ON THE FUTURE OF THE PLANET:

THE UNIVERSAL LAWS OF LIFE, GROWTH, DEATH & SUSTAINABILITY FROM ORGANISMS T0 CITIES

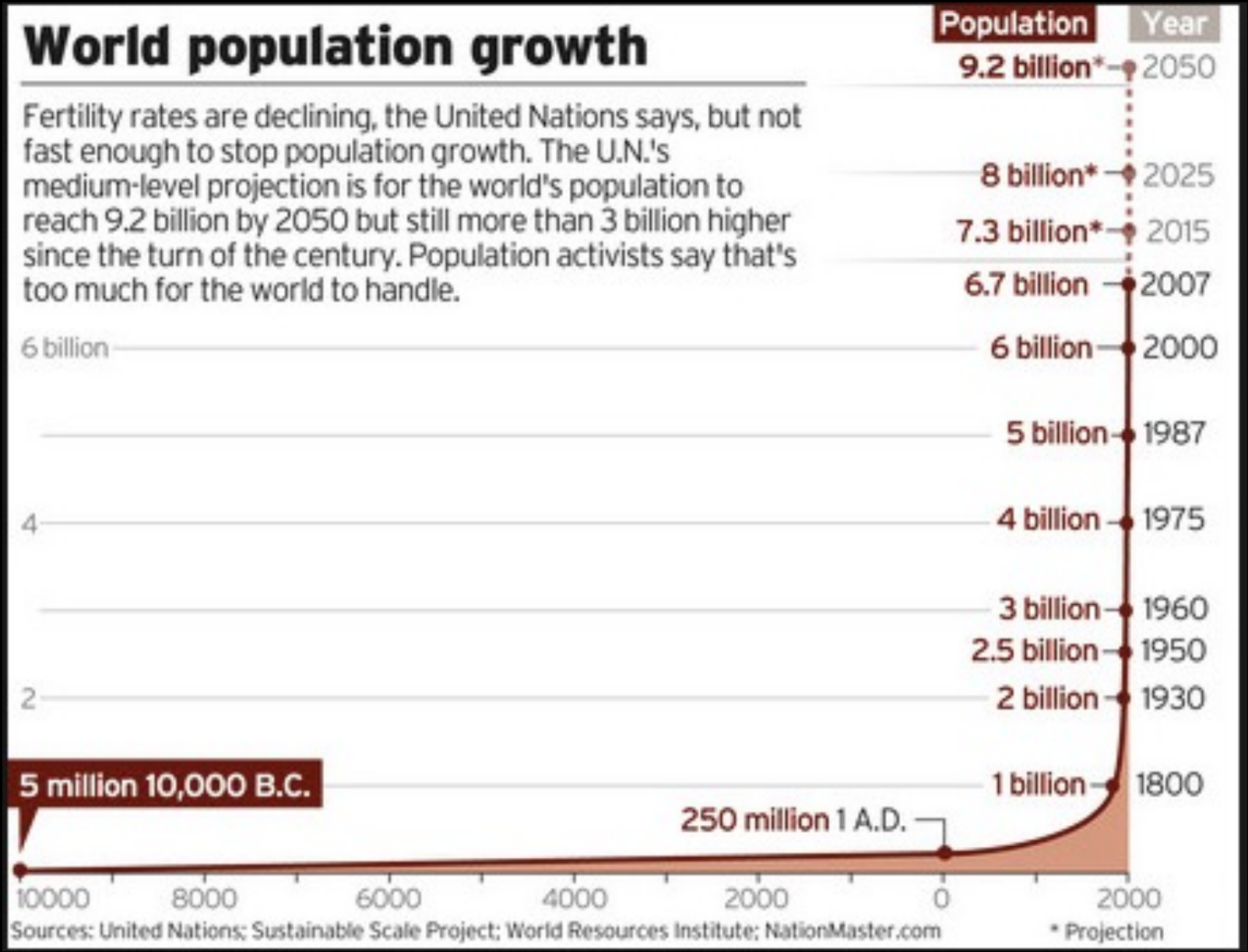
GEOFFREY WEST

SANTA FE INSTITUTE

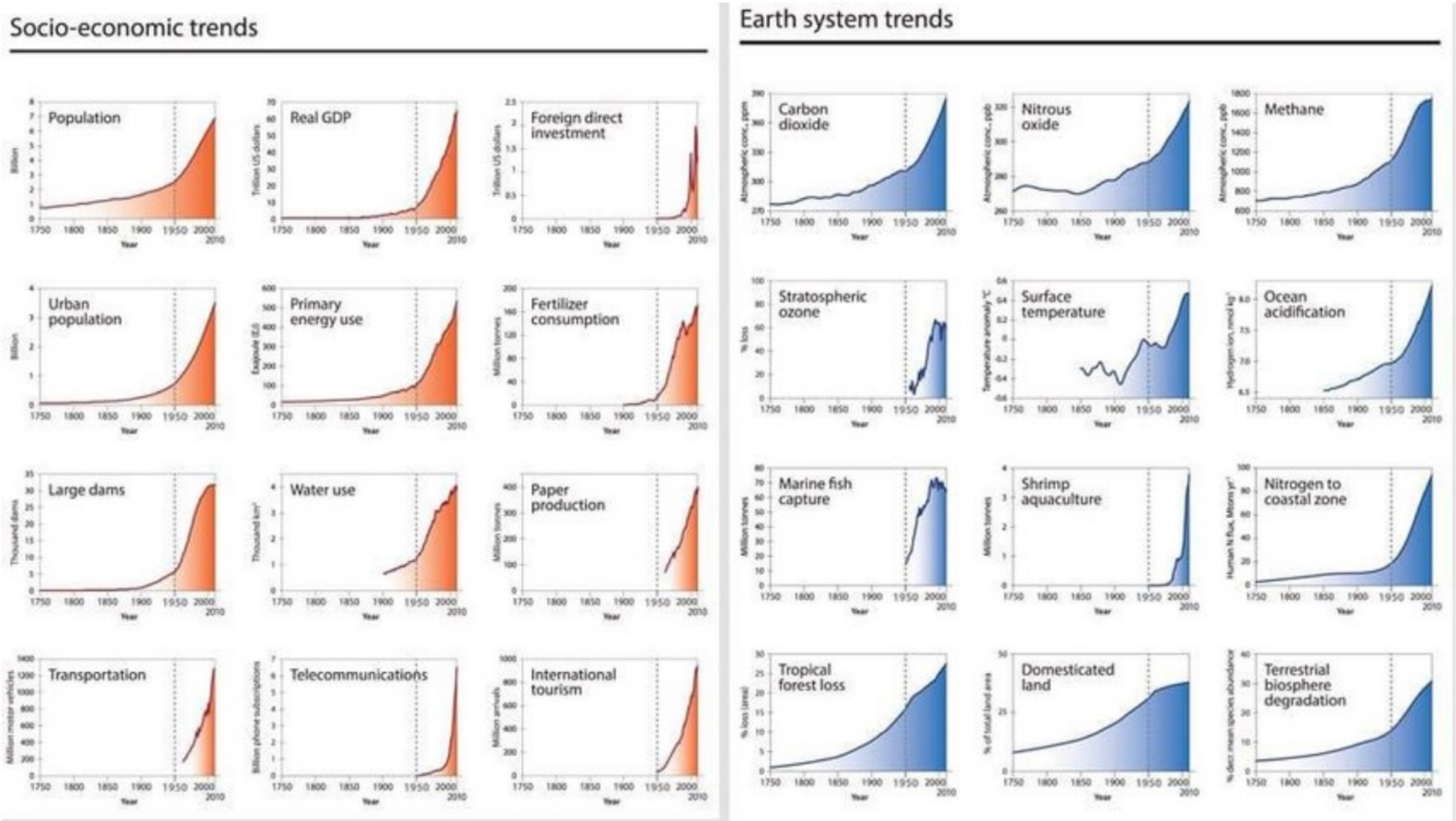
GREEN-TEMPLETON COLLEGE, OXFORD UNIVERSITY

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 (1953)


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.
Population
Year
9.2 billion* 2050
8 billion* 2025
7.3 billion* 2015
6.7 billion 2007
6 billion 2000
5 billion 1987
4 billion 1975
3 billion 1960
2.5 billion 1950
2 billion 1930
1 billion 1800
6 billion
4
2
5 million 10,000 B.C.
250 million 1 A.D.
10000
8000
6000
4000
2000
0
2000
Sources: United Nations; Sustainable Scale Project; World Resources Institute; NationMaster.com
* Projection

THE GREAT ACCELERATION



Updated Great Acceleration Graphs

Source: Will Steffen et al. "The trajectory of the Anthropocene: The Great Acceleration." The Anthropocene Review, March 2015

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

AVERAGED FROM FROM NOW TILL 2050 WE ARE URBANISING OVER ONE MILLION PEOPLE EVERY WEEK

AVERAGED FROM FROM NOW TILL 2050 WE ARE URBANISING OVER ONE MILLION PEOPLE EVERY WEEK

EQUIVALENT TO ADDING A NEW YORK METROPOLITAN AREA EVERY THREE MONTHS

AVERAGED FROM FROM NOW TILL 2050 WE ARE URBANISING OVER ONE MILLION PEOPLE EVERY WEEK

EQUIVALENT TO ADDING A NEW YORK METROPOLITAN AREA EVERY THREE MONTHS

OR…….A HAMBURG EVERY 9-10 DAYS


FATE OF OUR PLANET IS
the fate of our cities


M·AGRIPPA·L·F·COS·TERTIVM·FECIT

THE CITY IS THE MARVELLOUS MACHINE WE DEVELOPED FOR FACILITATING THE CREATION OF

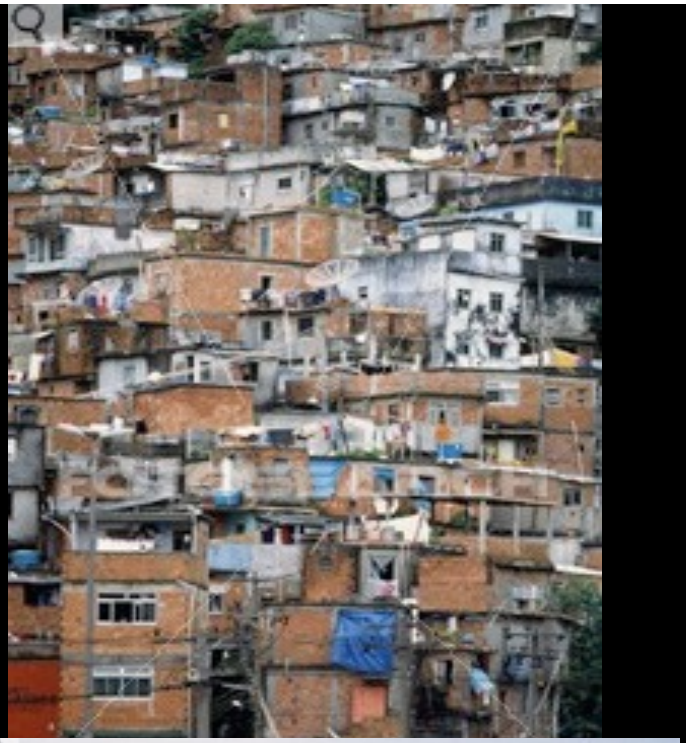
THE CITY IS THE MARVELLOUS MACHINE WE DEVELOPED FOR FACILITATING THE CREATION OF

- ***WEALTH***
- ***KNOWLEDGE, INNOVATION AND IDEAS***
- ***INCREASED STANDARDS & QUALITY OF LIFE***

BUT UNINTENTIONALLY AND INEVITABLY IT ALSO CREATES

SOCIAL AND PHYSICAL ENTROPY:


Evening Standard
Classified
MASSIVE INCREASE IN KNIFE CRIME SURVEYS
Evening Standard



DISEASE AND PANDEMICS!


SOCIAL UNREST!

ARE WE EXPERIENCING THE 6TH MASS EXTINCTION?

ECO Sapien ecosapien.org

CURRENT RATE OF SPECIES EXTINCTION IS THOUGHT TO BE UP TO 10,000x GREATER THAN WOULD NATURALLY BE EXPECTED WITHOUT HUMANS

THERE ARE NOW 7.4 BILLION HUMANS

PROPORTION OF EXINCTION-THREATENED SPECIES WITHIN TAXON

- 68% PLANTS
- 41% AMPHIBIANS
- 30% INVERTEBRATES
- 26% MAMMALS
- 21% FISH
- 21% REPTILES
- 13% BIRDS

ONLY 5% OF THE 1.9 MILION KNOWN SPECIES HAVE BEEN ASSESSED, SO THE TRUE EXTINCTION RISK OF OF MANY SPECIES MAY BE EVEN GREATER

OVER 1.5% OF IUCN ASSESSED VERTEBRATES ARE NOW EXTINCT

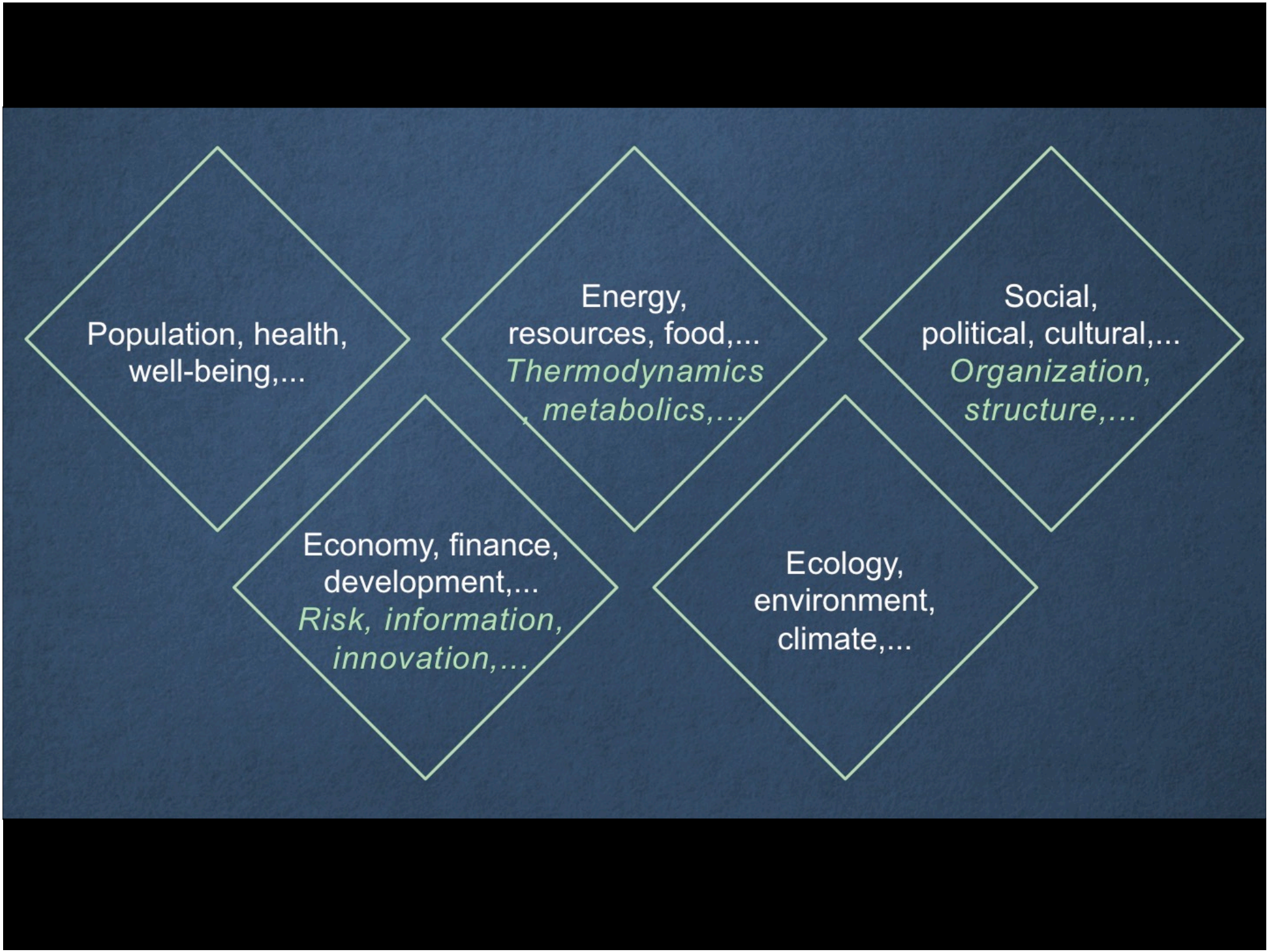
CUMULATIVE VERTEBRATE EXTINCTIONS

EXPECTED "NATURAL" EXTINCTIONS

GLOBAL HUMAN POPULATION

1500 1600 1700 1800 1900 2000

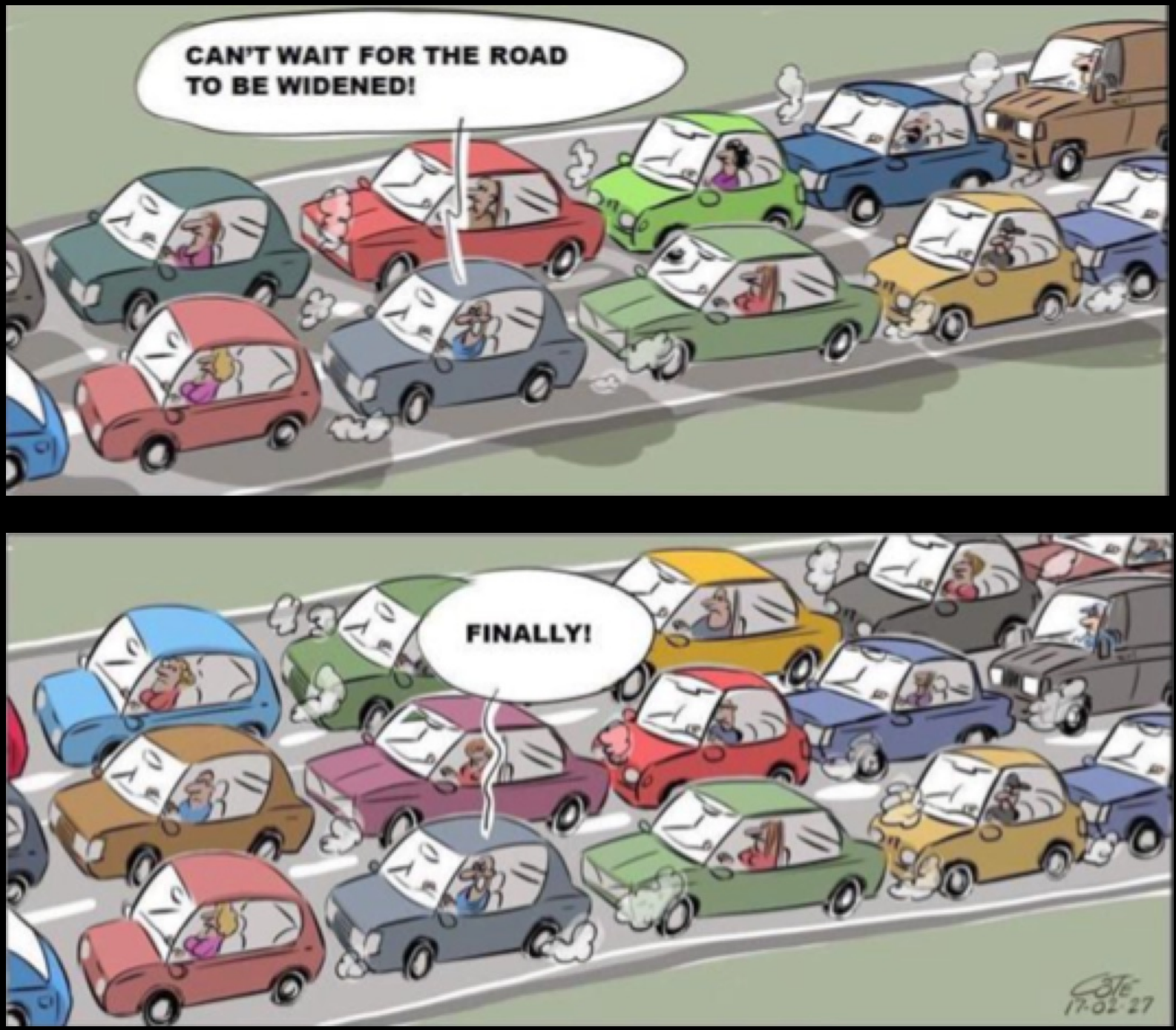
London After Climate Change?


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'T WAIT FOR THE ROAD
TO BE WIDENED!


CAN'T WAIT FOR THE ROAD TO BE WIDENED!
FINALLY!
17-02-27

CITIES ARE QUINTESSENTIAL COMPLEX ADAPTIVE SYSTEMS

ENERGY & RESOURCES (METABOLISM, INFRASTRUCTURE)

+

INFORMATION (GENOMICS, INNOVATION)

Q: *Some say that while the 20th century was the century of physics, we are now entering the century of biology. What do you think of this?*

Stephen Hawking interview, January, 2000

Q: *Some say that while the 20th century was the century of physics, we are now entering the century of biology. What do you think of this?*

A: *I think the next century will be the century of complexity.*

Stephen Hawking interview,
January, 2000

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

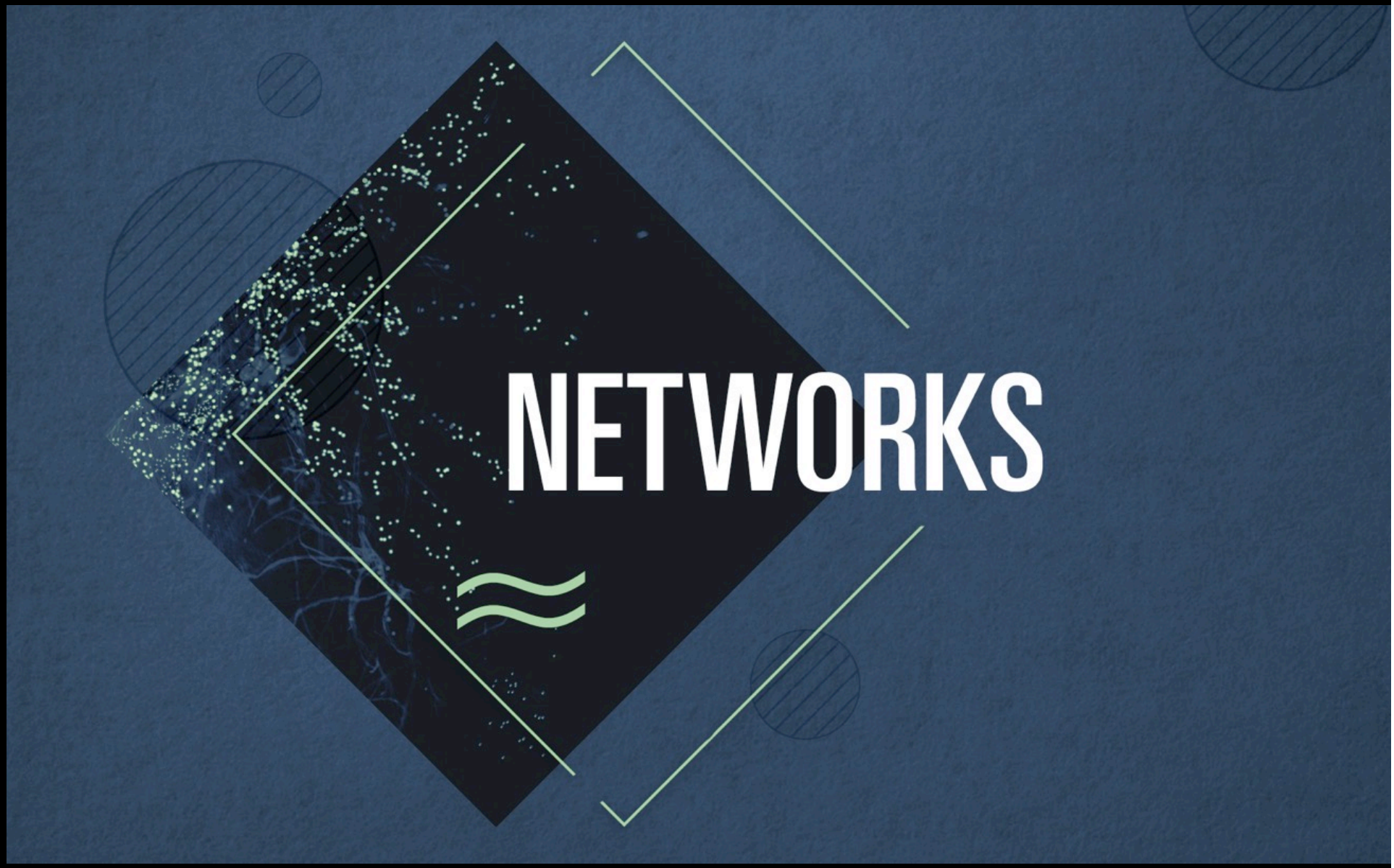
CAN THERE BE "NEWTON'S LAWS OF COMPLEX ADAPTIVE SYSTEMS"?

ALMOST CERTAINLY NOT!

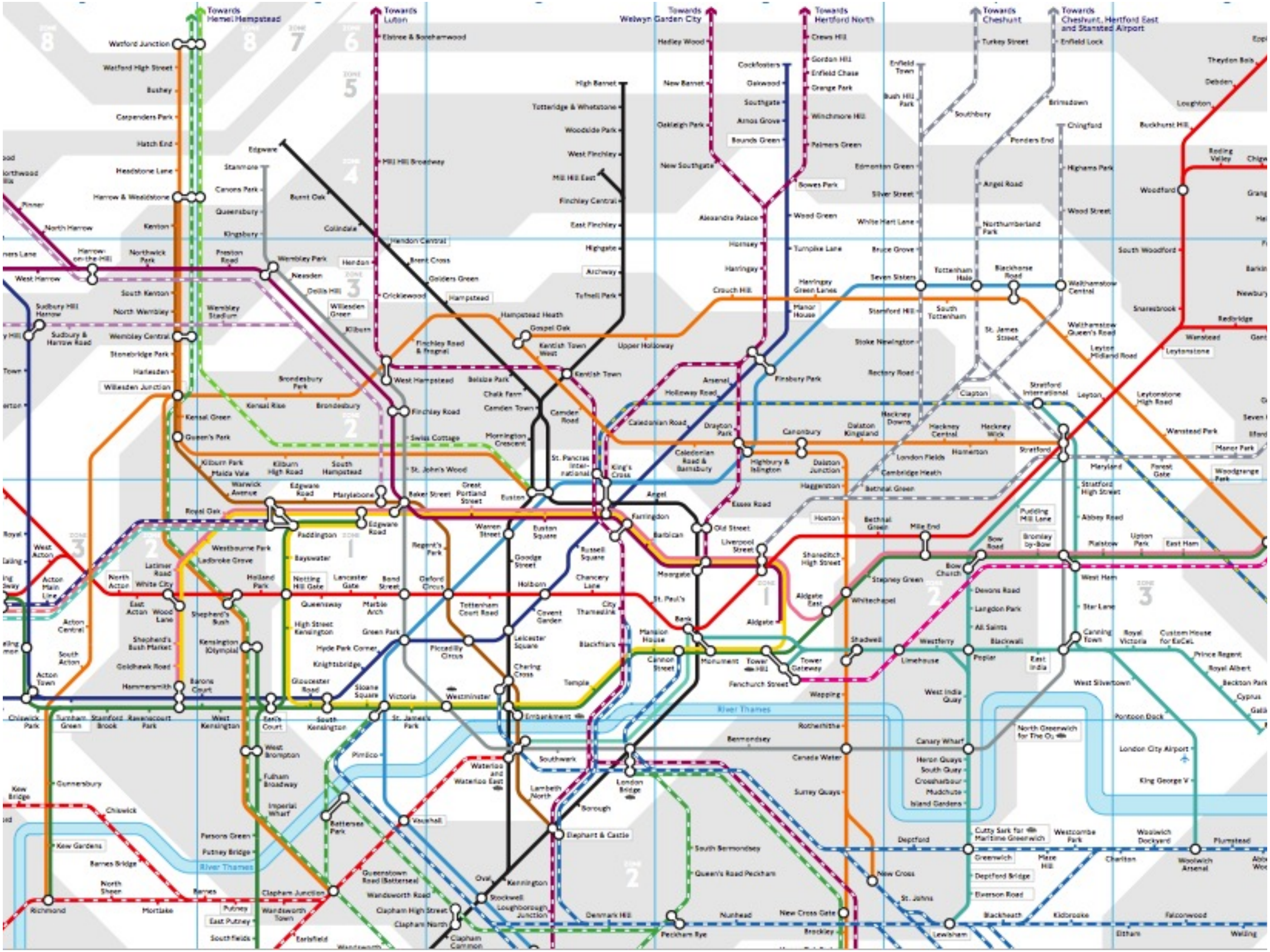
CAN THERE BE "NEWTON'S LAWS OF COMPLEX ADAPTIVE SYSTEMS"?

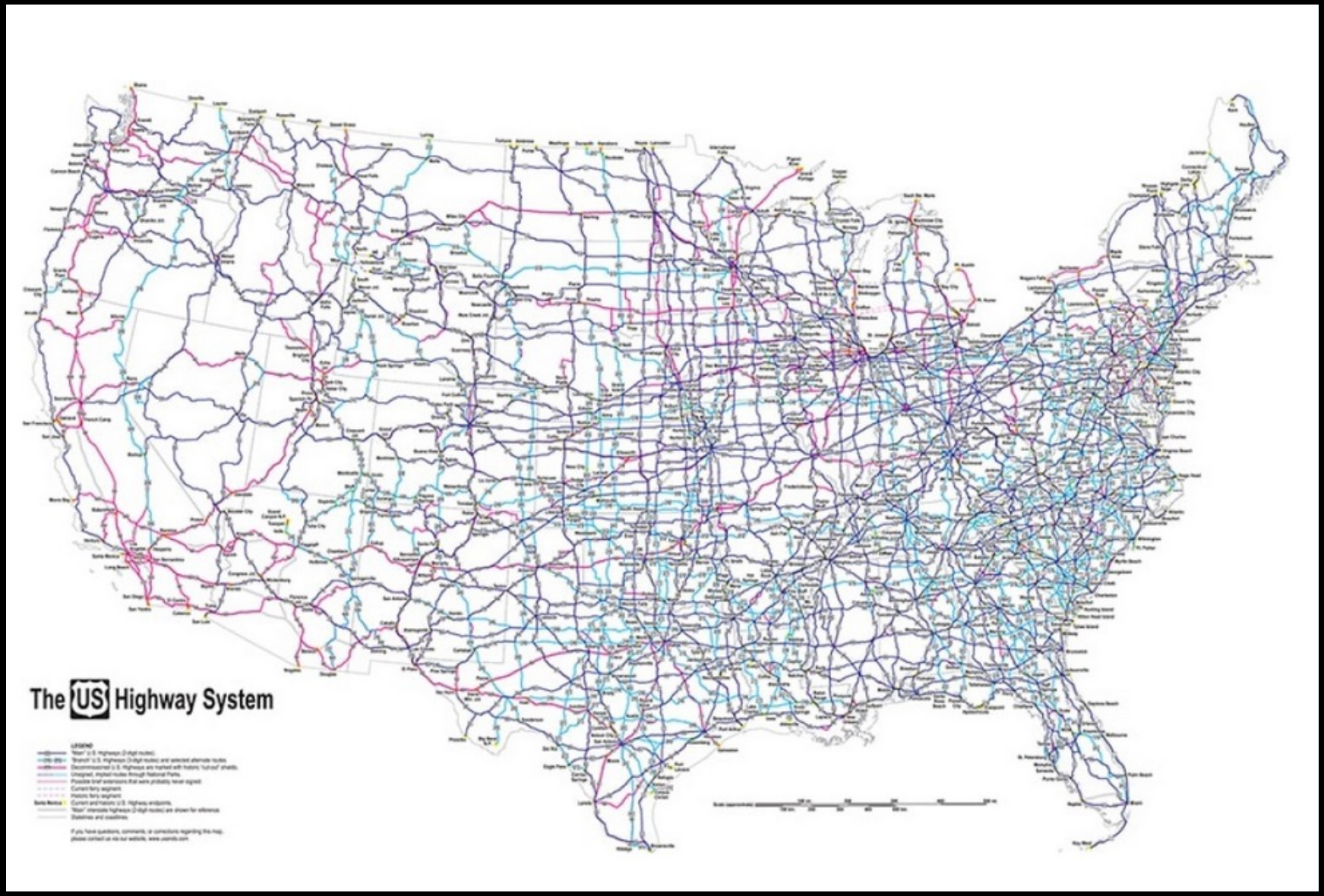
ALMOST CERTAINLY NOT!

