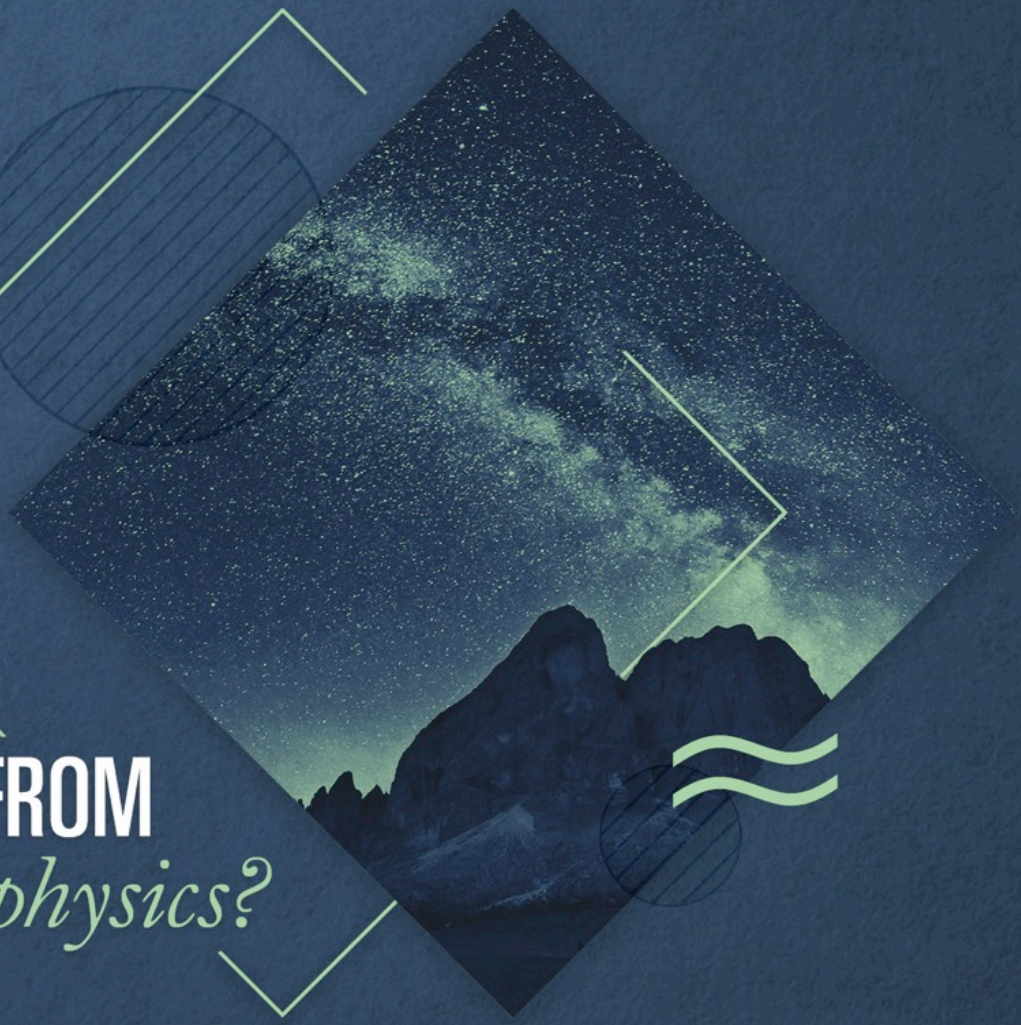
THE FUTURE OF THE PLANET:
LIFE, GROWTH AND DEATH IN ORGANISMS, CITIES & COMPANIES

Geoffrey West | Santa Fe Institute

WHAT CAN WE LEARN FROM

biology and physics?



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

1800 ***< 4% THE US POPULATION WAS URBAN***

2018 ***> 80% URBANISED***

2006 ***> 50% WORLD'S POPULATION URBANISED***

2050 ***> 75% URBANISED***

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

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

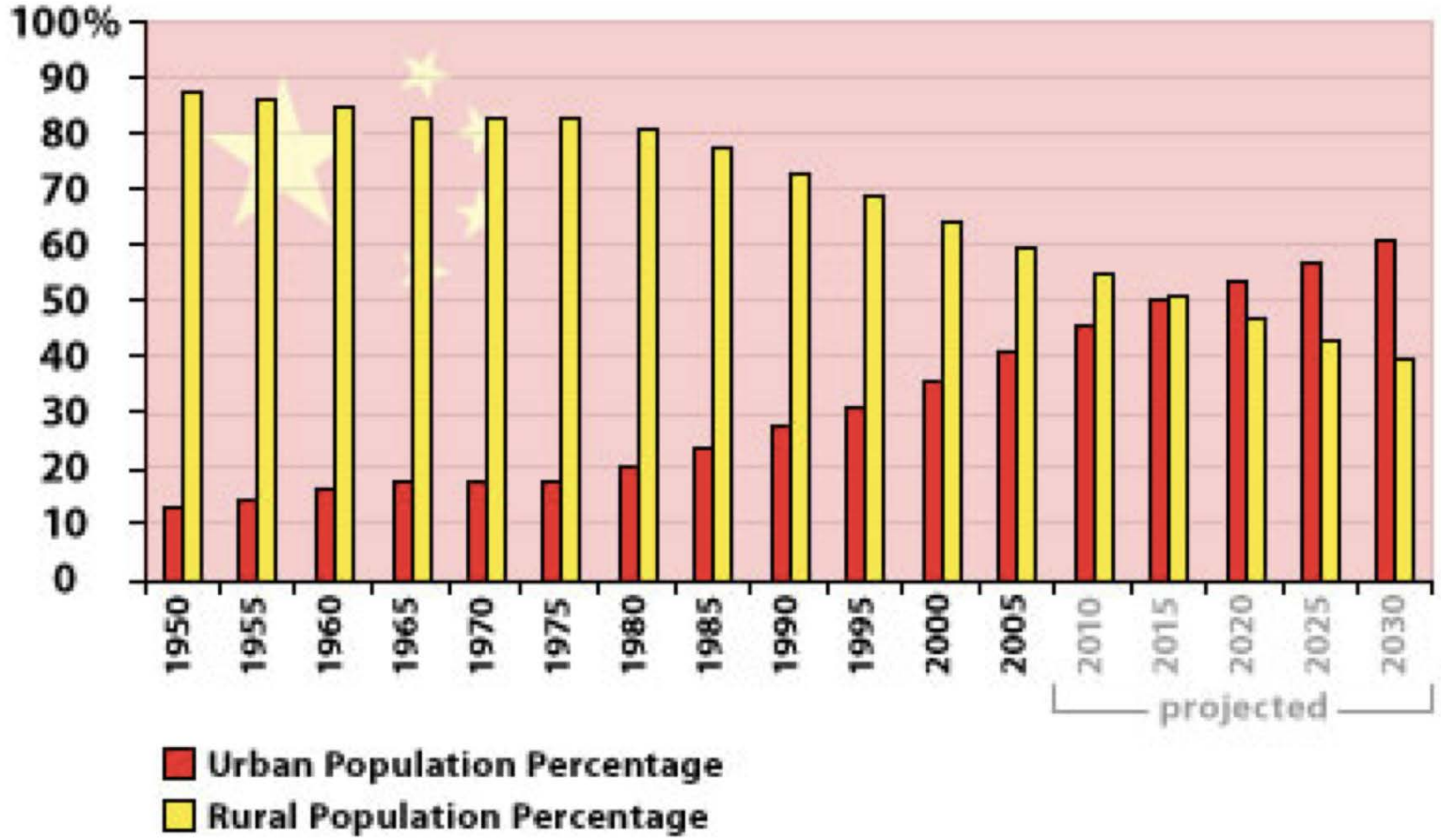
OR…….TO ADDING A NEW YORK METROPOLITAN AREA EVERY TWO MONTHS FROM NOW TO 2050

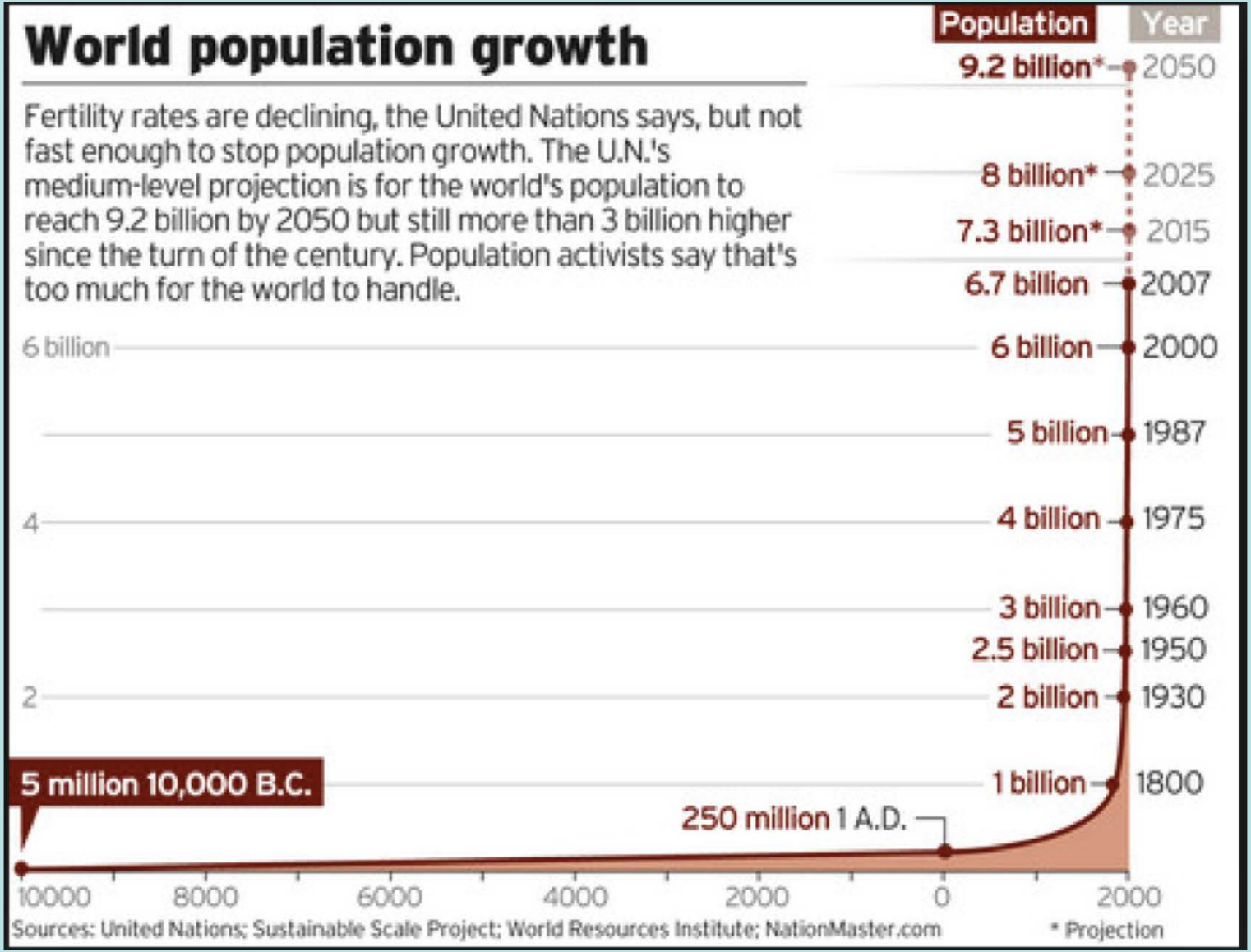
EQUIVALENT TO URBANISING OVER ONE MILLION PEOPLE EVERY WEEK FROM NOW TILL 2050

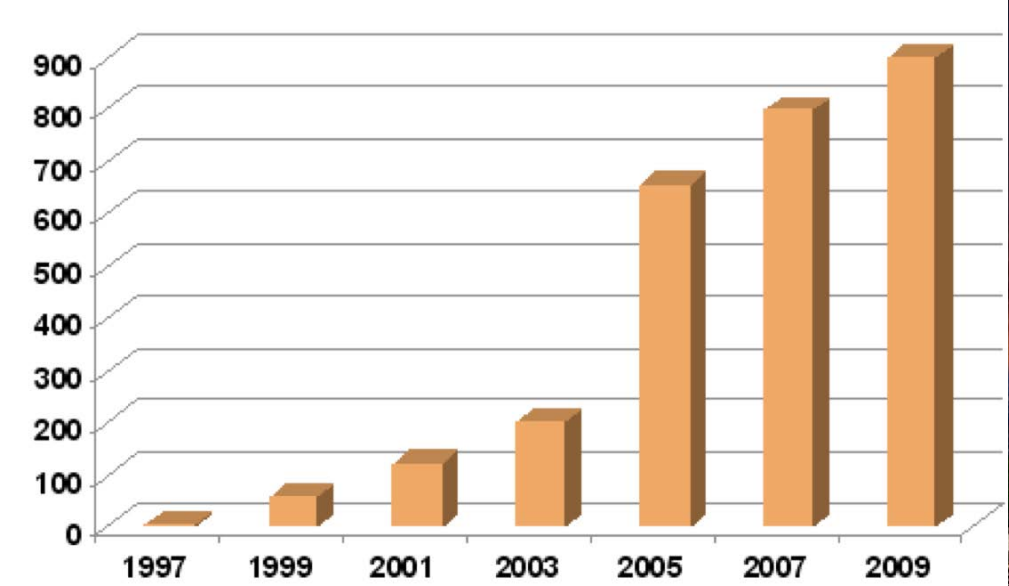
OR…….TO ADDING A NEW YORK METROPOLITAN AREA EVERY TWO MONTHS FROM NOW TO 2050

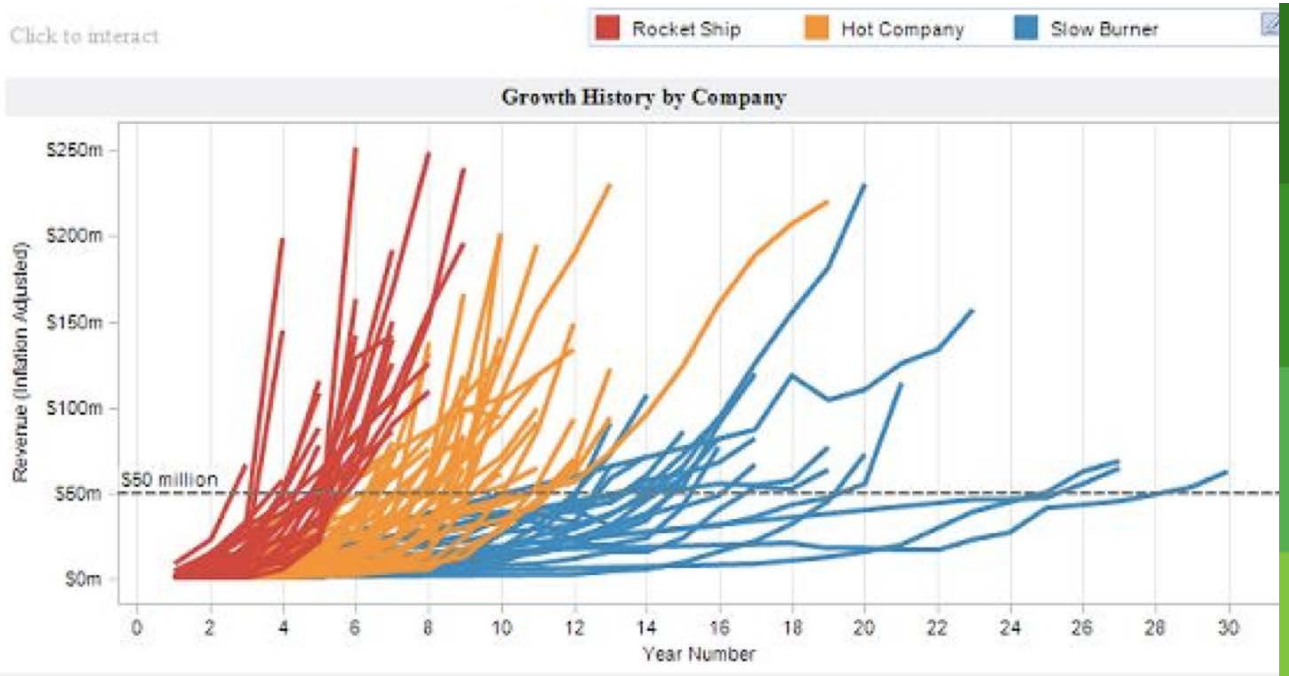
OR…….TO ADDING A VIENNA EVERY TWO WEEKS

CHINA URBAN/RURAL POPULATION GROWTH 1950-2030

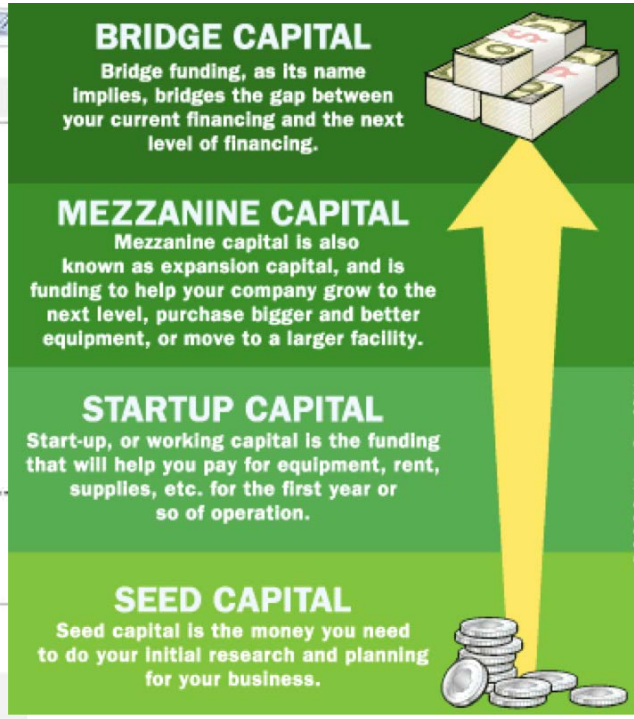



World population growth
Fertility rates are declining, the United Nations says, but not fast enough to stop population growth. The U.N.'s medium-level projection is for the world's population to reach 9.2 billion by 2050 but still more than 3 billion higher since the turn of the century. Population activists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





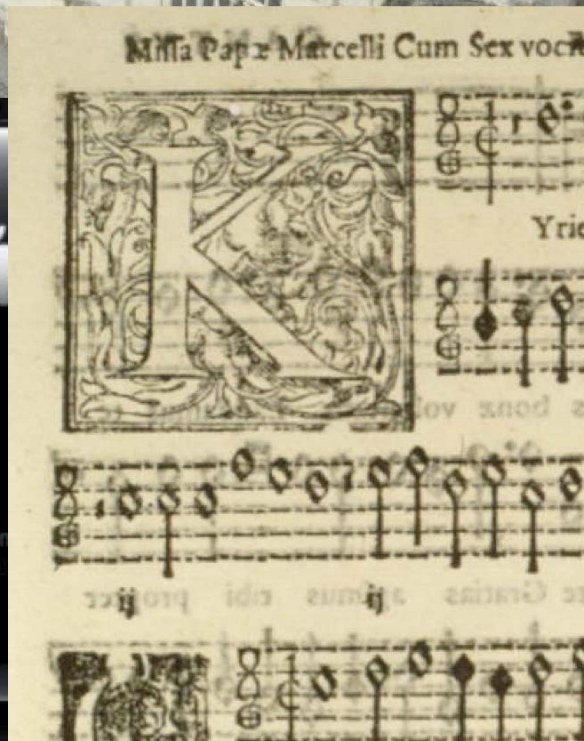
Growth rates of 100 software companies from IPO Dashboard

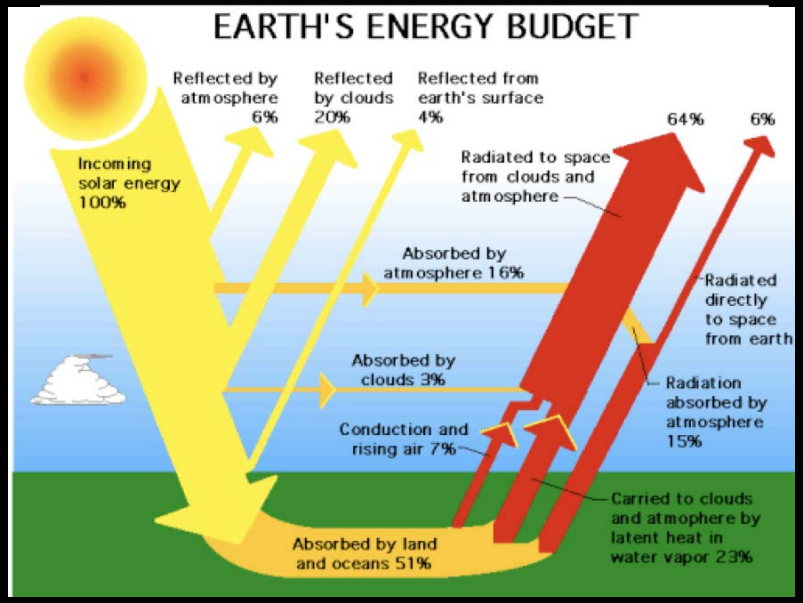



FATE OF OUR PLANET IS
the fate of our cities


lonelyplanetimages.com


THALDEN•BOYD ARCHITECTS


Missa Papæ Marcelli Cum Sex voc


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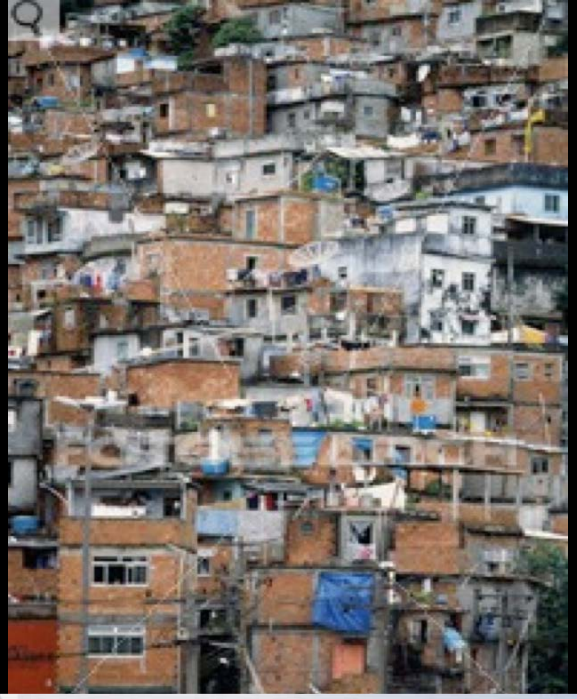
Evening Standard
Classified
MASSIVE INCREASE IN KNIFE CRIME SURVEYS
Evening Standard


GETTY IMAGES



London After Climate Change?


M·AGRIPPA·L·F·COS·TERTIVM·FECIT

ENERGY & RESOURCES (METABOLISM, INFRASTRUCTURE)

vs.

