THE EMERGENCE OF “UNIVERSAL” TIME IN LIVING SYSTEMS FROM CELLS TO CITIES

GEOFFREY WEST

SANTA FE INSTITUTE

"Complexities of Time” Conference, NTU, March 2018
The “Simplicity of Time”
The “Simplicity of Time”

Absolute, true, and mathematical time, in and of itself and of its own nature, without reference to anything external, flows uniformly and by another name is called duration. Relative, apparent, and common time is any sensible and external measure (precise or imprecise) of duration by means of motion; such as a measure—for example, an hour, a day, a month, a year—is commonly used instead of true time.

— Sir Isaac Newton
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\[ F = ma = m \frac{d^2x}{dt^2} \]

“\( t = \text{Time} \)”
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.
THIS IS A DIGITAL CLOCK
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The “Simplicity of Time”

The “Complexity of Time”??
Definition of TIME!

Slow, when you wait!
Fast, when you are Late!
Deadly, when you are Sad!
Short, when you are Happy!
Endless, when you are in Pain!
Long, when you feel bore!
Sometimes, time is determined by your feelings and your psychological conditions not by clocks...

So, Have A Nice Time Always!!
WHY DO WE STOP GROWING?

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

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

HOW IS IT GENERATED FROM FUNDAMENTAL MOLECULAR TIME-SCALES OF GENES AND RESPIRATORY ENZYMES?
WHY DO ALL MAMMALS HAVE APPROXIMATELY THE SAME NUMBER OF HEART-BEATS IN THEIR LIFETIME?

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

WHY DO ALL COMPANIES DIE WHEREAS (ALMOST) ALL CITIES SURVIVE?
WHY DO CITIES KEEP GROWING WHEREAS ALL COMPANIES STOP?

WHY DOES THE PACE OF LIFE CONTINUE TO GET FASTER?

IS ANY OF THIS SUSTAINABLE?

IS THERE AN END TO SOCIO-ECONOMIC TIME?
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?
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
SOME CHARACTERISTICS OF COMPLEX SYSTEMS

• MANY COMPONENTS
• MANY INDIVIDUAL ACTORS / AGENTS
• MULTI SPATIAL AND TEMPORAL SCALES
• STRONGLY COUPLED / INTERACTING
• NON-LINEAR
• SENSITIVITY TO BOUNDARY CONDITIONS (CHAOS)
• EMERGENT PHENOMENA / MULTIPLE PHASES
• UNINTENDED CONSEQUENCES
• ADAPTIVE / EVOLVING
• HISTORICALLY CONTINGENT / PATH DEPENDENT
• ROBUST / RESILIENT
• NON-EQUILIBRIUM
• UNDERLYING SIMPLICITY
• COMPLICATED vs COMPLEX
• SEARCH FOR UNDERLYING LAWS AND PRINCIPLES LEADING TO A QUANTITATIVE PREDICTIVE CONCEPTUAL FRAMEWORK

• CAN THERE BE “NEWTON’S LAWS OF LIVING SYSTEMS (INCLUDING CITIES AND COMPANIES)”?

• COMPLEXITY
COARSE - GRAINED DESCRIPTION
WITH INCREASING RESOLUTION AND GRANULARITY
STATISTICAL/PROBABILISTIC
QUANTITATIVE, PREDICTIVE
• **METABOLISM**

• **GROWTH**

• **AGING/DEATH**

• **EVOLUTION (ADAPTATION)**

• **SLEEP/REPAIR**

• **DISEASE/CANCER**
Mammals vary in size by 8 orders of magnitude.
SLOPE $= \frac{3}{4} < 1$  NON-LINEAR!!
METABOLIC RATE INCREASES NON-LINEARLY WITH SIZE

\[ B \sim M^{3/4} \]

OVER 27 ORDERS OF MAGNITUDE

SINCE \( N_{\text{cells}} \sim M \) NAIVELY MIGHT EXPECT \( B \sim M \)

HOWEVER, IF MASS (SIZE) INCREASES BY A FACTOR OF 10,000 (10^4)