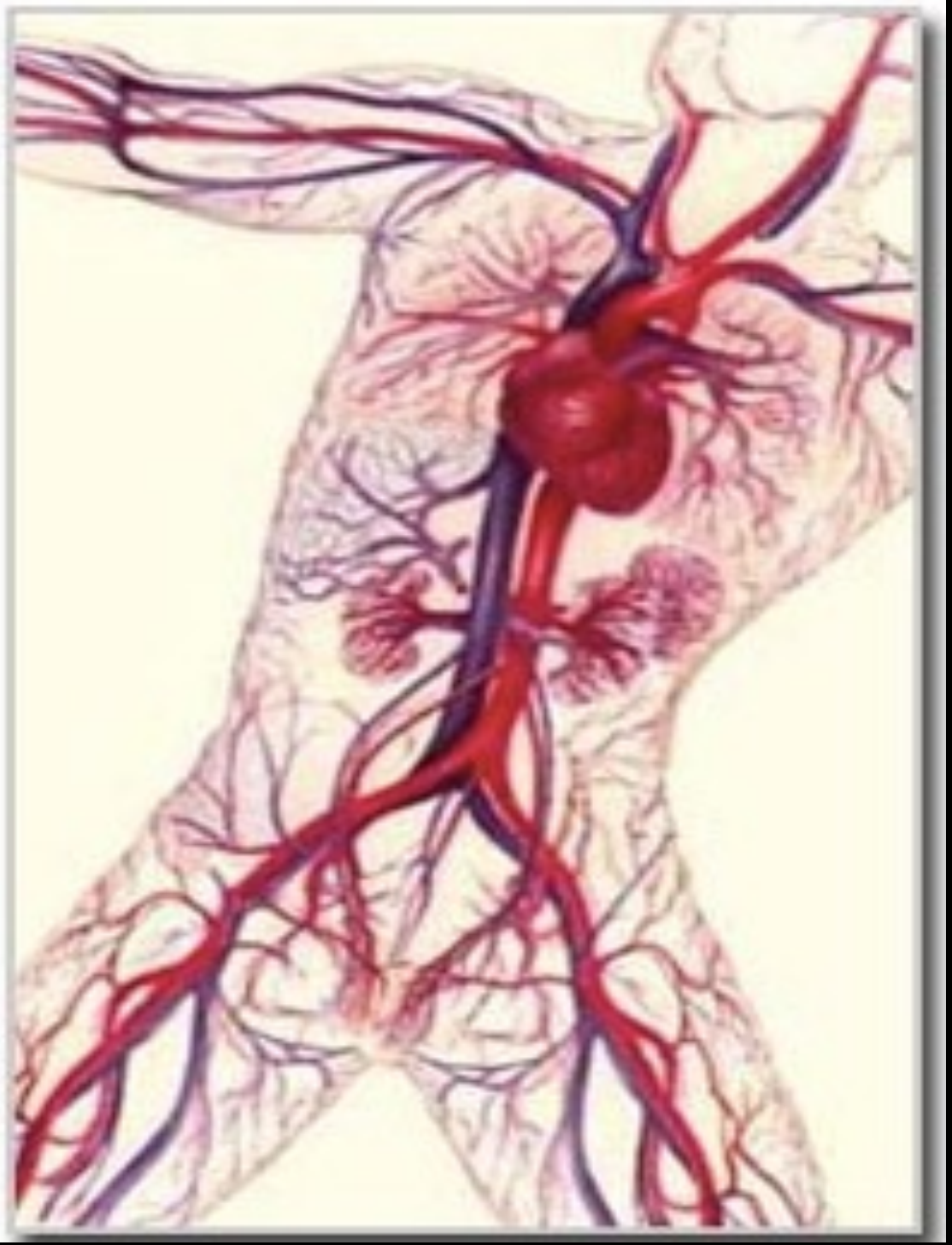
BUT, CAN STILL ASK WHETHER THERE ARE EMERGENT COARSE - GRAINED LAWS AND PRINCIPLES THAT LEAD TO A QUANTITATIVE COMPUTATIONAL (MATHEMATISABLE) PREDICTIVE CONCEPTUAL FRAMEWORK


NETWORKS

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

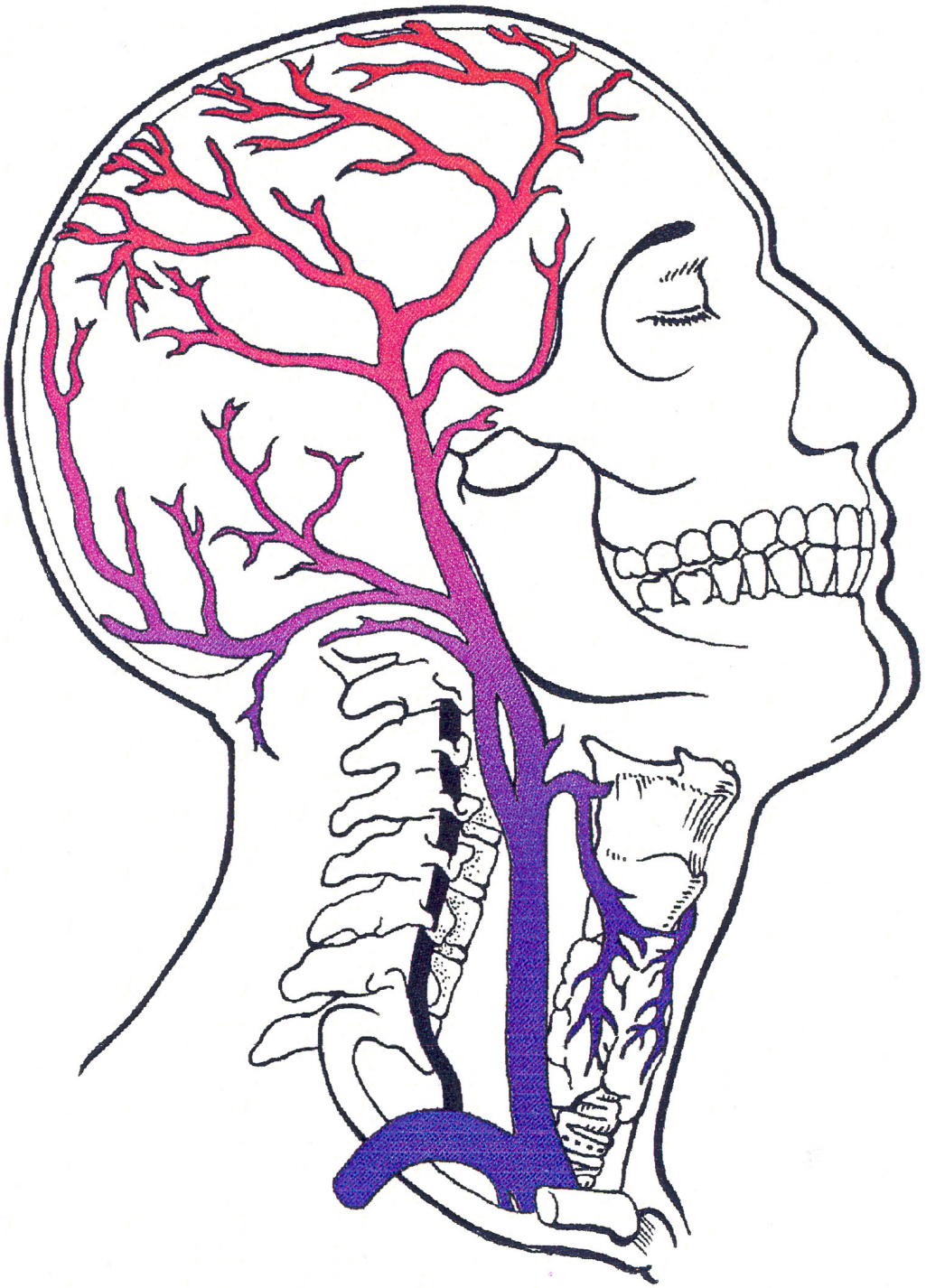

The US Highway System

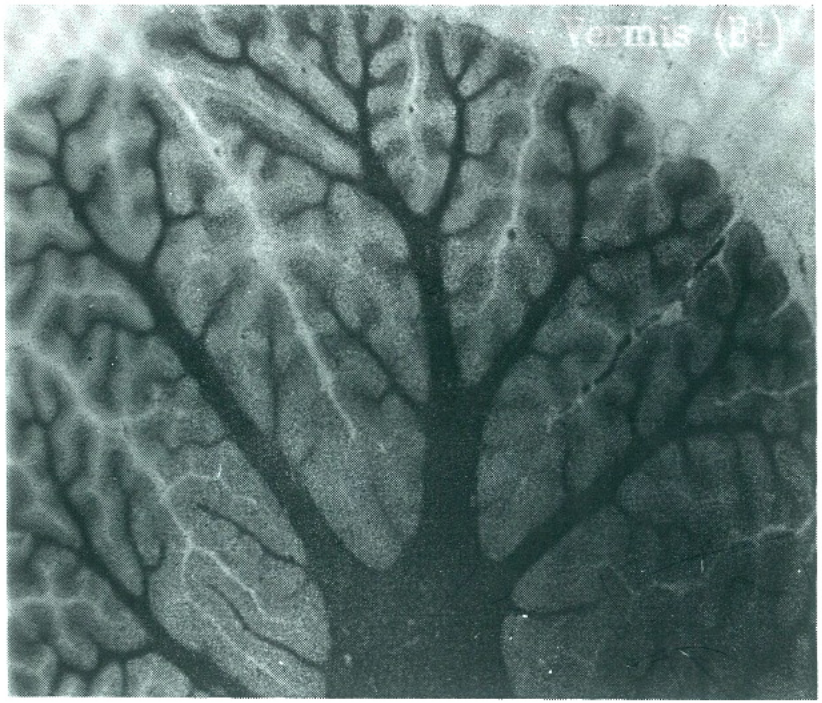


Large vessels branch into smaller ones

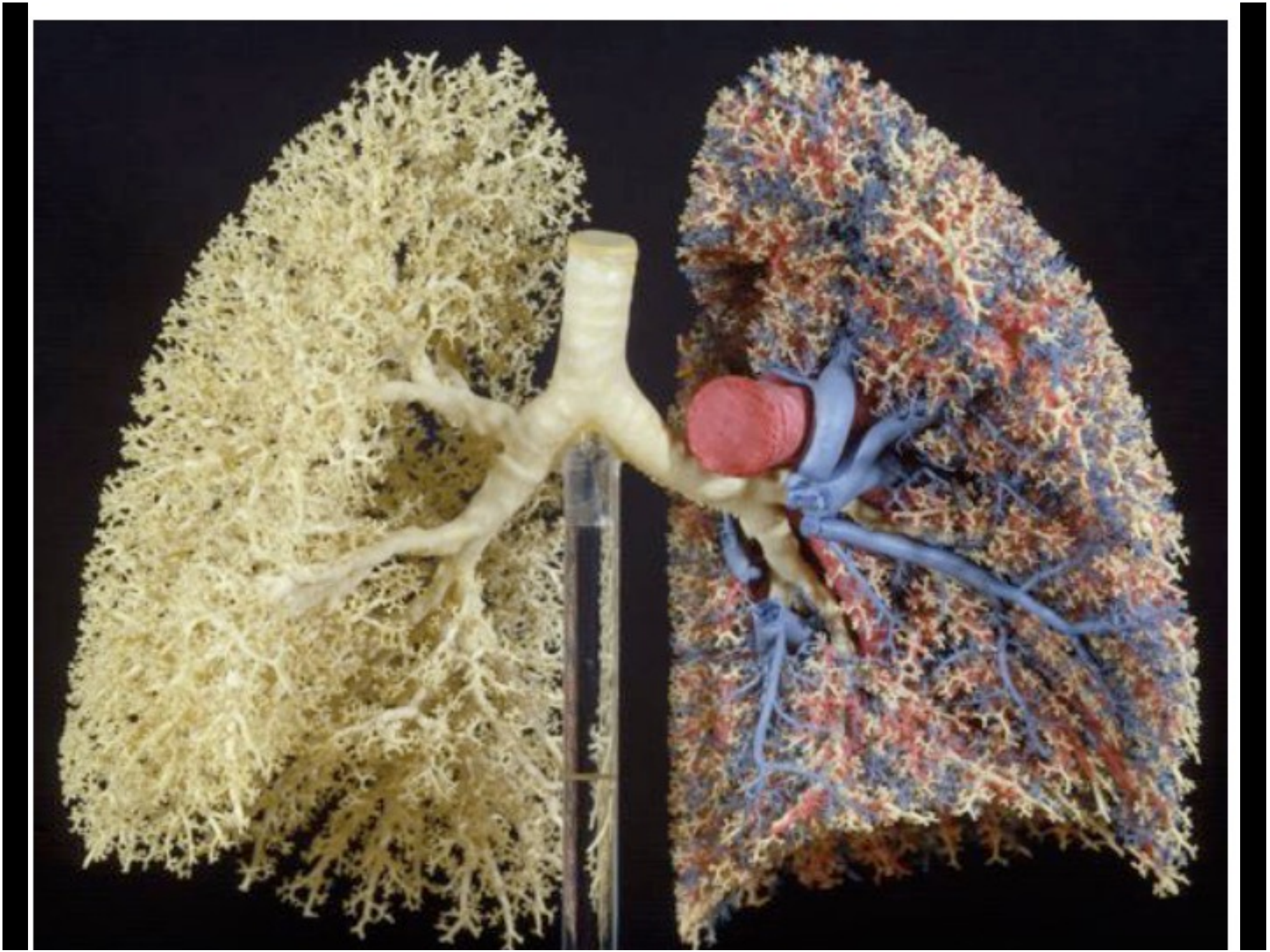
Beating heart

Pulse wave propagates through elastic vessels

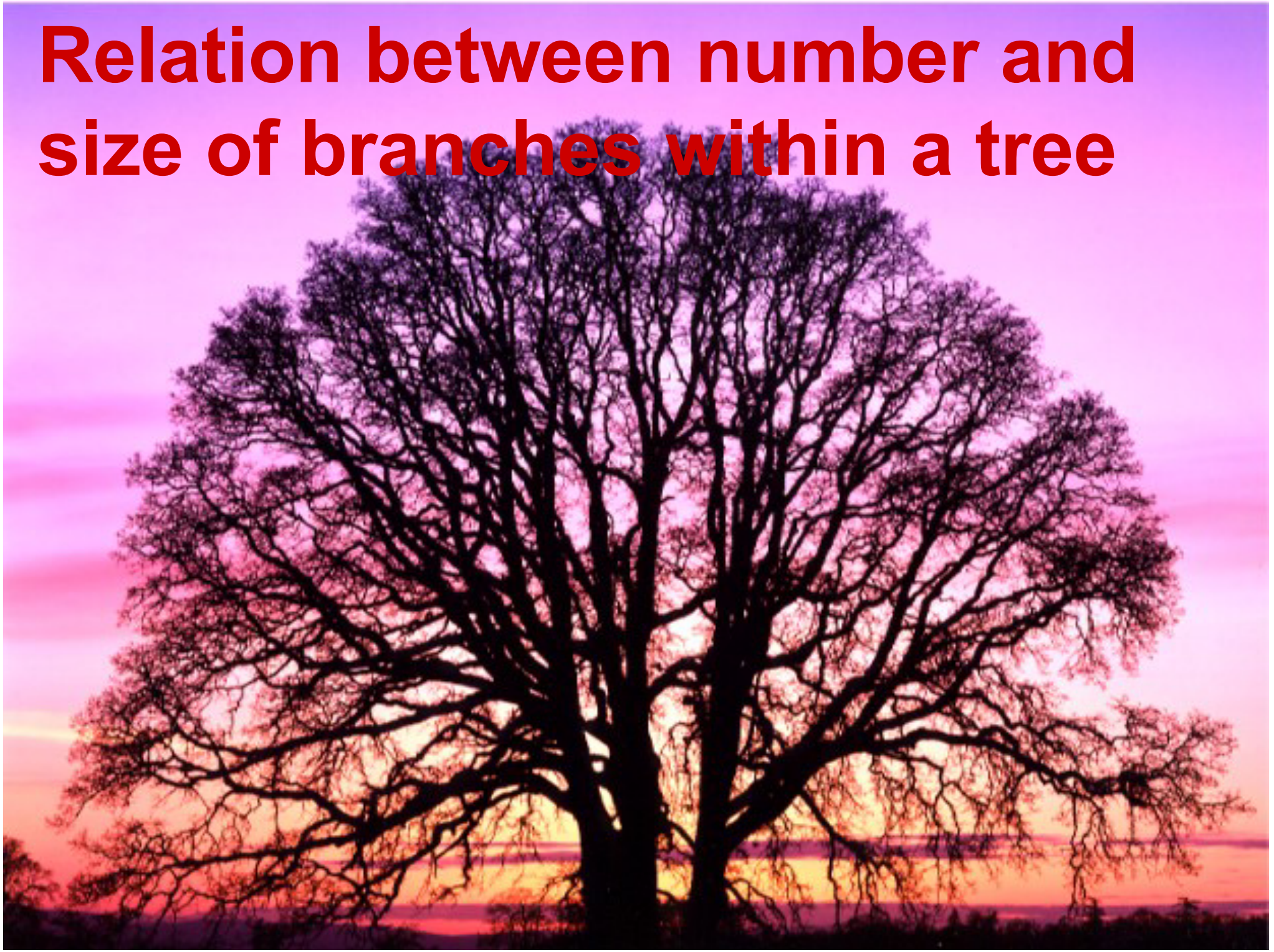


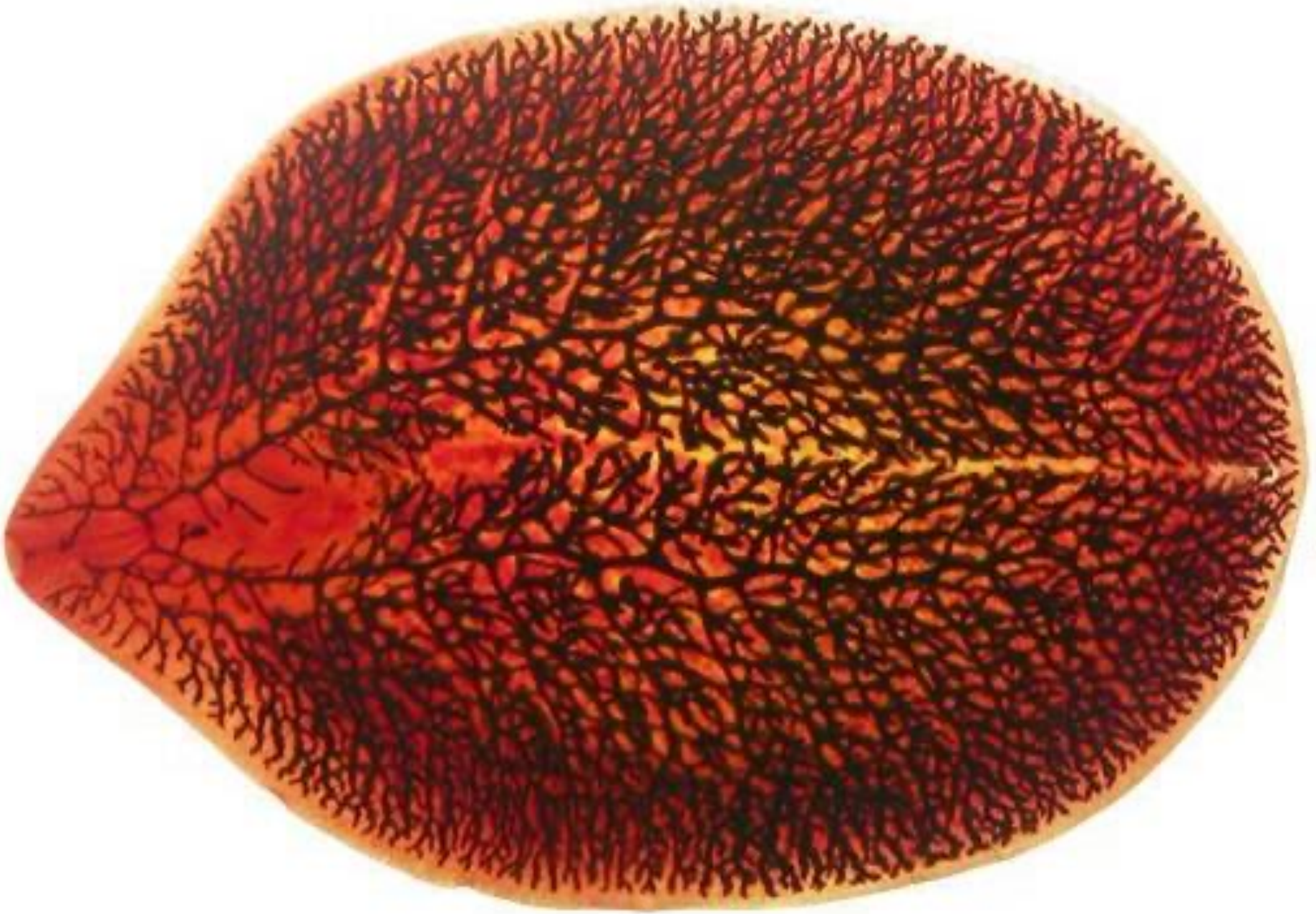


: 5 A slice through the cerebellum showing the progressive branching structure
vhite matter is distributed throughout the cerebellar volume. The geometric
:ity of these structures provides for rapid dissemination of information (or
e) via a large surface area in a compact space. This feature is a hallmark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



Relation between number and size of branches within a tree





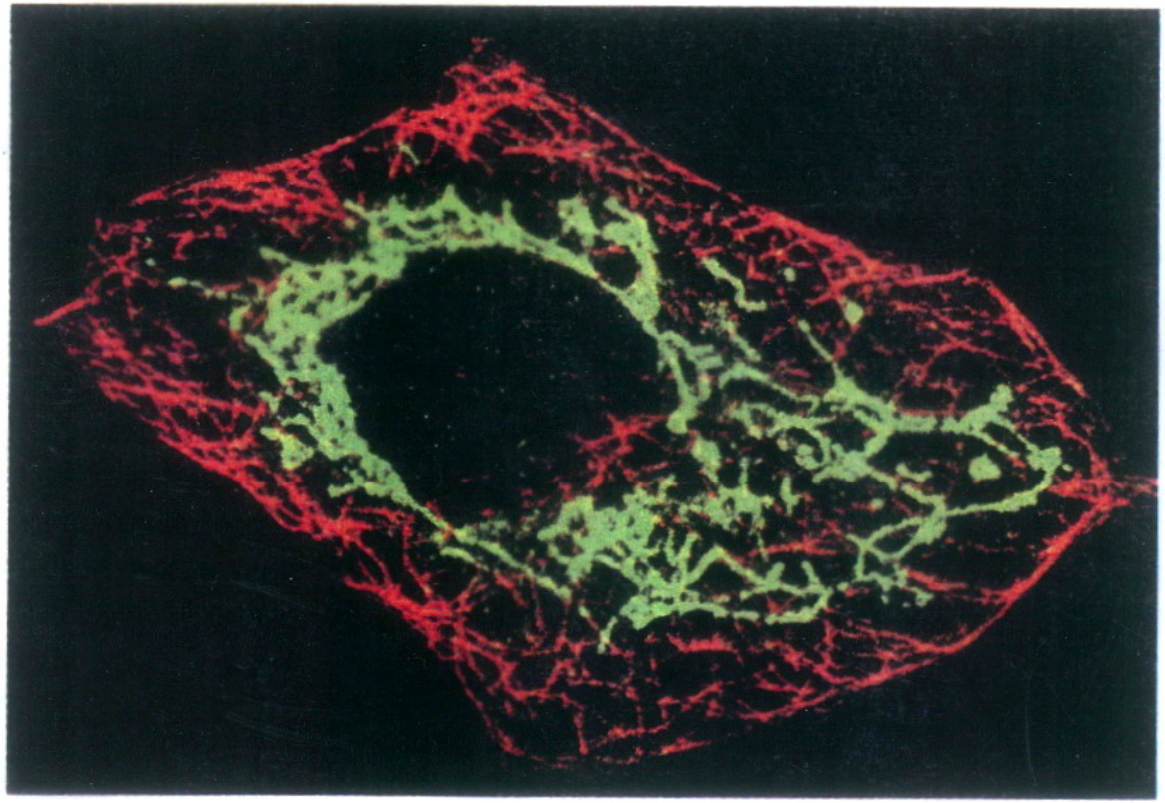
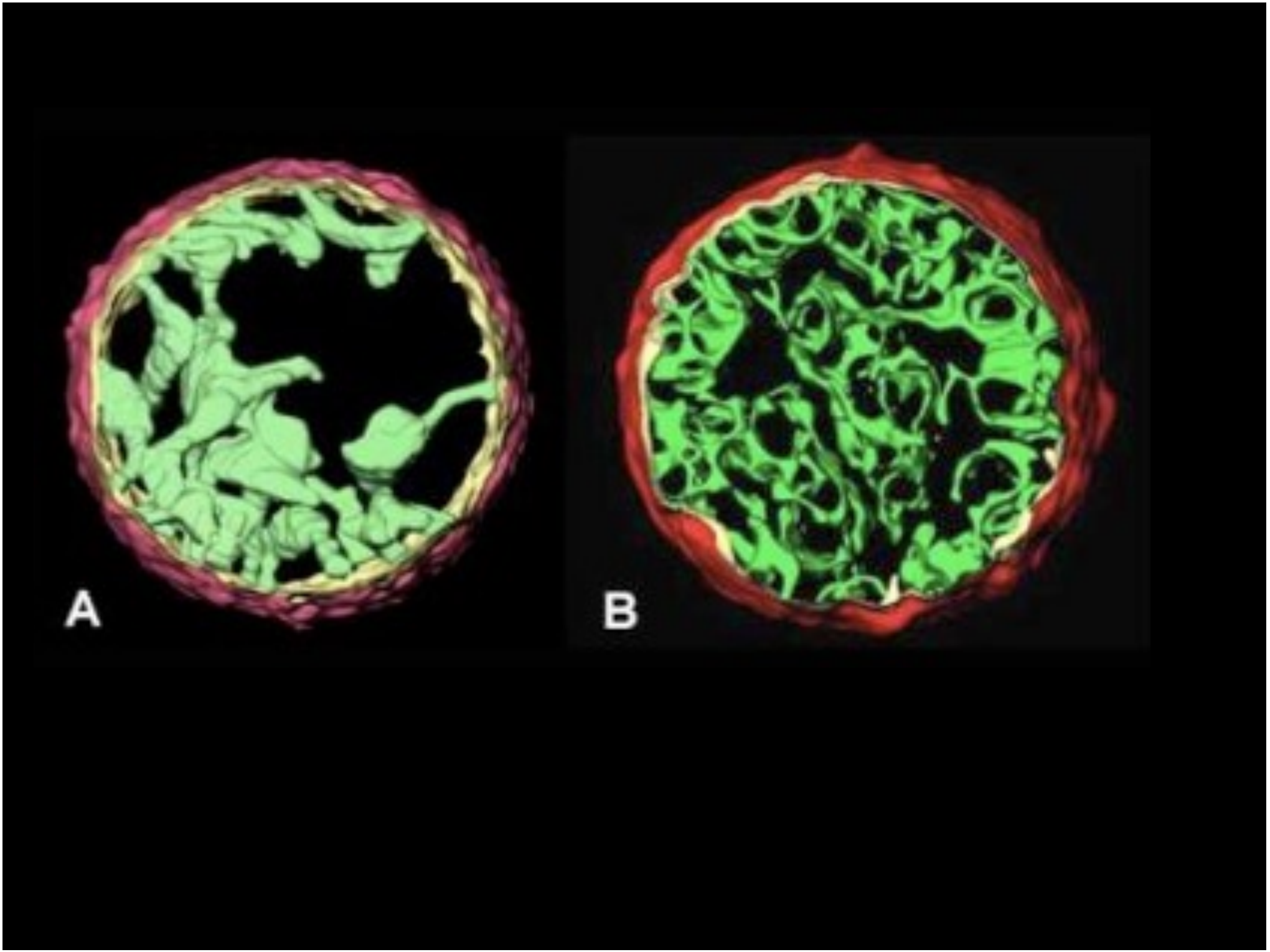


Fig. 1. Mitochondrial network in a mammalian fibroblast. A COS-7 cell labeled to visualize mitochondria (green) and microtubules (red) was analyzed by indirect immunofluorescence confocal microscopy. Mitochondria were labeled with antibodies to the β subunit of the F_1-ATPase and a rhodamine-conjugated 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,……..

"EVERYTHING" FOLLOWS FROM THE 4 BASIC PRINCIPLES

I. HIERARCHICAL "FRACTAL-LIKE" BRANCHING NETWORKS

II. SPACE-FILLING

III. INVARIANT TERMINAL UNITS

IV. ENERGY DISSIPATED IS MINIMISED

"AVERAGE IDEALISED ORGANISM OR SYSTEM"

II ⇒ i) SPACE-FILLING $\frac{l_{k+1}}{l_k} = \frac{1}{2^{1/3}}$ $\frac{1}{n^{1/3}}$

III ⇒ ii) INV. TERMINAL UNITS

IV ⇒
- iii) AREA-PRESERVING BRANCHING $\frac{r_{k+1}}{r_k} = \frac{1}{2^{1/2}}$
- iv) VOLUME OF NETWORK (BLOOD) ~ VOLUME OF WHOLE BODY ~ M

$\Rightarrow B \propto M^{3/4}$ (AND MUCH MORE)

[MORE GENERALLY : $B \sim M^{b(M)}$ WITH $b(M) \simeq 3/4$ M LARGE
$< 3/4$ M SMALL
$= 1$ $M < \mu$]

NOT A STRICT POWER LAW!