INFORMATION (GENOMICS, INNOVATION)

CITIES AND UBANISATION ARE THE PROBLEM

CITIES AND UBANISATION ARE THE PROBLEM

BUT THEY ARE ALSO THE SOLUTION!!

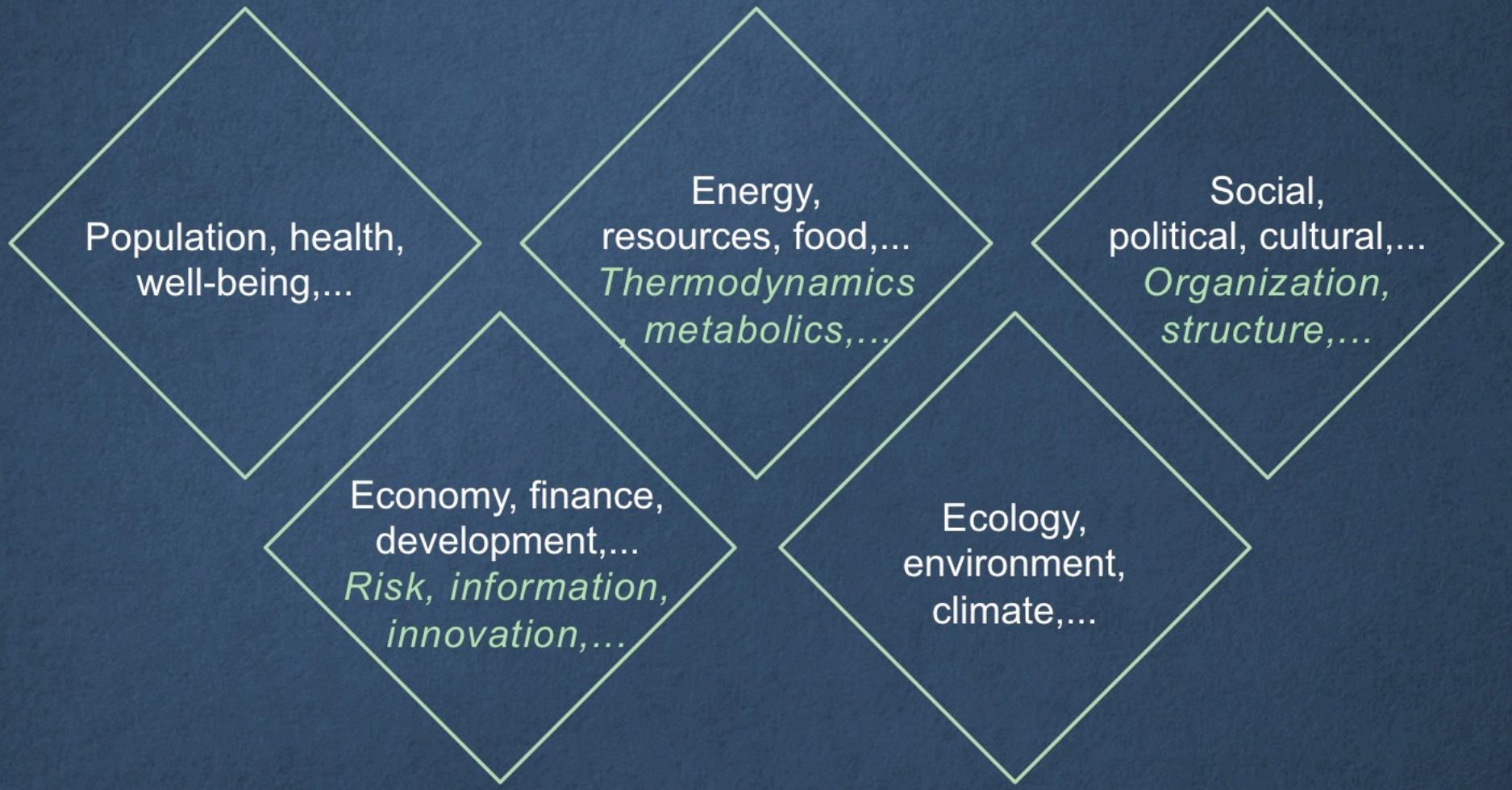
URGENTLY NEED A QUANTITATIVE, PREDICTIVE SCIENCE OF CITIES

RESILIENCE

EVOLVABILITY

GROWTH

SCALABILITY


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

THESE ARE NOT INDEPENDENT

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

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

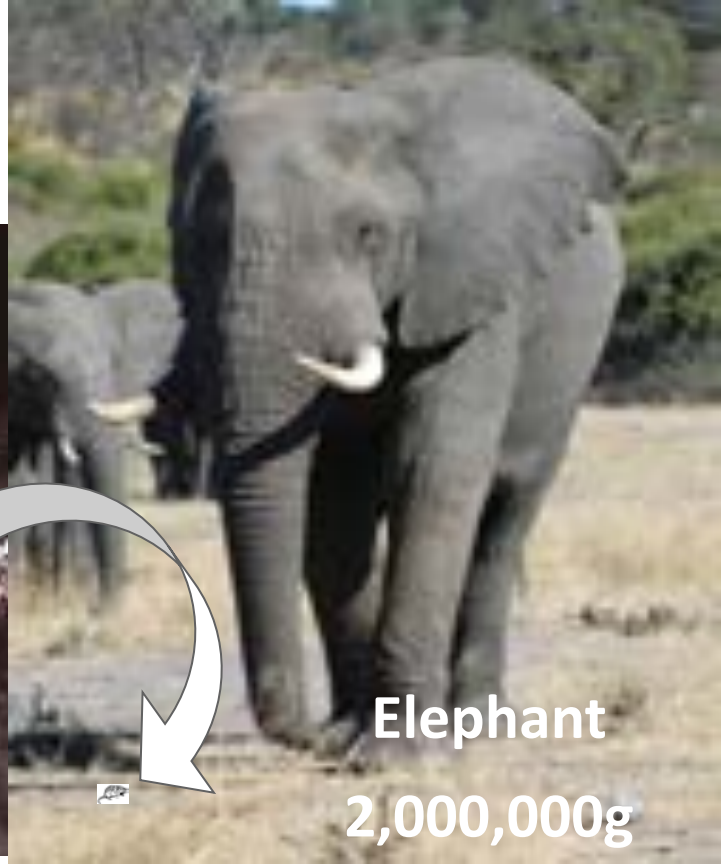

GM


LEHMAN BROTHERS

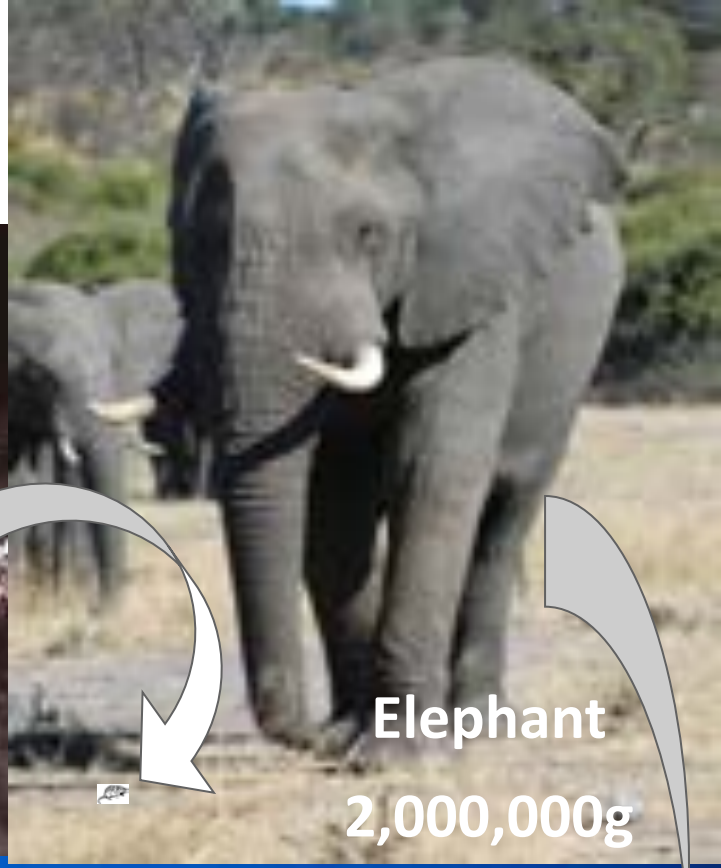

This Business
is now
CLOSED

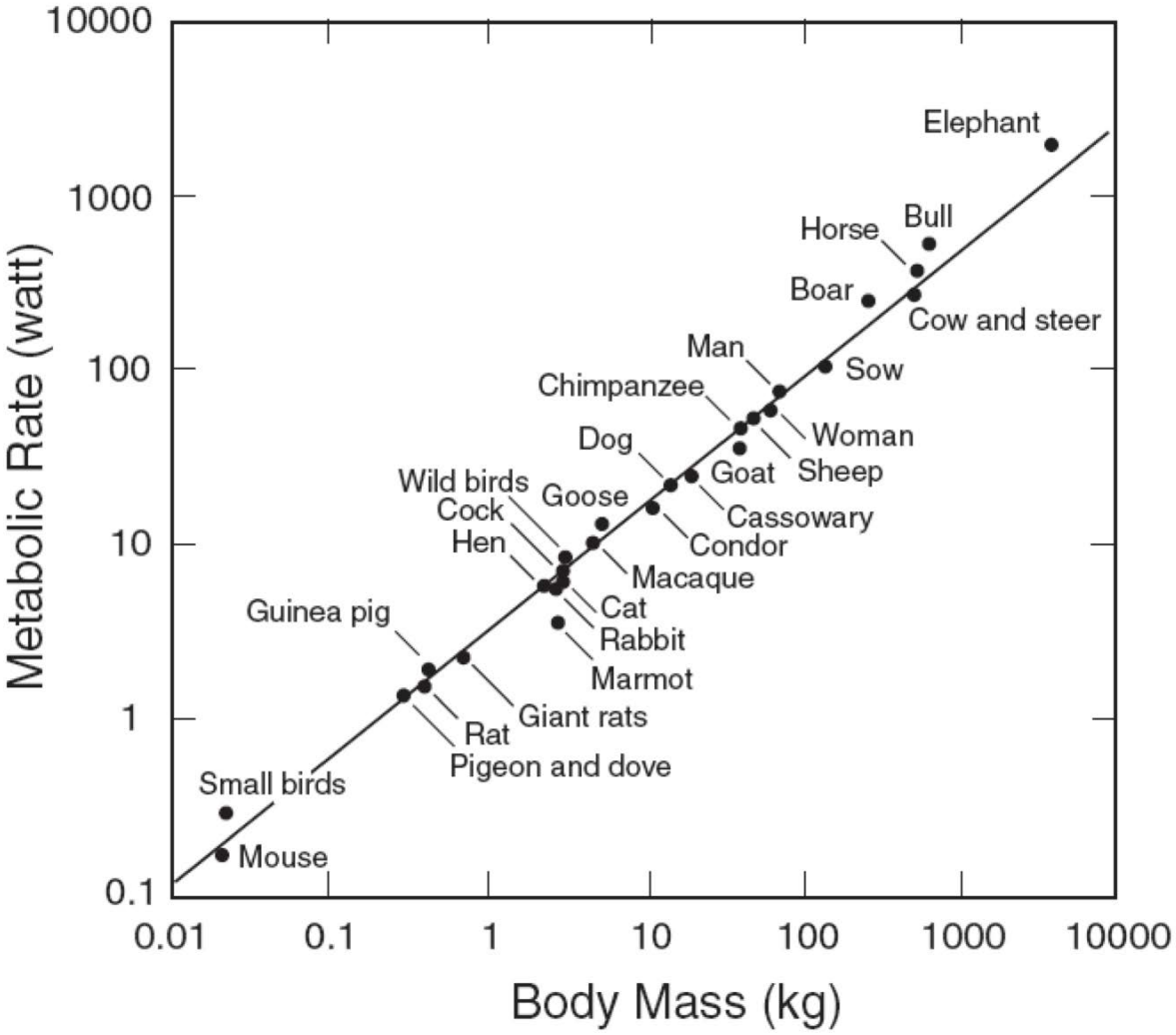
Mammals vary in size by 8 orders of magnitude

Mammals vary in size by 8 orders of magnitude



Mammals vary in size by 8 orders of magnitude





SLOPE = ¾ < 1 SUB-LINEAR ECONOMY OF SCALE

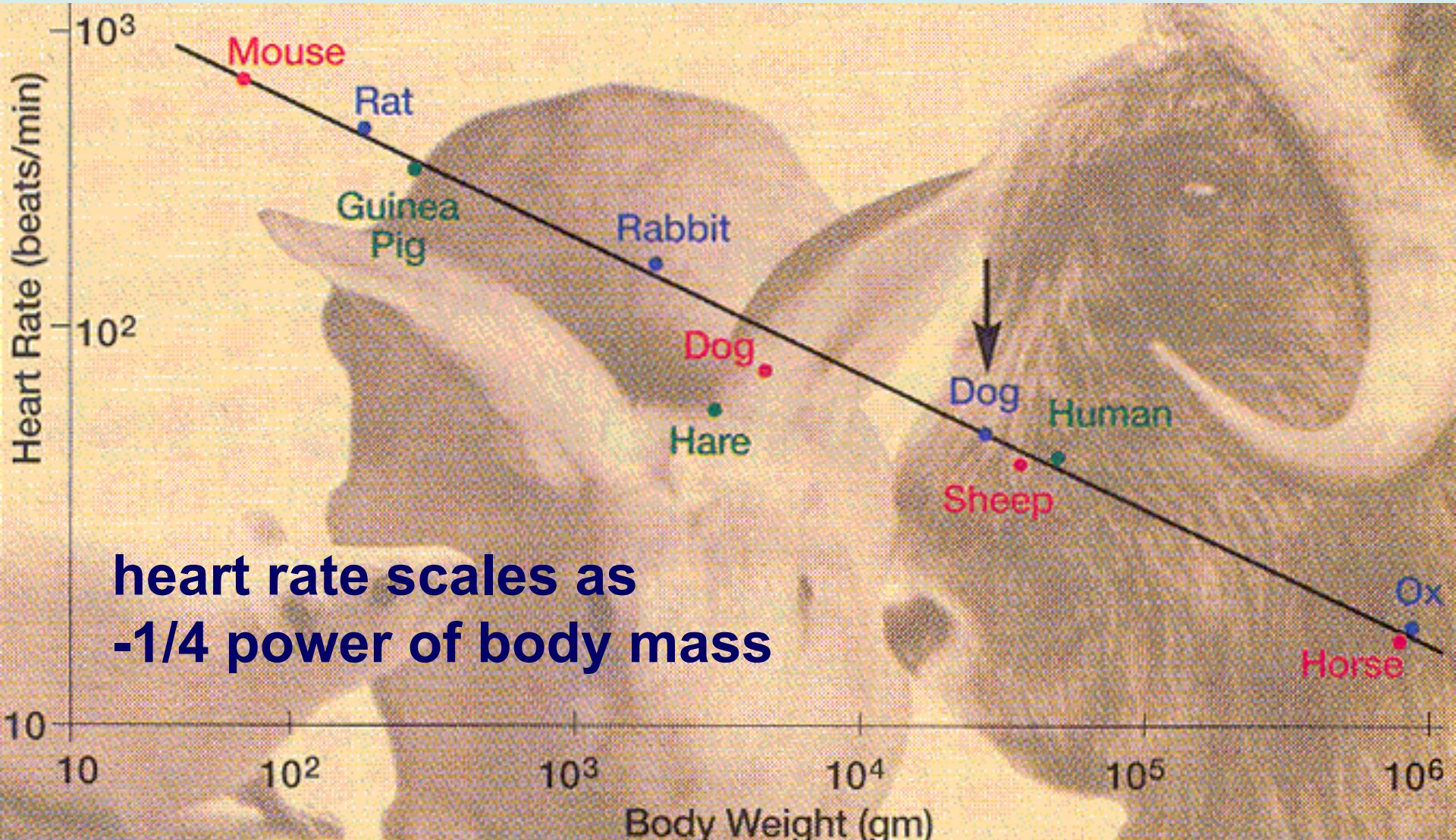
SCALABILITY RESILIENCE ADAPTABILITY

EVOLVABILITY

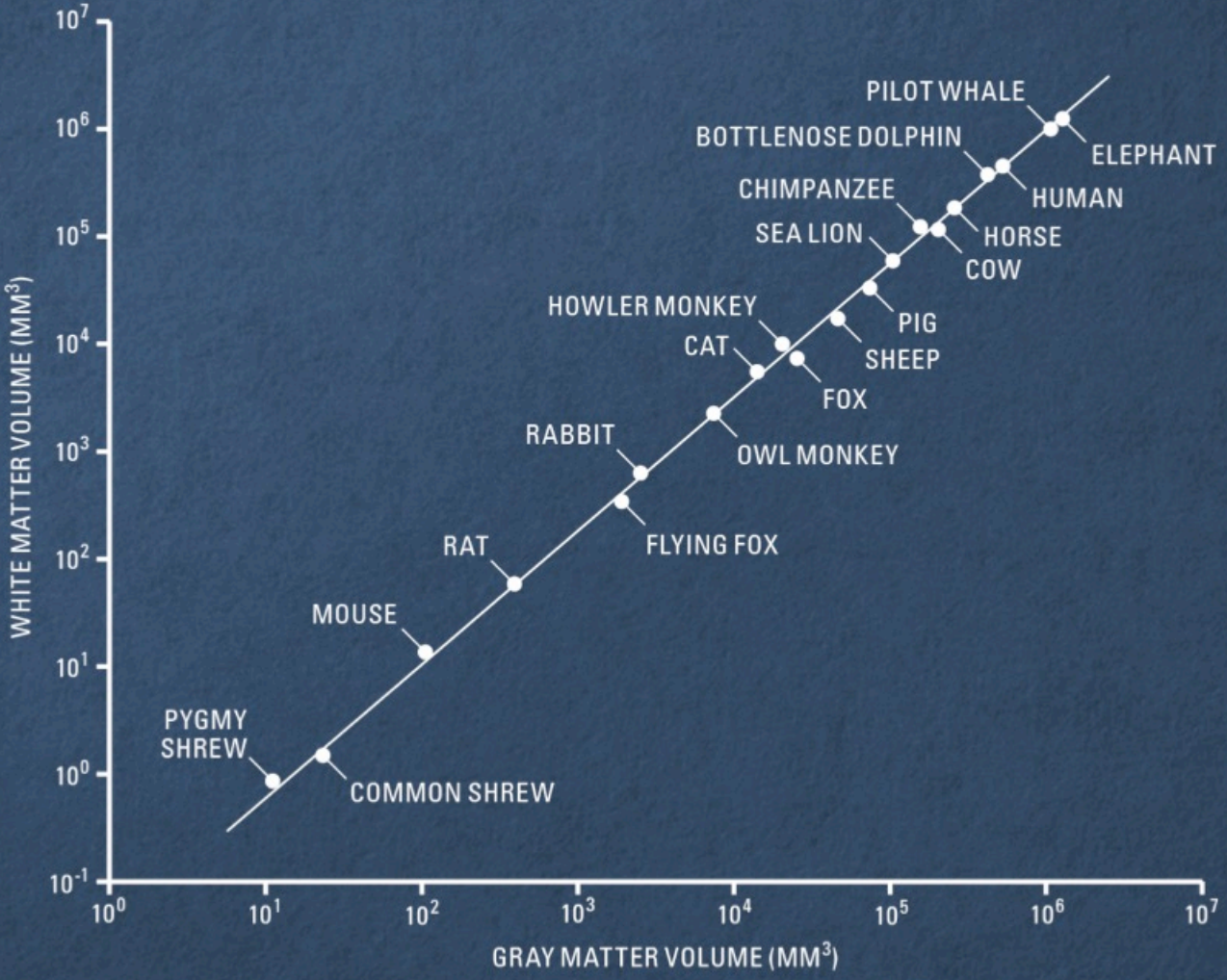
EXTRAORDINARY SYSTEMATIC ECONOMY OF SCALE (THE BIGGER YOU ARE, THE LESS NEEDED PER "CAPITA")

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

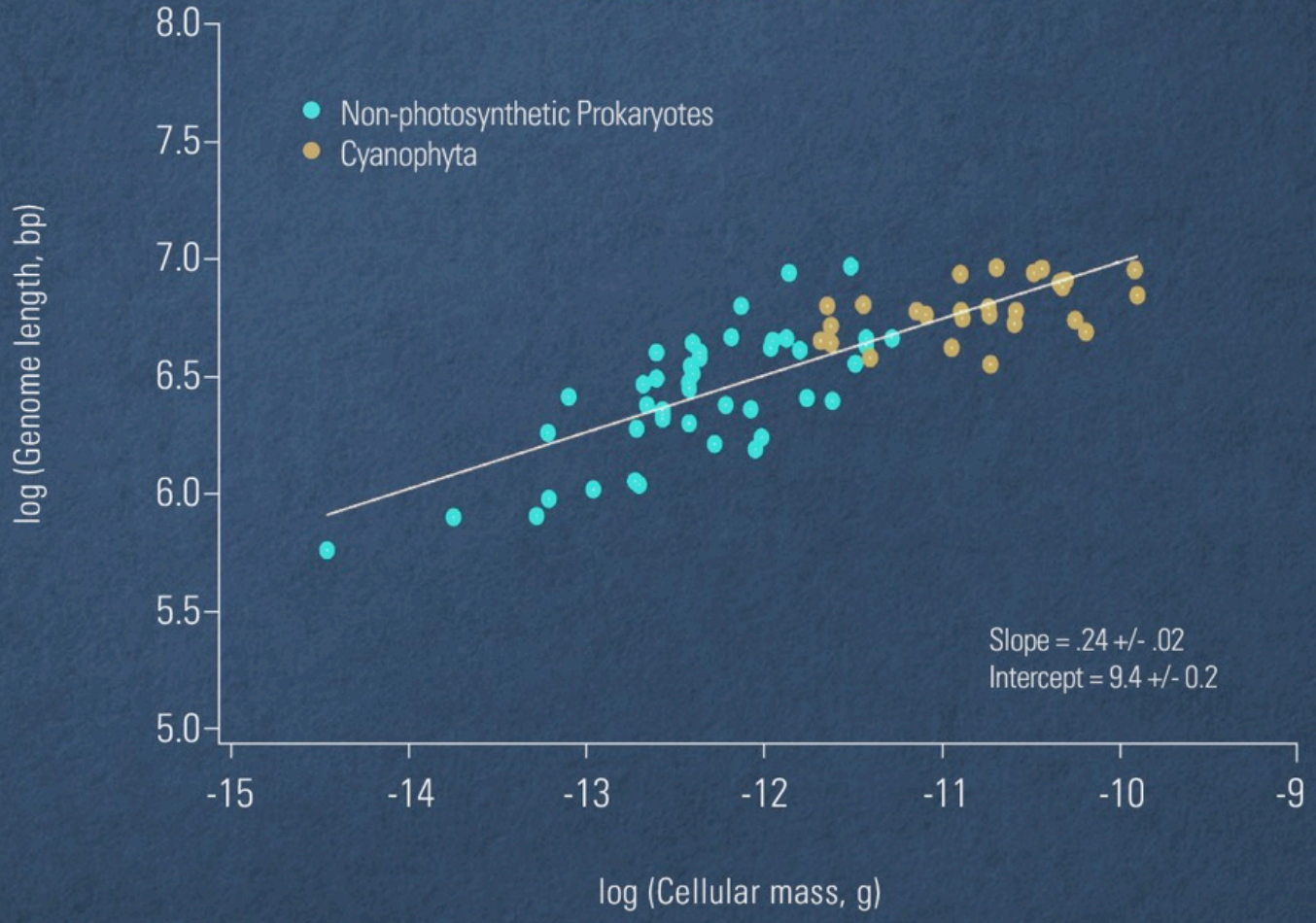
Metabolic rate sets the pace of life
Small animals live fast and die young