THEN

METABOLIC RATE INCREASES BY ONLY A FACTOR OF 1,000 (10^3)
SPECIFIC METABOLIC RATE (PER UNIT MASS)

\[ \frac{B}{M} \mu M^{1/4} \]

SO METABOLIC RATE OF AVERAGE CELL

\[ B_{cell} \mu M^{1/4} \]
Metabolic rate sets the pace of life
Small animals live fast and die young

heart rate scales as 
-\( \frac{1}{4} \) power of body mass
FIG. 4 — VARIATION IN RADIUS OF AORTA WITH BODY WEIGHT

\[ r \sim M^{3/8} \]

SAME SCALING FOR TREE TRUNKS
\[ L \propto M^{0.264} \]
\[ r^2 = 0.995 \]
WHITE AND GRAY MATTER OF BRAINS

Diagram showing the relationship between white matter volume and gray matter volume for various species, with a logarithmic scale on both axes.
DEPENDENCE OF GENOME LENGTH ON CELLULAR MASS

- Non-photosynthetic Prokaryotes
- Cyanophyta

Slope = 0.24 +/- 0.02
Intercept = 9.4 +/- 0.2
Slopes (exponents) are typically sub-linear and simple multiples of $\frac{1}{4}$.

“quarter-power scaling”
Lifespan

\[ T \sim M^{1/4} \]

If heart-rate (number of beats per sec.)
\[ \sim M^{-1/4} \]

⇒ 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

![Graph showing the number of heartbeats per lifetime of animals versus their weight. The x-axis represents weight in kilograms (10^1 to 10^5), and the y-axis represents the number of heartbeats (10^7 to 10^12). The graph includes data points for various animals, such as rat, marmot, cat, dog, lion, tiger, horse, giraffe, and elephant, with whales at the highest end.]
NETWORKS!!!

(FRACTAL-LIKE)
FUNDAMENTAL PRINCIPLES

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 IN Variant 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
IN d DIMENSIONS

\[ B \propto M^{\frac{d}{d+1}} \]

WE LIVE IN 3 SPATIAL DIMENSIONS so \( B \propto M^{\frac{3}{4}} \)

⇒ "3" REPRESENTS DIMENSIONALITY OF SPACE

"4" INCREASE IN DIMENSIONALITY DUE TO

FRACAL-LIKE SPACE FILLING

LIFE HAS TAKEN ADVANTAGE OF THE POSSIBILITY OF

USING SPACE-FILLING FRACAL-LIKE SURFACES

(WHERE ENERGY AND RESOURCES ARE EXCHANGED)

TO MAXIMISE ENERGY TRANSFER FROM THE

ENVIRONMENT

\[
\begin{align*}
\text{NON-FRACAL:} & \quad M^{\frac{2}{3}} \\
\text{BIOLICAL (FRACAL):} & \quad M^{\frac{3}{4}}
\end{align*}
\]