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)

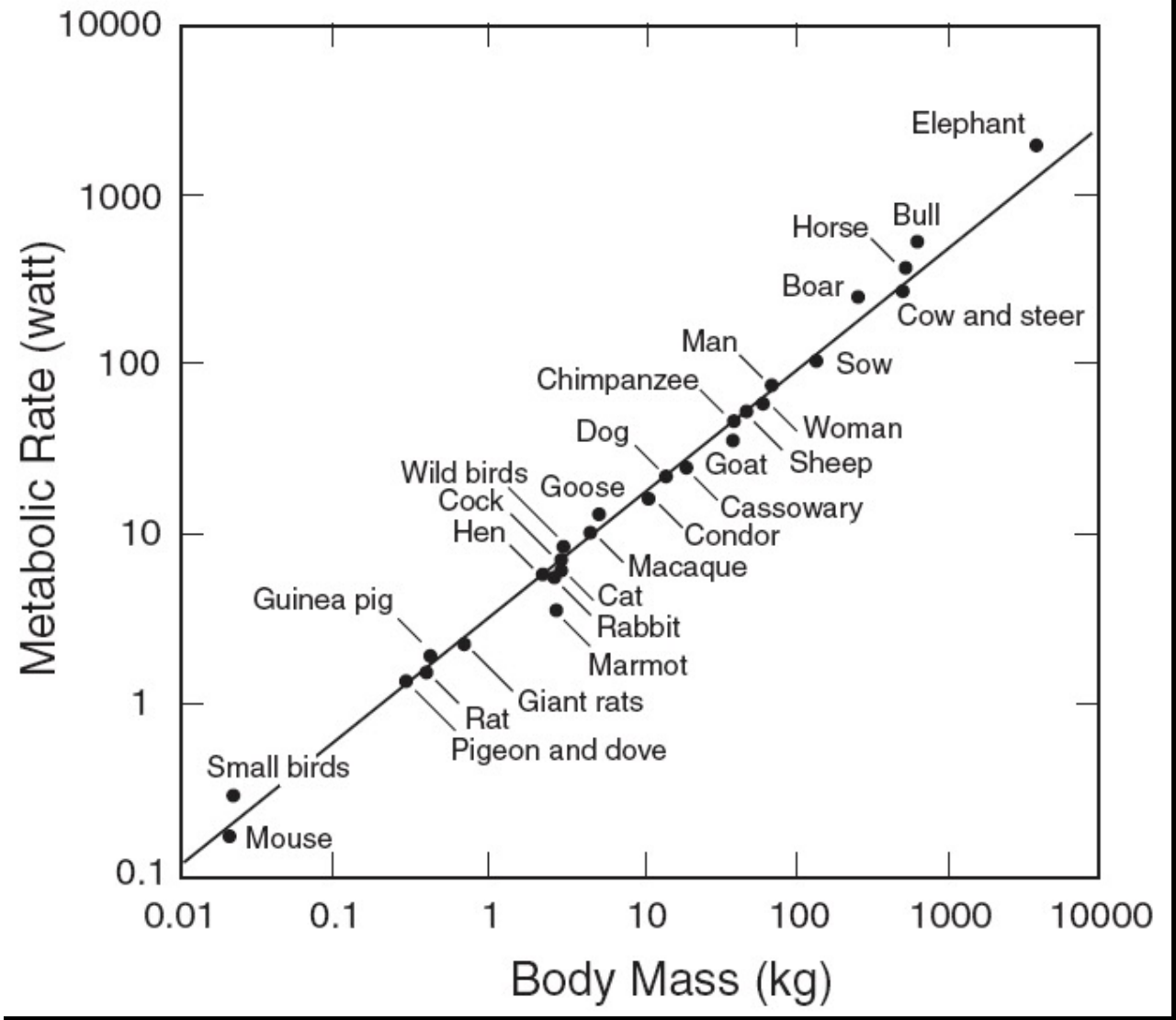
TO MAXIMISE ENERGY TRANSFER FROM THE ENVIRONMENT

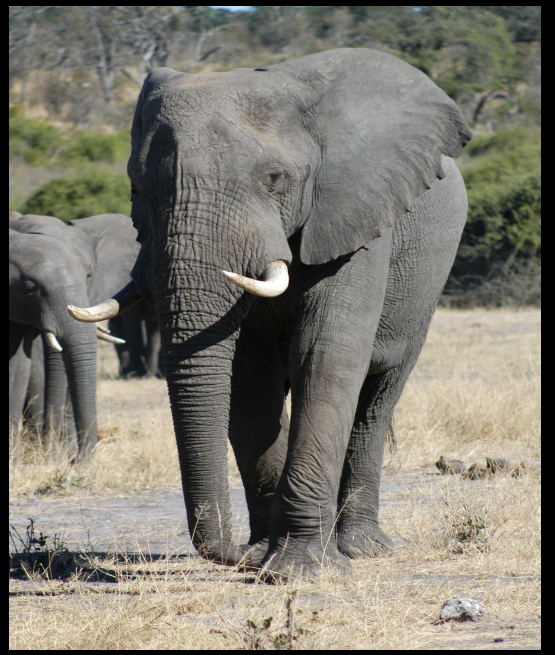
NON-FRACTAL : $M^{2/3}$ ← AREA; ← DIMENSIONALITY OF SPACE (VOLUME)

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

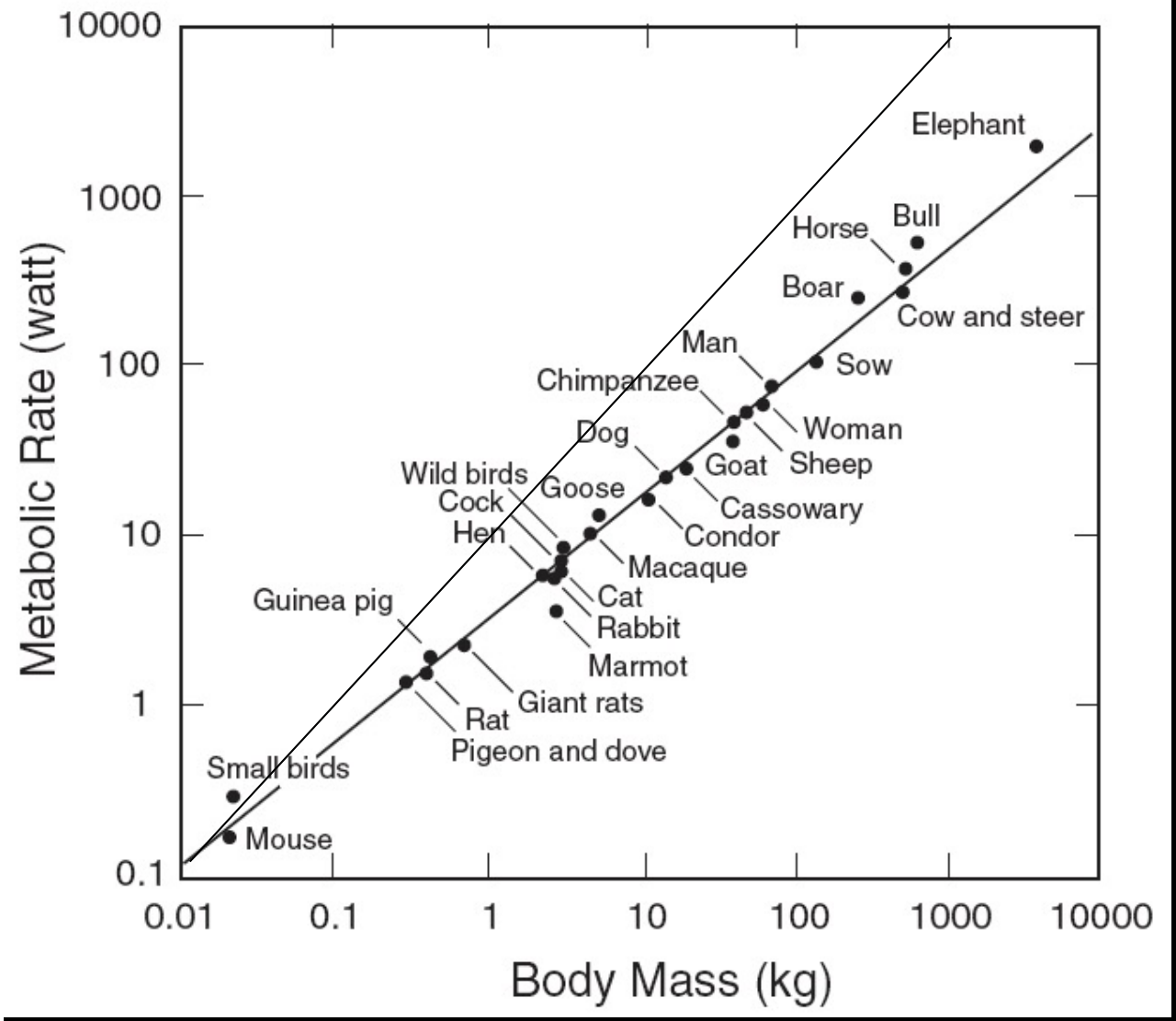
BY ANALOGY : LIFE EFFECTIVELY OPERATES IN FOUR SPATIAL DIMENSIONS

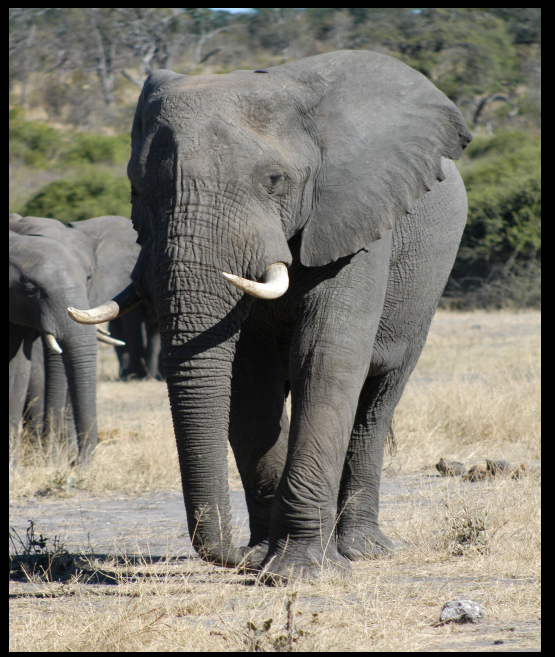
[FIVE IF TIME IS INCLUDED]





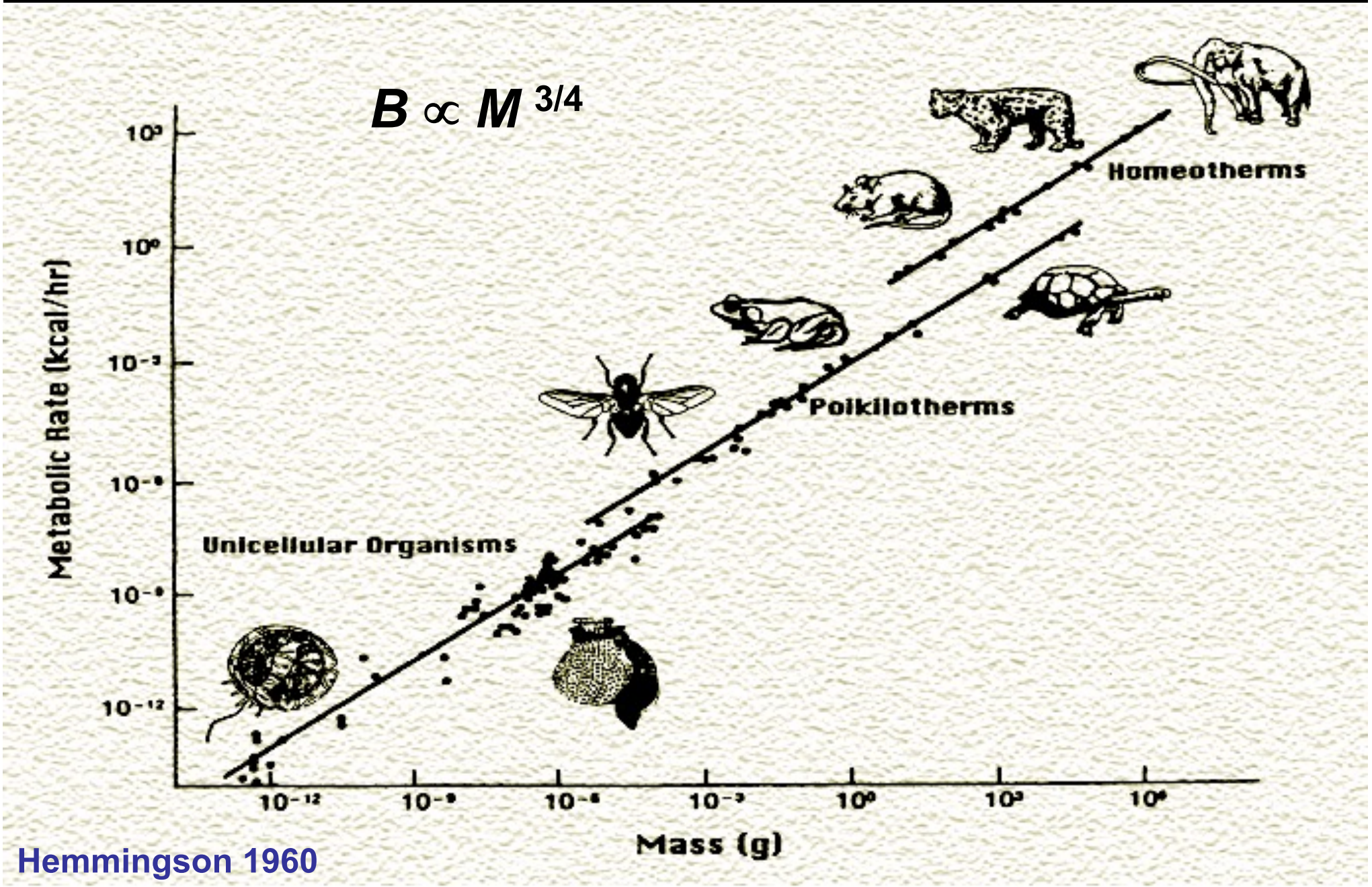
SLOPE = ¾ < 1 SUB-LINEAR ECONOMY OF SCALE





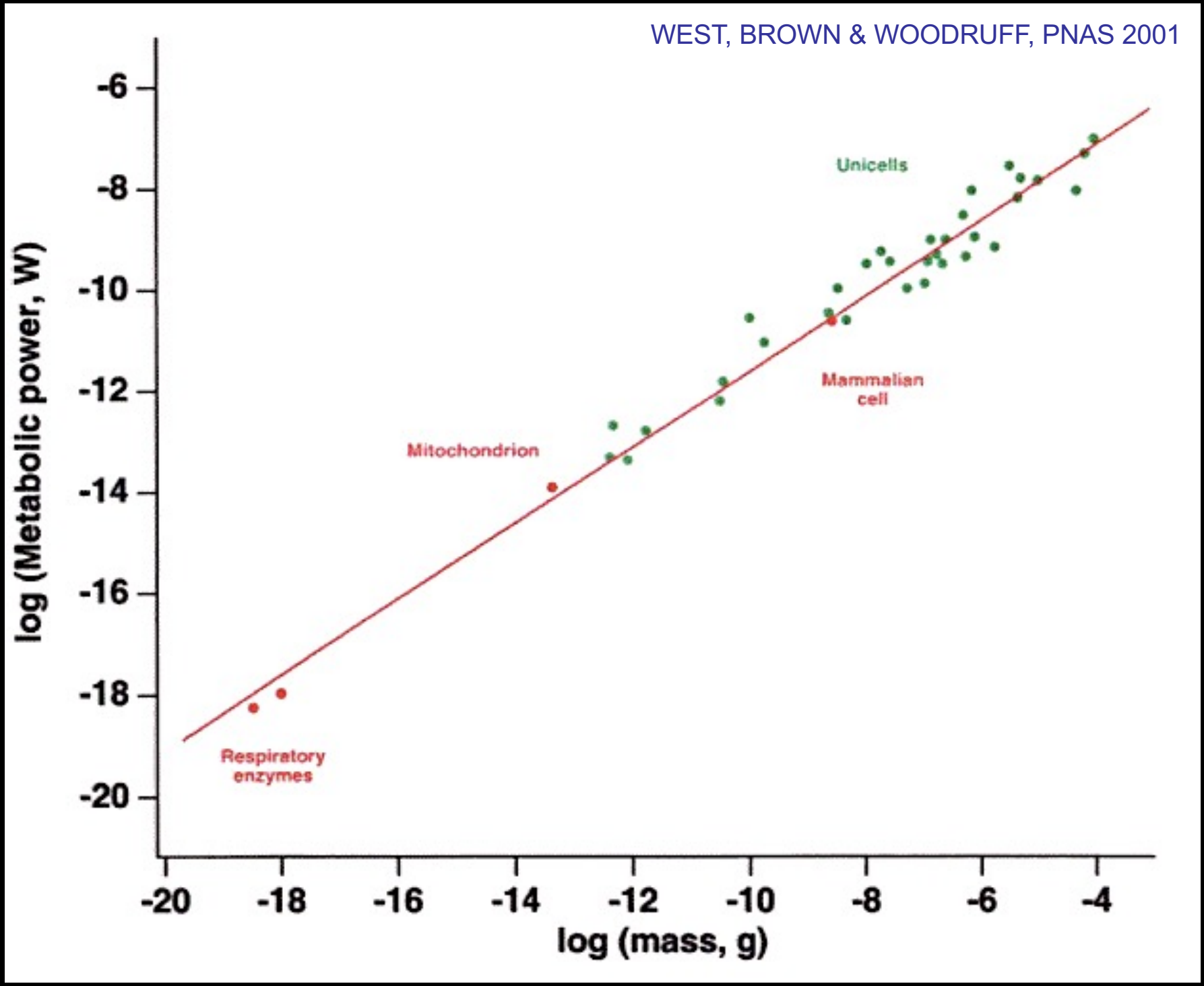
SLOPE = ¾ < 1 SUB-LINEAR ECONOMY OF SCALE

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



Hemmingson 1960

WEST, BROWN & WOODRUFF, PNAS 2001



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

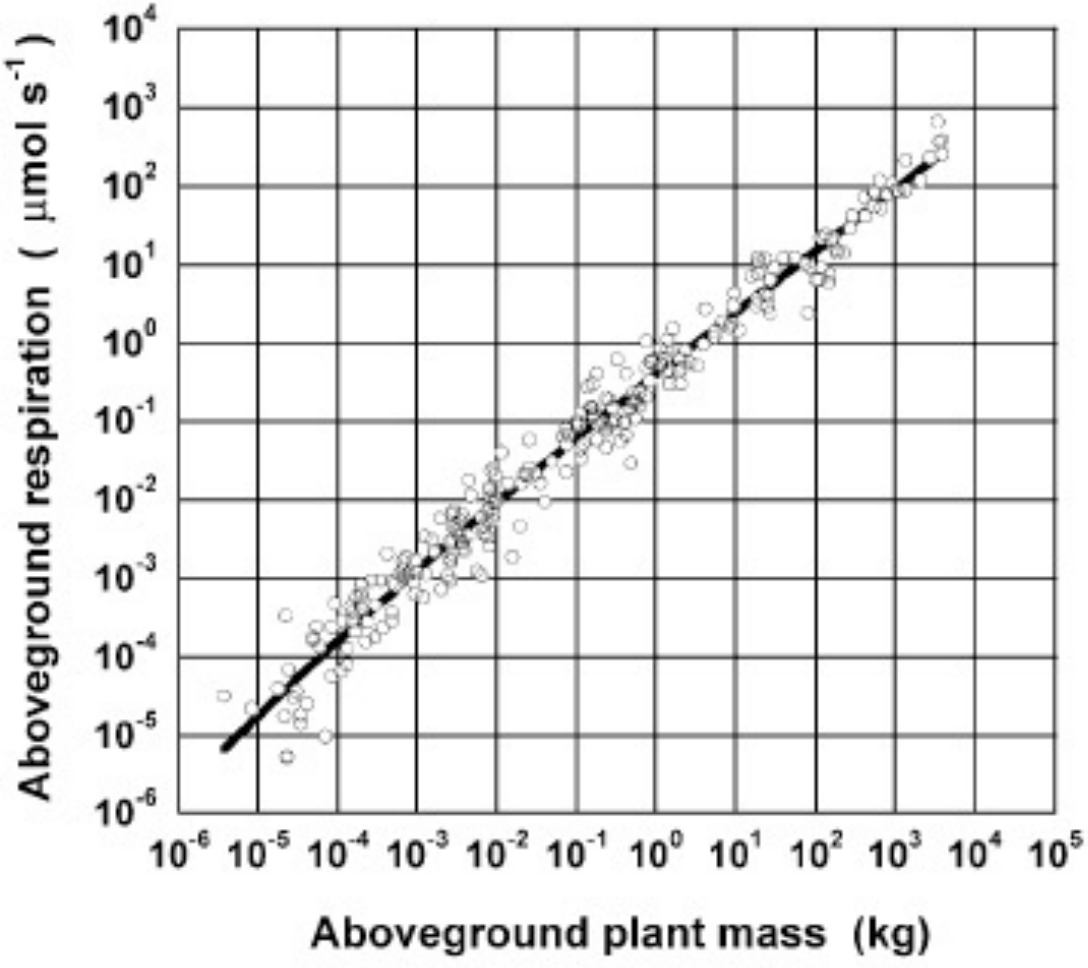
VERY DIFFERENT EVOLVED ENGINEERING DESIGN (NON-PULSATILE FIBRE BUNDLES) BUT SAME NETWORK PRINCIPLES

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	$r_k^{can} \propto r_k^{2/3}$
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	$B_{Tot} \propto \Sigma \Delta n_k r_k^2 \leq \dot{R}$
Mortality rate	$\mu_k \approx A r_k^{-2/3}$
Size distribution	$N_k \approx \frac{\dot{R}}{(K+1) b_0} r_k^{-2}$

PLANTS/TREES



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

SINCE $B \sim M^{3/4}$

(OVER 27 ORDERS OF MAGNITUDE)

SPECIFIC METABOLIC RATE (PER UNIT MASS)

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

AND METABOLIC RATE OF AVERAGE CELL

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

THIS DECREASE OF B_c WITH SIZE IS DRIVEN

BY THE HEGEMONY OF THE NETWORK

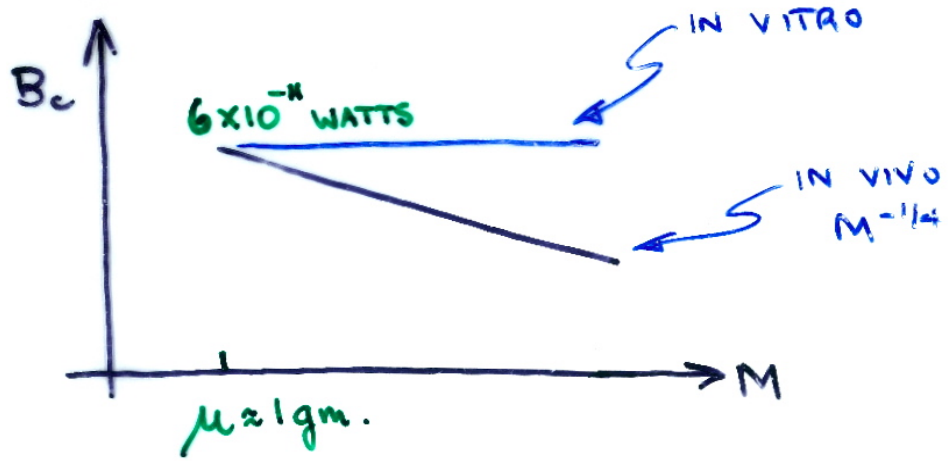
(CONTROLS FUNDAMENTAL BIOCHEMICAL RATES)

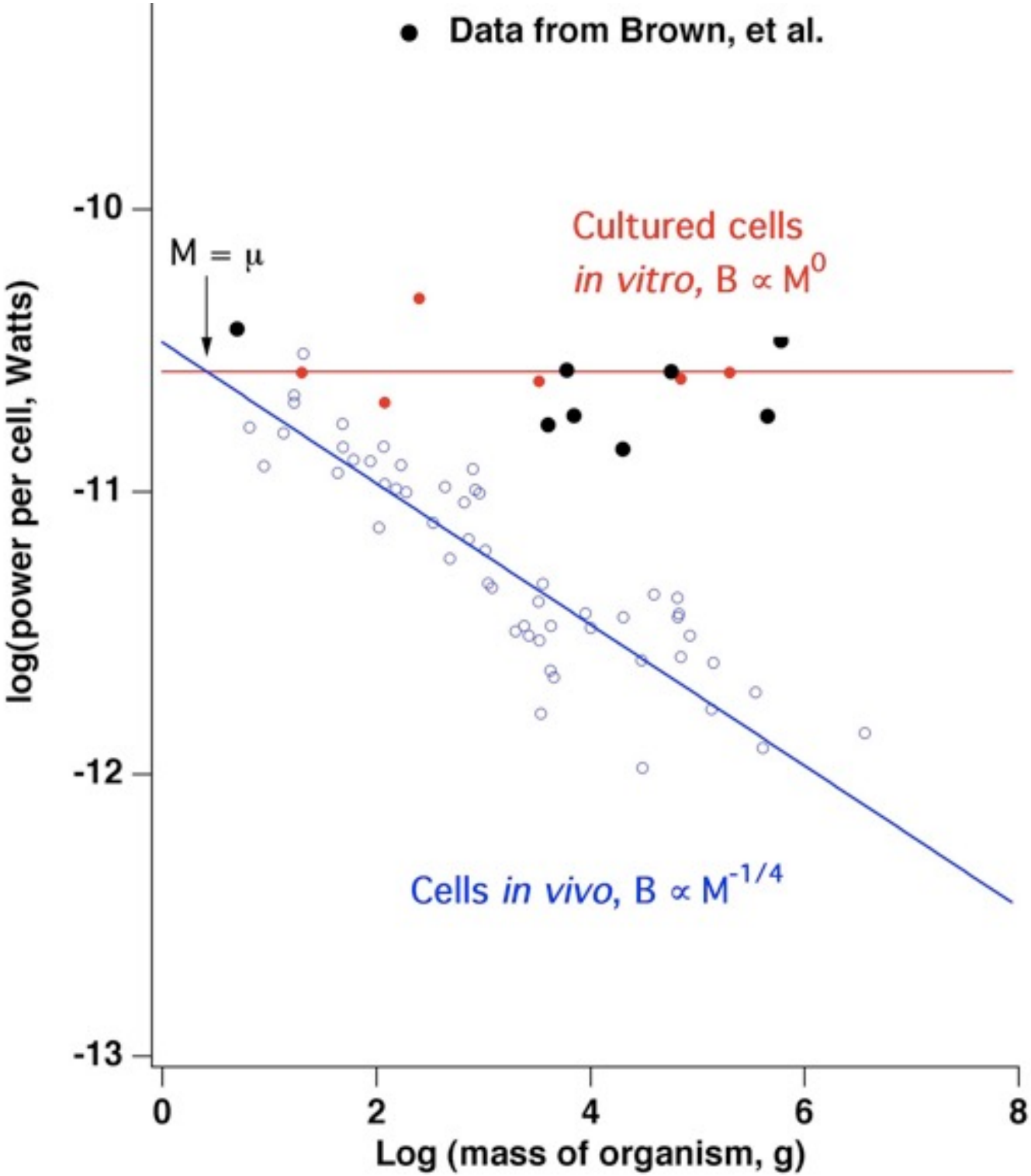
⇒ IF THE NETWORK WERE REMOVED SO CELLS

BECOME FREE (IN VITRO) B_c SHOULD BECOME

INDEPENDENT OF WHAT MAMMAL THEY ORIGINATED

IN: PREDICT




Data from Brown, et al.
M = μ
Cultured cells
in vitro, B ∝ M^0
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)

EXTRAORDINARY SYSTEMATIC
ECONOMY OF SCALE
(THE BIGGER YOU ARE, THE LESS ENERGY/FOOD YOU NEED PER CELL)

EXTRAORDINARY SYSTEMATIC
ECONOMY OF SCALE
(THE BIGGER YOU ARE, THE LESS ENERGY/FOOD YOU NEED PER CELL)

SIMILAR SCALING LAWS HOLD FOR ALMOST ALL PHYSIOLOGICAL AND LIFE HISTORY EVENTS ACROSS THE ENTIRE SPECTRUM OF LIFE FROM CELLS TO ECOSYSTEMS

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

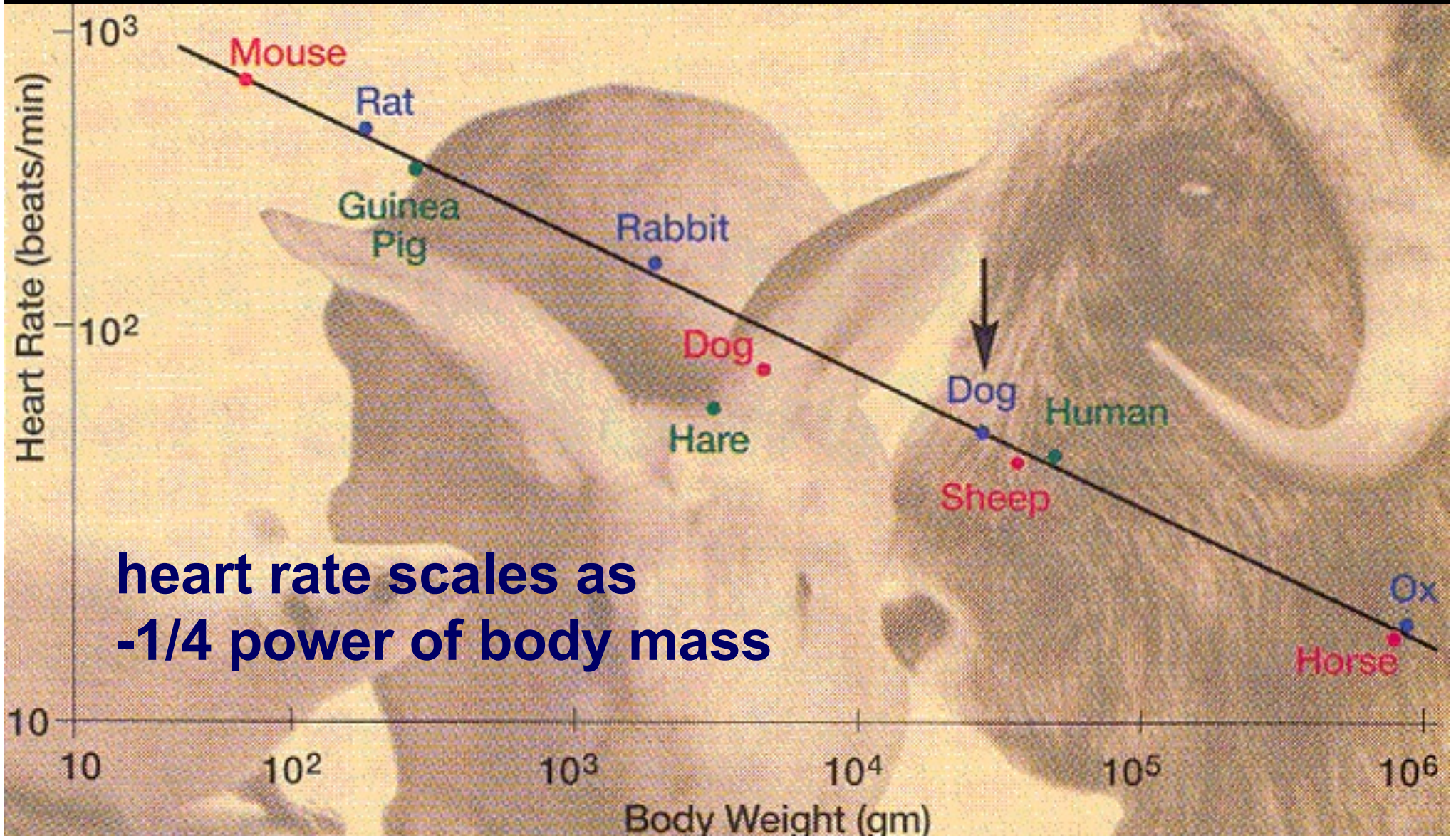
“quarter-power scaling”