WHITE AND GRAY MATTER OF BRAINS



DEPENDENCE OF GENOME LENGTH ON CELLULAR MASS



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

“quarter-power scaling”

LIFESPAN

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

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

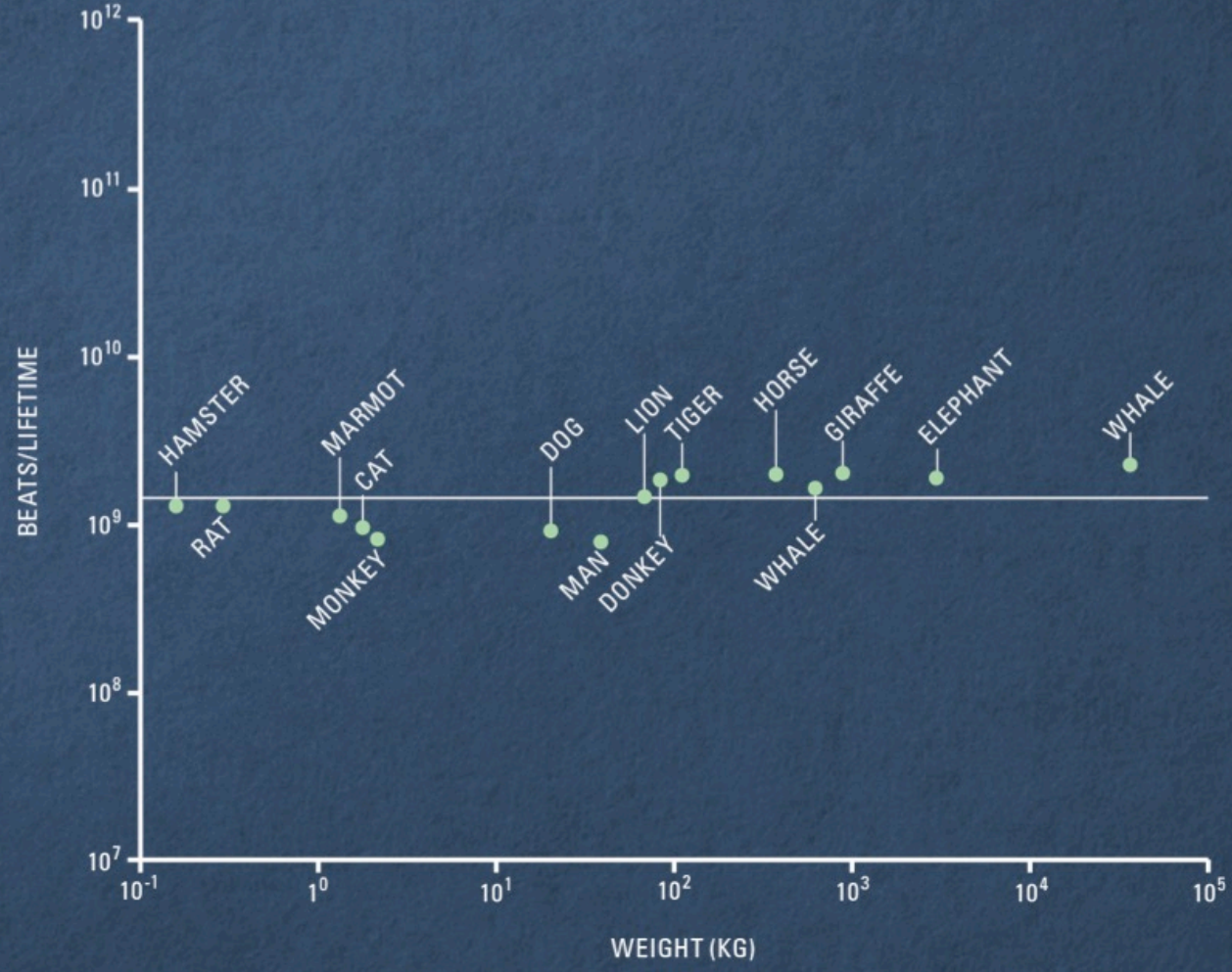
$$\sim M^{-1/4}$$

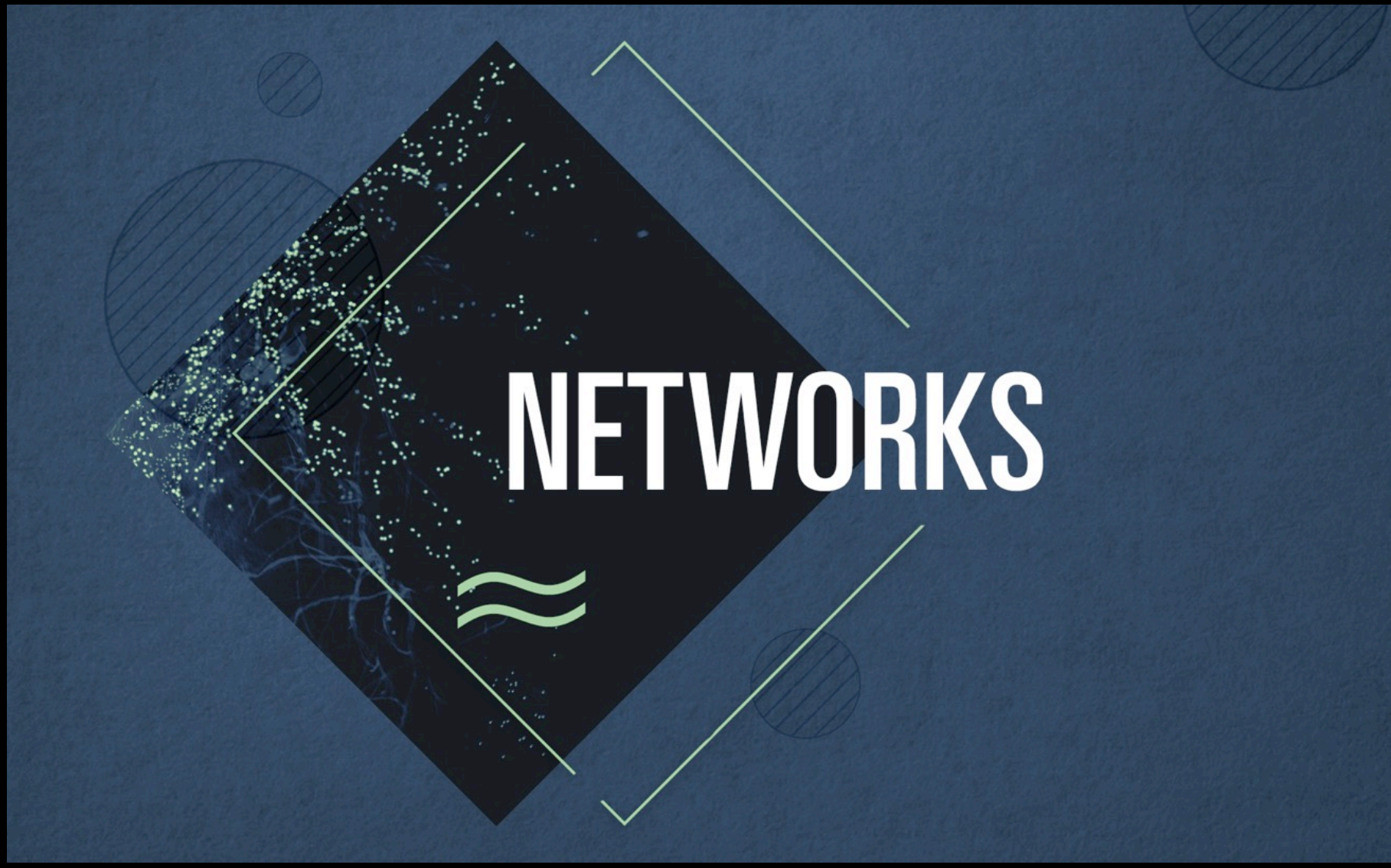
$\Rightarrow$ TOTAL NUMBER OF HEART-BEATS IN A TYPICAL LIFE-TIME IS INDEPENDENT OF SIZE!

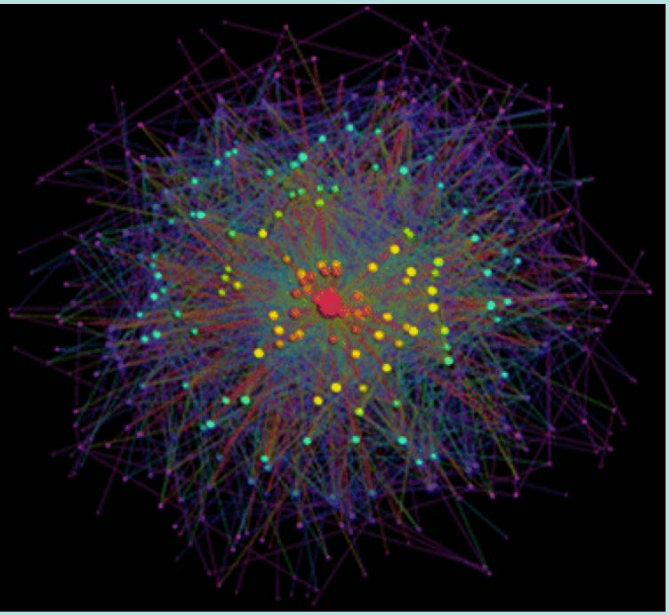
$$\approx 1.5 \times 10^9$$

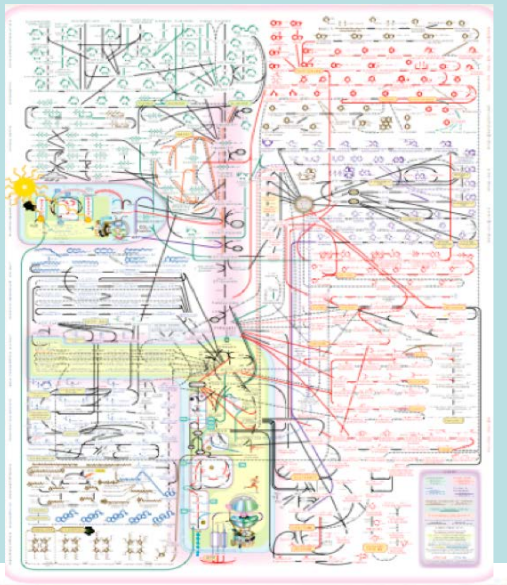
EACH ANIMAL SPECIES REGARDLESS OF SIZE HAS APPROXIMATELY THE SAME NUMBER OF HEART-BEATS IN ITS LIFE-TIME (ROUGHLY 1 BILLION)

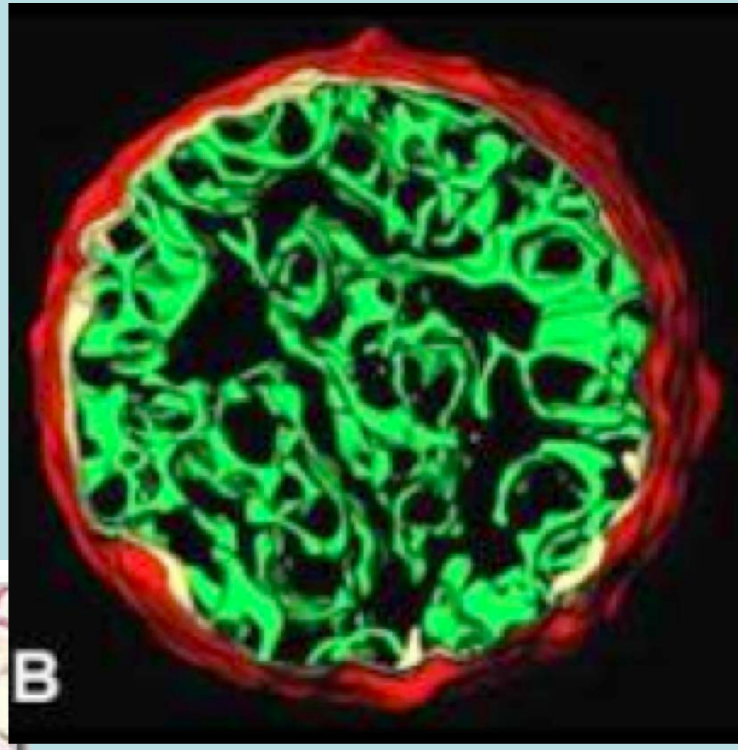
NUMBER OF HEARTBEATS PER LIFETIME OF ANIMALS




NETWORKS



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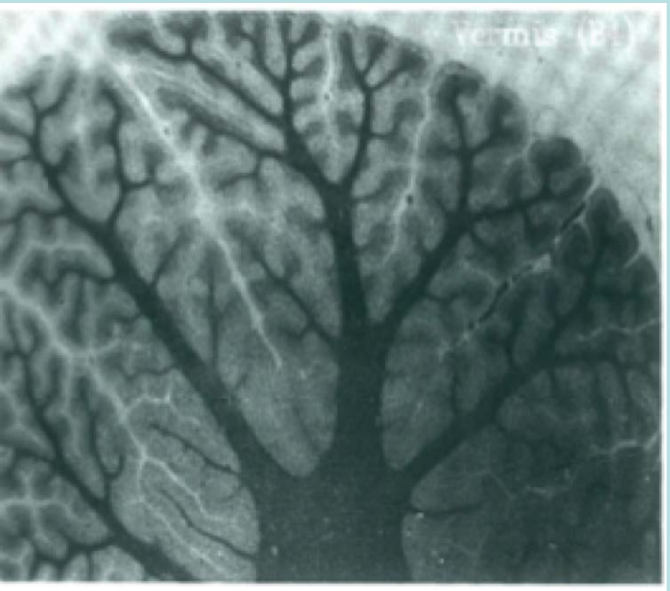
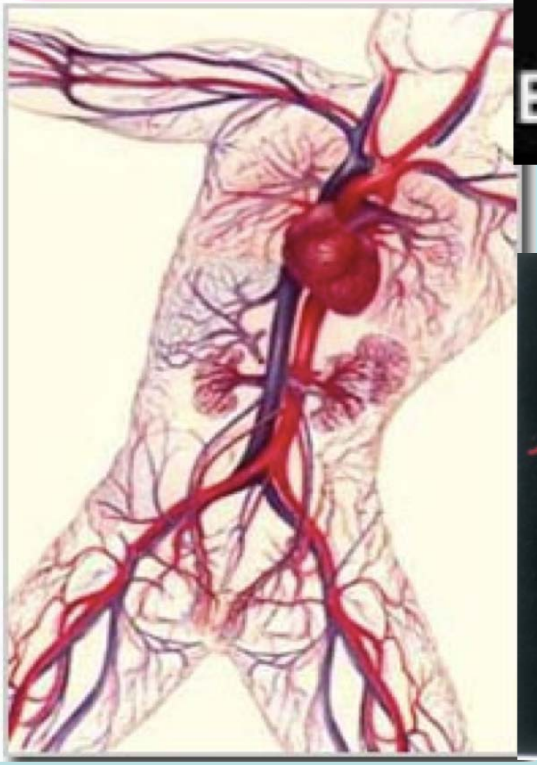
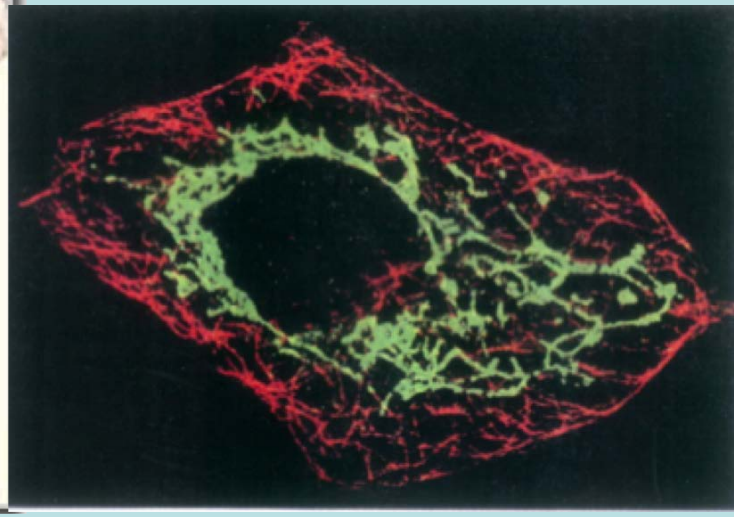
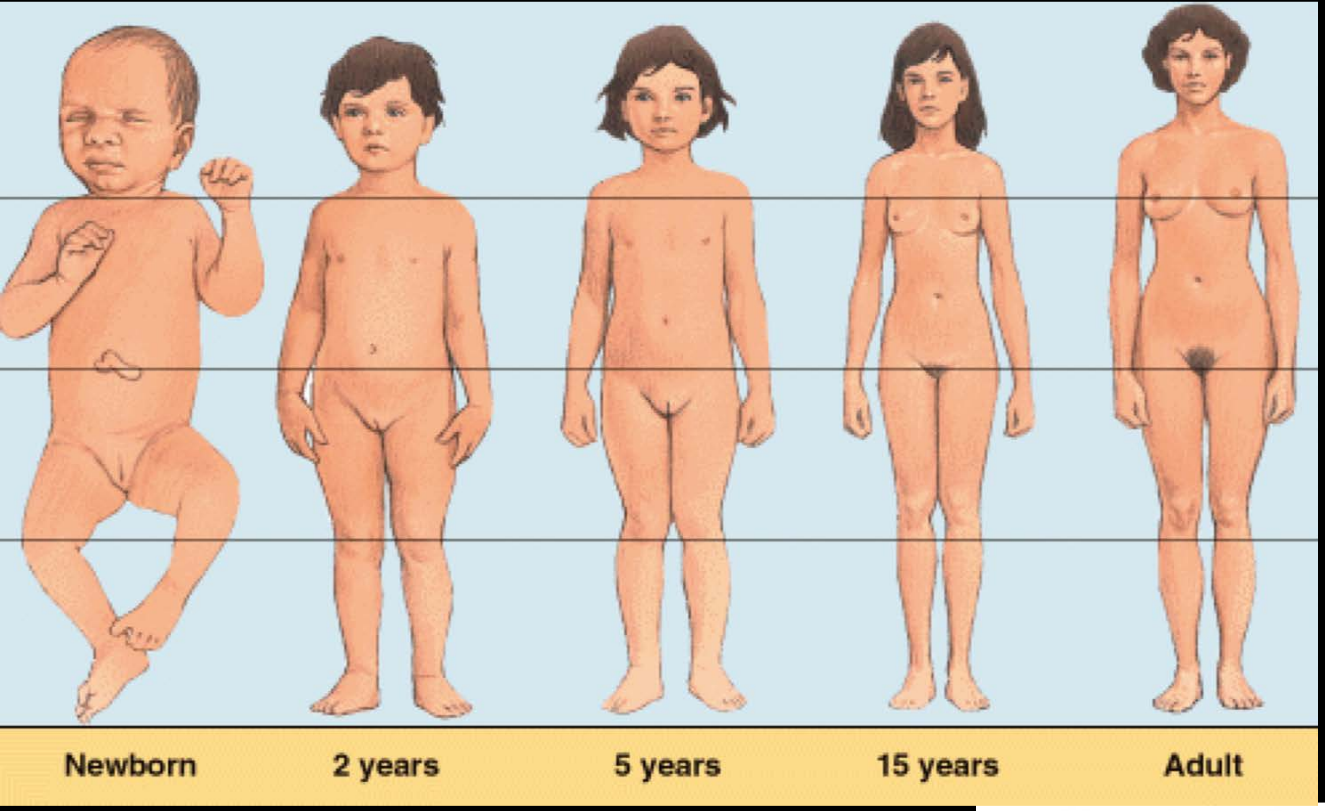
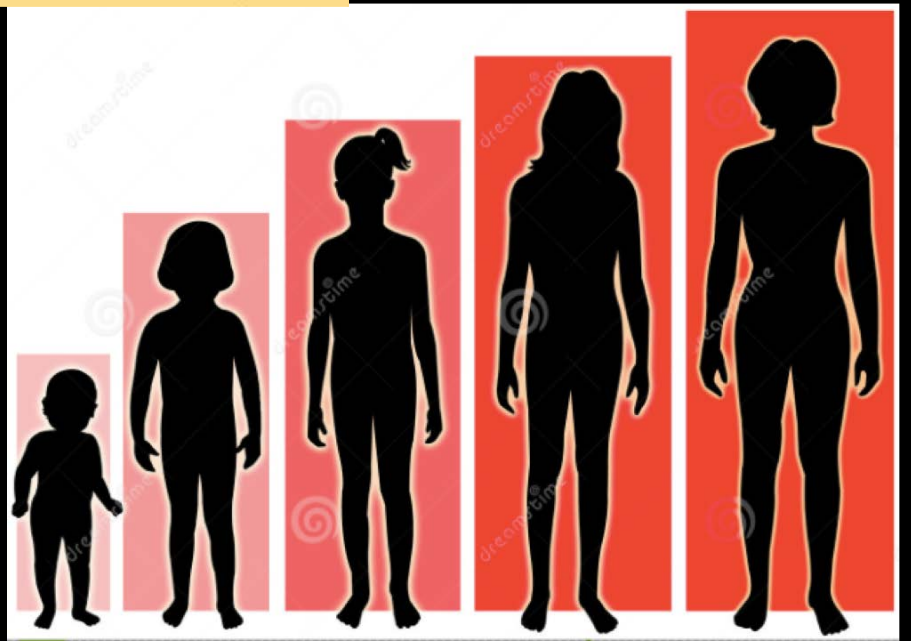






