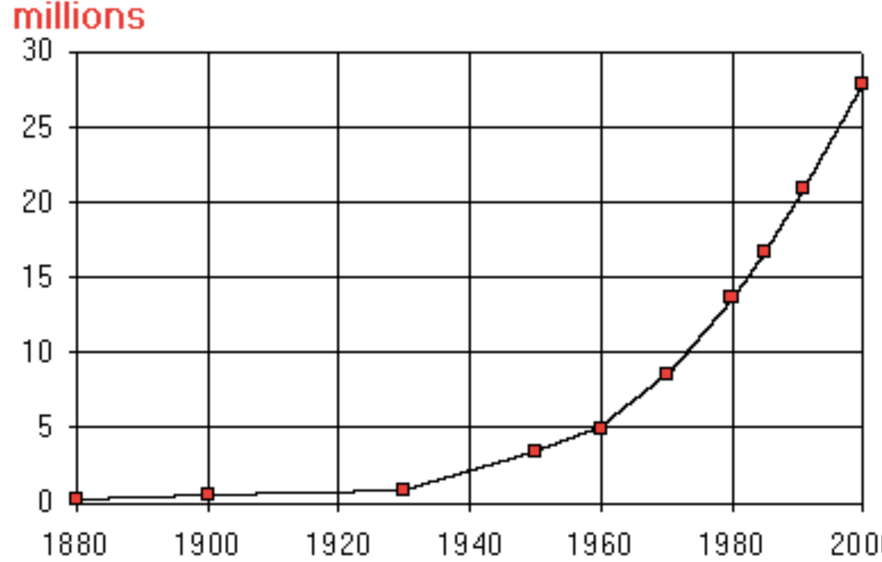


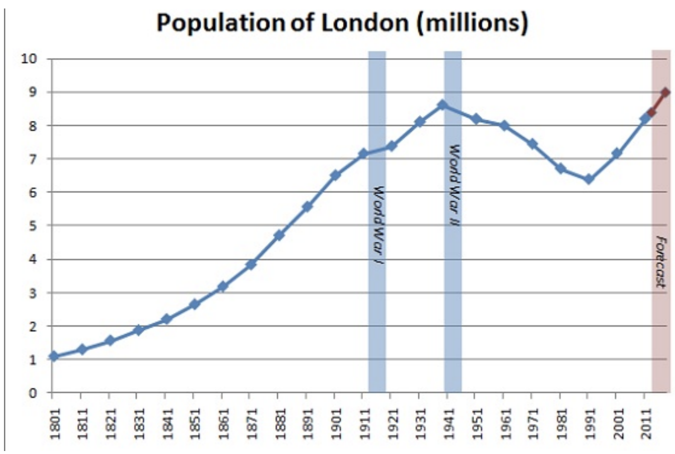
Years to reach 10 million customers (US)

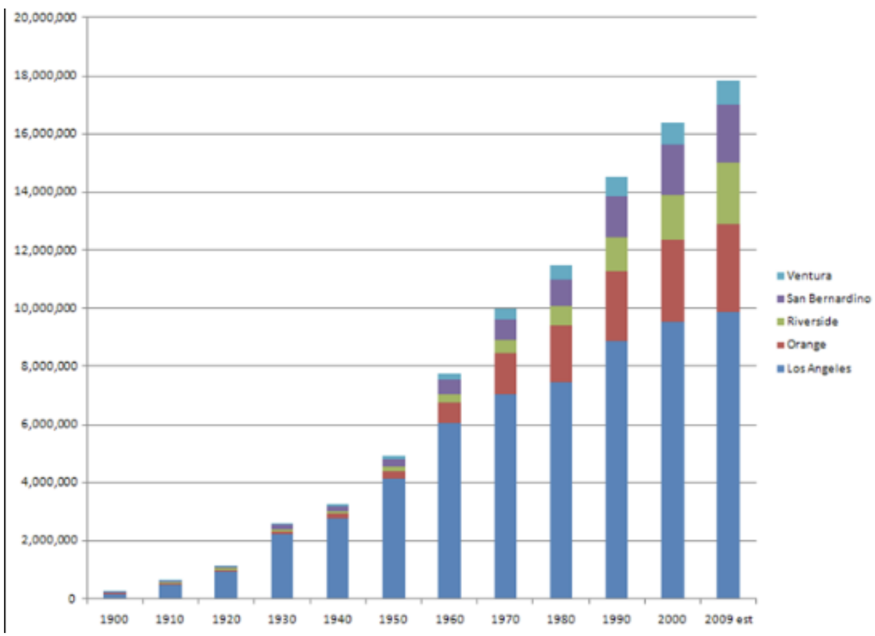
Time

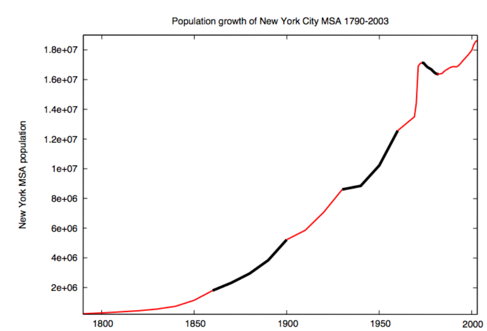

Countdown to Singularity
Linear Plot
Life
Eukaryotic cells, multicellular organisms
Cambrian Explosion (body plans)
Reptiles
Class Mammalia
Primates
Superfamily Hominoidea
Family Hominidae
Human ancestors walk upright
Genus Homo, Homo erectus, specialized stone tools
Homo sapiens
Homo sapiens sapiens
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)
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
4x10^9
3x10^9
2x10^9
10^9
0