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

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



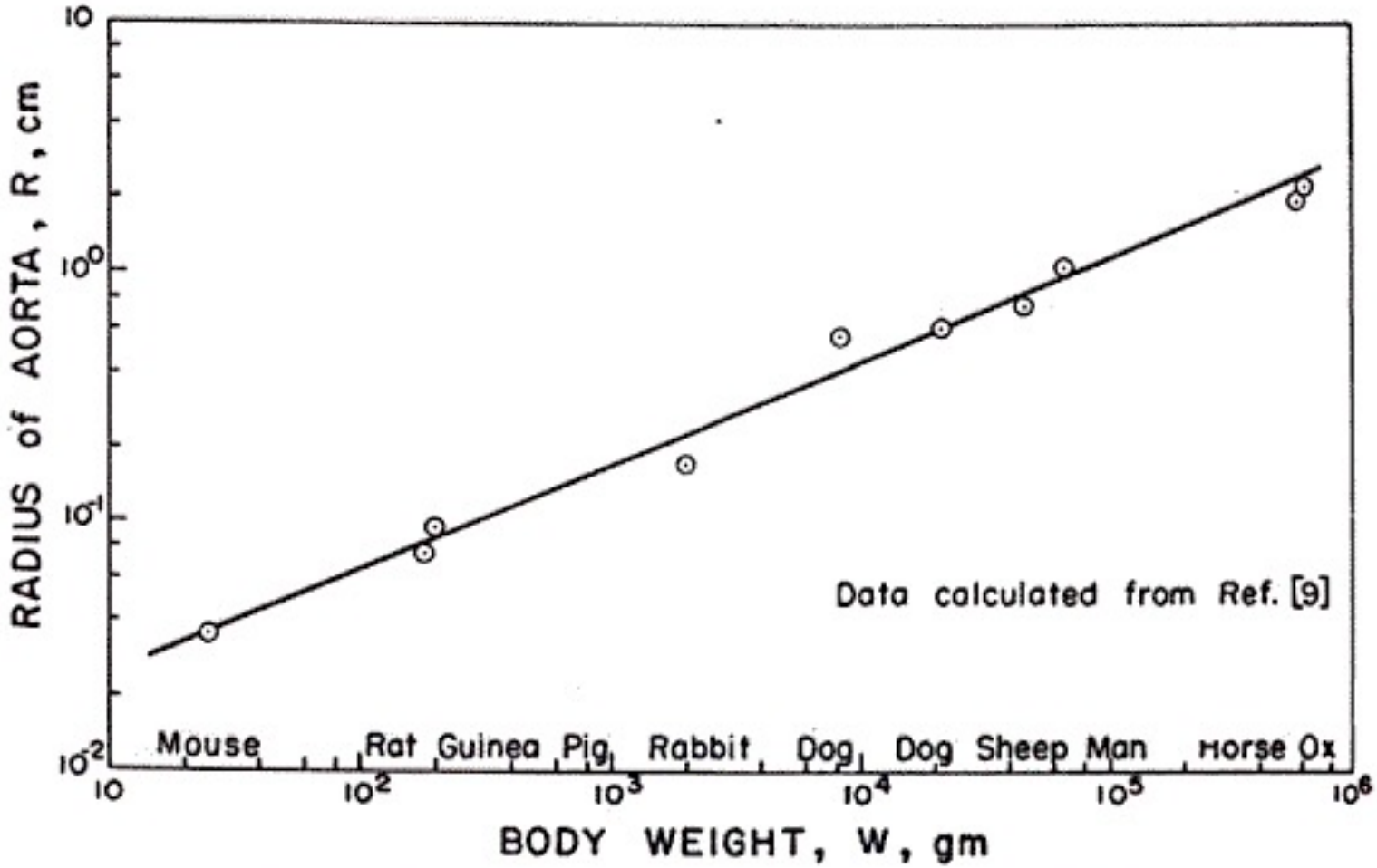
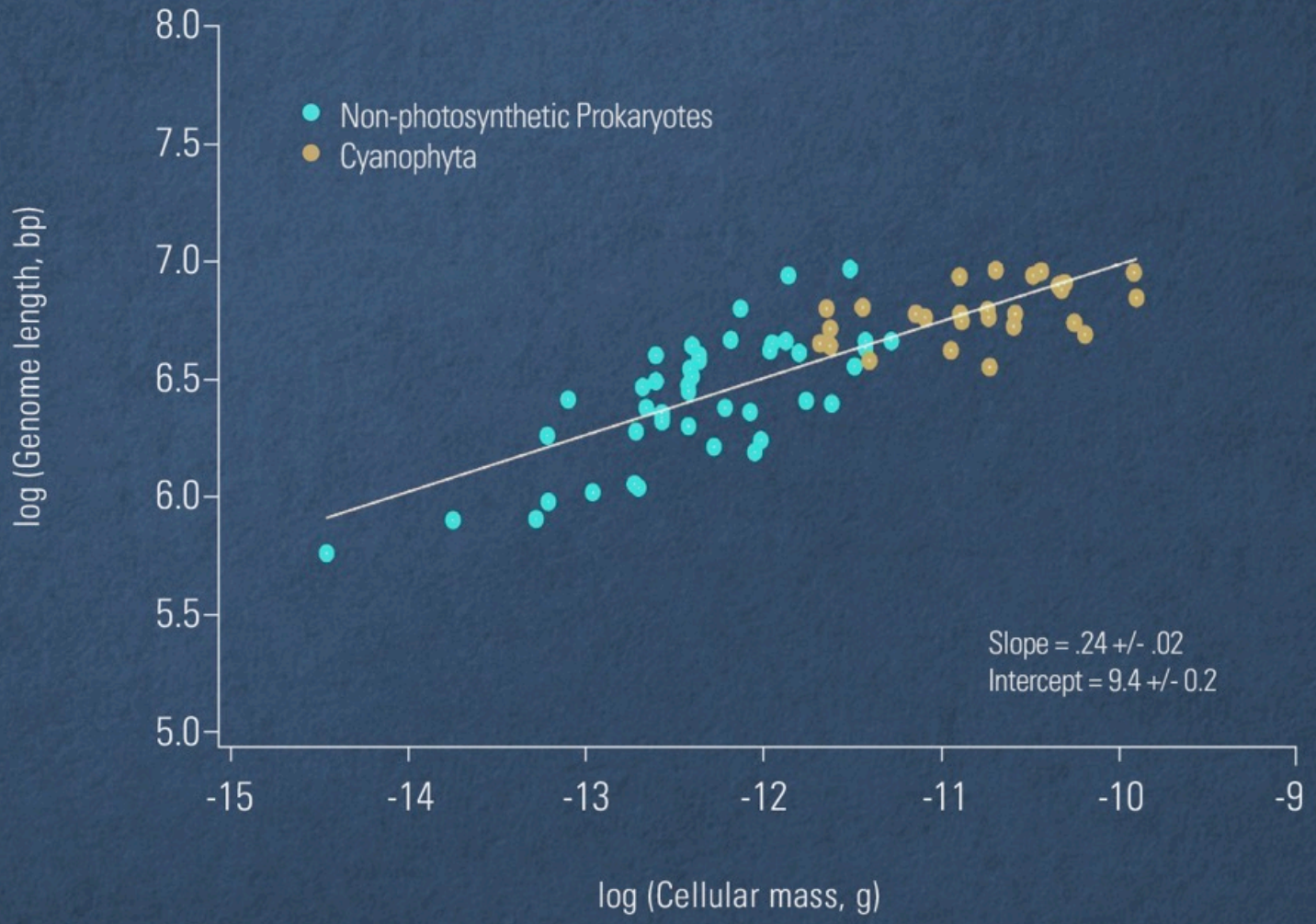


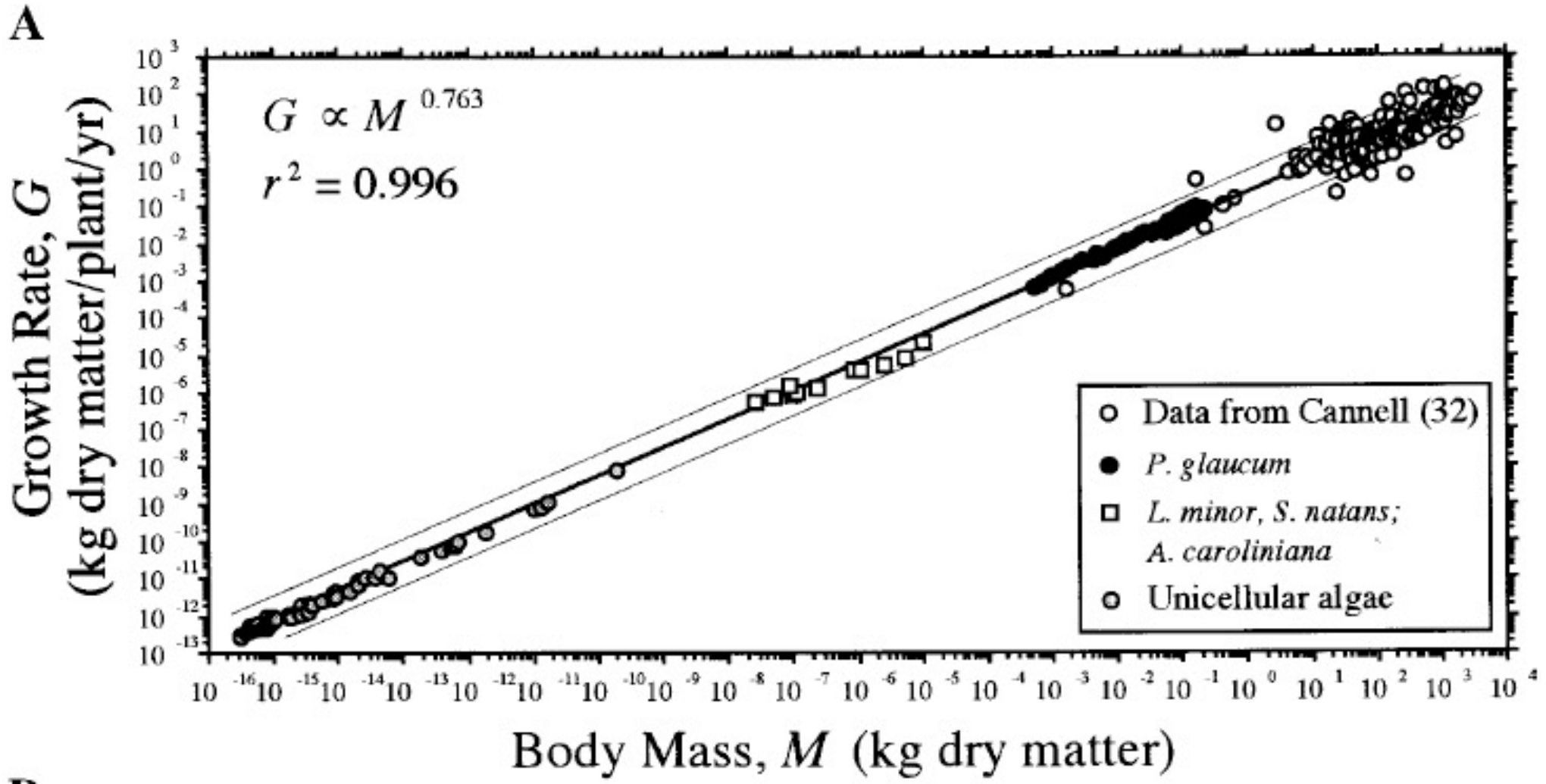
FIG. 4 – VARIATION IN RADIUS OF AORTA WITH BODY WEIGHT

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

SAME SCALING FOR TREE TRUNKS

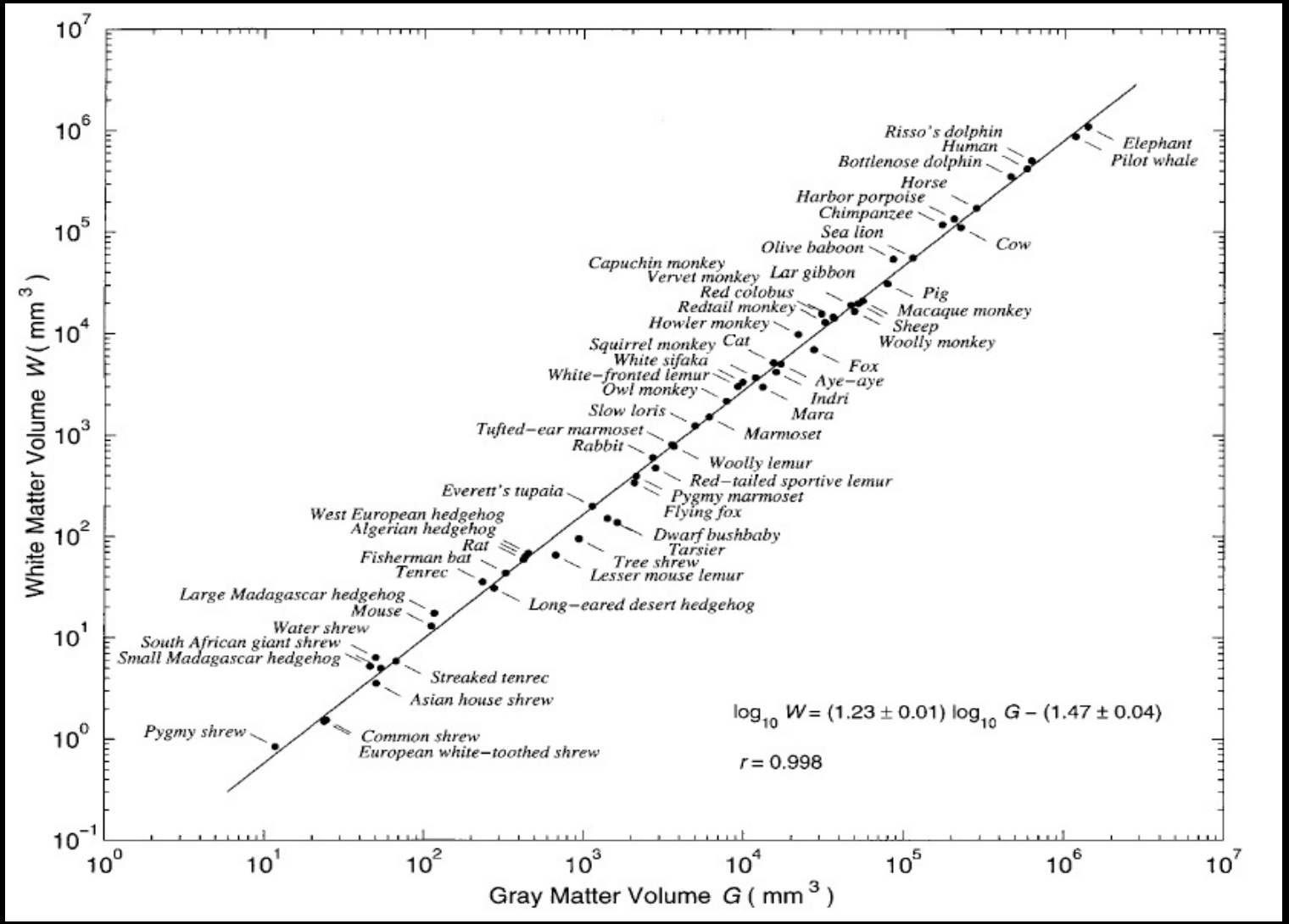
DEPENDENCE OF GENOME LENGTH ON CELLULAR MASS





B.J. Enquist,J.H. Brown & GBW, *Nature* 2003

WHITE & GREY MATTER IN BRAINS



K. Zhang, T.J.A. Sejnowski, *PNAS* 2000

LIFESPAN

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

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

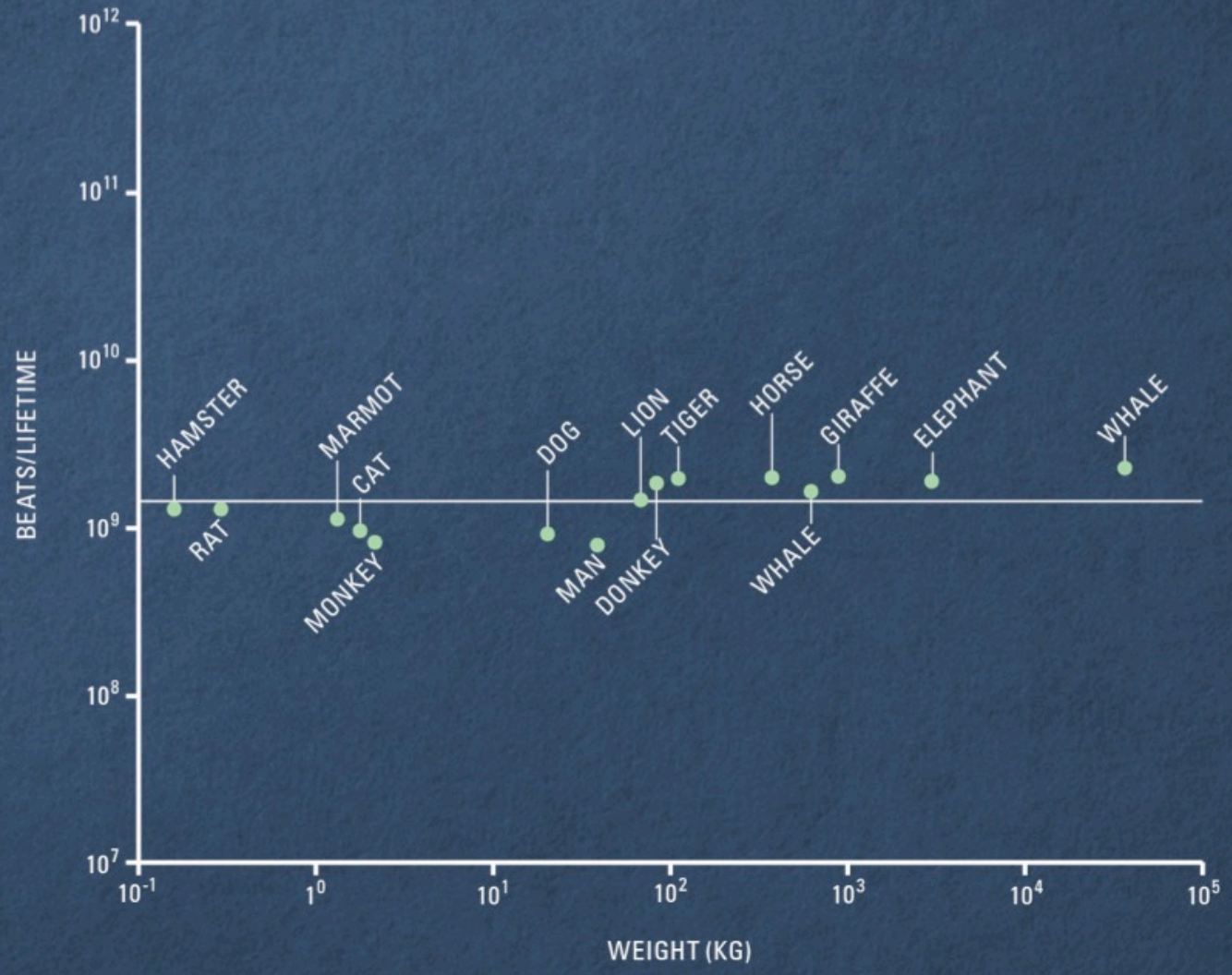
$$\sim M^{-1/4}$$

$\Rightarrow$ 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:

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

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

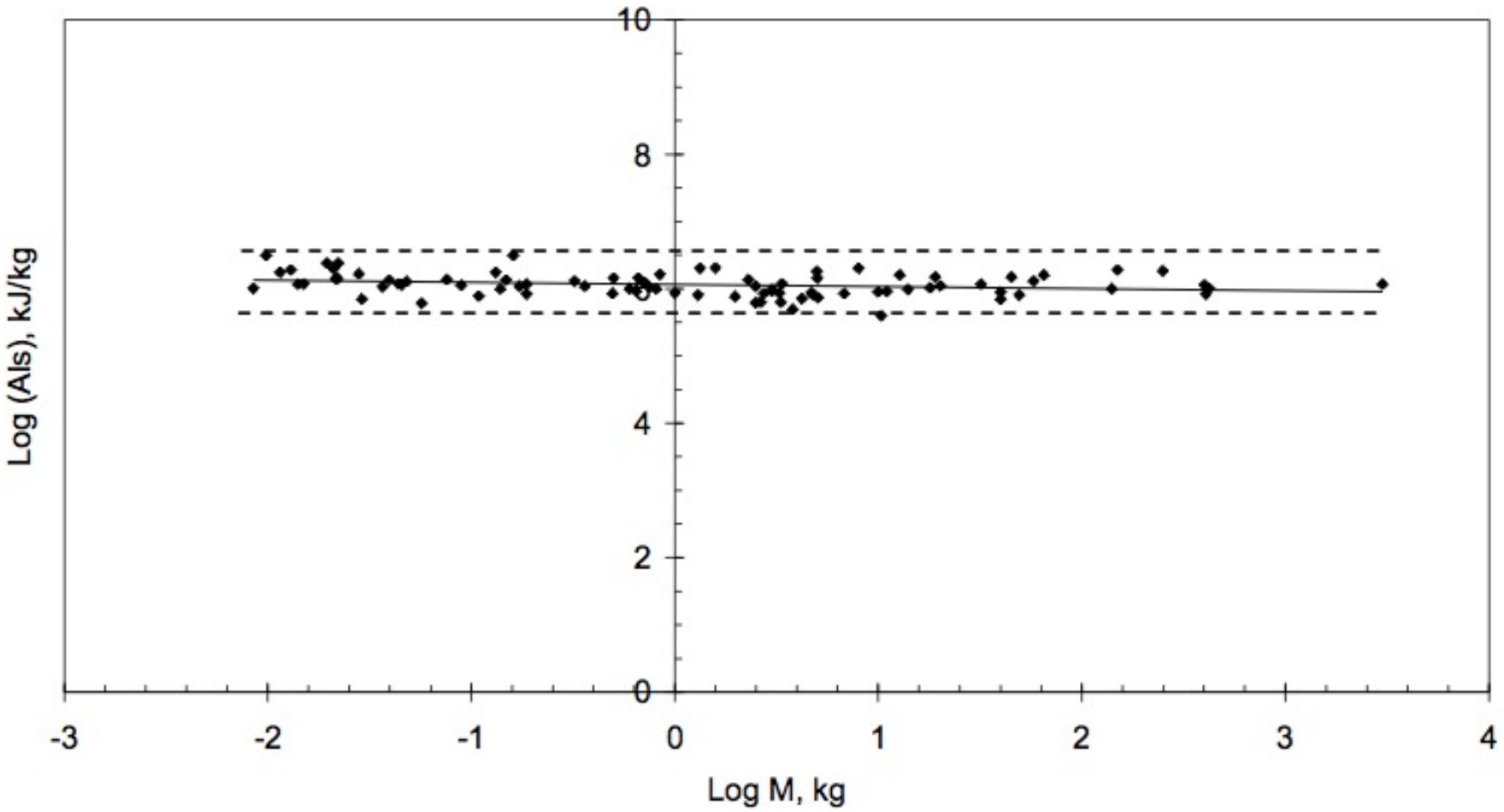


Fig. 2. Relationship between the total metabolic energy per life span per unit body mass ($A_{ls}=PT_{ls}/M$ kJ/kg) and the body mass (M, kg) for 86 terrestrial mammals in captivity (Prototheria, Metatheria and Eutheria). The 95% confidence limits are shown by dashed lines.

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

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 ~ 2×10^{-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 STATISTICAL PHYSICS (BOLTZMANN-ARRENHIUS)

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

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

METABOLISM
GROWTH
EVOLUTION
LONGEVITY
DIFFUSION
FLUXES

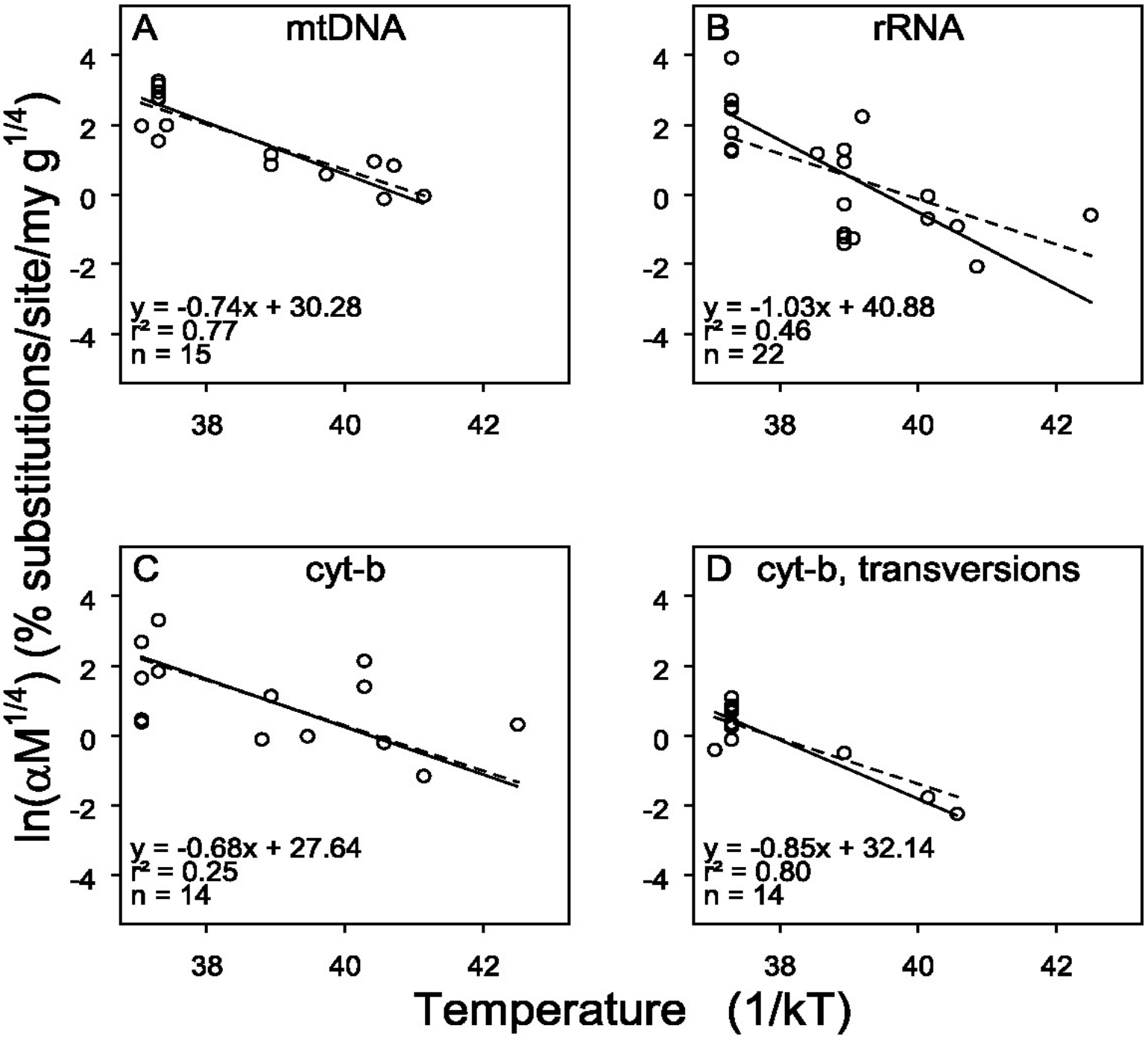
.....