GROWTH





Energy and human life

Chemical energy
- Carbohydrates
- Fats
- Others

Chemical waste
- Carbon dioxide
- Water

Heat

ATP
- body's "energy currency"

metabolism

Heat

Growth

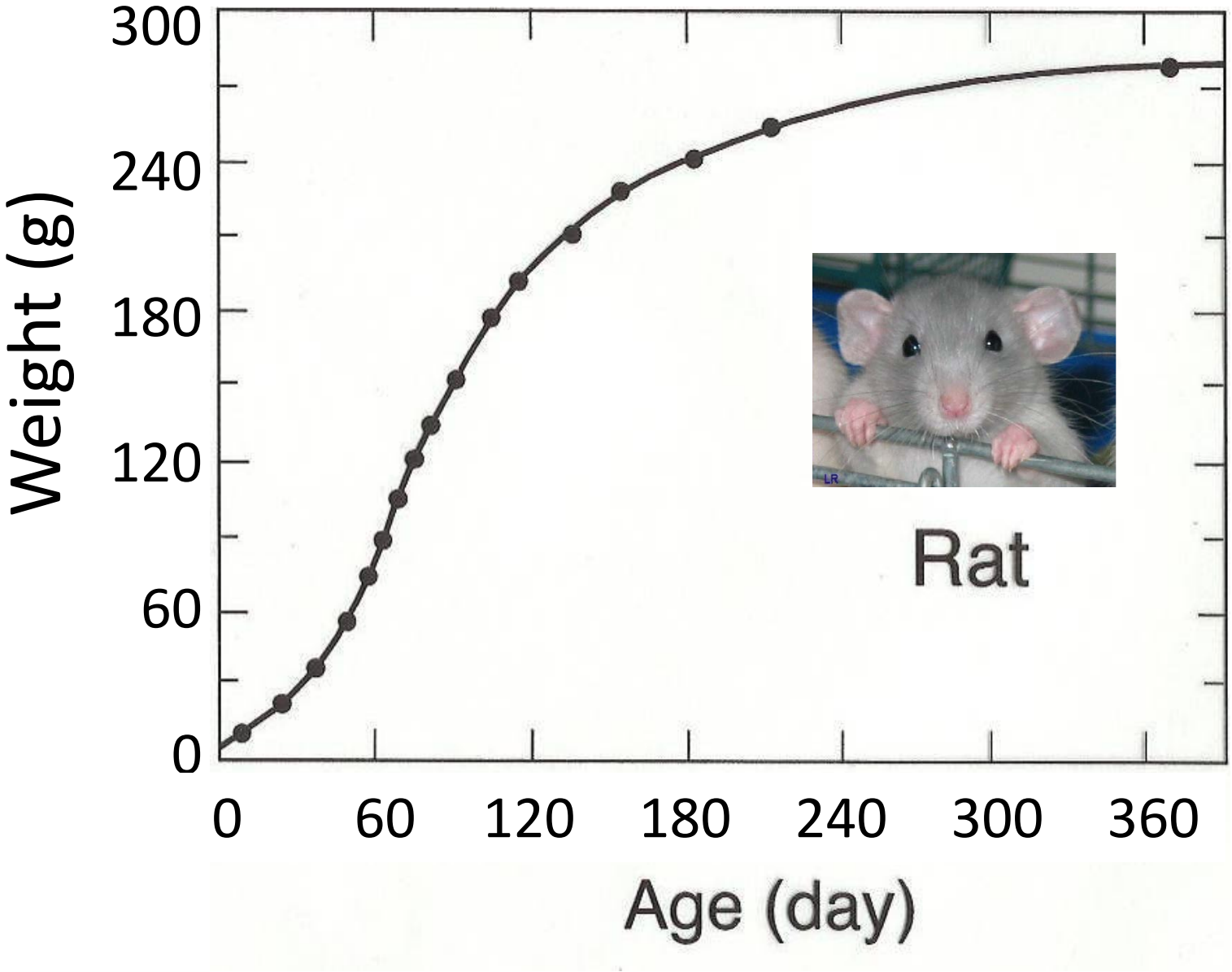
Incoming
Metabolized Energy

↓

Maintenance
(of Existing Cells)

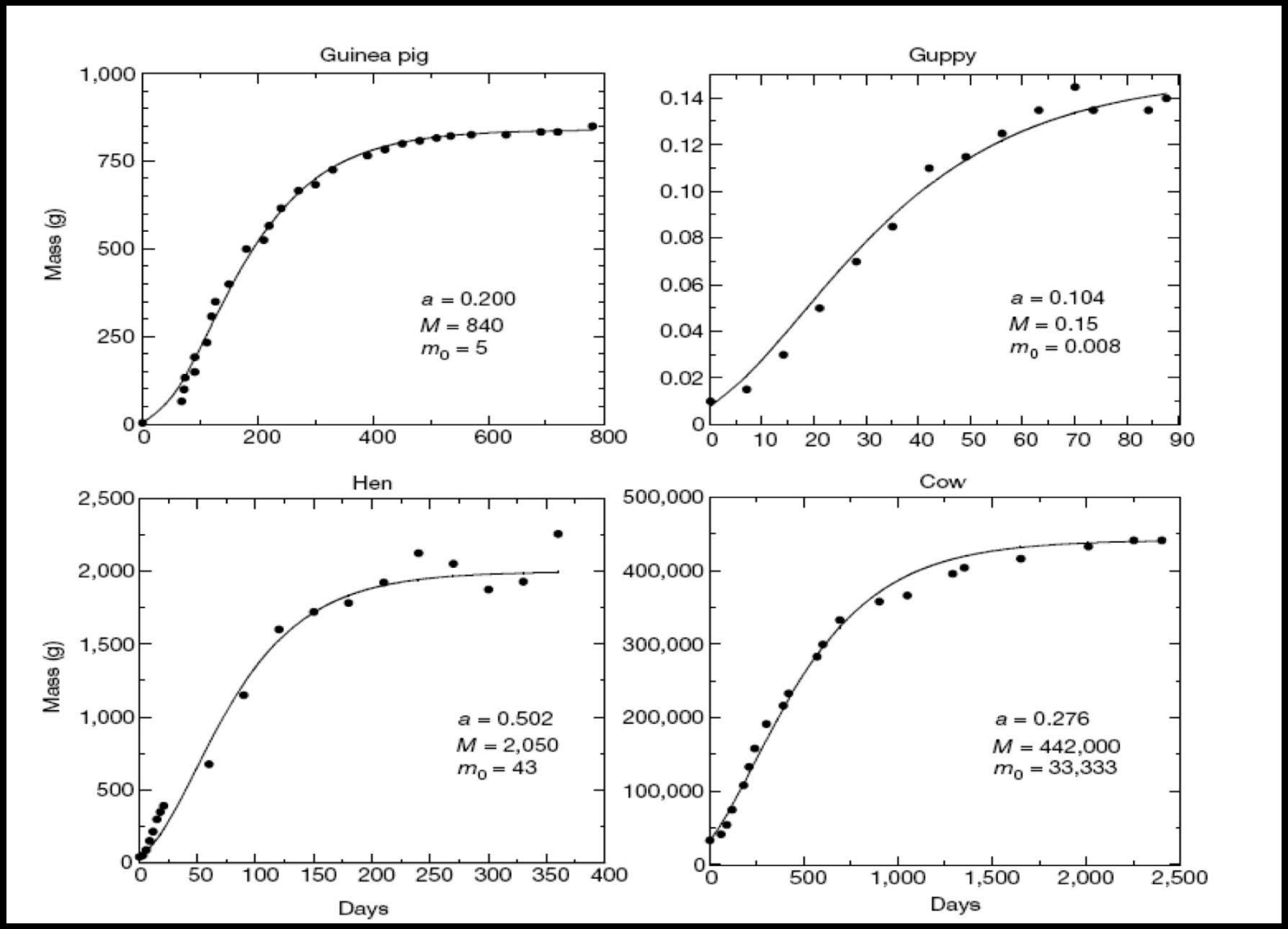
+

New Growth
(of New Cells)



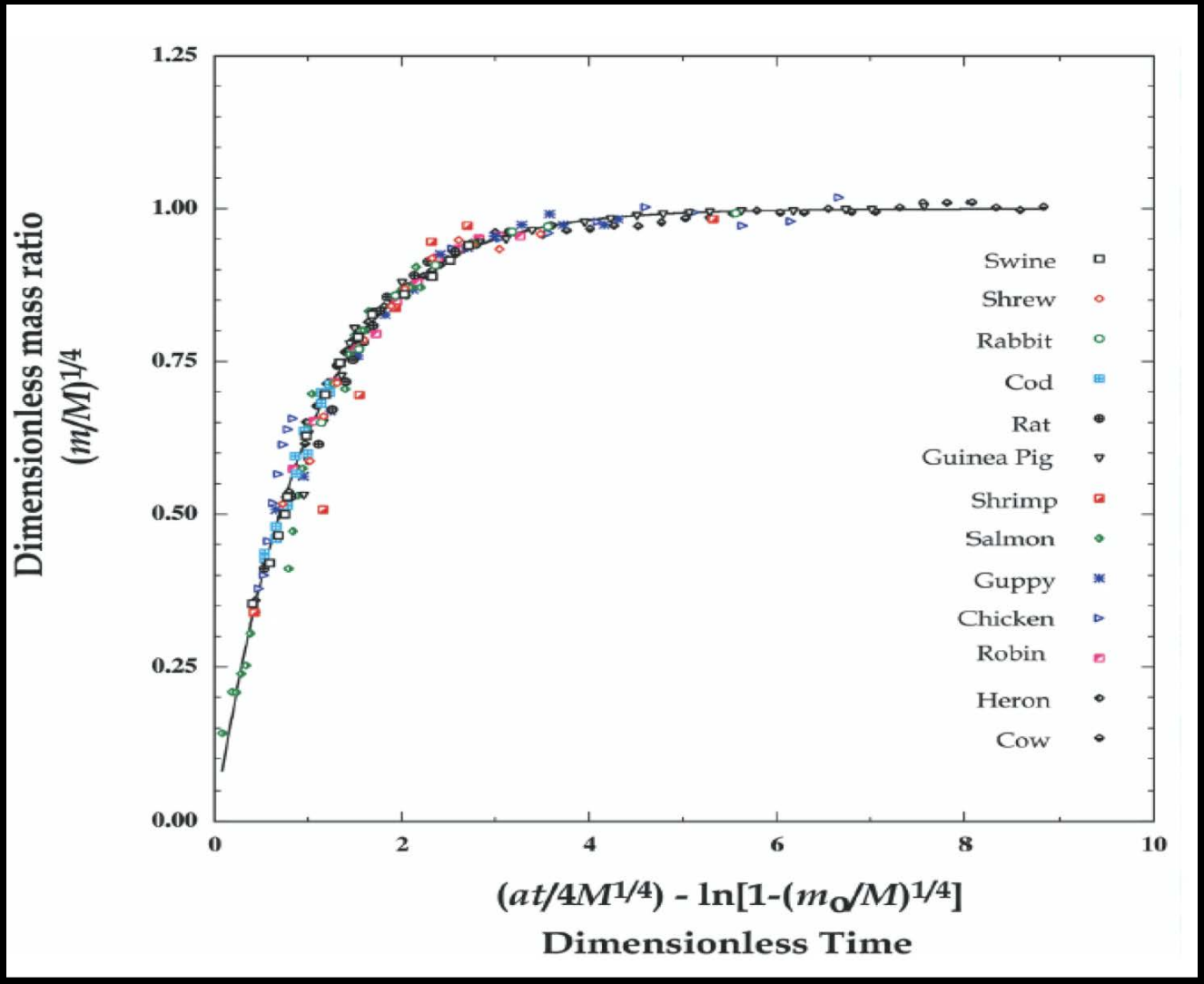
SUB-LINEAR SCALING
LEADS TO BOUNDED GROWTH

GROWTH CURVES OF ANIMALS



UNIVERSAL COLLAPSED GROWTH CURVE

RESCALED MASS VS. RESCALED AGE



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

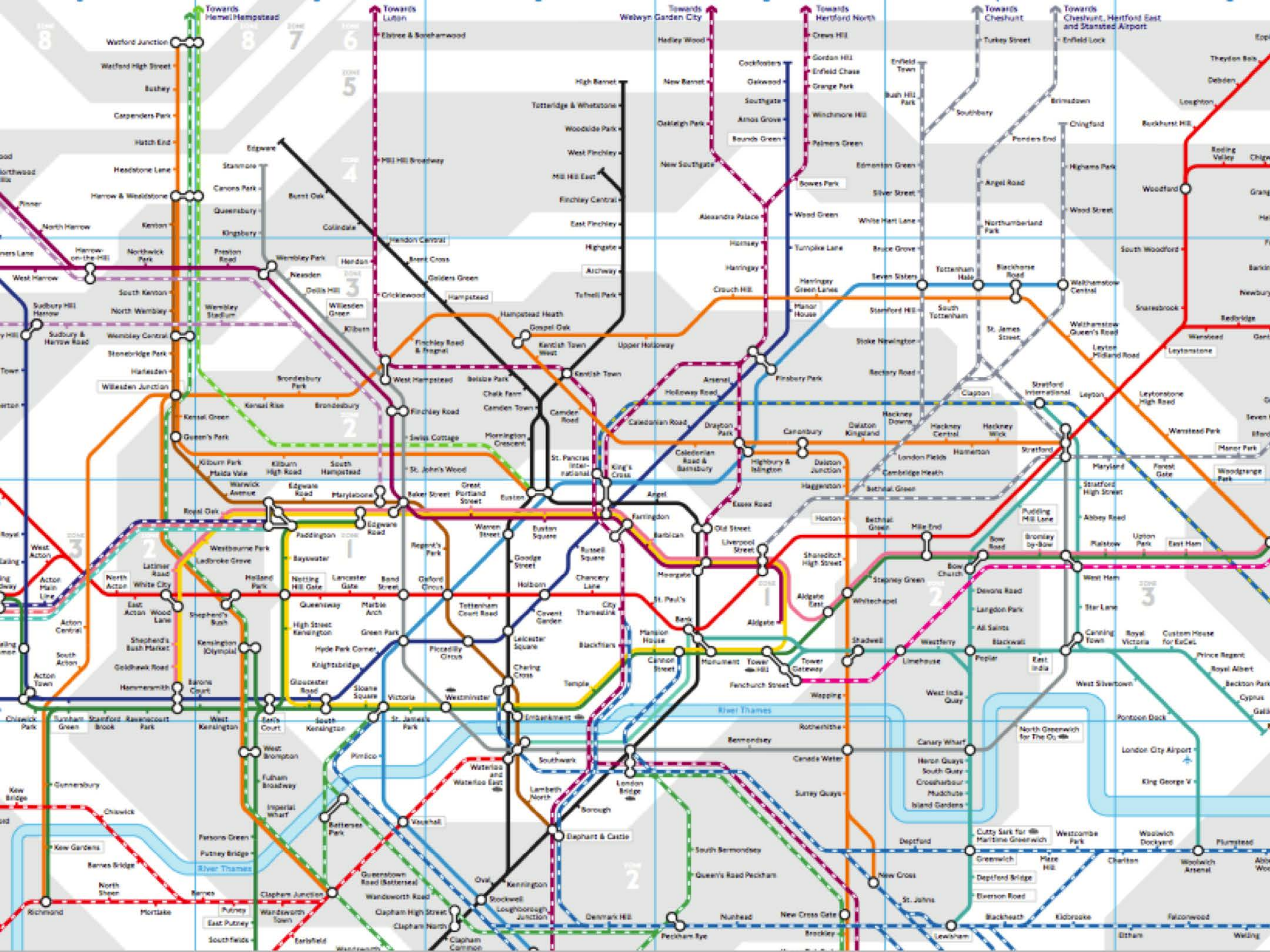
e) FINITE LIFESPAN

e) EXPLAINED BY DYNAMICS OF NETWORKS

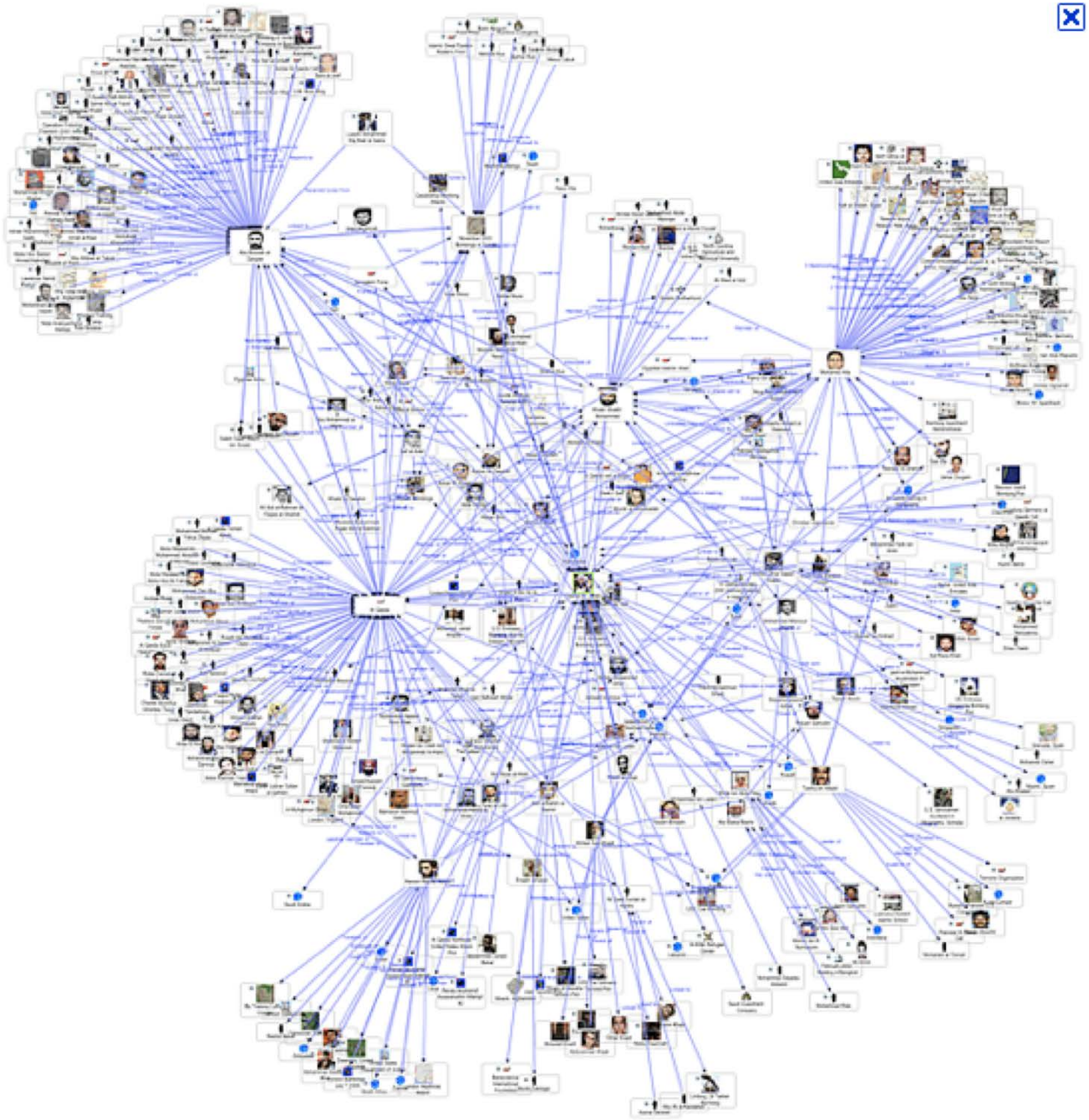
ARE CITIES (AND COMPANIES) SCALED VERSIONS OF EACH OTHER?

DO THEY MANIFEST "UNIVERSALITY"?

SATELLITE IMAGING CORPORATION
12777 JONES ROAD, SUITE 370
HOUSTON, TEXAS 77070-4647 USA
TEL: 1.832.237.2900
FAX: 1.832.237.2910

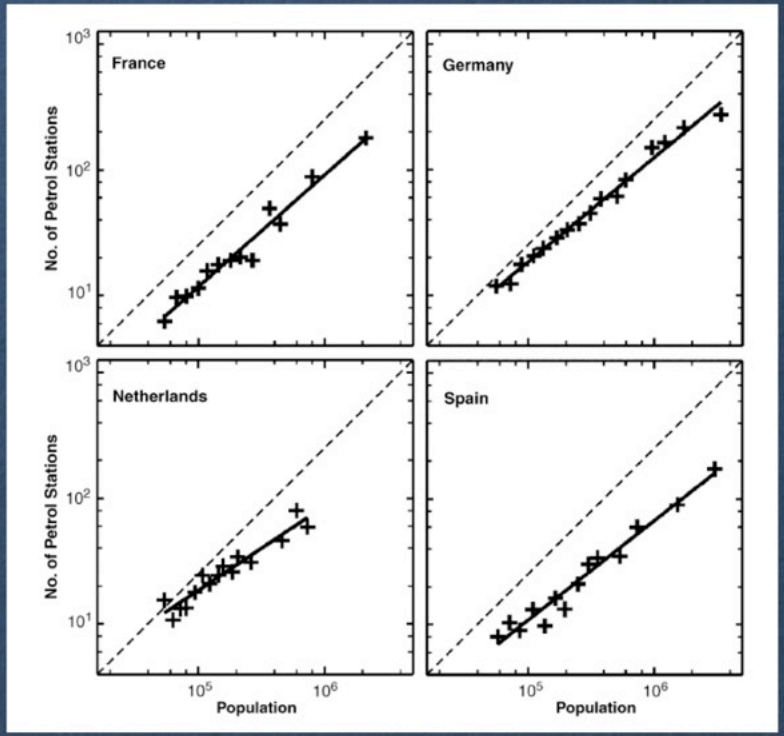


Towards Hemel Hempstead
Towards Luton
Towards Welwyn Garden City
Towards Hertford North
Towards Cheshunt
Towards Cheshunt, Hertford East and Stansted Airport
Watford Junction
Watford High Street
Bushey
Carpenders Park
Hatch End
Headstone Lane
Harrow & Wealdstone
Kenton
North Harrow
Pinner
Harrow-on-the-Hill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



INFRASTRUCTURE

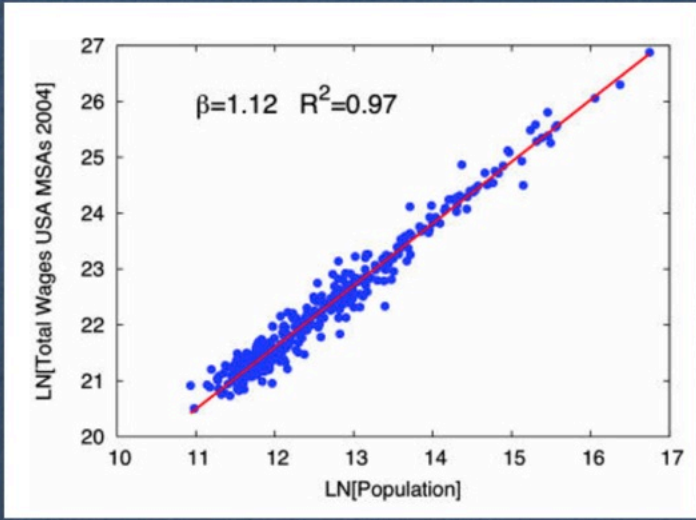
NUMBER OF PETROL STATIONS VS. POPULATION