Population of Bombay (millions)
City
Greater Bombay
Bombay Metropolitan Region
14
12
10
8
6
4
2
1650
1700
1750
1800
1850
1900
1950
2000
Year


millions
30
25
20
15
10
5
0
1880
1900
1920
1940
1960
1980
2000


Population of London (millions)
10
9
8
7
6
5
4
3
2
1
0
1801
1811
1821
1831
1841
1851
1861
1871
1881
1891
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
World War I
World War II
Forecast


20,000,000
18,000,000
16,000,000
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2009 est
Ventura
San Bernardino
Riverside
Orange
Los Angeles


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

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 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.

Pin it

Image: Eva Vazquez

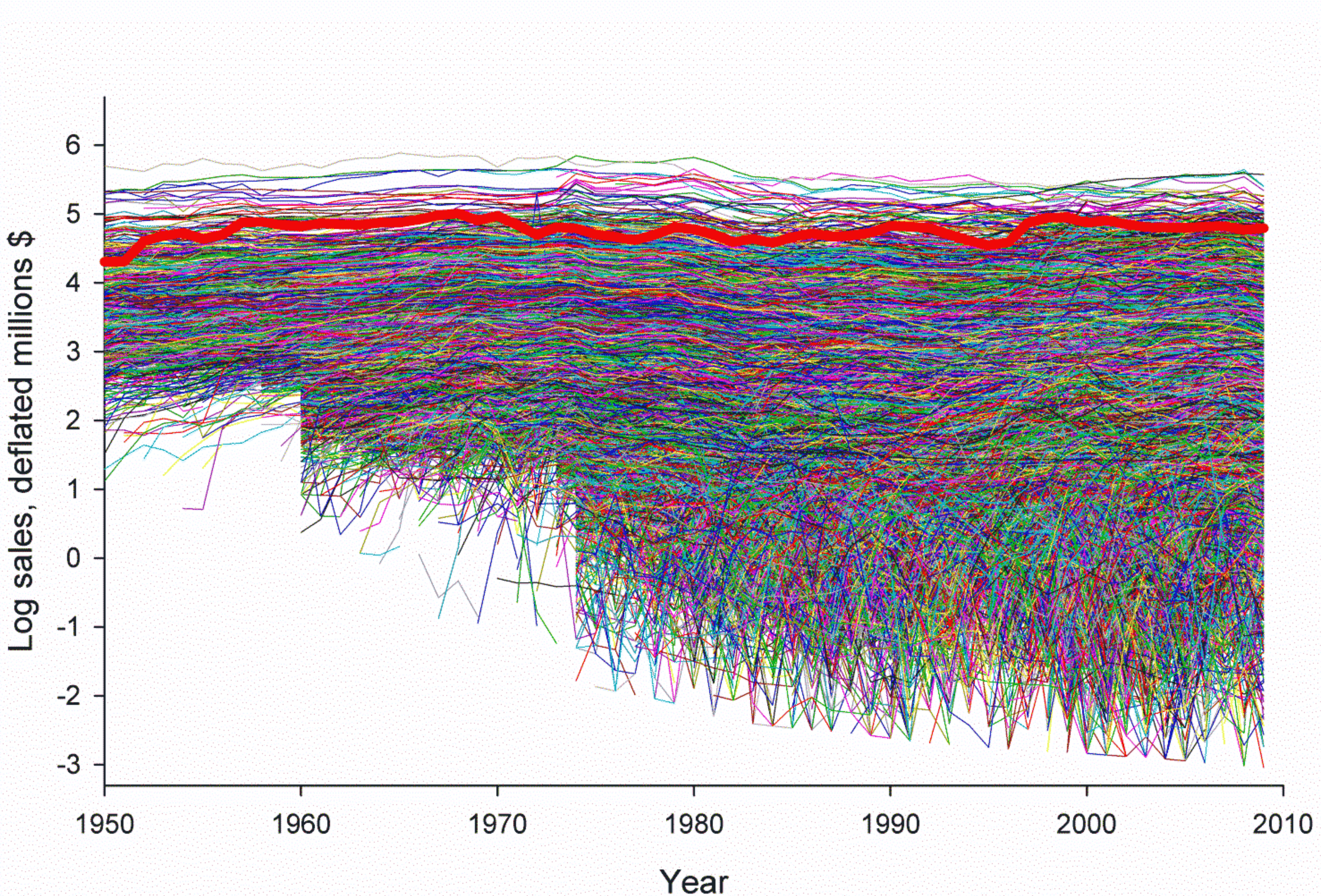
OUR “NATURAL” METABOLIC RATE ~ 90 watts

OUR SOCIAL METABOLIC RATE ~ 11,000 watts !!!

WE ARE EQUIVALENT TO A 30,000 Kg GORILLA !!!

REPRODUCTION RATE OF ~ ONE OFFSPRING PER 15 years

Net Income (0.74)
Net Income
Gross Profit (0.91)
Gross Profit
Employees
Total Assets (0.88)
Total Assets
Employees
Sales (1.00)
Sales
Employees


Log sales, deflated millions $
6
5
4
3
2
1
0
-1
-2
-3
1950
1960
1970
1980
1990
2000
2010
Year