LIFESPANS
TURNOVER TIMES
TIMES TO MATURITY
CIRCULATION TIMES

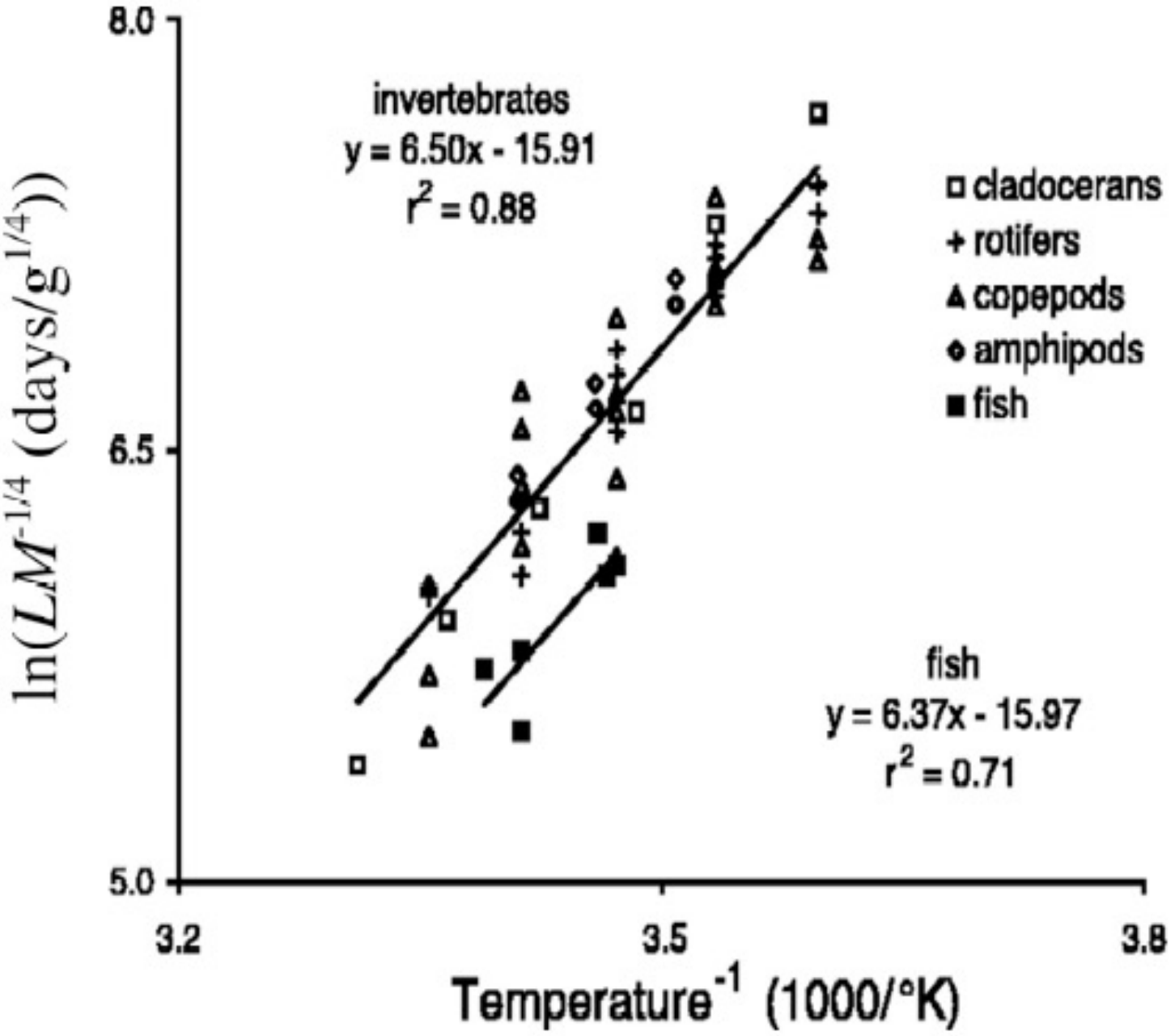
.....

Rates of molecular evolution

temperature dependence



Gillooly et al. 2005


8.0
6.5
5.0
3.2
3.5
3.8
ln(LM^-1/4 (days/g^1/4))
Temperature^-1 (1000/°K)
invertebrates
y = 6.50x - 15.91
r^2 = 0.88
fish
y = 6.37x - 15.97
r^2 = 0.71
cladocerans
rotifers
copepods
amphipods
fish

MASS AND TEMPERATURE ARE THE MAJOR DETERMINANTS OF THE MEASURABLE TRAITS OF ORGANISMS ACROSS THE ENTIRE SPECTRUM OF LIFE

GOVERNED BY JUST TWO PARAMETERS:

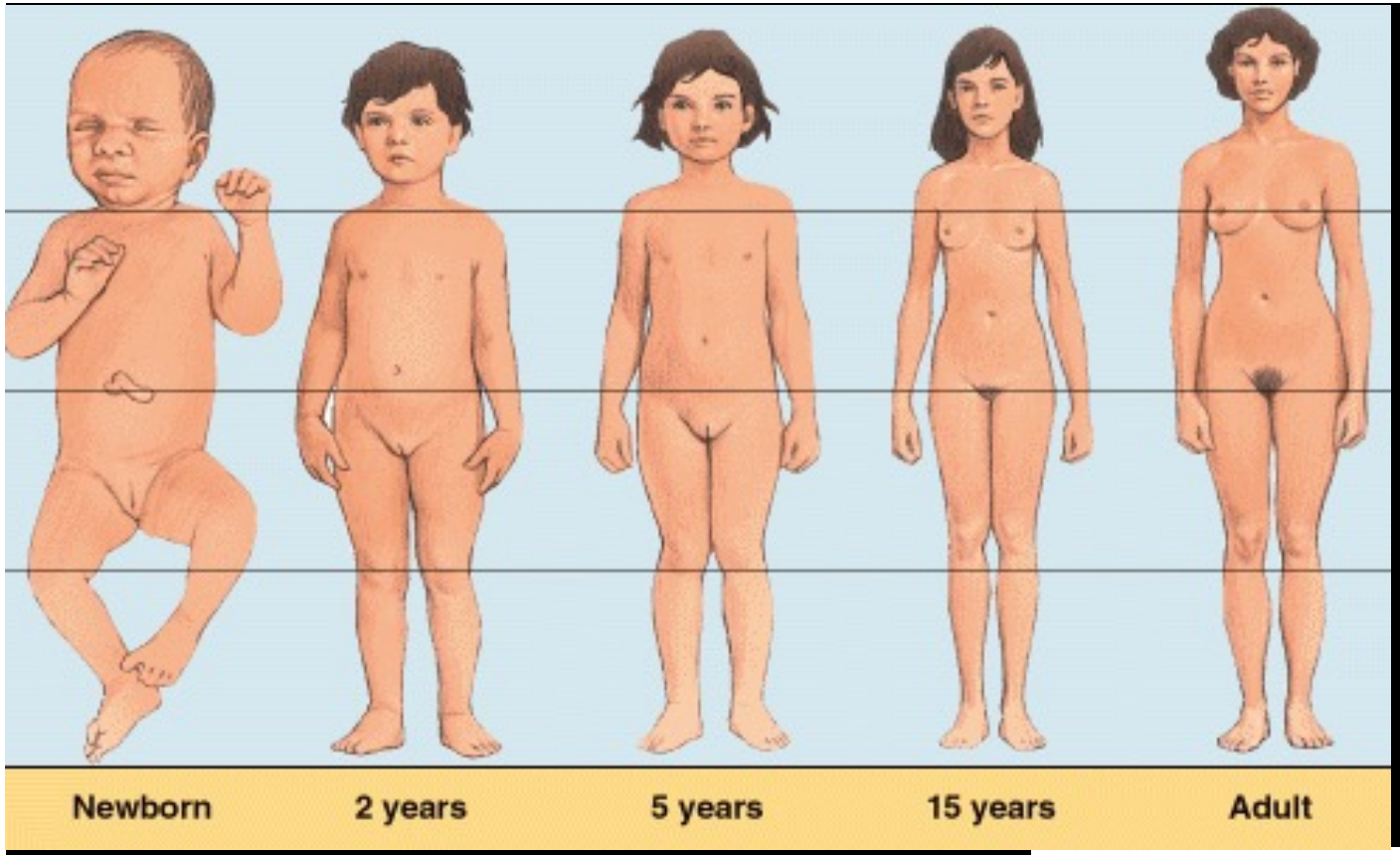
1/4 AND E ~ 0.7 ev

IF THE MASS AND TEMPERATURE DEPENDENCIES ARE ACCOUNTED FOR, OR COMPENSATED 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,……

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)

GBW, J.H. Brown & B.J. Enquist, *Nature* 2001

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

IN TERMS OF MASS AT AGE t

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

wher
e

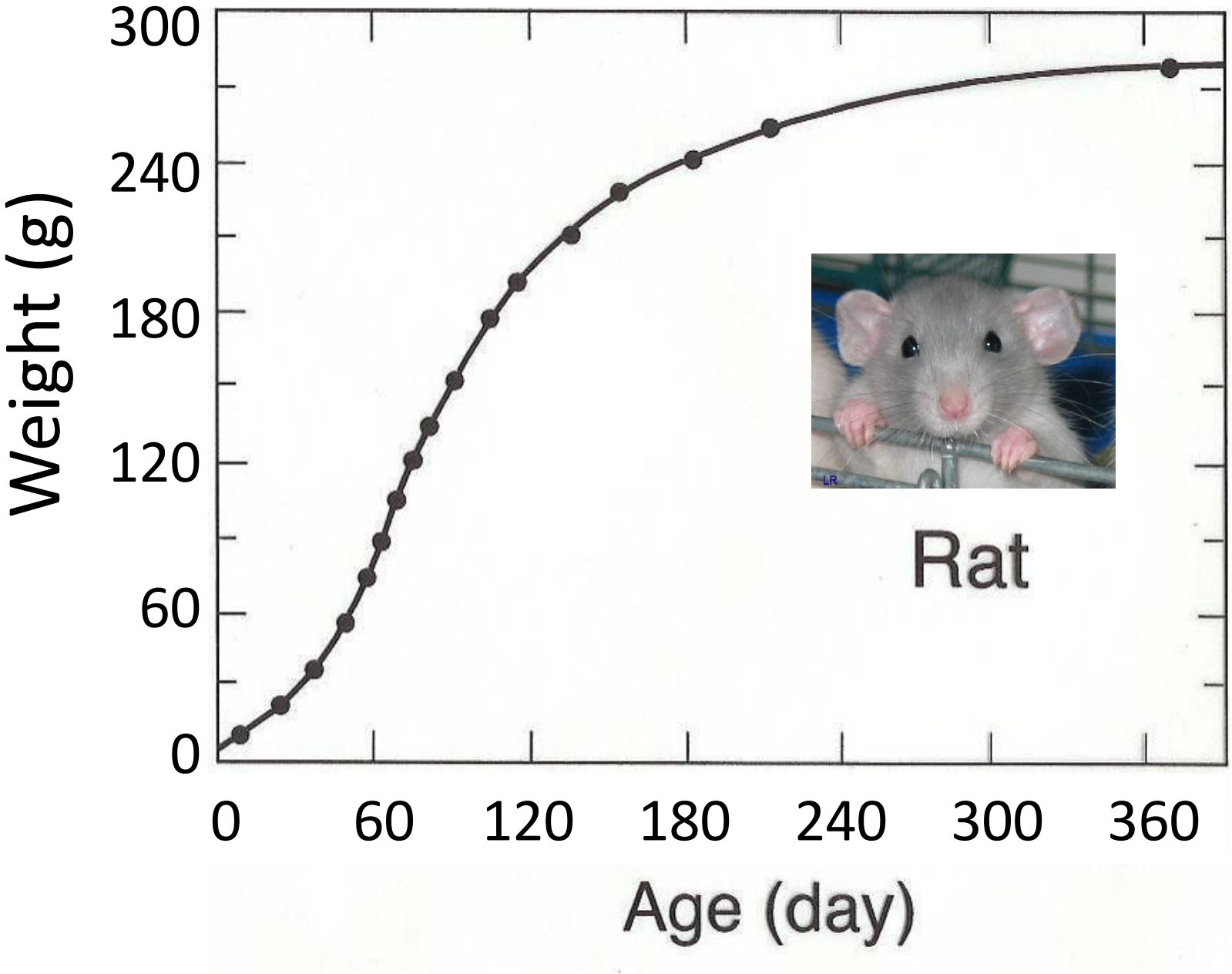
$$a \equiv \frac{B_0 m_c}{E_c}$$

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

SOLUTION:

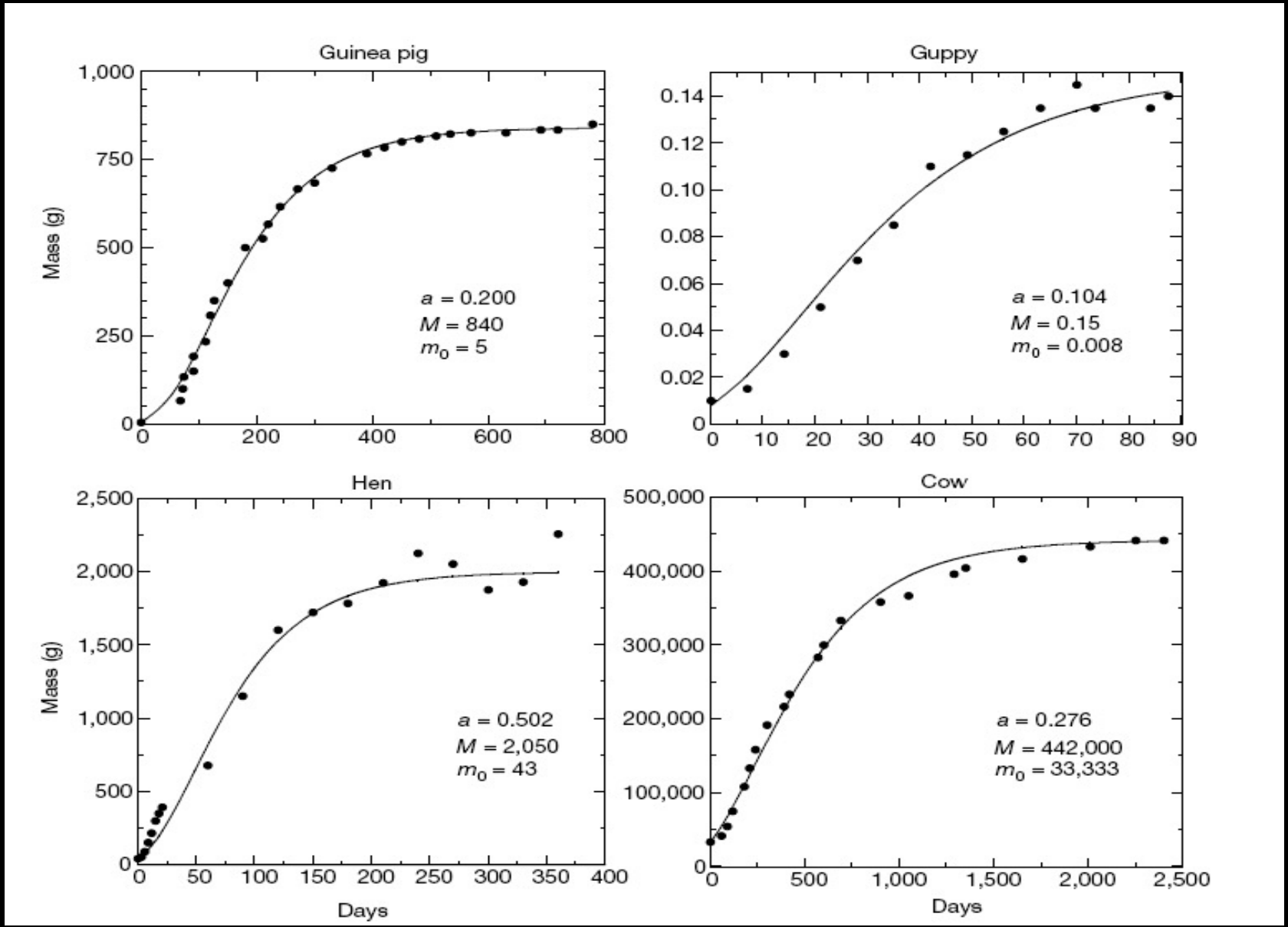
$$\left(\frac{m}{M}\right)^{1/4} = 1 - \left[1 - \left(\frac{m_0}{M}\right)^{1/4}\right] e^{-at/4M^{1/4}}$$

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



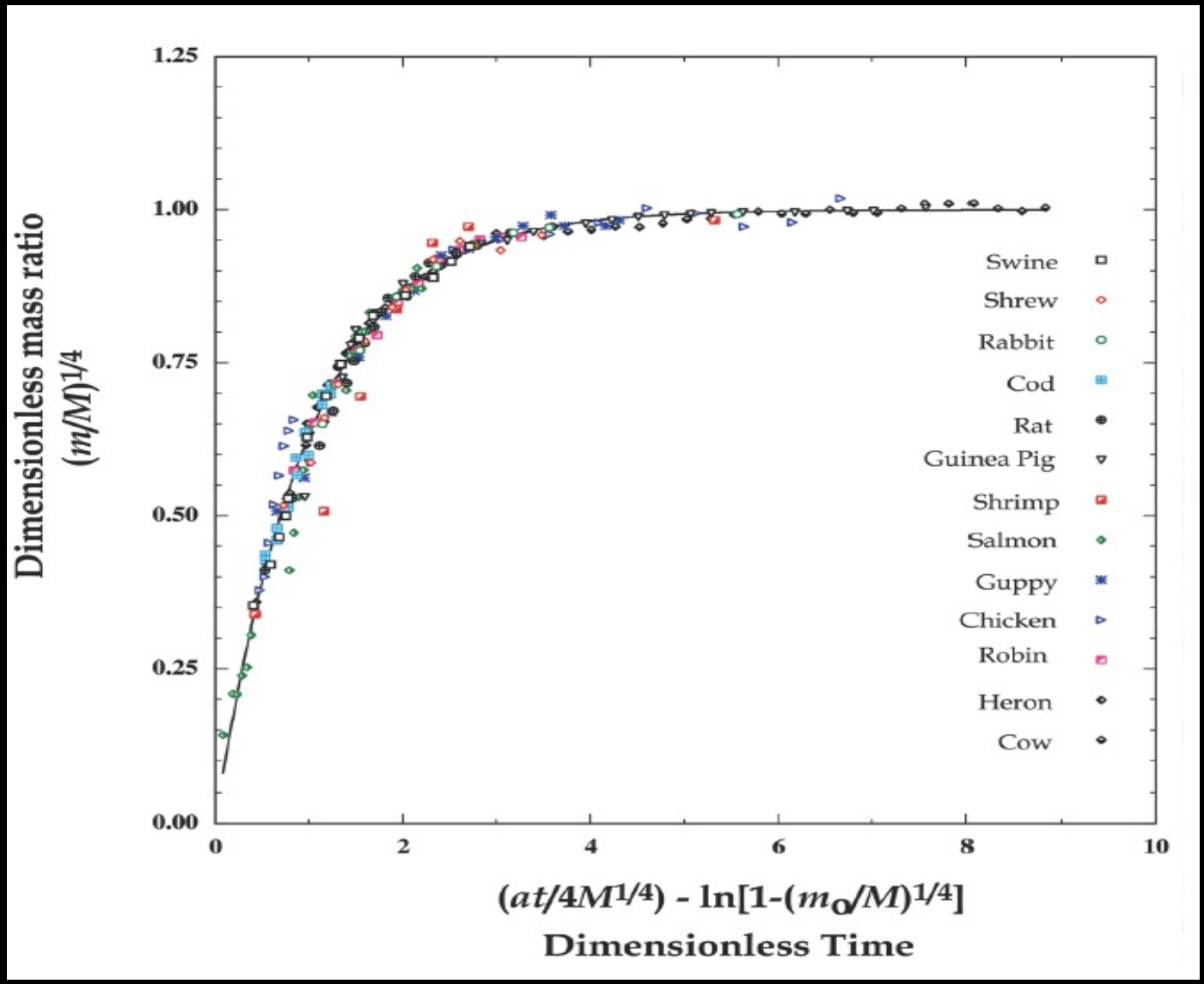
SUB-LINEAR SCALING
LEADS TO BOUNDED GROWTH

PREDICTED GROWTH CURVES OF ANIMALS



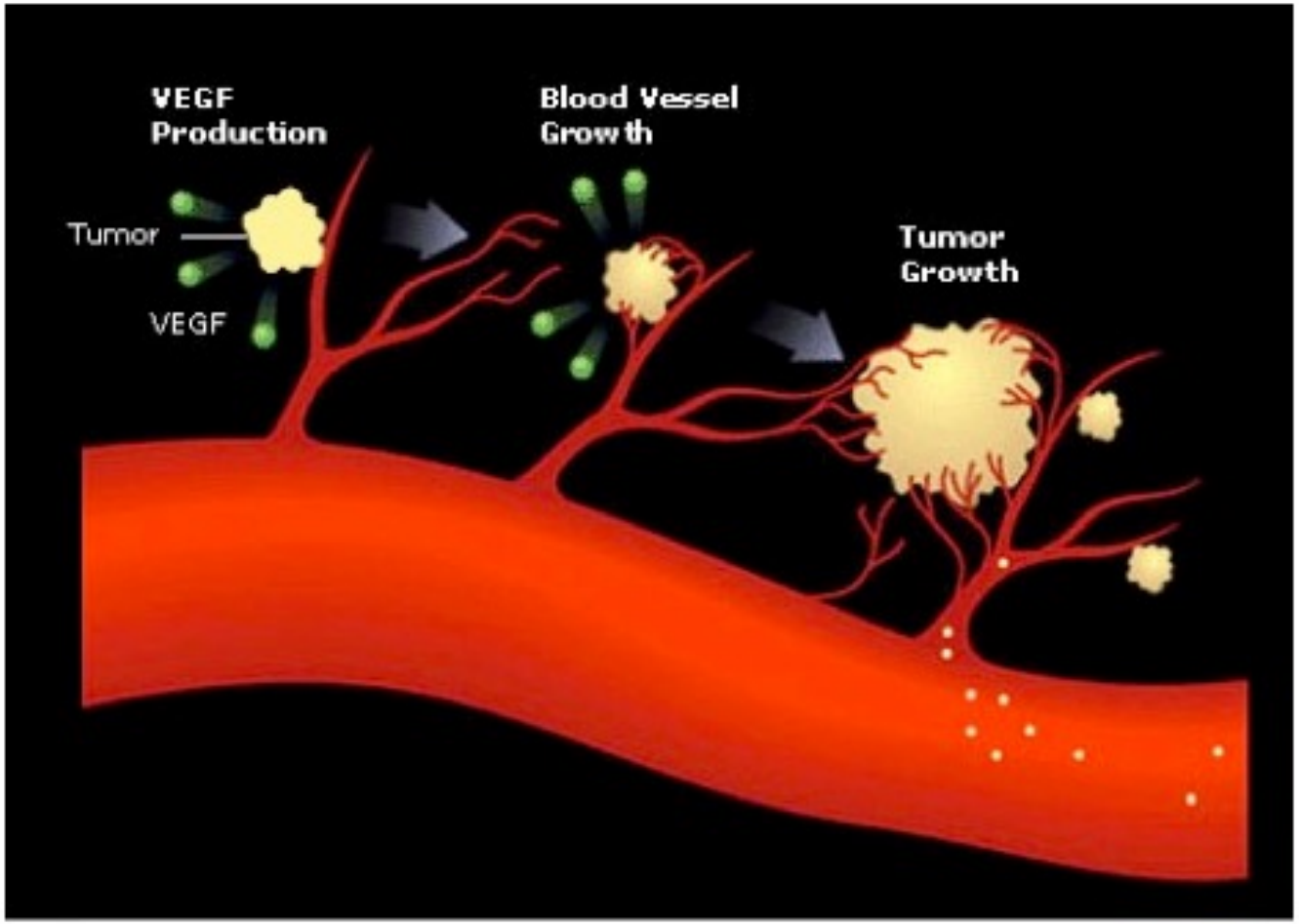
UNIVERSAL COLLAPSED GROWTH CURVE

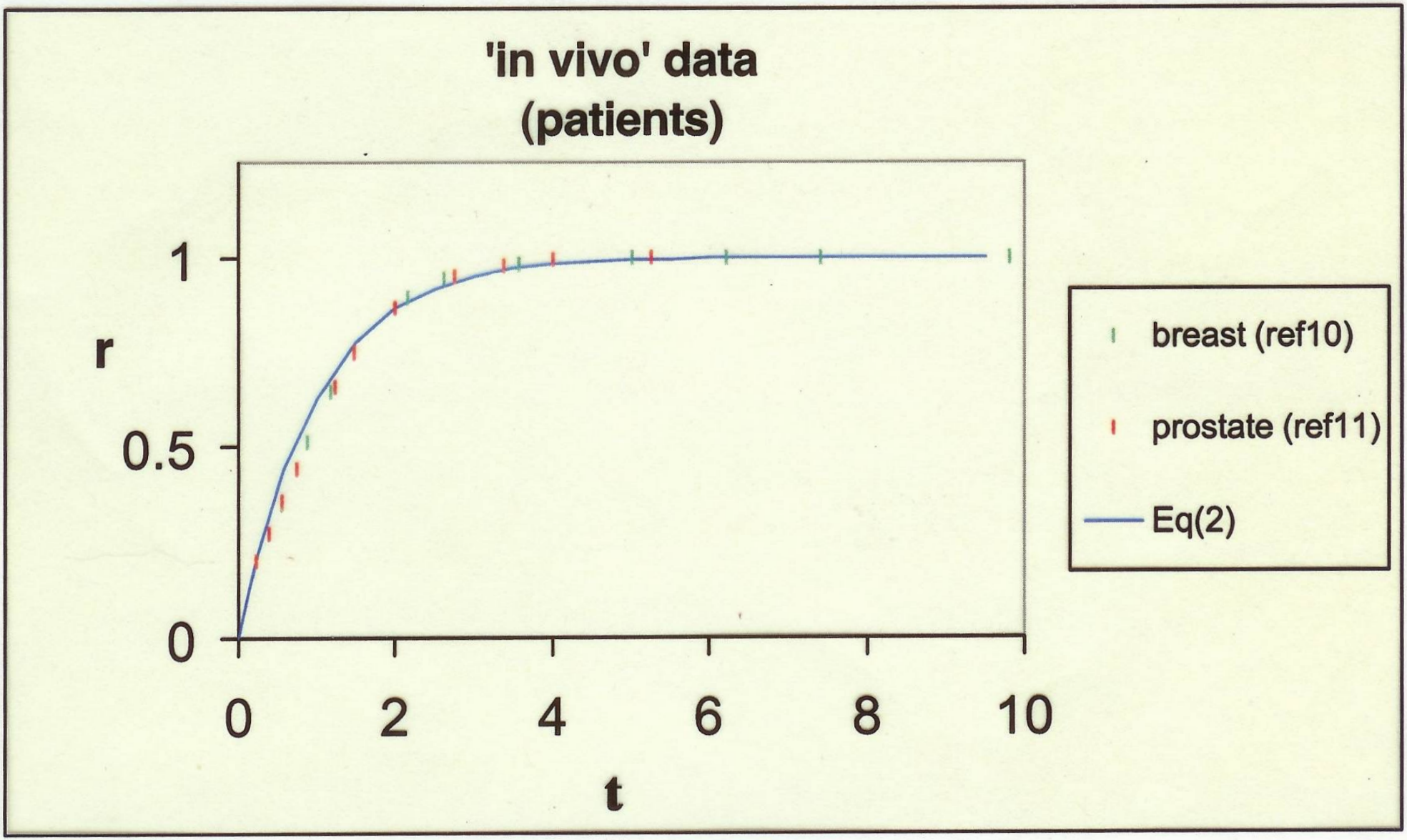
RESCALED MASS VS. RESCALED AGE

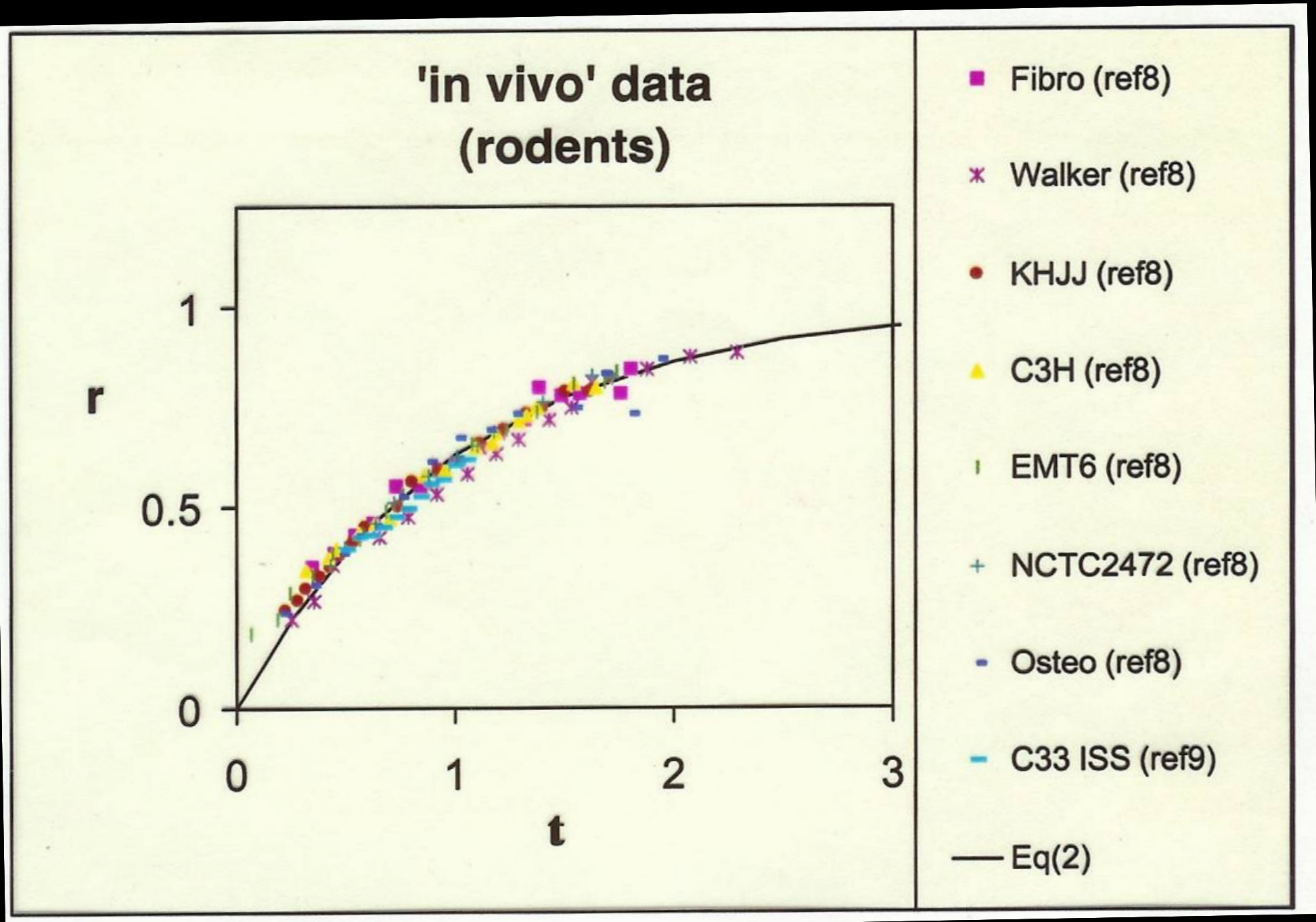


COUPLED NETWORK PROBLEM: TUMORS

Pre- and post-angiogenesis




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

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***

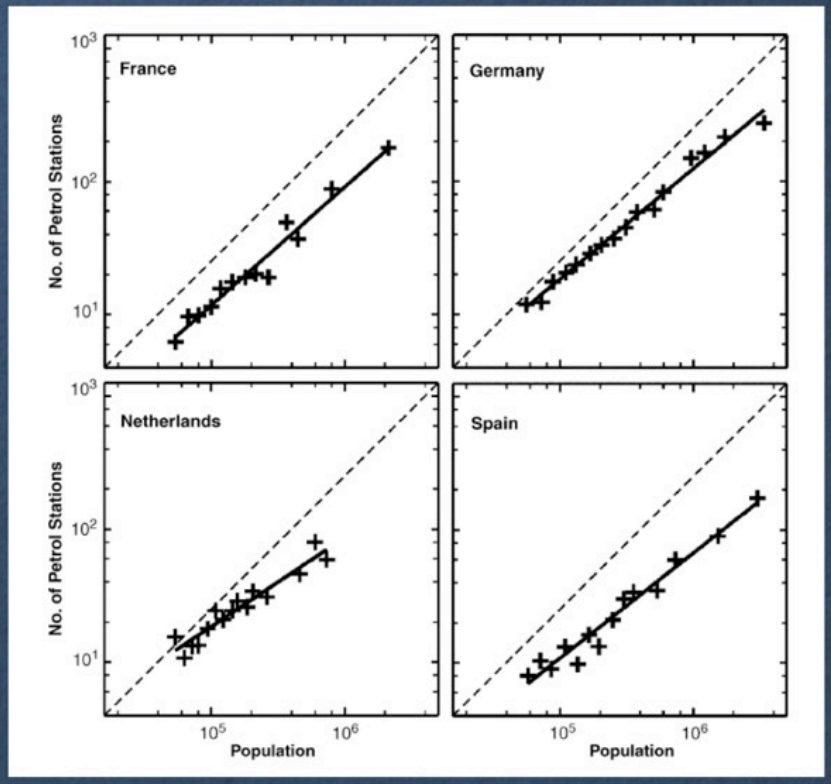
ARE CITIES (AND COMPANIES) SCALED VERSIONS OF EACH OTHER?