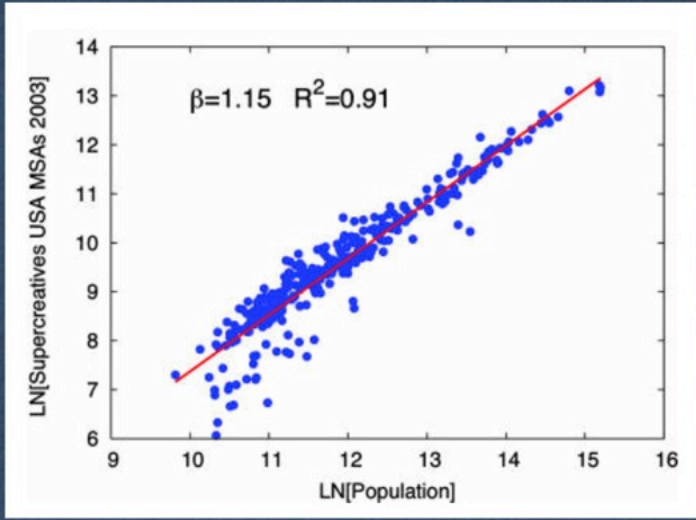
SUB-LINEAR SCALING

ECONOMY OF SCALE

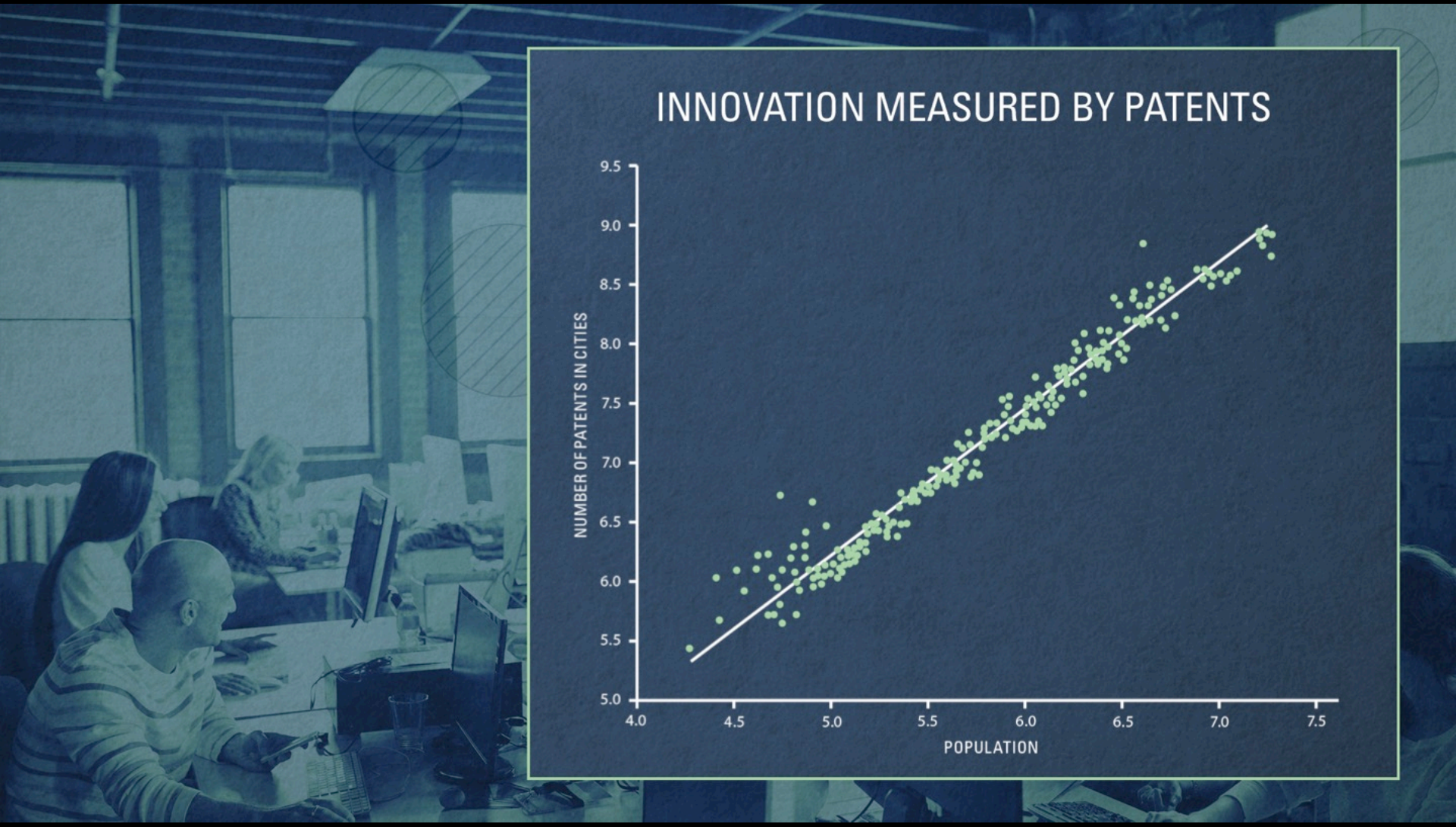
SUPER-LINEAR SCALING



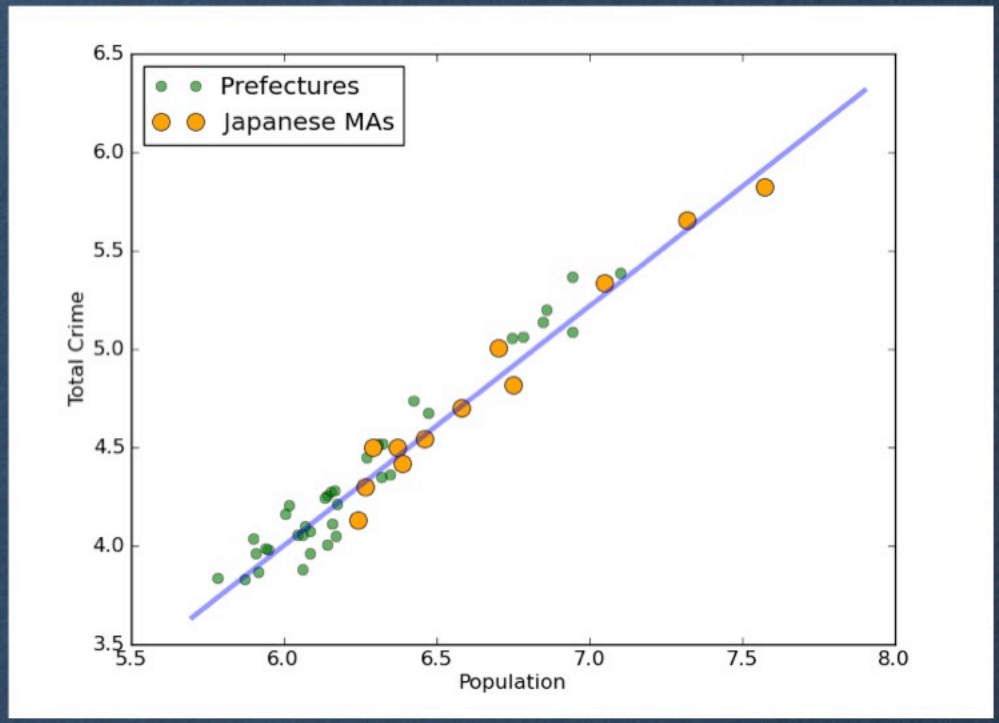
Total wages per MSA in 2004 for the USA vs. metropolitan population.



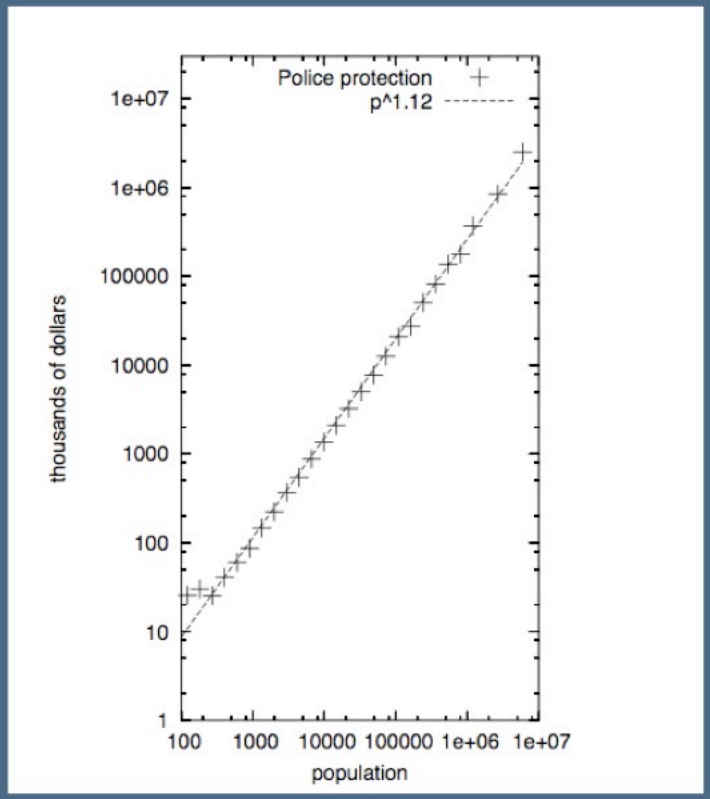
Supercreative employment per MSA in 2003, for the USA vs. metropolitan population.

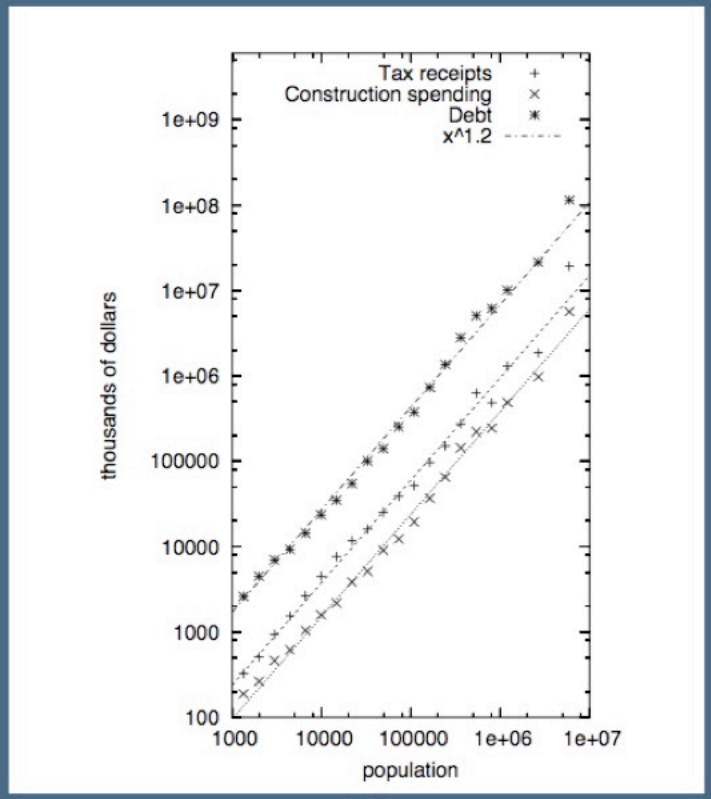

INNOVATION MEASURED BY PATENTS
NUMBER OF PATENTS IN CITIES
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
POPULATION

TOTAL CRIME (JAPAN)

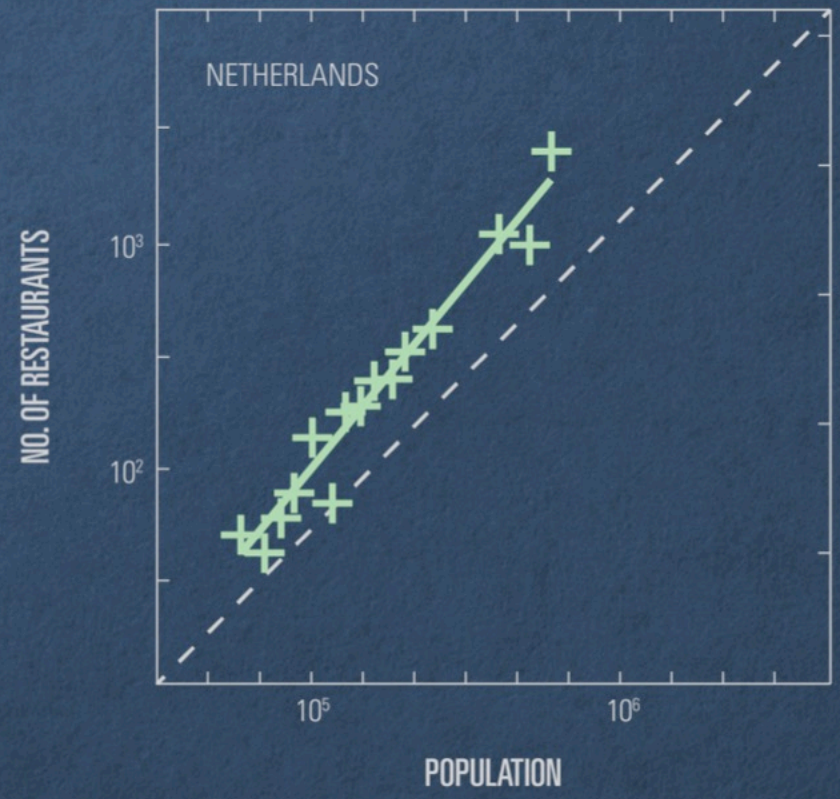


Slope = 1.21 [1.08, 1.35]

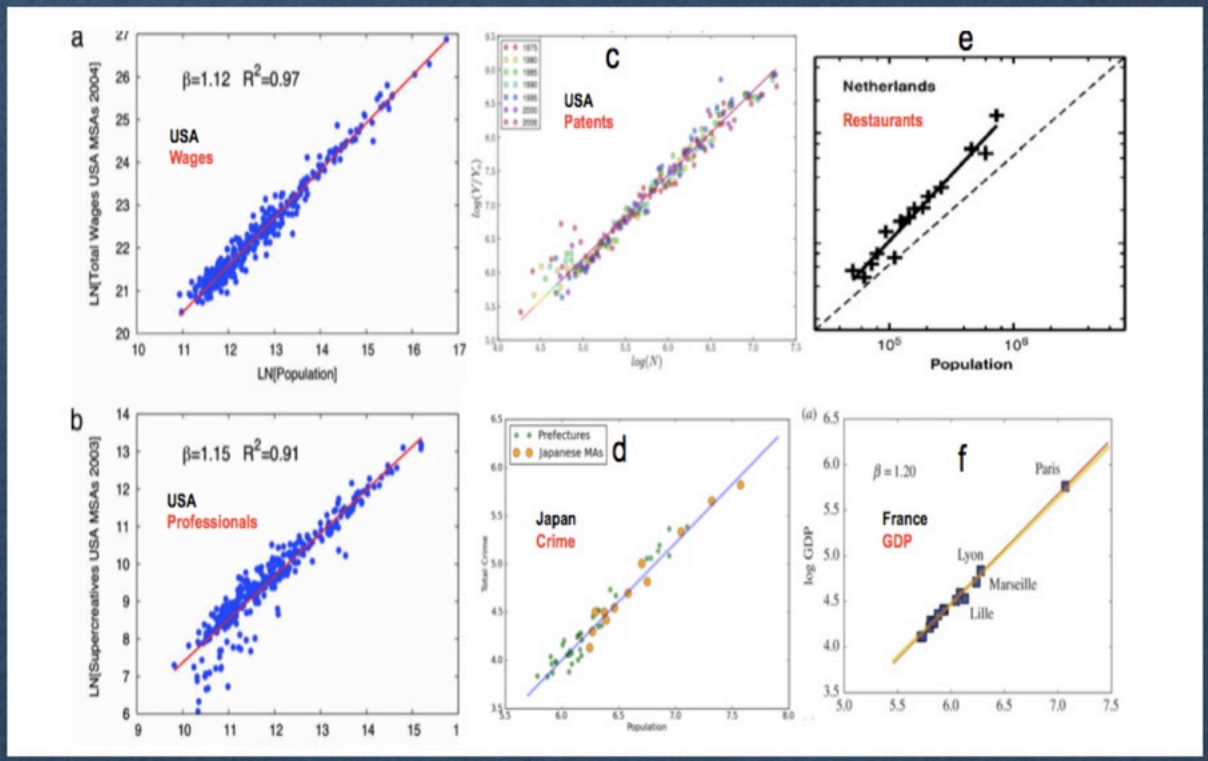

Police protection
p^1.12
thousands of dollars
population
1e+07
1e+06
100000
10000
1000
100
10
1
100
1000
10000
100000
1e+06
1e+07


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

RESTAURANTS IN THE NETHERLANDS



UNIVERSALITY OF URBAN SCALING



THE GOOD, THE BAD, THE UGLY

ON AVERAGE DOUBLING THE SIZE OF A CITY

SYSTEMATICALLY INCREASES

ON AVERAGE DOUBLING THE SIZE OF A CITY

SYSTEMATICALLY INCREASES

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

ON AVERAGE DOUBLING THE SIZE OF A CITY

SYSTEMATICALLY INCREASES

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

ALL BY APPROXIMATELY 15%

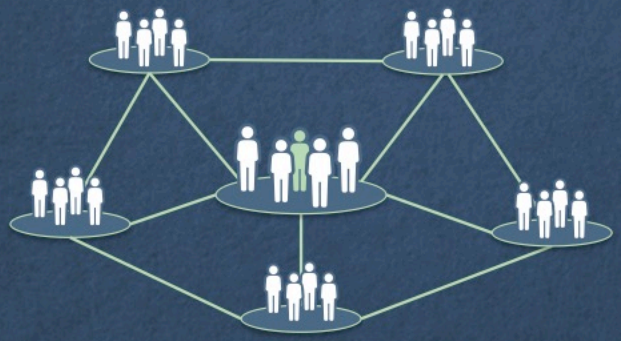
REGARDLESS OF CITY

AND**.....**

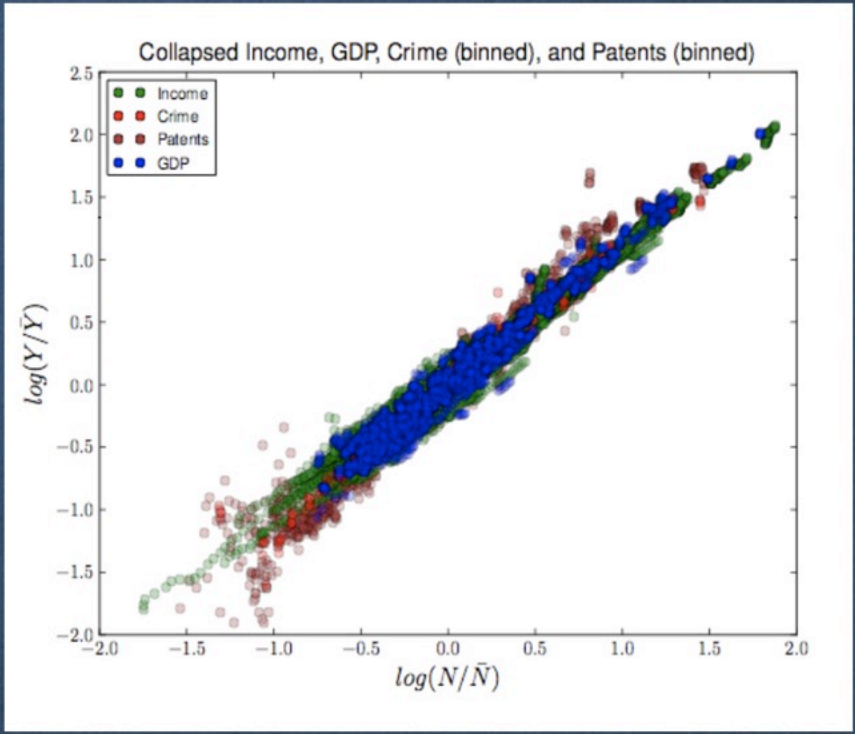
AND**.....**

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

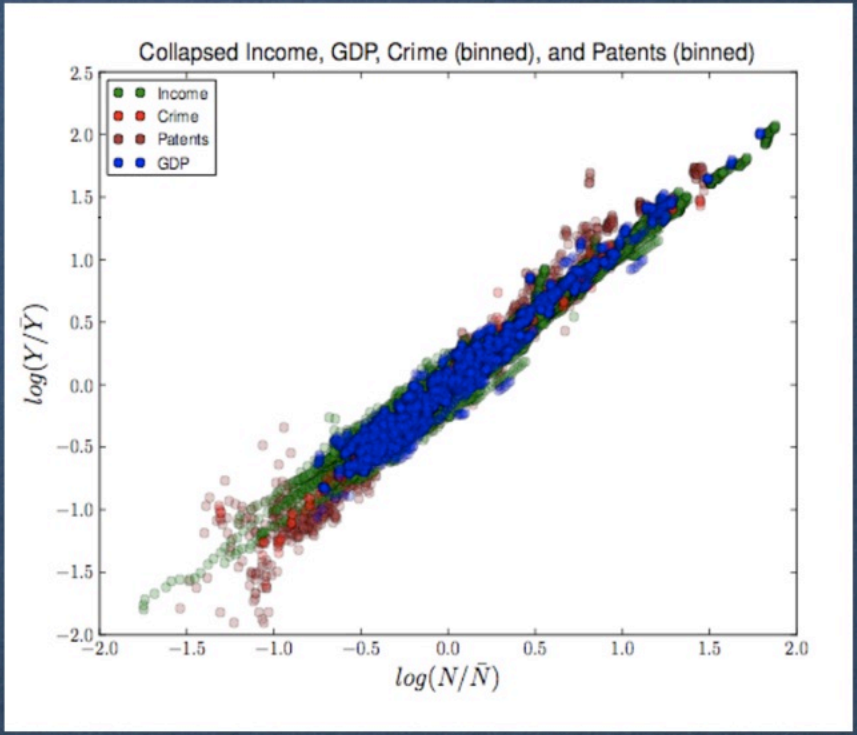
Universality of Social Networks
(clustering hierarchies)