DO THEY MANIFEST "UNIVERSALITY"?

HIDDEN LAWS OF BIOLOGY ⟶ HIDDEN LAWS OF CITIES

HIDDEN LAWS OF BIOLOGY ⟶ HIDDEN LAWS OF CITIES

NUMBER OF PETROL STATIONS VS. POPULATION



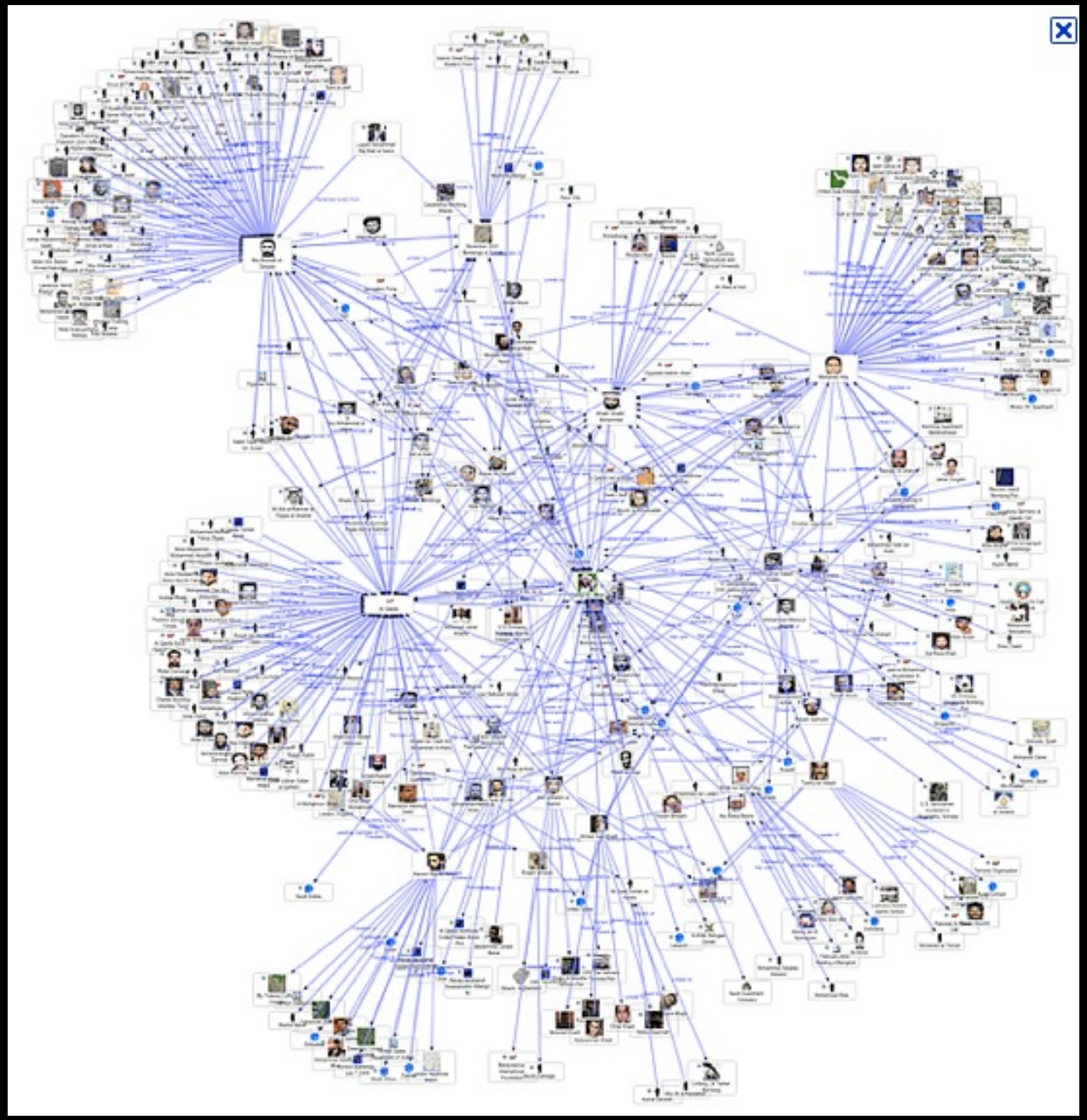
INFRASTRUCTURE

SUB-LINEAR SCALING

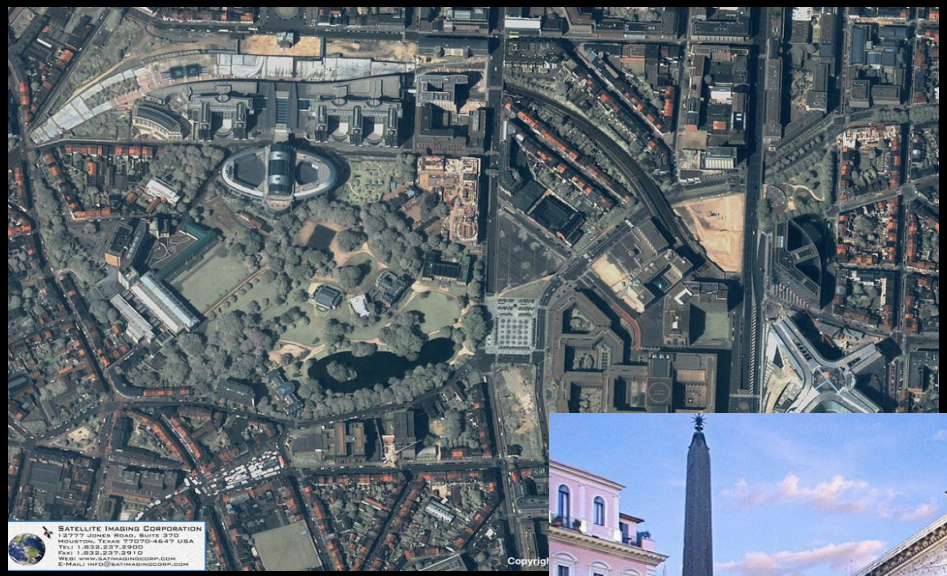
ECONOMY OF SCALE

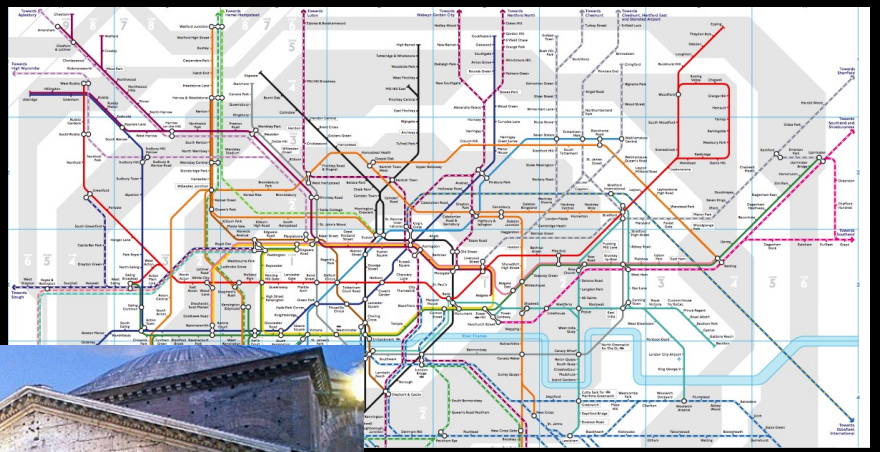
C. Kuhnert, D. Helbing & G.B. West, *Physica A* (2005)

SOCIAL NETWORKS

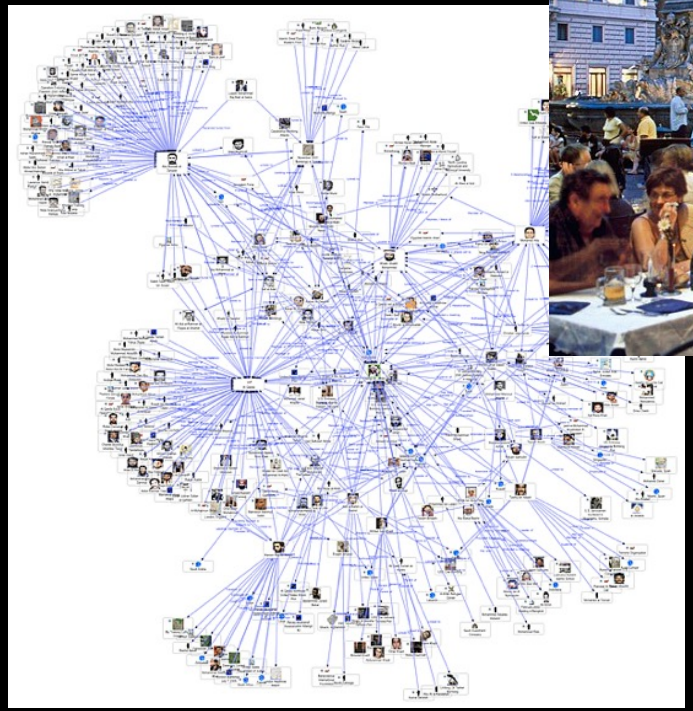


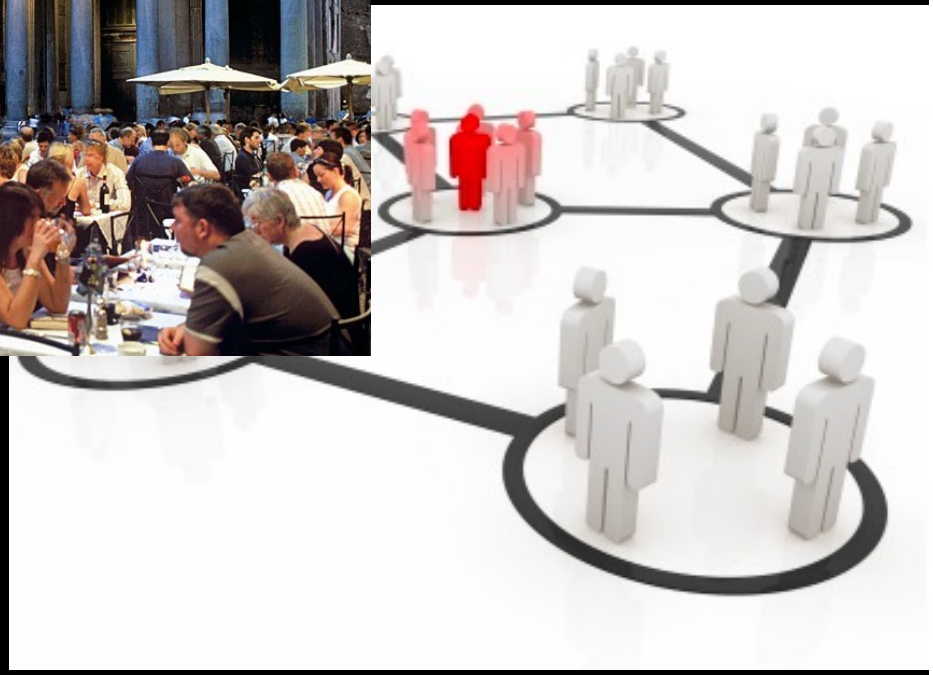
MODULARITY AND ***PLACE***


SATELLITE IMAGING CORPORATION
12777 JONES ROAD, SUITE 370
HOUSTON, TEXAS 77070-4647 USA
TEL: 1.832.237.2900
FAX: 1.832.237.2910
E-MAIL: INFO@SATIMAGINGCORP.COM

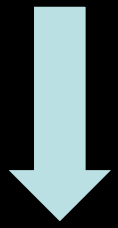



M·AGRIPPA·L·F·COS·TERTIVM·FECIT



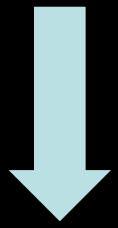


POSITIVE FEEDBACK MECHANISM IN SOCIAL NETWORKS



SUPERLINEAR SCALING

POSITIVE FEEDBACK MECHANISM IN SOCIAL NETWORKS



SUPERLINEAR SCALING

& INCREASING PACE OF LIFE

L.M.A. Bettencourt, D. Helbing, C. Kuhnert, J. Lobo, G.B. West PNAS, 2007
L. M. A. Bettencourt & G. B. West *Nature* 2010
L. M. A. Bettencourt *Science* 2017

NETWORK “PRINCIPLES”

i) SOCIO-ECONOMIC SYSTEMS ARE SUSTAINED BY THE TRANSPORT OF ENERGY, RESOURCES AND INFORMATION THROUGH (HIERARCHICAL) BRANCHING NETWORKS IN ORDER TO SUPPLY AND SUSTAIN ALL LOCAL PARTS OF THE SYSTEM (PEOPLE, BUILDINGS, BUSINESSES,...)

ii) NETWORKS ARE SPACE-FILLING

iii) TERMINAL UNITS ARE INVARIANT

iv) EVOLVED TO (JOINTLY) MINIMISE TRAVEL TIME AND DISTANCE AND MAXIMISE SOCIAL INTERACTION VIA EXCHANGE OF INFORMATION TO CREATE “WEALTH” AND “INNOVATE”

v) UNIVERSALITY OF HIERARCHICAL MODULAR STRUCTURES

WITHIN SOCIO-ECONOMIC ORGANISATIONS THESE LEAD TO FRACTAL-LIKE STRUCTURES AND FLOWS

AND TO (APPROXIMATE) POWER LAW SCALING ACROSS ORGANISATIONS:

$$Y(N) \propto N^{b}$$

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

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

THE CONSTRAINTS AND DYNAMICS OF SOCIAL & INFRASTRUCTURAL NETWORKS (AND THE DATA!) LEAD TO

$$N_{\text{int}} \sim N^{1.15}$$

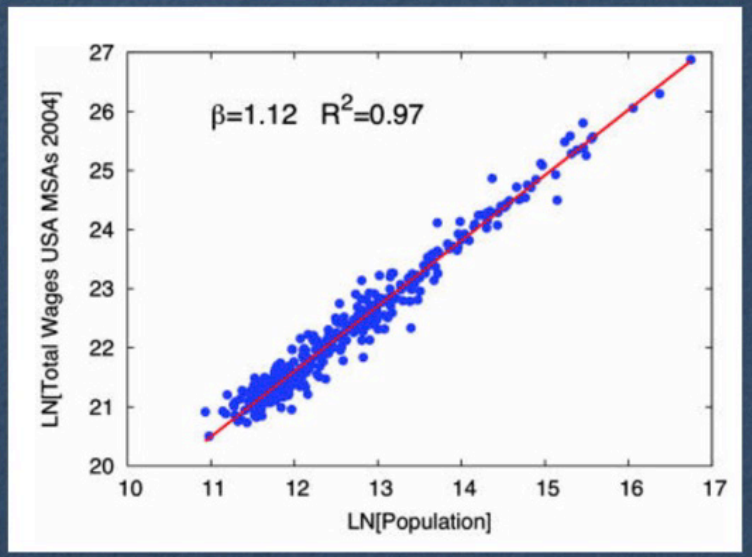
SO, FOR THE AVERAGE INDIVIDUAL, THE NUMBER OF INTERACTIONS $\sim N^{0.15}$

CONSEQUENTLY,

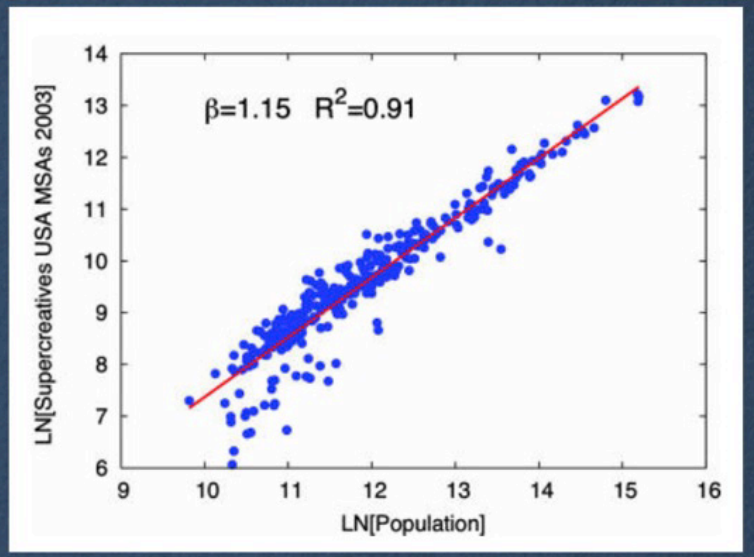
$$Y(N) \propto N_{\text{int}} \propto N^{1.15}$$

L. M. A. Bettencourt and G.B. West, *Nature* 467, 912 (2010); L. M. A. Bettencourt, *Science* 340, 1438 (2013).

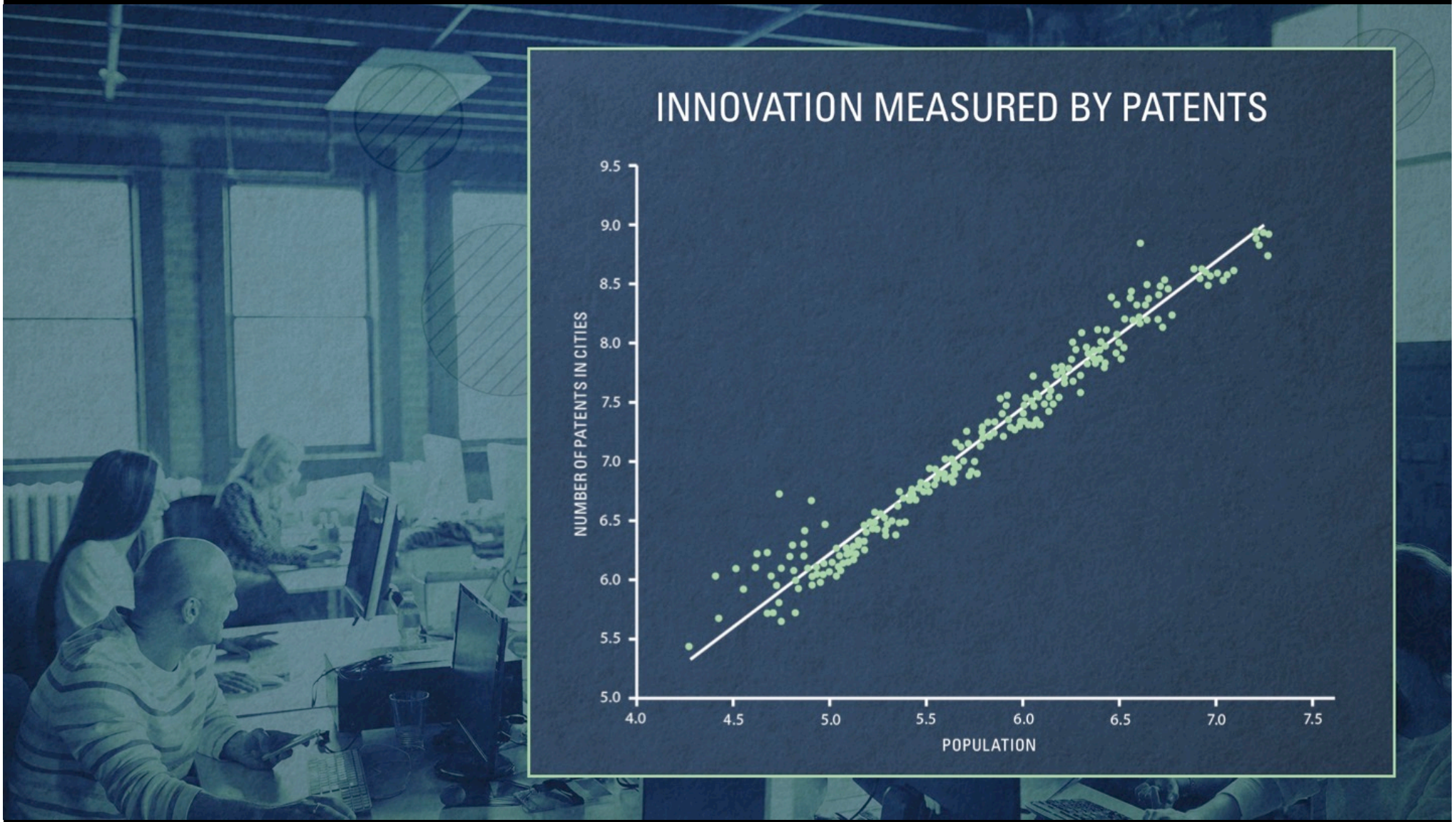
SUPER-LINEAR SCALING



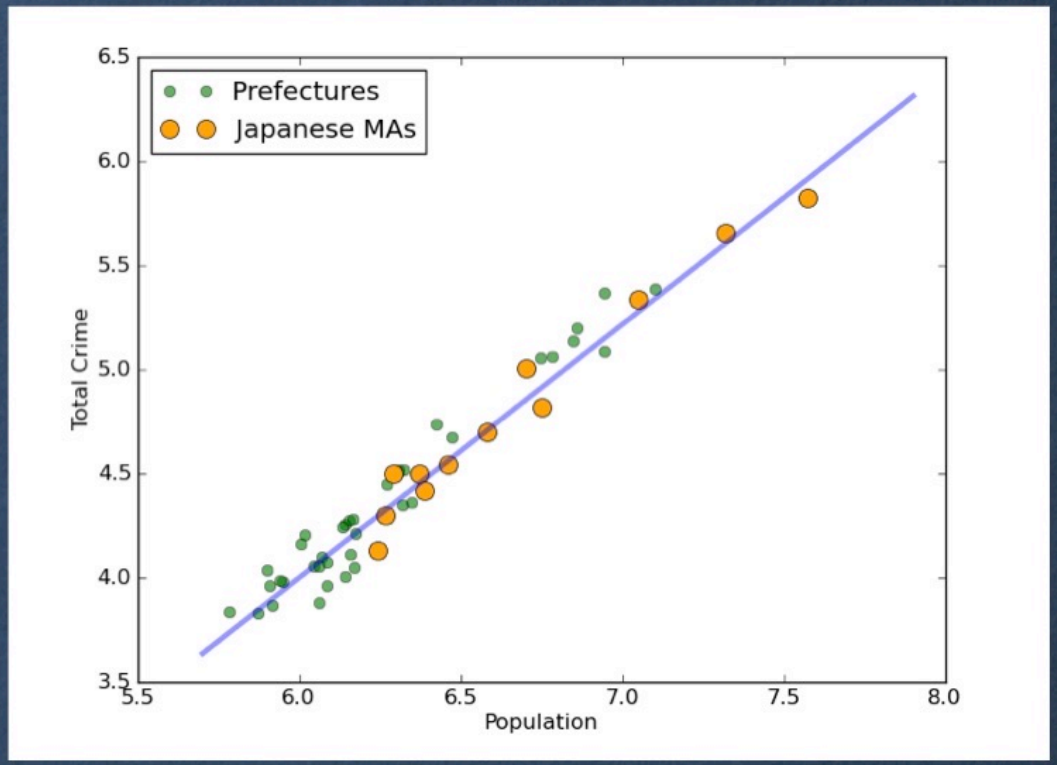
Total wages per MSA in 2004 for the USA vs. metropolitan population.



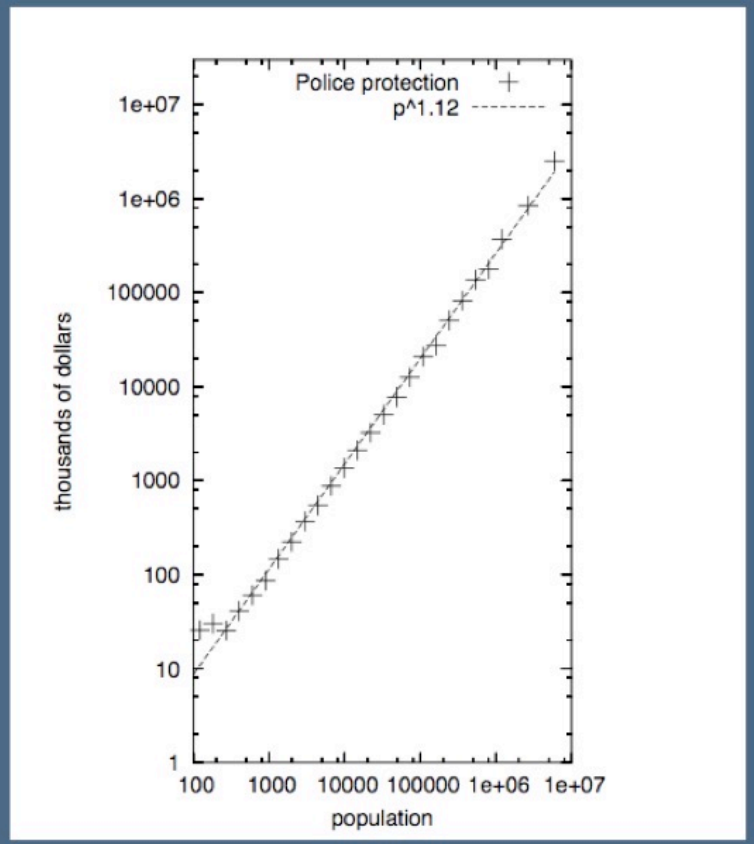
Supercreative employment per MSA in 2003, for the USA vs. metropolitan population.

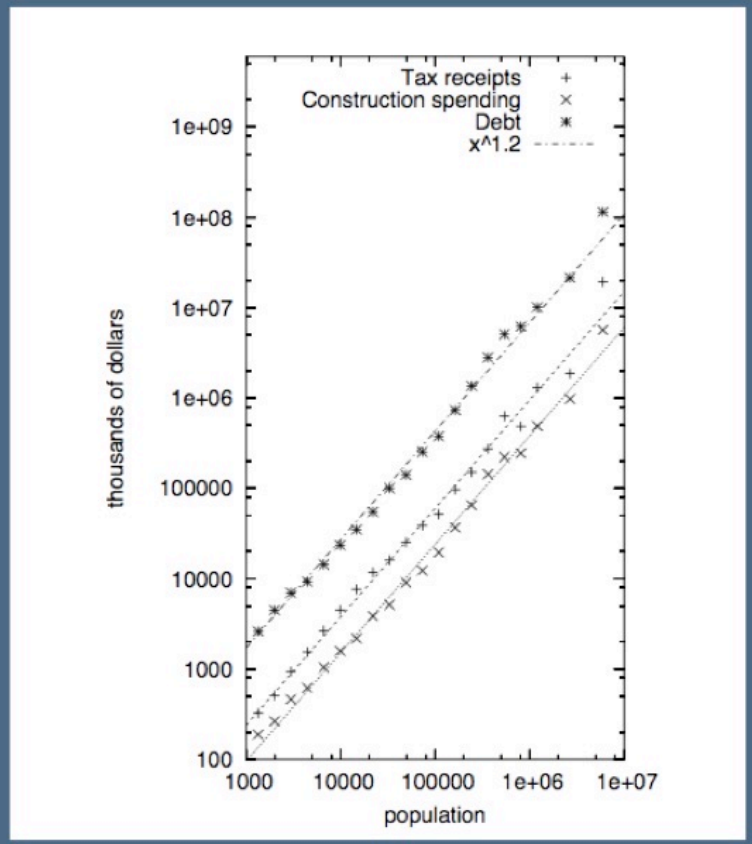

INNOVATION MEASURED BY PATENTS
NUMBER OF PATENTS IN CITIES
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
POPULATION

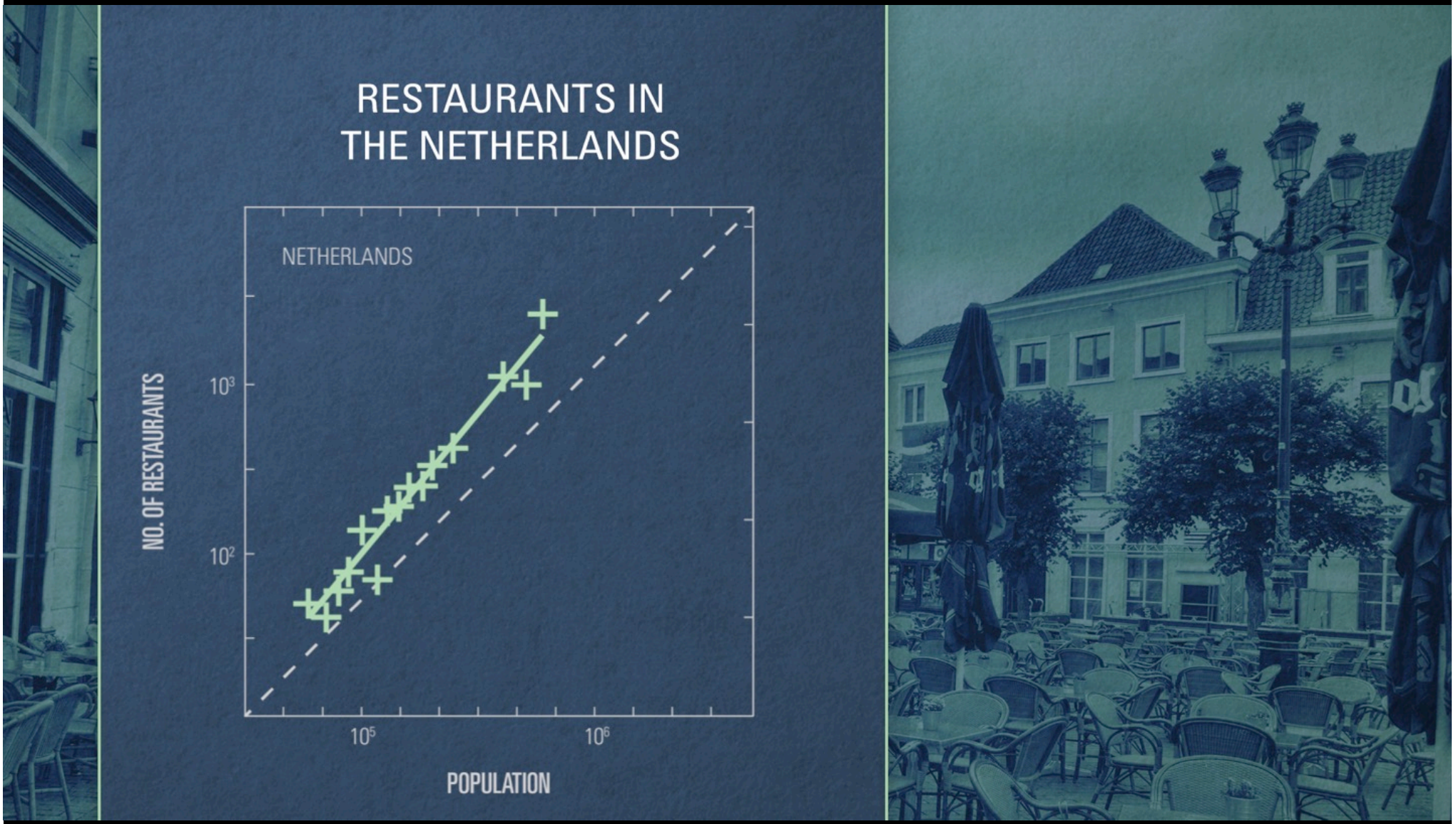
TOTAL CRIME (JAPAN)