UNIVERSALITY

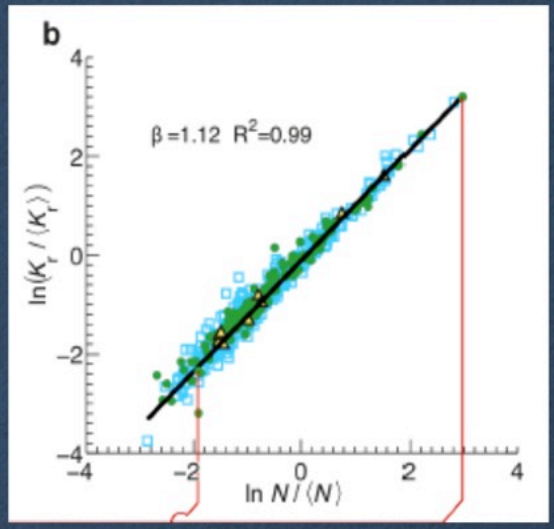


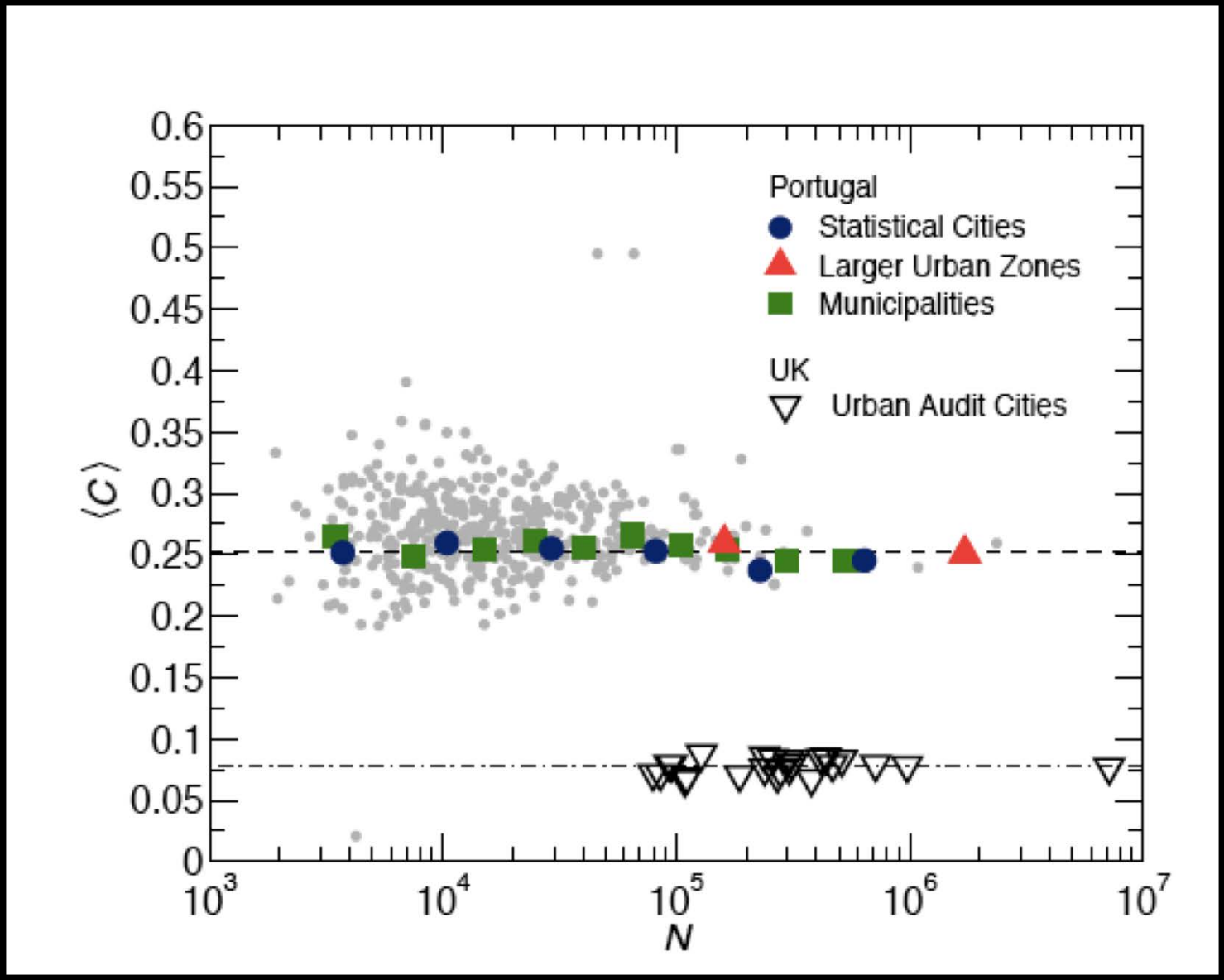
UNIVERSALITY



SOCIAL CONNECTIVITY

(Cell Phone Data)



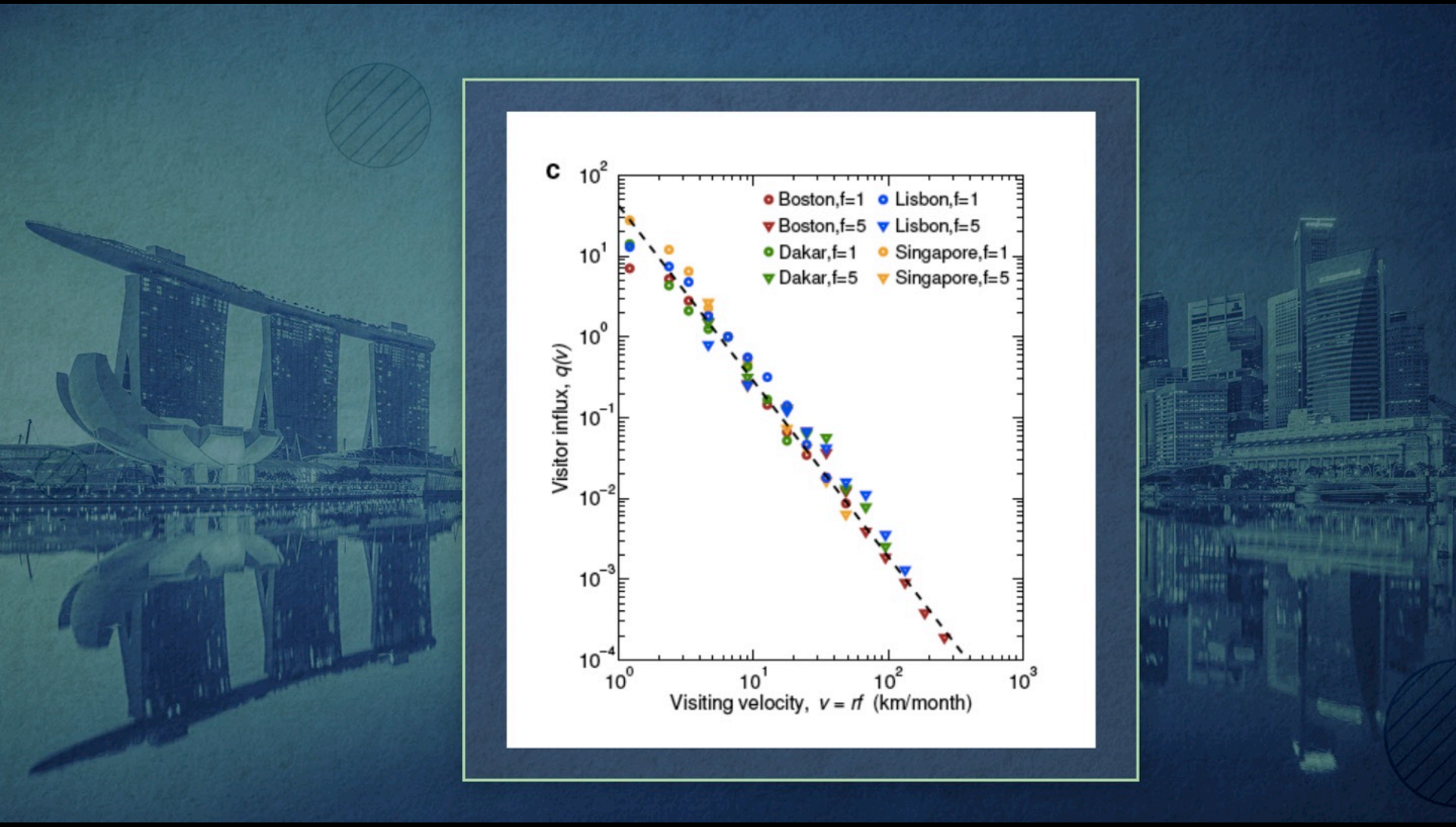

0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
⟨C⟩
10^3
10^4
10^5
10^6
10^7
N
Portugal
Statistical Cities
Larger Urban Zones
Municipalities
UK
Urban Audit Cities

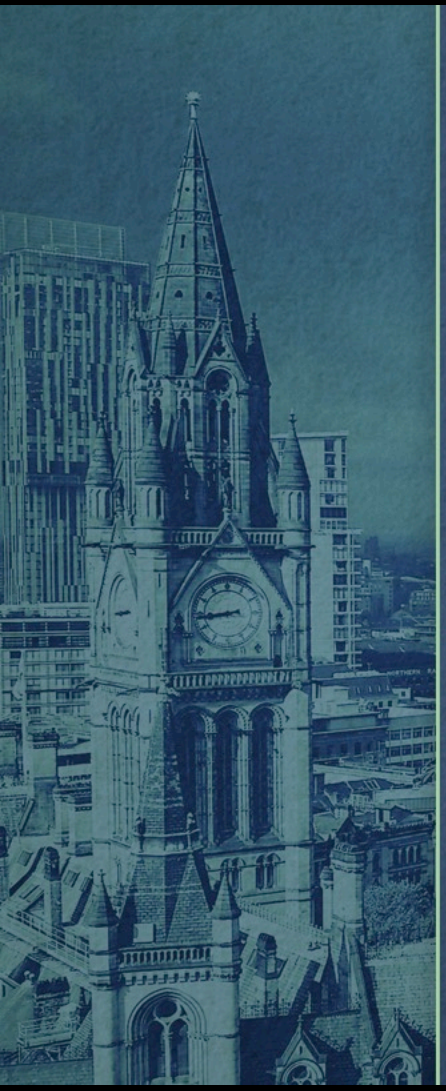
MOVEMENT IN CITIES

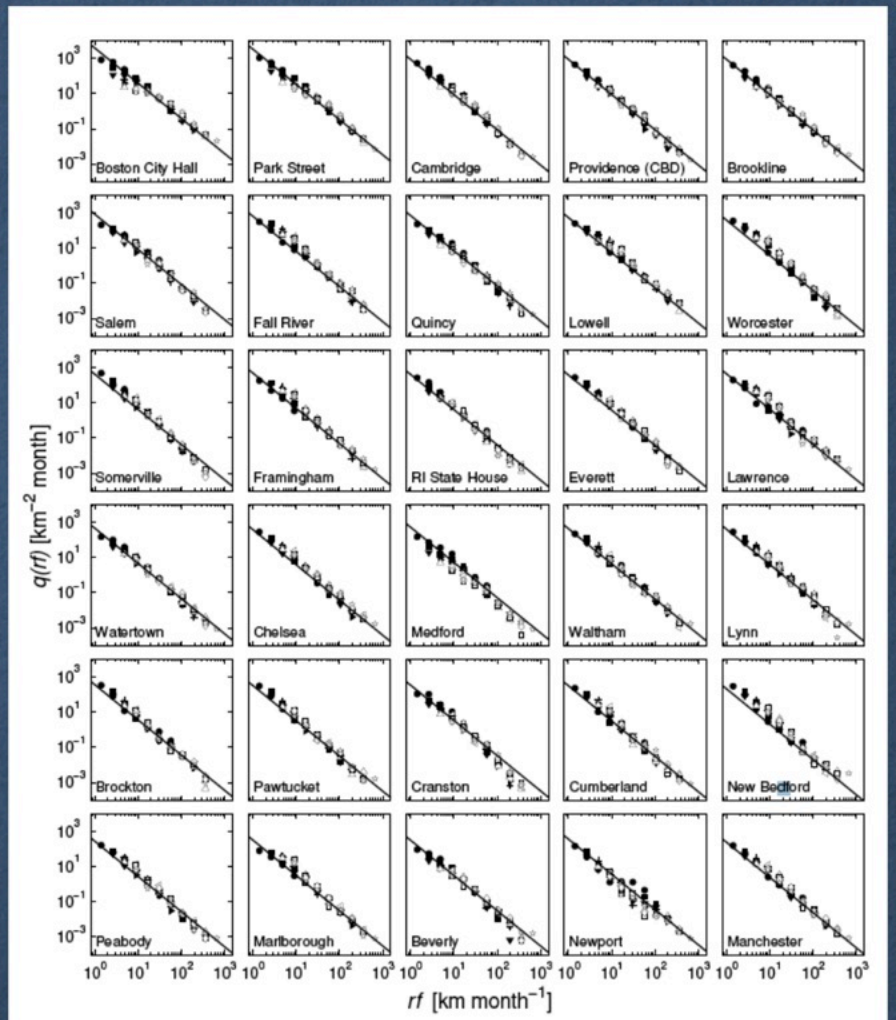
People on average minimize travel time and distance.

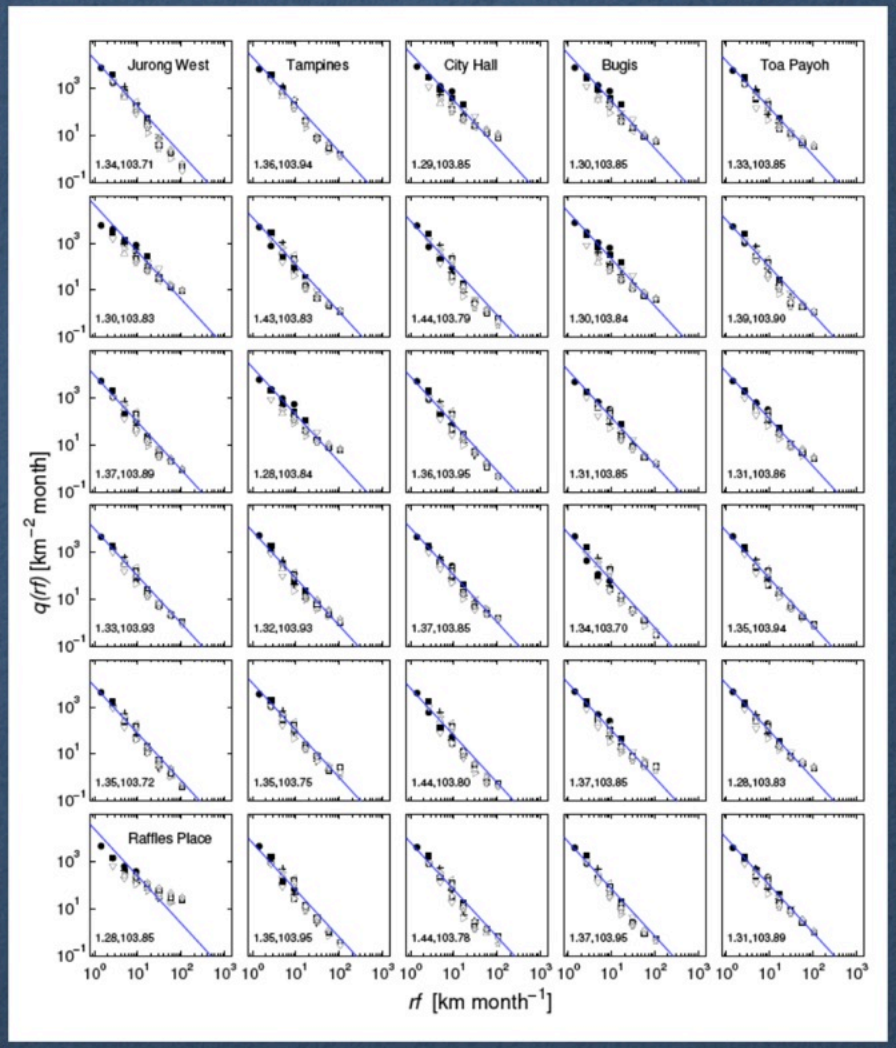
"Theorem": the number traveling to any location in any city from a distance r away f times a month is:

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


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



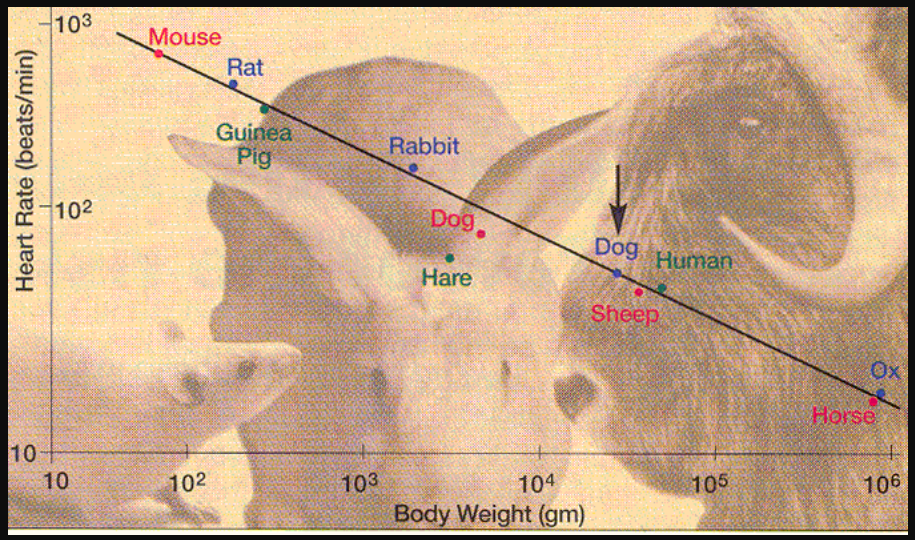

Boston City Hall
Park Street
Cambridge
Providence (CBD)
Brookline
Salem
Fall River
Quincy
Lowell
Worcester
Somerville
Framingham
RI State House
Everett
Lawrence
Watertown
Chelsea
Medford
Waltham
Lynn
Brockton
Pawtucket
Cranston
Cumberland
New Bedford
Peabody
Marlborough
Beverly
Newport
Manchester
$q(rf)$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


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

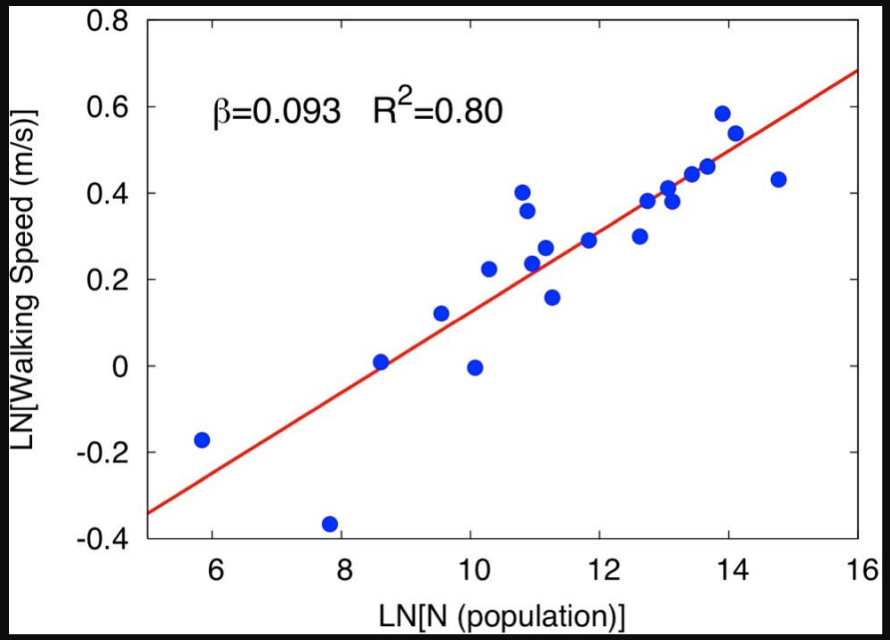
NETWORK DYNAMICS DETERMINES THE PACE OF LIFE

IF THE SLOPE IS < 1 (SUBLINEAR)	*PACE OF LIFE SLOWS DOWN*
IF THE SLOPE IS > 1 (SUPERLINEAR)	*PACE OF LIFE SPEEDS UP*

Pace of biological life vs. Pace of social life



Heart Rate vs Body Weight



Walking Speed vs. Population Size

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

GROWTH EQUATION

Total Incoming Rate

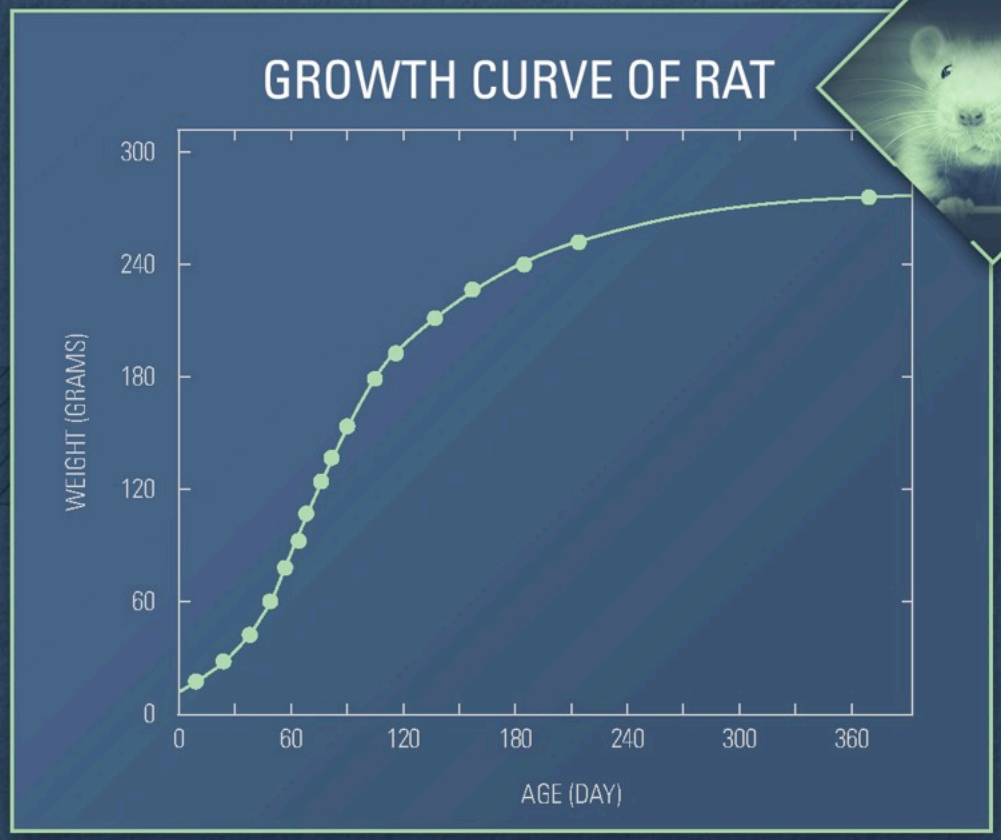
(resources, products, patents, . . . “energy” or “dollar” equivalent)

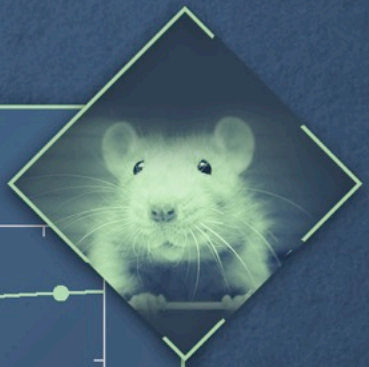
≈ Maintenance

(repair, replacement, sustenance, . . .)

+

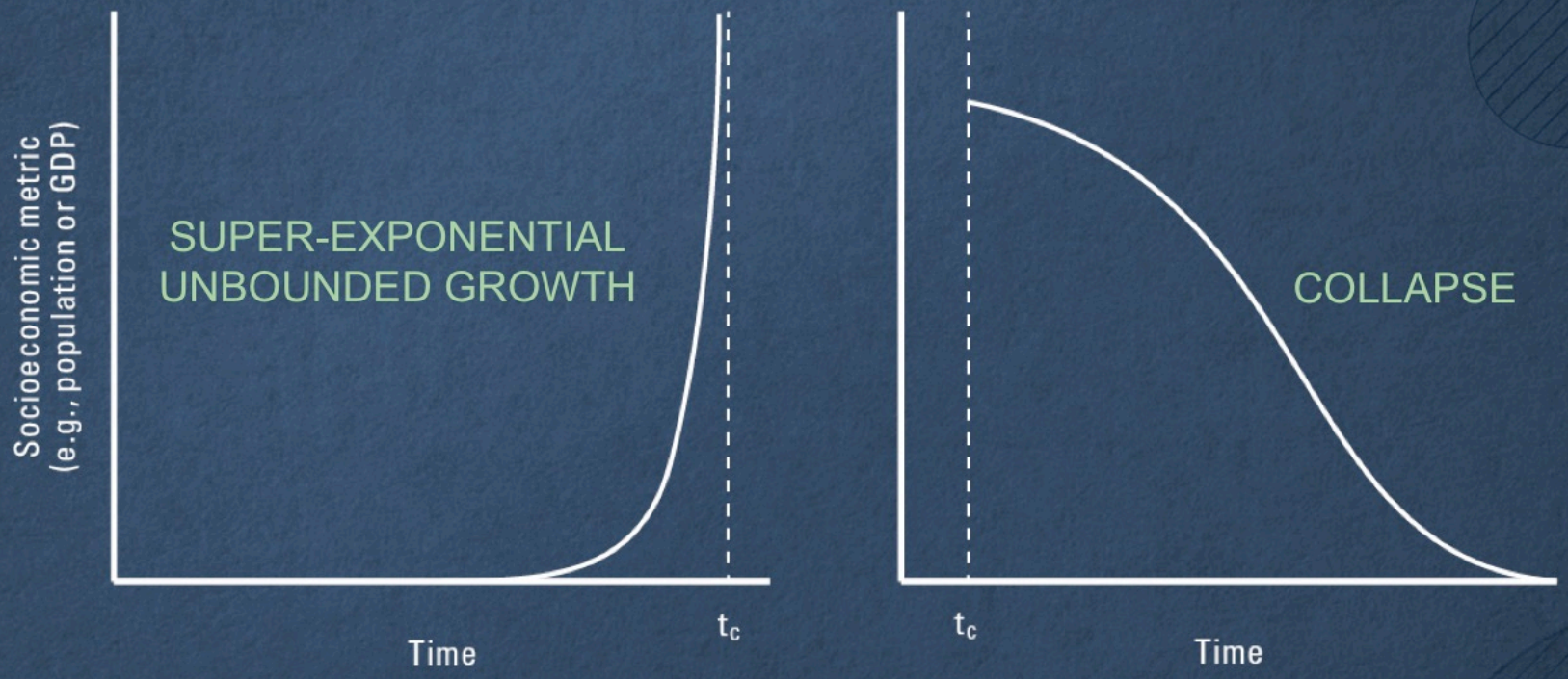
Growth

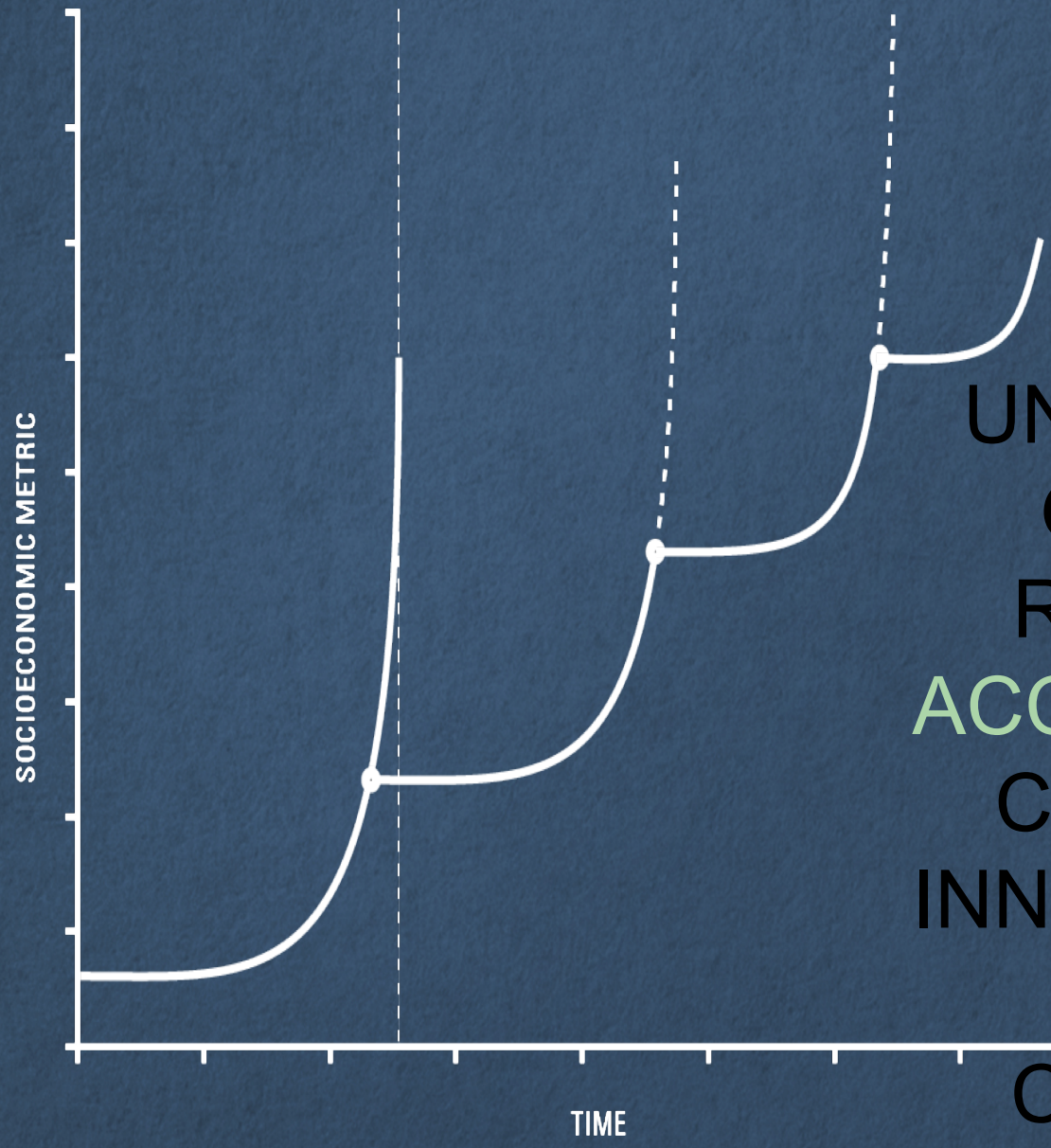




SUB-LINEAR SCALING LEADS TO BOUNDED GROWTH

SUPER-LINEAR

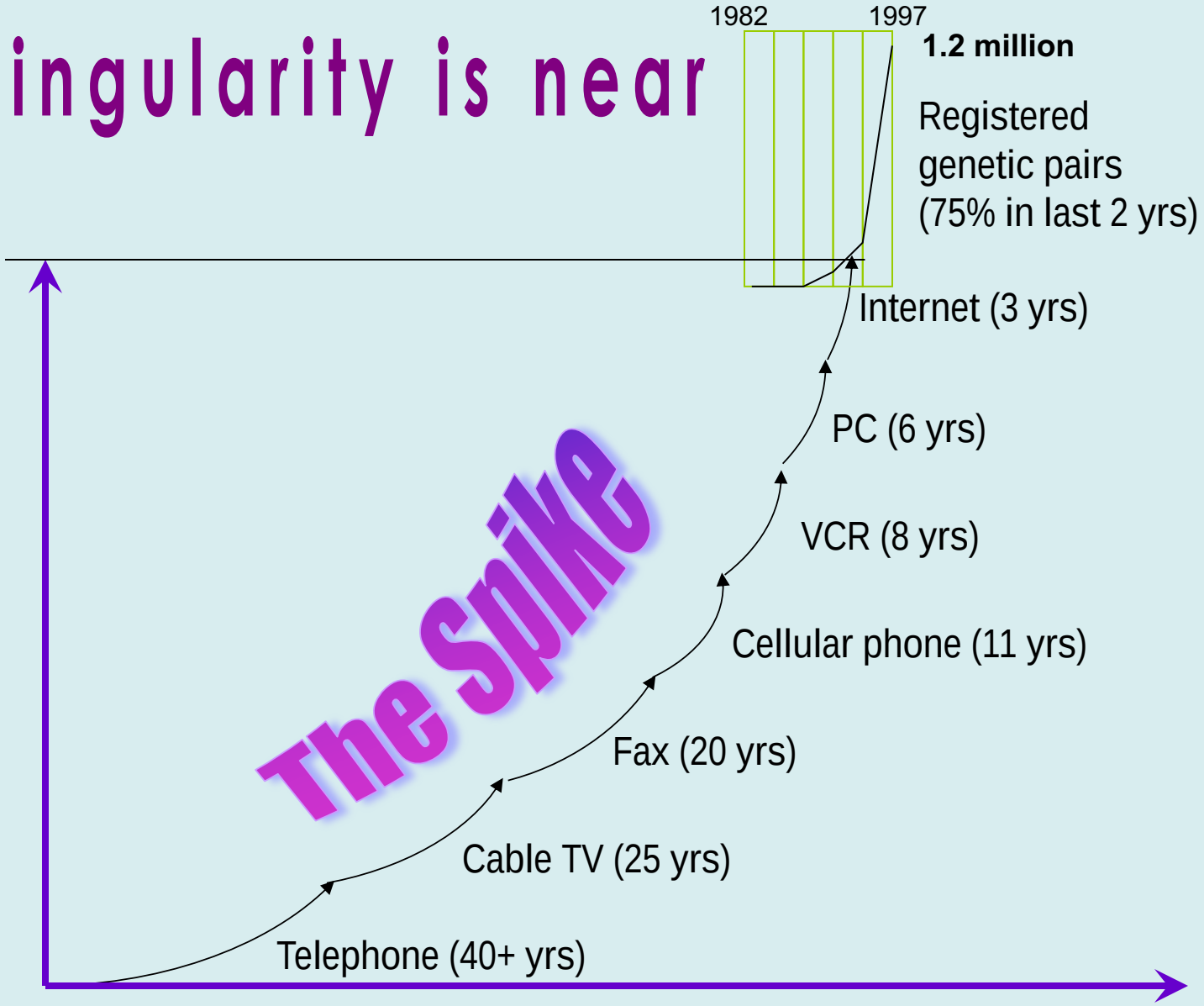




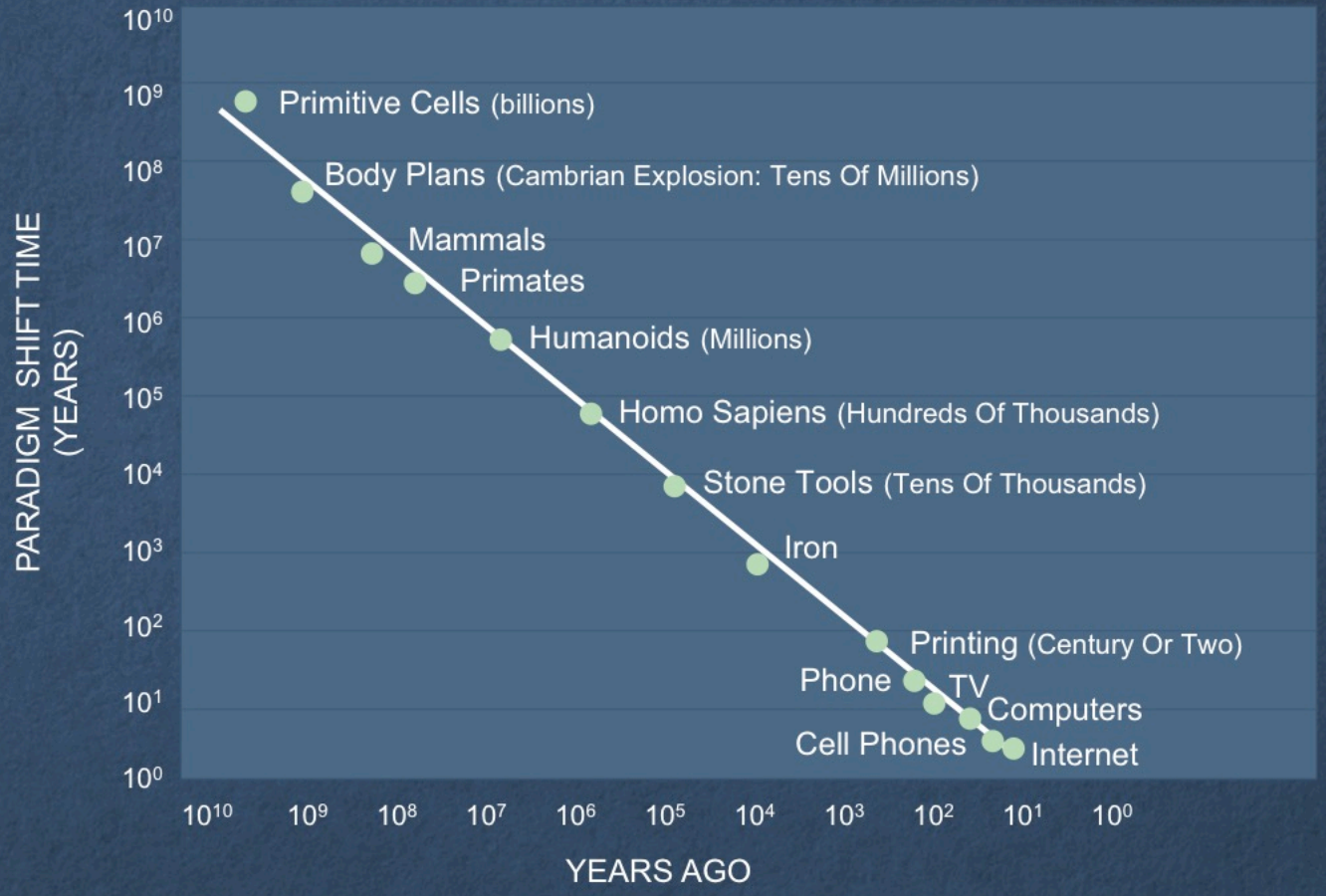
UNBOUNDED GROWTH REQUIRES ACCELERATING CYCLES OF INNOVATION TO AVOID COLLAPSE

Damien Broderick

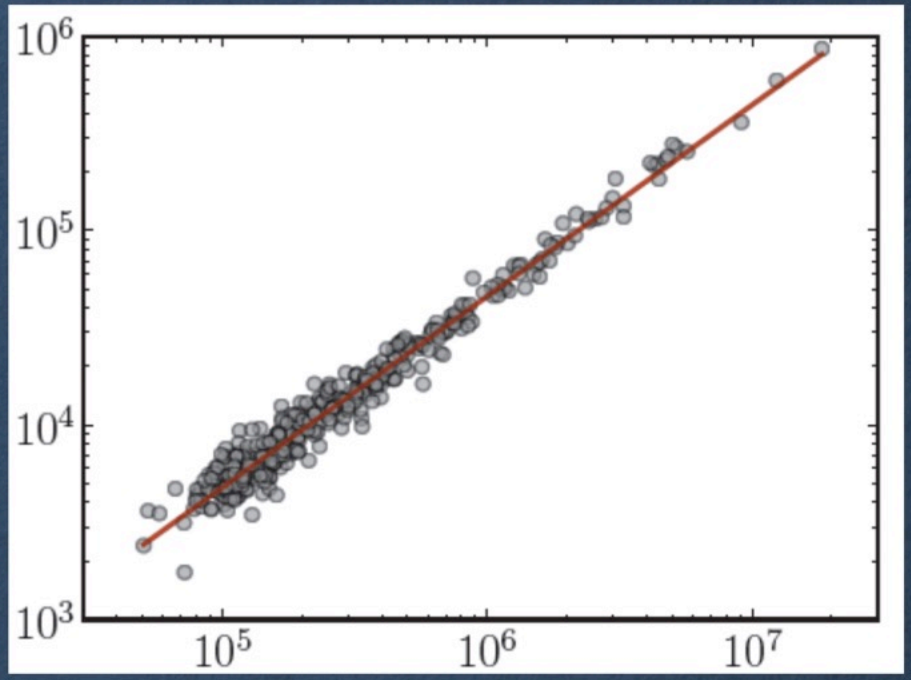
Singularity is near



SEQUENCE OF SINGULARITIES

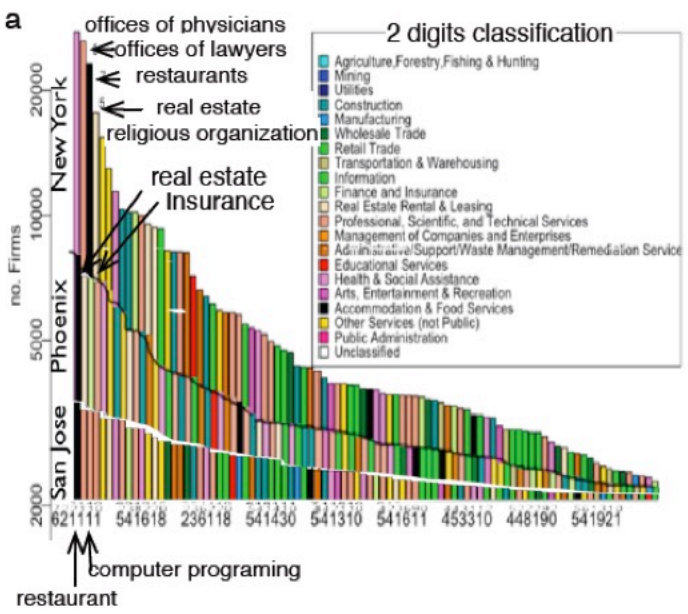


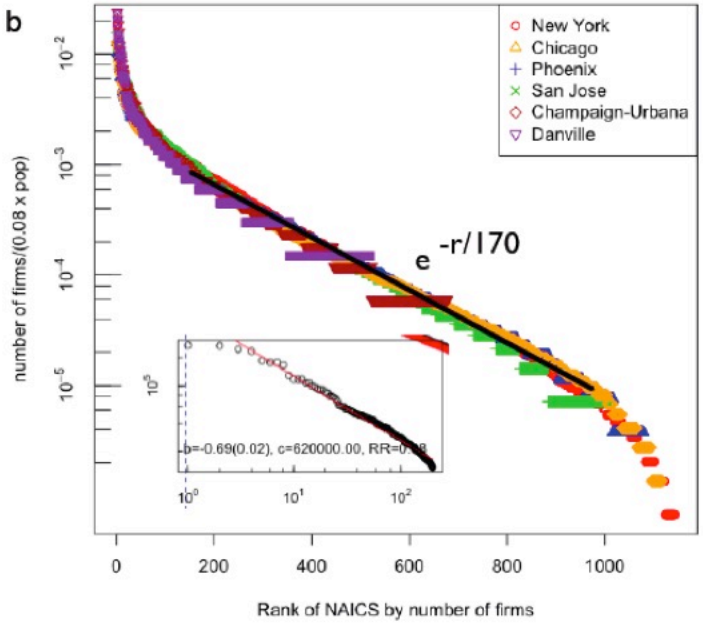
NUMBER OF FIRMS



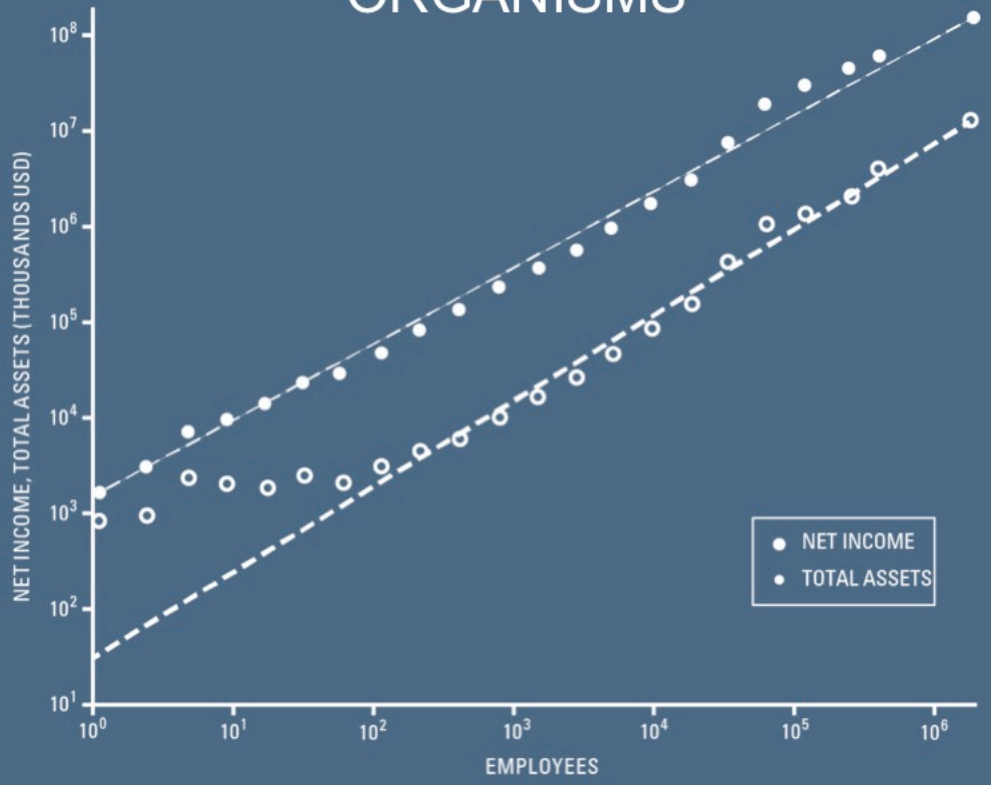
$N_f \approx \eta N$ $\eta \approx 21.6^{-1}$ $N_e / N_f \approx 11.9$