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
NETHERLANDS
NO. OF RESTAURANTS
10^3
10^2
10^5
10^6
POPULATION

THE GOOD, THE BAD, THE UGLY

ON AVERAGE DOUBLING THE SIZE OF A CITY SYSTEMATICALLY

ON AVERAGE DOUBLING THE SIZE OF A CITY SYSTEMATICALLY

SAVES APPROXIMATELY 15% ON ALL INFRASTRUCTURE

(ROADS, ELECTRICAL LINES, GAS STATIONS,……)

ON AVERAGE DOUBLING THE SIZE OF A CITY SYSTEMATICALLY

SAVES APPROXIMATELY 15% ON ALL INFRASTRUCTURE

(ROADS, ELECTRICAL LINES, GAS STATIONS,……)

AND

INCREASES

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

AND

INCREASES

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

AND

COVID-19

ALL BY ABOUT 15%

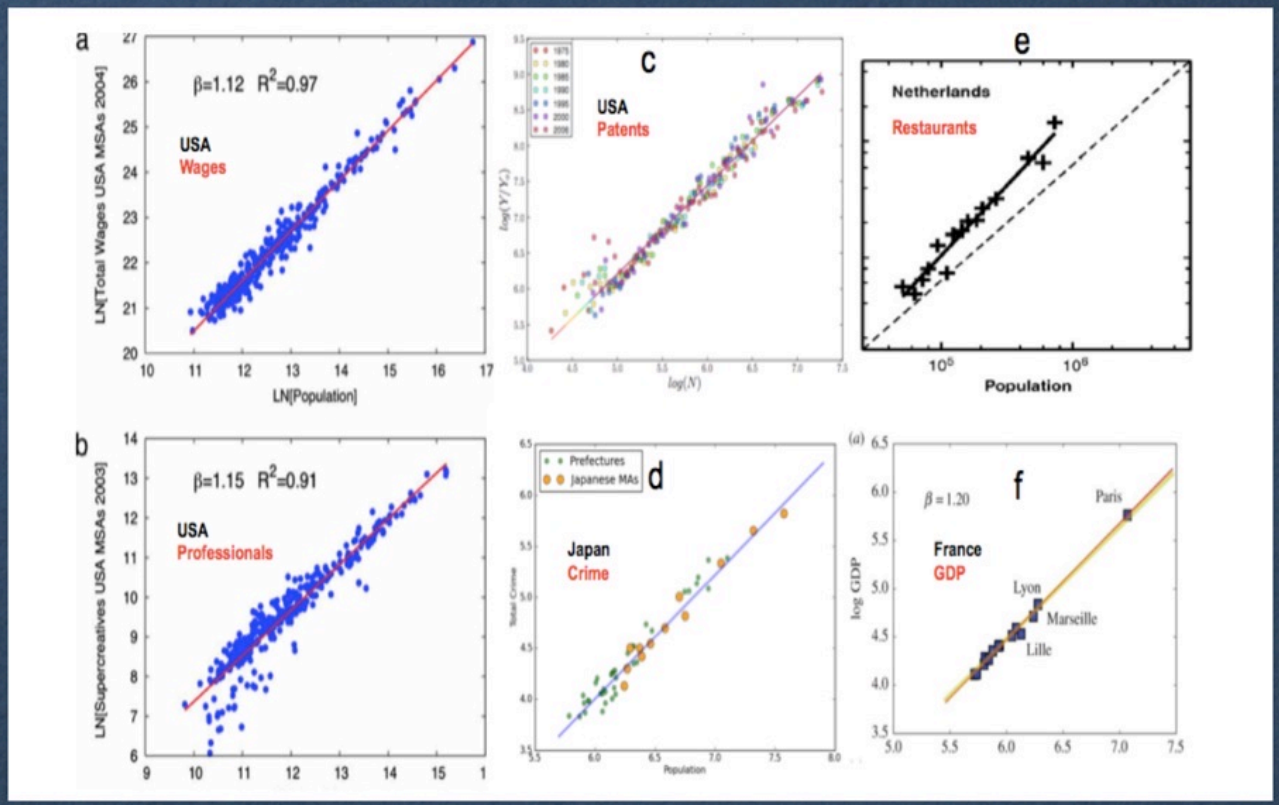
A CITY OF 10 MILLION WILL HAVE DOUBLE

THE NUMBER OF COVID CASES IN HALF

THE TIME A CITY OF 100,000 WILL.....

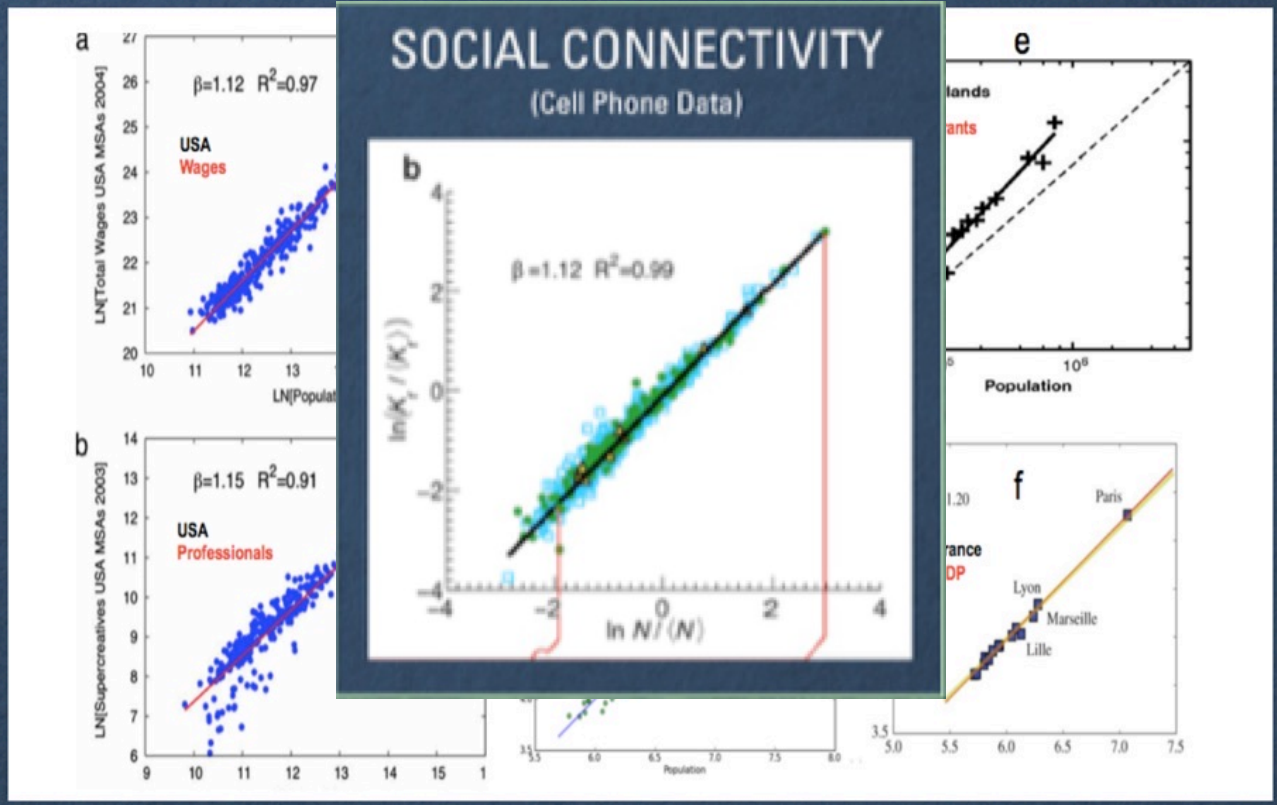
AND HAVE ~ 200 TIMES AS MANY CASES

UNIVERSALITY OF URBAN SCALING



L.M.A. Bettencourt, D. Helbing, C. Kuhnert, J. Lobo, G.B. West PNAS, 2007 104 (17) 7301

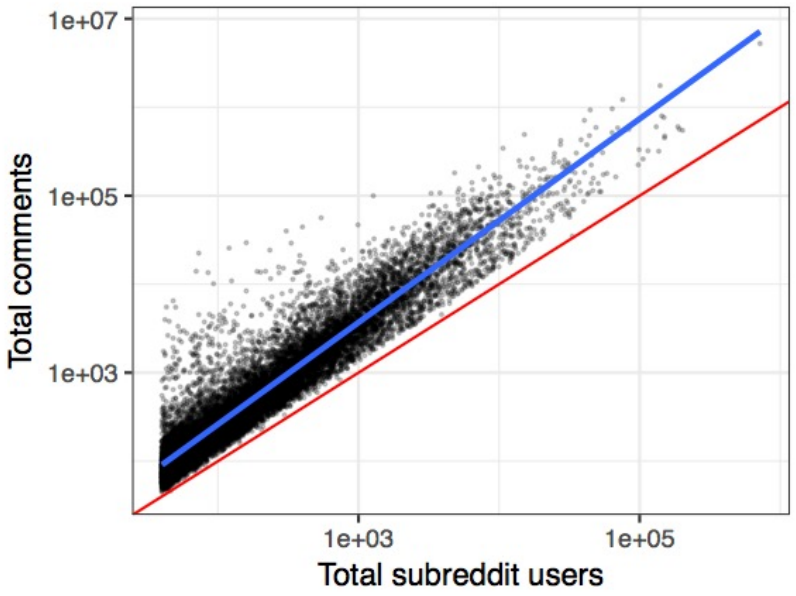
UNIVERSALITY OF URBAN SCALING



M. Schlapfer, L.M.A.Bettencourt, M. Raschke, R, Claxton, Z. Smoreda, G.B. West, C. Ratti
J. R. Soc. Interface 11 (98), 20130789 (2014)

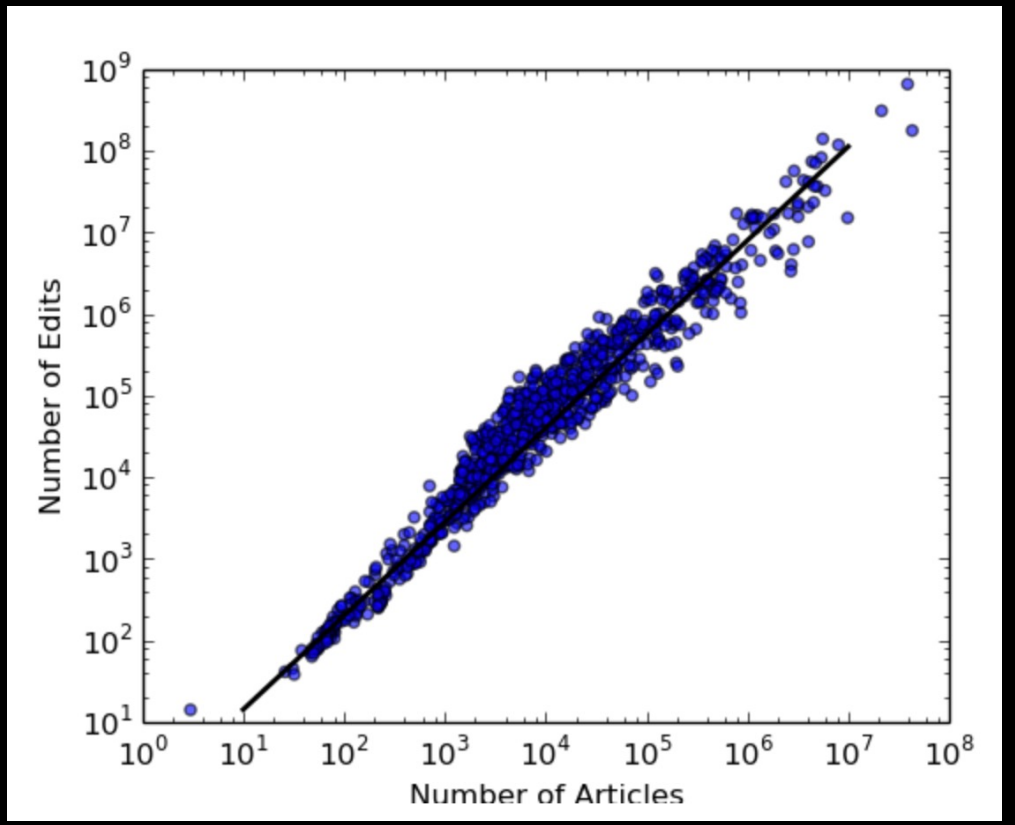
?


Turn on Original Sound
Speaker View
Mute
Start Video
Invite
Participants
Share Screen
Chat
Record
Leave Meeting



SUBREDDIT

BOTH HAVE SLOPE ~ 1.15



WIKIPEDIA

Growth

Incoming "Social Metabolic Rate"
(Resources, Products, Patents,… … "Energy" or "Dollar" equivalent)

≈ **Maintenance** (Repair, Replacement, Sustenance of Infrastructure, People, Institutions, Companies …)

+

New Growth (of Infrastructure, People, Institutions, Companies …)

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

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

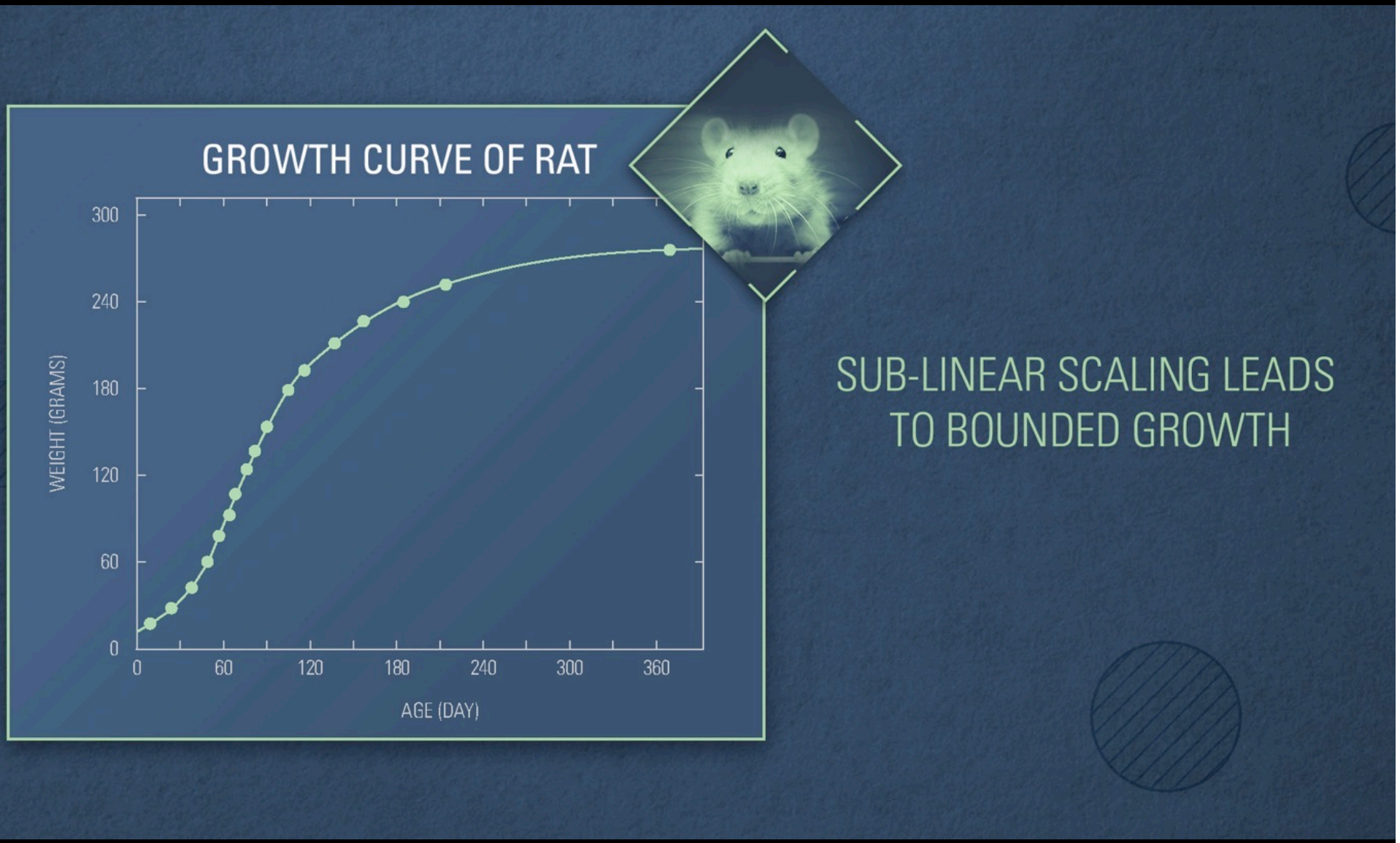
$$R \approx NR_O + E_O \frac{dN}{dt}$$

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

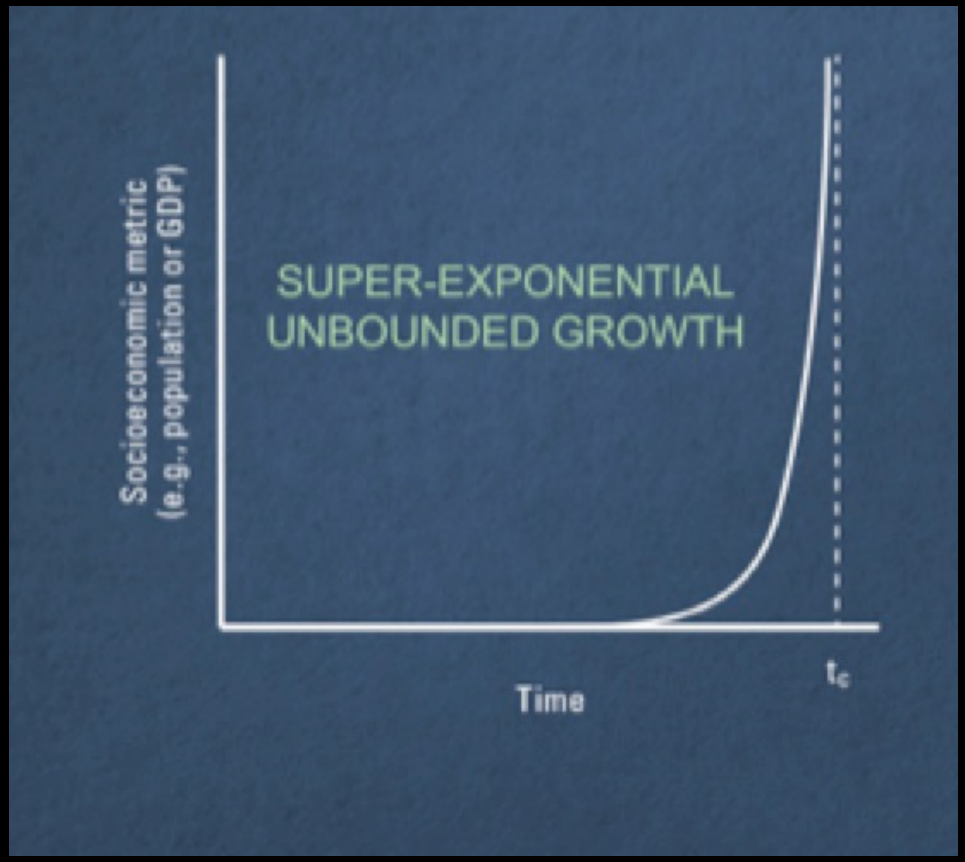
SOLUTION:

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

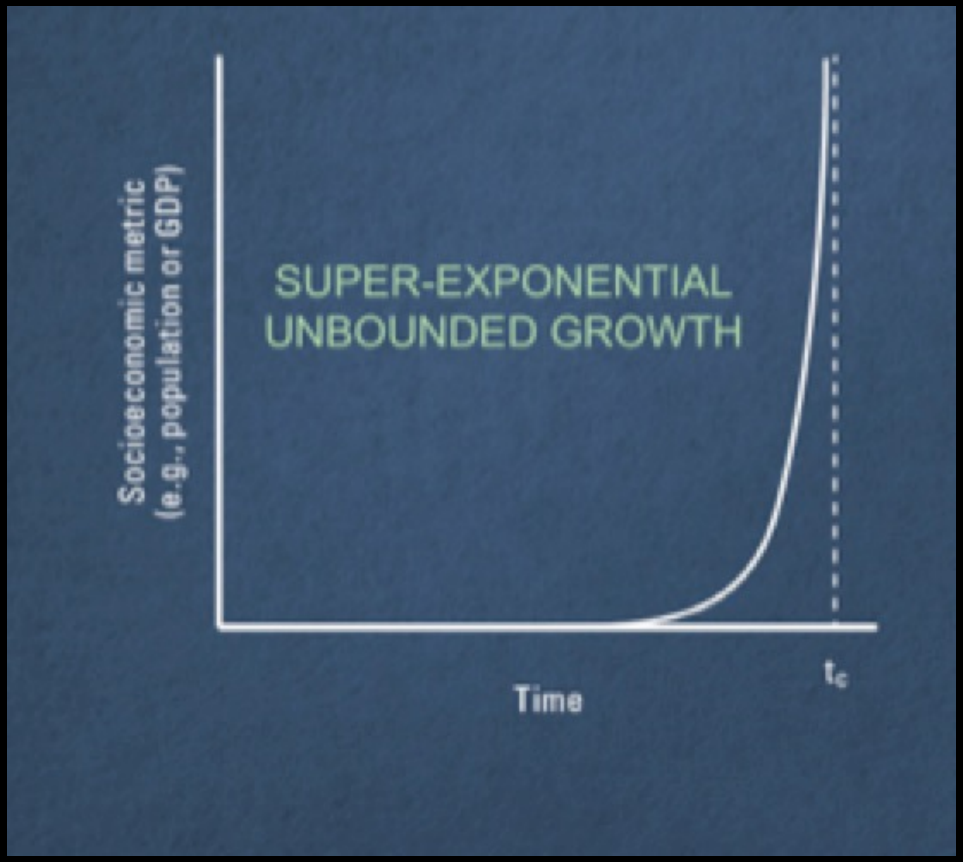
CHARACTER OF SOLUTION SENSITIVE TO $\beta >,=,< 1$


GROWTH CURVE OF RAT
300
240
180
120
60
0
WEIGHT (GRAMS)
0
60
120
180
240
300
360
AGE (DAY)
SUB-LINEAR SCALING LEADS
TO BOUNDED GROWTH

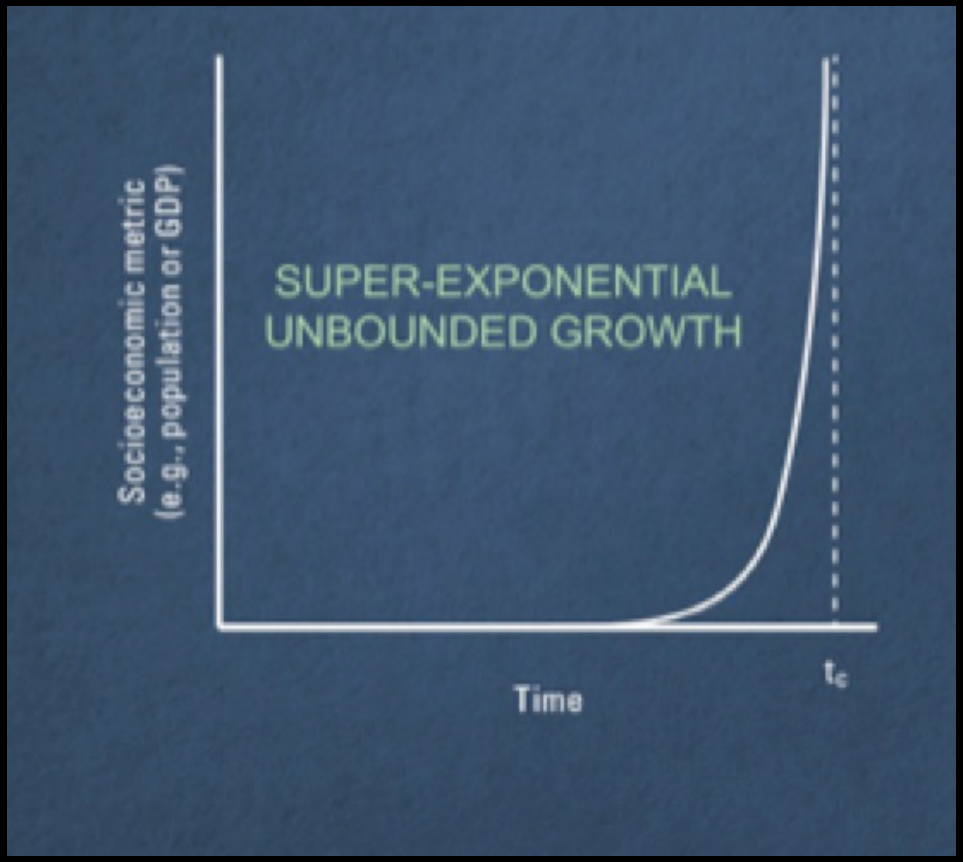
SUPERLINEAR SCALING LEADS TO UNBOUNDED GROWTH



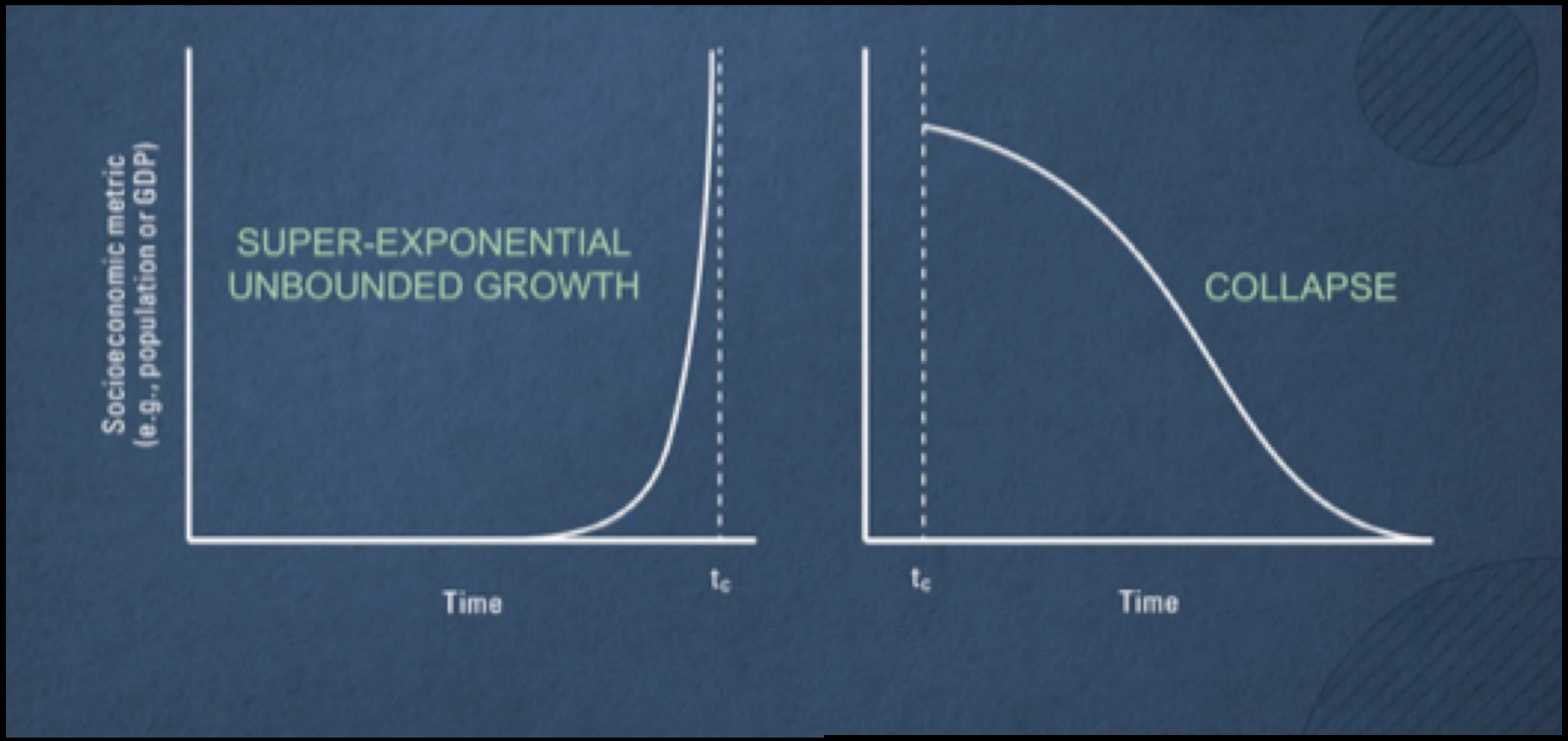
SUPERLINEAR SCALING LEADS TO UNBOUNDED GROWTH BUT ALSO TO A