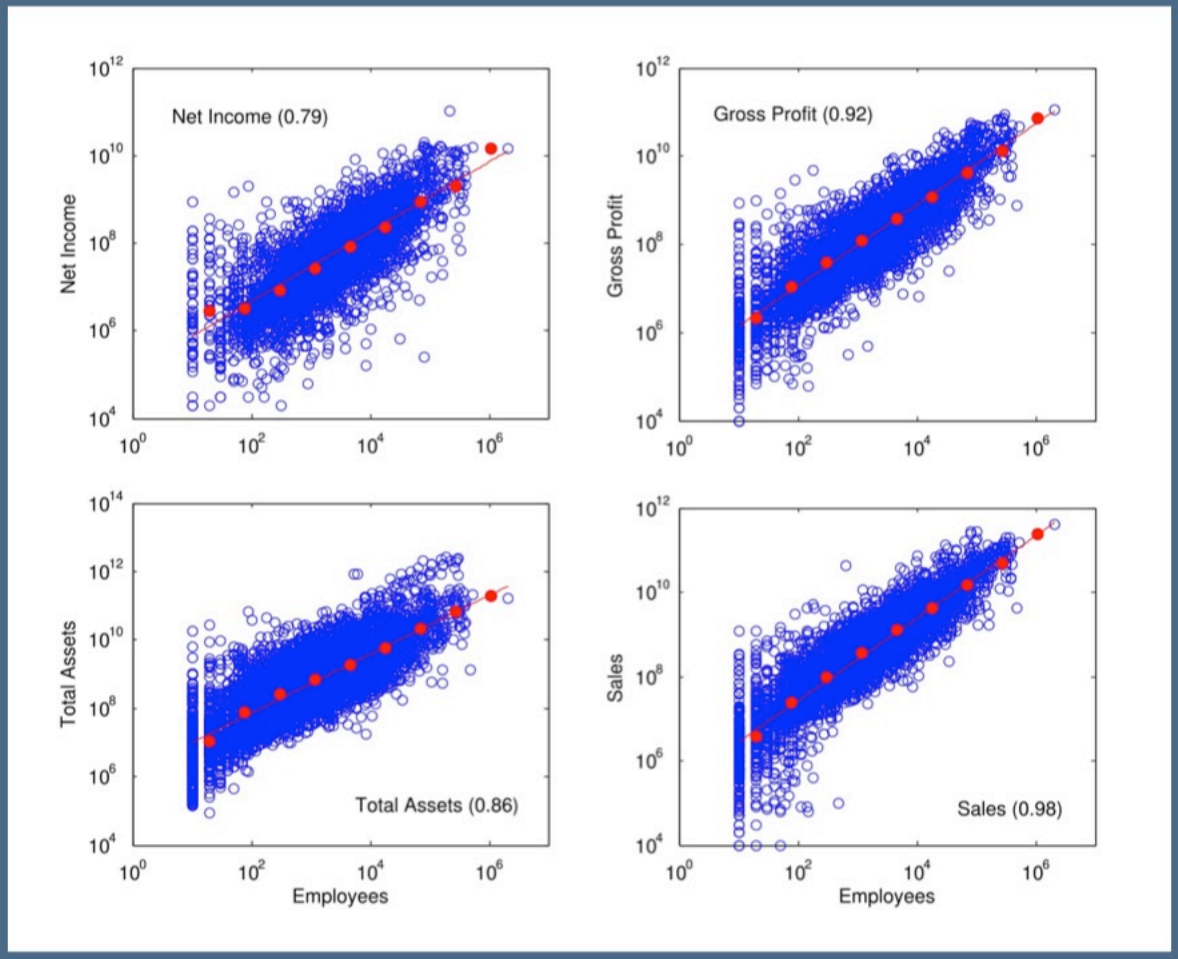
DIVERSITY OF FIRMS AND OCCUPATIONS



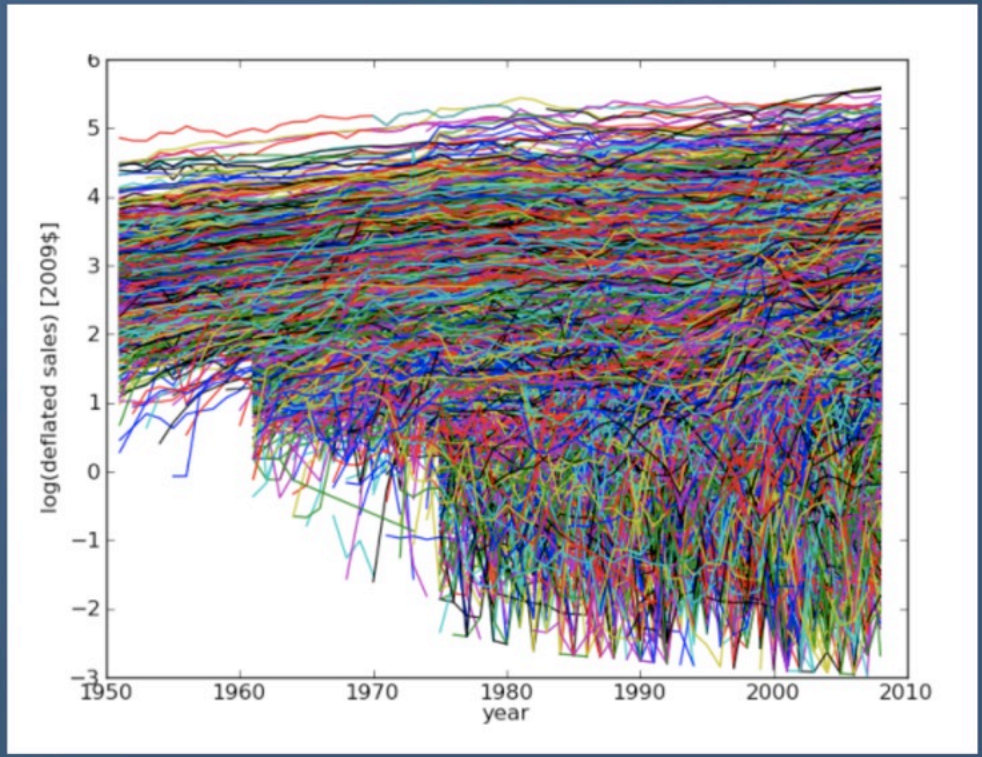


COMPANIES SCALE SUB-LINEARLY ANALOGOUS TO ORGANISMS

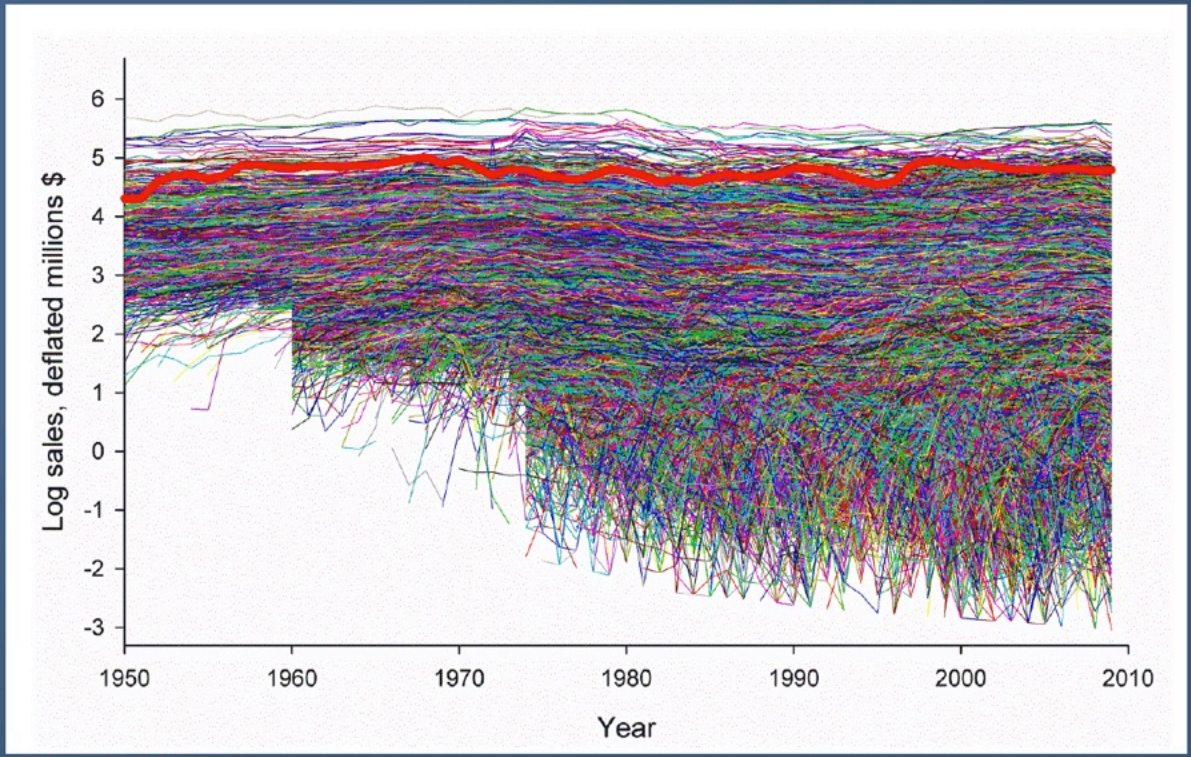



Net Income (0.79)
Net Income
Gross Profit (0.92)
Gross Profit
Total Assets (0.86)
Total Assets
Sales (0.98)
Sales
Employees
Employees

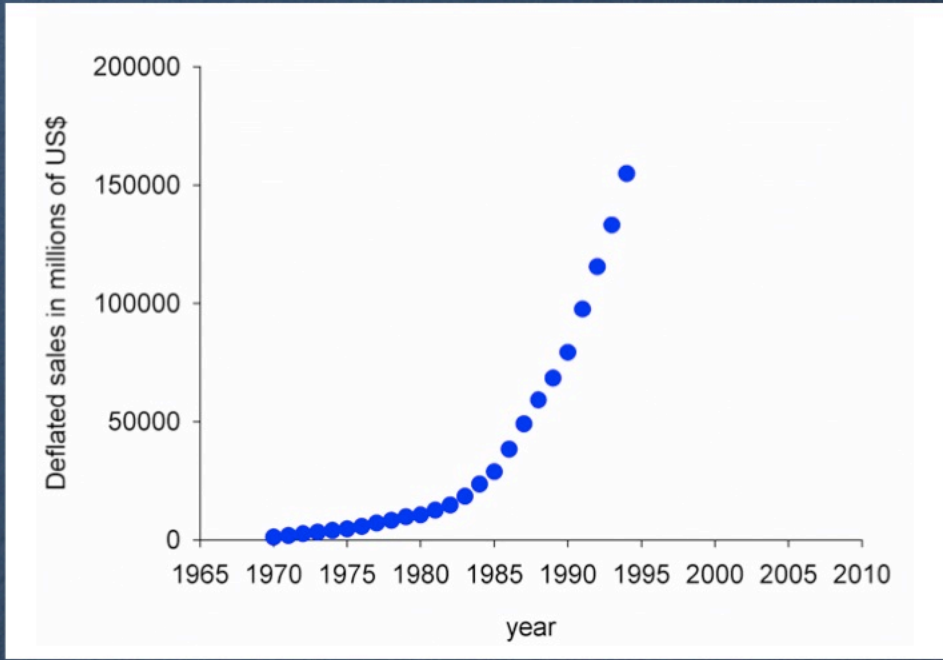
GROWTH OF FIRMS



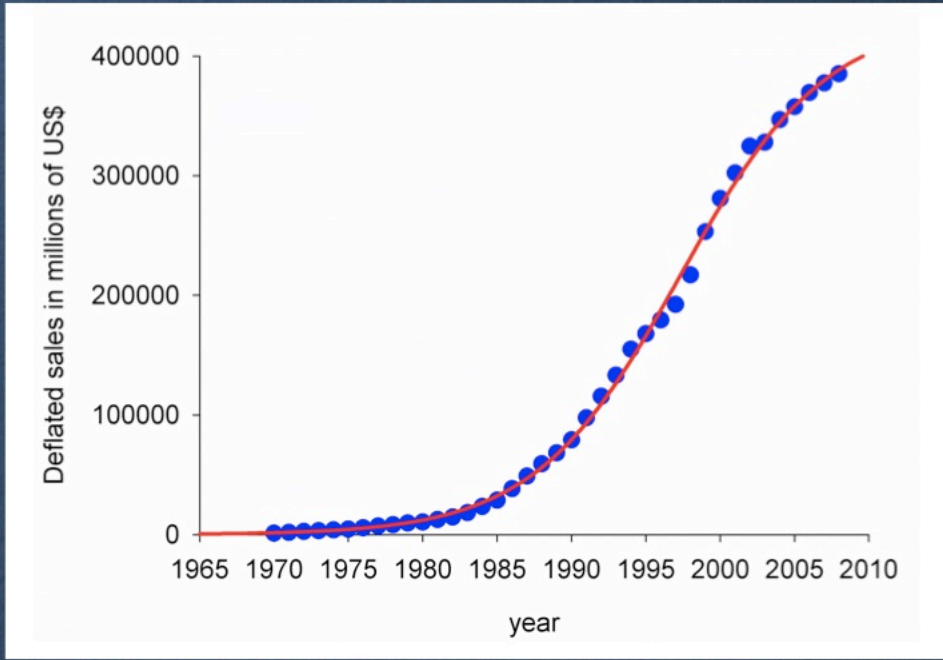
GROWTH OF FIRMS RELATIVE TO GDP

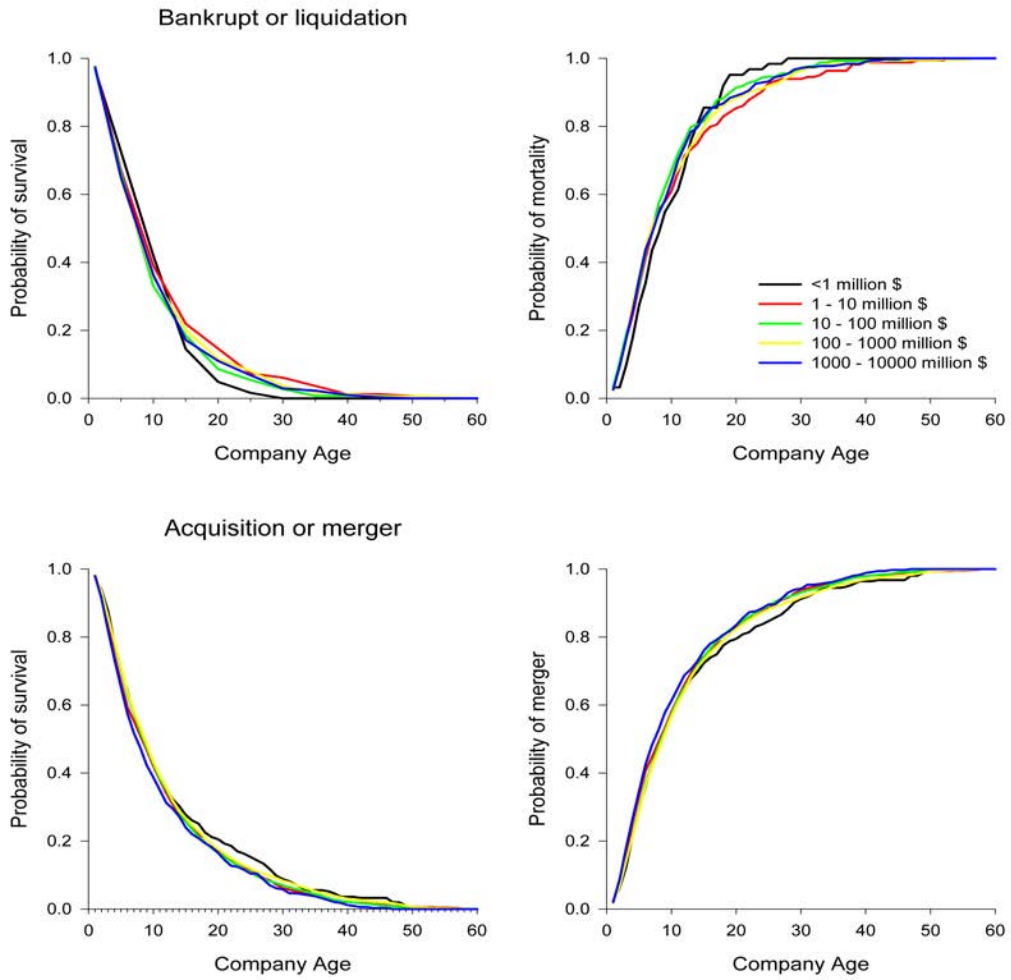


WALMART, 1970-1994



WALMART, 1970-2008



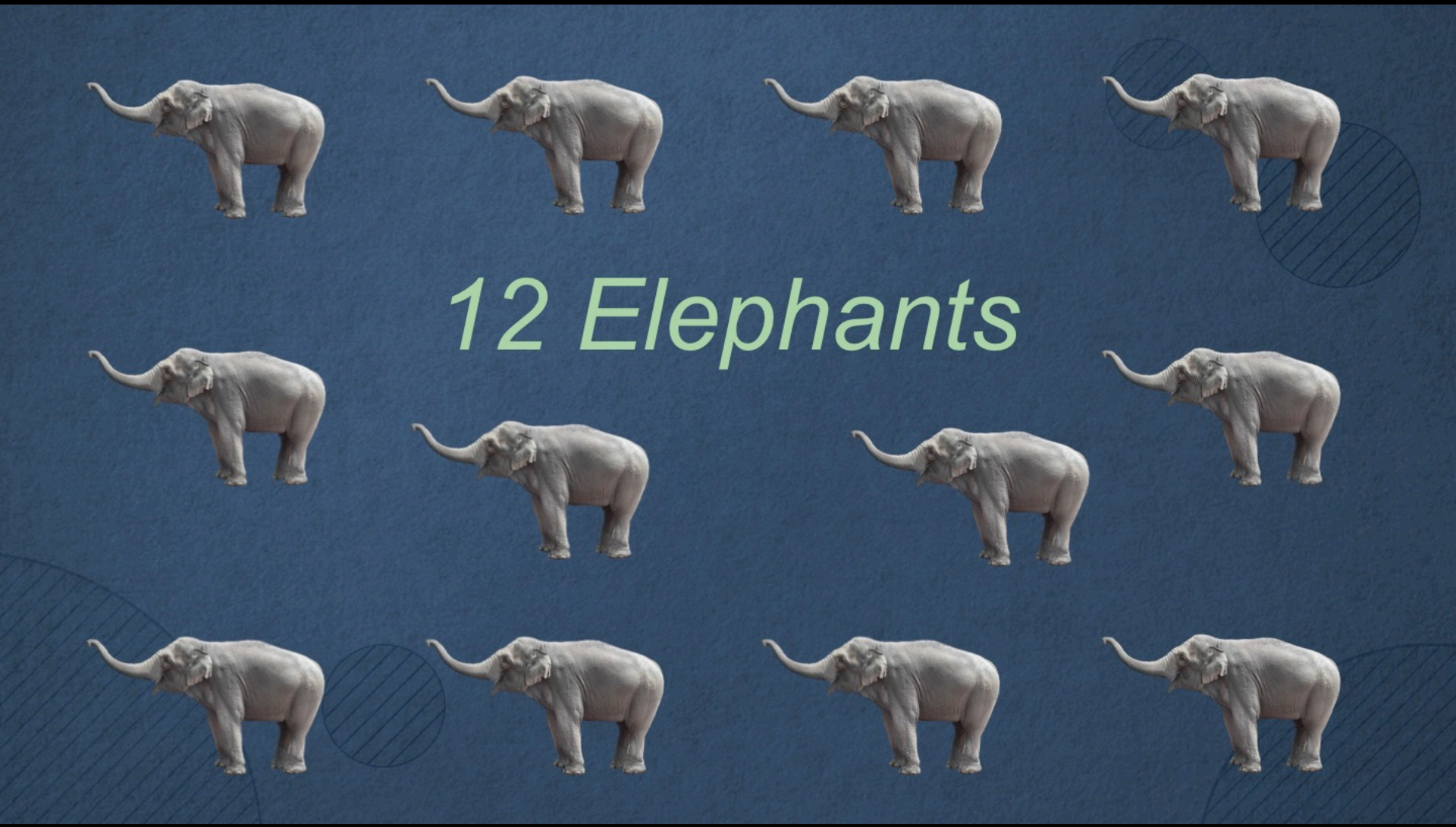

Bankrupt or liquidation
Probability of survival
Company Age
Probability of mortality
Company Age
<1 million $
1 - 10 million $
10 - 100 million $
100 - 1000 million $
1000 - 10000 million $
Acquisition or merger
Probability of survival
Company Age
Probability of merger
Company Age

Our “natural” metabolic rate *~90 watts*

Our social metabolic rate *~11,000 watts*

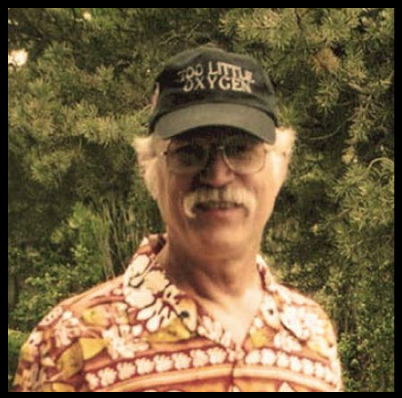
We are equivalent to a

30,000 kg Gorilla


12 Elephants

Jim Brown (UNM)

Brian Enquist (U of Arizona)



Woody Woodruff (LANL)

Van Savage (UCLA)

Jamie Gillooly (U of Florida)

Drew Allen (MacQuarie U)

Chen Hou (MissouriTech)

Melanie Moses (UNM)

Alex Herman (UCSF)

Ric Charnov (UNM)

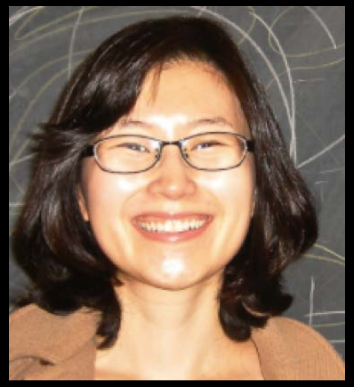
Chris Kempes (SFI)

Wenyun Zhuo (UNM)

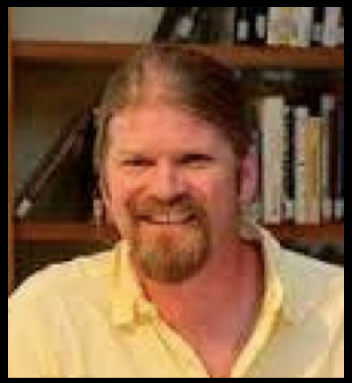
Luis Bettencourt (SFI)

Jose Lobo (U of Arizona)

Debbie Strumsky (U of Arizona)



Hyejin Youn (Oxford U)



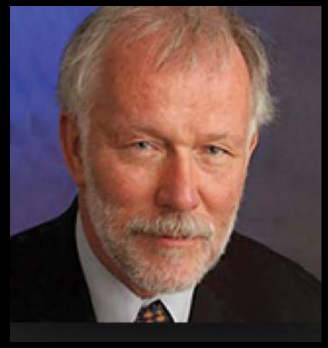
Marcus Hamilton (U of Missouri)

Madeleine Daepp (MIT)

Markus Schlapfer (ETH Zurich)

Carlo Ratti (MIT)

David Lane (U of Reggio)



Sander van der Leeuw (U of Arizona)

Denise Pumain (U of Paris)

Dirk Helbing (ETH Zurich)

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GENE & CLARE THAW CHARITABLE TRUST

BRYAN & JUNE ZWAN FOUNDATION

ROCKEFELLER FOUNDATION

McDONNELL FOUNDATION