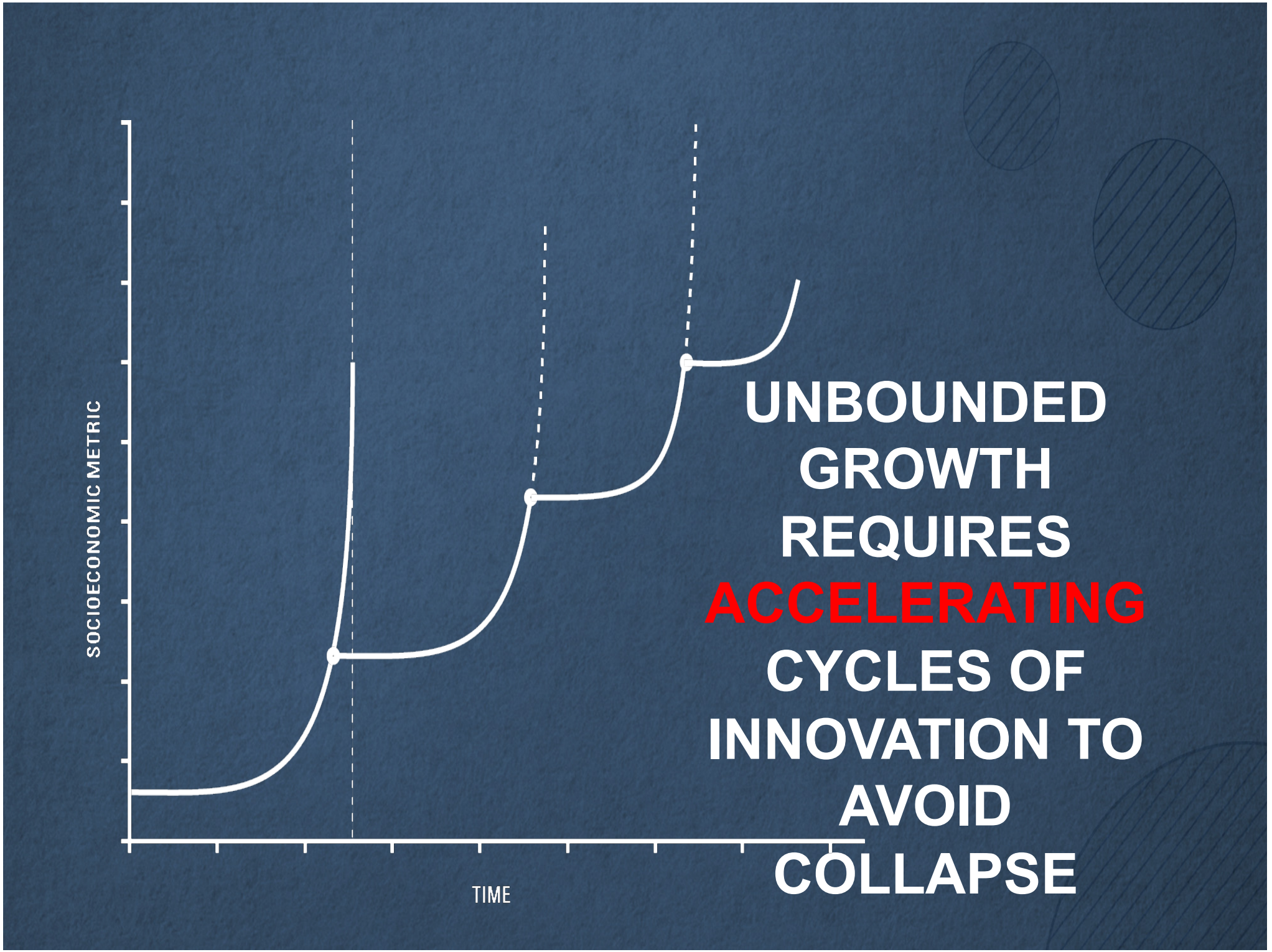


FINITE TIME SINGULARITY

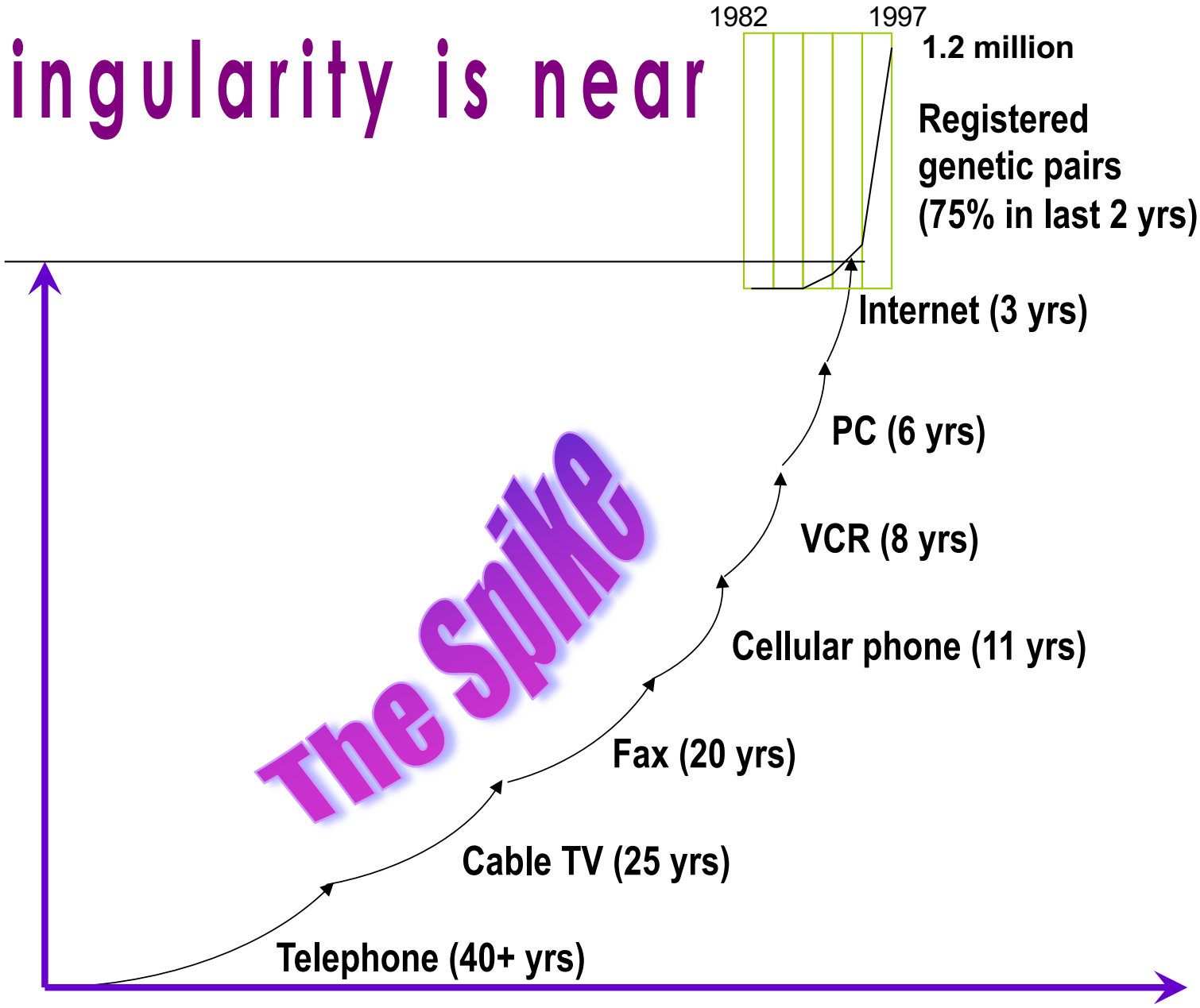


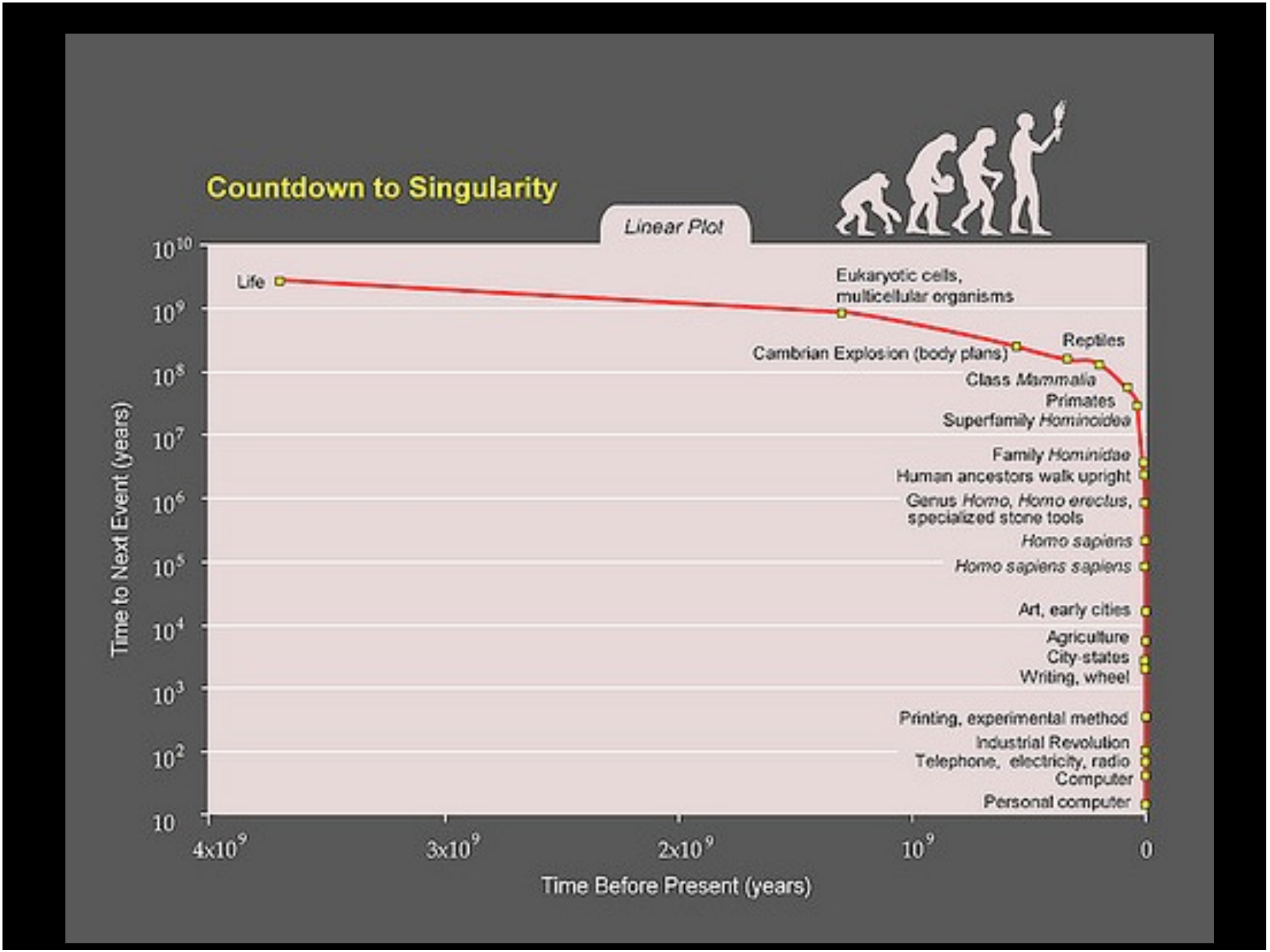
FINITE TIME SINGULARITY



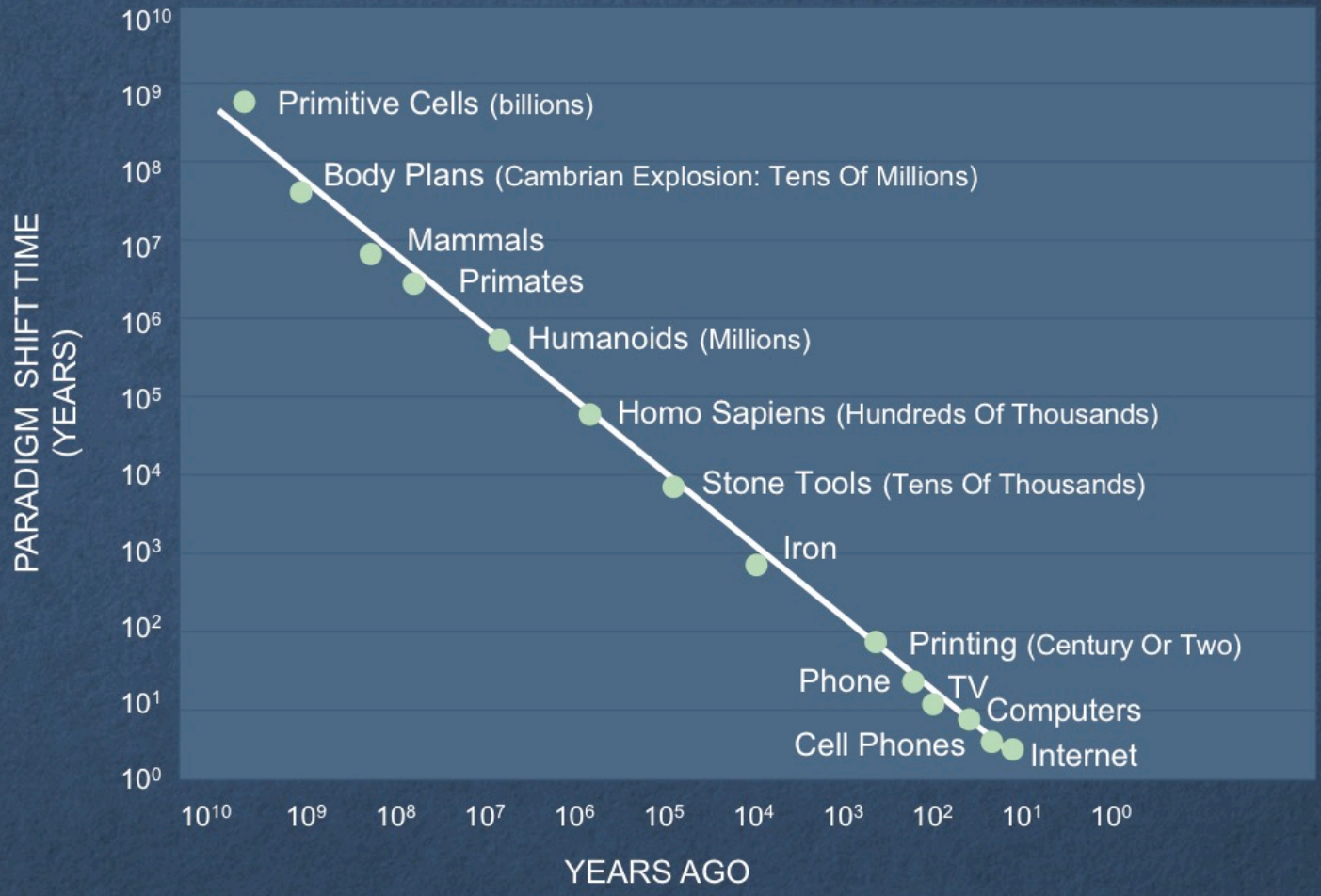

SOCIOECONOMIC METRIC
TIME
UNBOUNDED GROWTH REQUIRES ACCELERATING CYCLES OF INNOVATION TO AVOID COLLAPSE

Singularity is near




Countdown to Singularity
Linear Plot
Time to Next Event (years)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
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
$4x10^9$
$3x10^9$
$2x10^9$
10^9
0
Time Before Present (years)

SEQUENCE OF SINGULARITIES



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

UNLESS INNOVATIONS OCCCUR (SYSTEMATICALLY) FASTER AND FASTER

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

UNLESS INNOVATIONS OCCCUR (SYSTEMATICALLY) FASTER AND FASTER

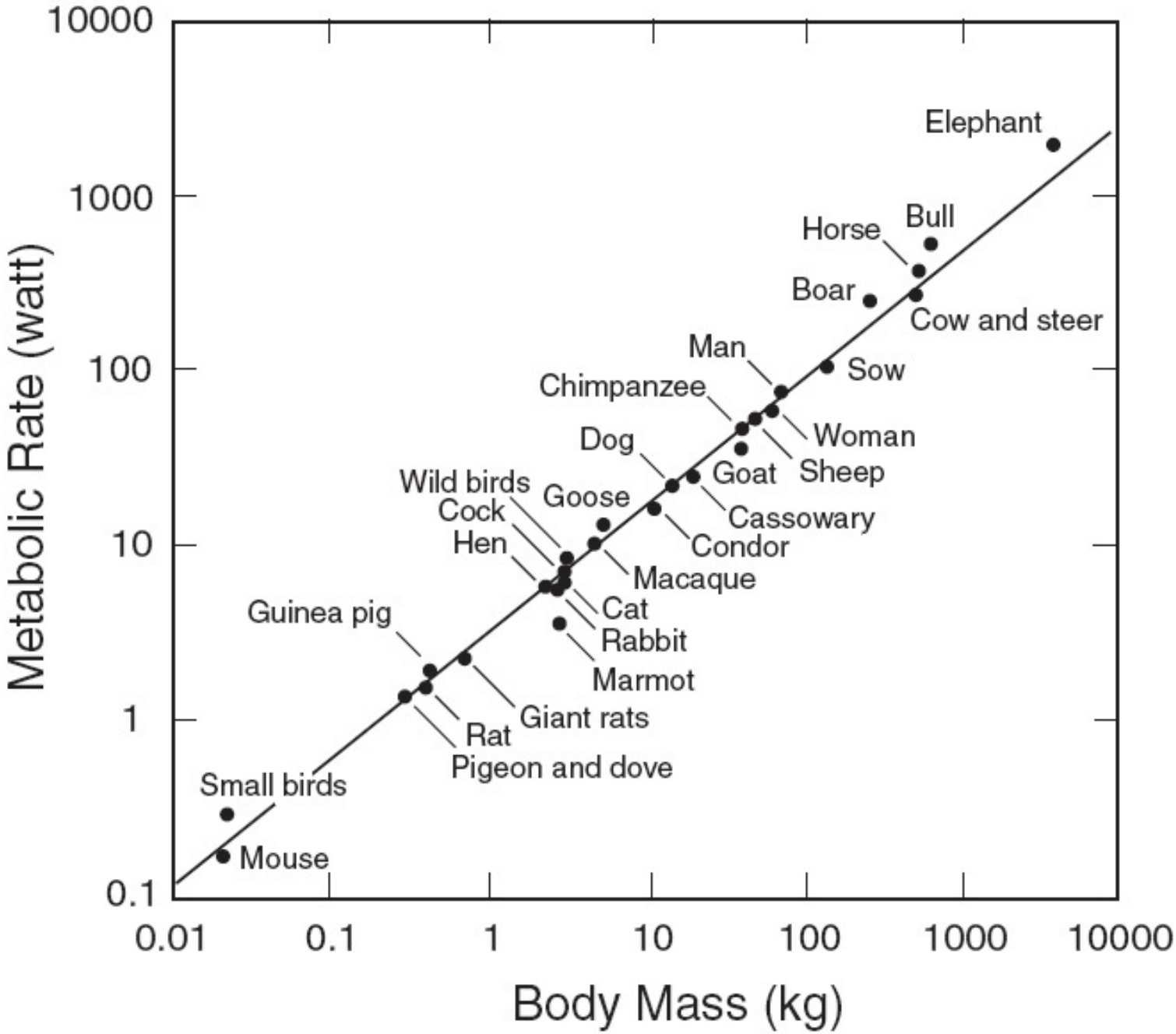
EXAMPLE OF THE ACCELERATING PACE OF ALL SOCIO-ECONOMIC LIFE!!

NEED TO ADAPT FASTER AND FASTER USING THE SAME BRAIN AND BIOLOGY WE'VE ALWAYS HAD!

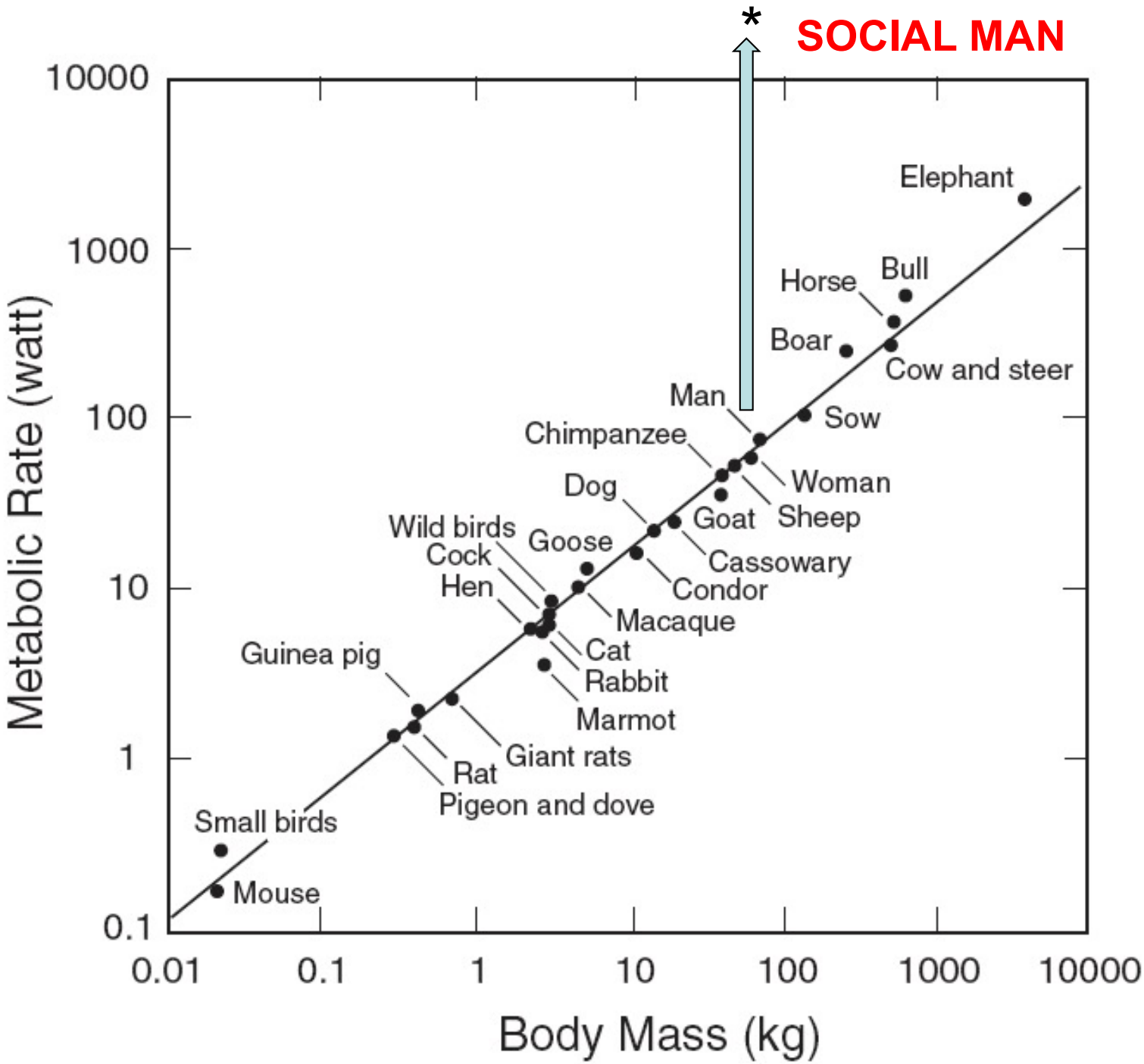
SUSTAINABLE????

Our “natural” metabolic rate *~90 watts*

Our social metabolic rate *~11,000 watts*



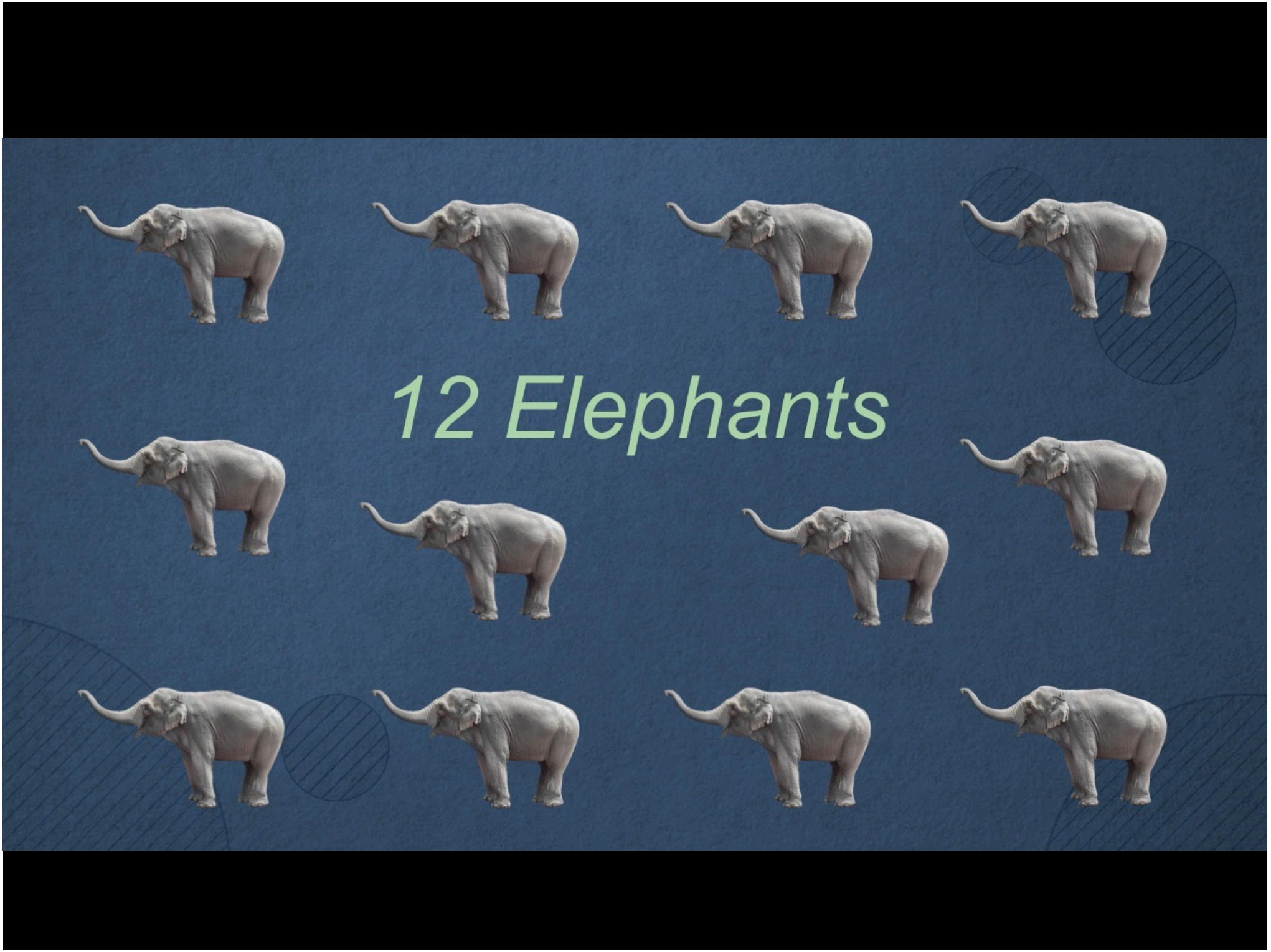
SLOPE = ¾ < 1; SUB-LINEAR; ECONOMY OF SCALE



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

We are equivalent to a

30,000 kg Gorilla


12 Elephants

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 (Minnesota)

Ric Charnov (UNM)

Chris Kempes (SFI)

Wenyun Zhuo (Stanford)

Luis Bettencourt (Chicago)

Jose Lobo (U of Arizona)

Debbie Strumsky (U of Arizona)

Hyejin Youn (N'western)

Marcus Hamilton (U of Texas)

Madeleine Daepp (MIT)

Markus Schlapfer (ETH Zurich)

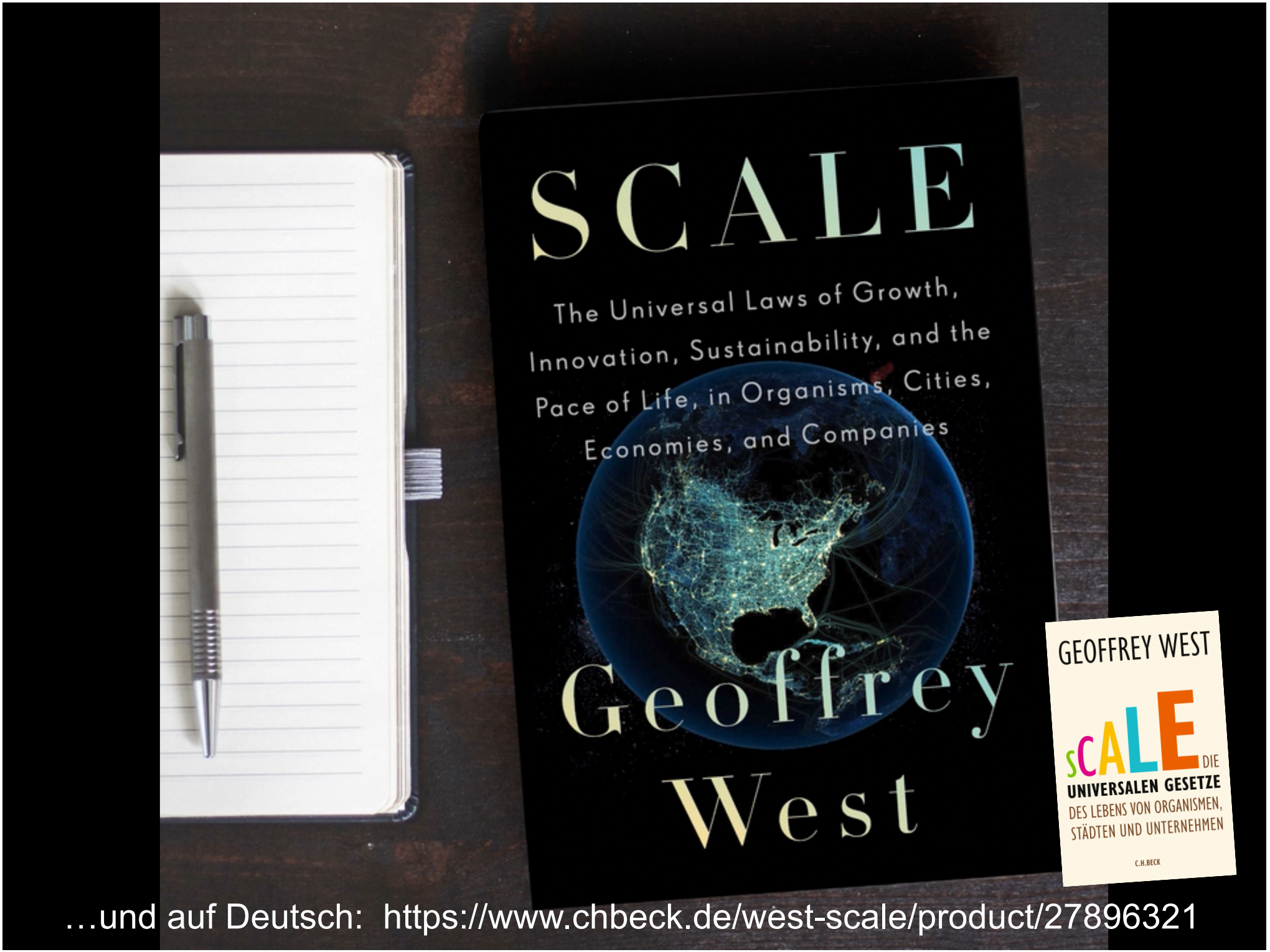
Carlo Ratti (MIT)

David Lane (U of Reggio)

Sander van der Leeuw (U of Arizona)

Denise Pumain (U of Paris)

Dirk Helbing (ETH Zurich)



…und auf Deutsch: https://www.chbeck.de/west-scale/product/27896321