BY ANALOGY: LIFE EFFECTIVELY OPERATES IN

FOUR SPATIAL DIMENSIONS

[FOUR IF TIME IS INCLUDED]
<table>
<thead>
<tr>
<th>Variable</th>
<th>Exponent Predicted</th>
<th>Exponent Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta radius ( r_0 )</td>
<td>3/8 = 0.375</td>
<td>0.36</td>
</tr>
<tr>
<td>Aorta pressure ( \Delta p_0 )</td>
<td>0 = 0.00</td>
<td>0.032</td>
</tr>
<tr>
<td>Aorta blood velocity ( u_0 )</td>
<td>0 = 0.00</td>
<td>0.07</td>
</tr>
<tr>
<td>Blood volume ( V_b )</td>
<td>1 = 1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Circulation time</td>
<td>1/4 = 0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Circulation distance ( l )</td>
<td>1/4 = 0.25</td>
<td>ND</td>
</tr>
<tr>
<td>Cardiac stroke volume</td>
<td>1 = 1.00</td>
<td>1.03</td>
</tr>
<tr>
<td>Cardiac frequency ( \omega )</td>
<td>-1/4 = -0.25</td>
<td>-0.25</td>
</tr>
<tr>
<td>Cardiac output ( E )</td>
<td>3/4 = 0.75</td>
<td>0.74</td>
</tr>
<tr>
<td>Number of capillaries ( N_c )</td>
<td>3/4 = 0.75</td>
<td>ND</td>
</tr>
<tr>
<td>Service volume radius</td>
<td>1/12 = 0.083</td>
<td>ND</td>
</tr>
<tr>
<td>Womersley number ( \alpha )</td>
<td>1/4 = 0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Density of capillaries</td>
<td>-1/12 = -0.083</td>
<td>-0.095</td>
</tr>
<tr>
<td>( O_2 ) affinity of blood ( P_{50} )</td>
<td>-1/12 = -0.083</td>
<td>-0.089</td>
</tr>
<tr>
<td>Total resistance ( Z )</td>
<td>-3/4 = -0.75</td>
<td>-0.76</td>
</tr>
<tr>
<td>Metabolic rate ( B )</td>
<td>3/4 = 0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Variable</td>
<td>Exponent Predicted</td>
<td>Exponent Observed</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>--------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Tracheal radius</td>
<td>$3/8 = 0.375$</td>
<td>0.39</td>
</tr>
<tr>
<td>Interpleural pressure</td>
<td>$0 = 0.00$</td>
<td>0.004</td>
</tr>
<tr>
<td>Air velocity in trachea</td>
<td>$0 = 0.00$</td>
<td>0.02</td>
</tr>
<tr>
<td>Lung volume</td>
<td>$1 = 1.00$</td>
<td>1.05</td>
</tr>
<tr>
<td>Volume flow to lung</td>
<td>$3/4 = 0.75$</td>
<td>0.80</td>
</tr>
<tr>
<td>Volume of alveolus $V_A$</td>
<td>$1/4 = 0.25$</td>
<td>ND</td>
</tr>
<tr>
<td>Tidal volume</td>
<td>$1 = 1.00$</td>
<td>1.041</td>
</tr>
<tr>
<td>Respiratory frequency</td>
<td>$-1/4 = -0.25$</td>
<td>-0.26</td>
</tr>
<tr>
<td>Power dissipated</td>
<td>$3/4 = 0.75$</td>
<td>0.78</td>
</tr>
<tr>
<td>Number of alveoli $N_A$</td>
<td>$3/4 = 0.75$</td>
<td>ND</td>
</tr>
<tr>
<td>Radius of alveolus $r_A$</td>
<td>$1/12 = 0.083$</td>
<td>0.13</td>
</tr>
<tr>
<td>Area of alveolus $A_A$</td>
<td>$1/6 = 0.166$</td>
<td>ND</td>
</tr>
<tr>
<td>Area of lung $A_L$</td>
<td>$11/12 = 0.92$</td>
<td>0.95</td>
</tr>
<tr>
<td>$O_2$ diffusing capacity</td>
<td>$1 = 1.00$</td>
<td>0.99</td>
</tr>
<tr>
<td>Total resistance</td>
<td>$-3/4 = -0.75$</td>
<td>-0.70</td>
</tr>
<tr>
<td>$O_2$ consumption rate</td>
<td>$3/4 = 0.75$</td>
<td>0.76</td>
</tr>
</tbody>
</table>
Table 1: Predicted values of scaling exponents for physiological and anatomical variables of plant vascular systems.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Plant mass</th>
<th>Branch radius</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exponent predicted</td>
<td>Symbol</td>
</tr>
<tr>
<td>Number of leaves</td>
<td>$\frac{3}{4}$ (0.75)</td>
<td>$n_0^k$</td>
</tr>
<tr>
<td>Number of branches</td>
<td>$\frac{3}{4}$ (0.75)</td>
<td>$N_0$</td>
</tr>
<tr>
<td>Number of tubes</td>
<td>$\frac{3}{4}$ (0.75)</td>
<td>$n_0$</td>
</tr>
<tr>
<td>Branch length</td>
<td>$\frac{1}{4}$ (0.25)</td>
<td>$l_0$</td>
</tr>
<tr>
<td>Branch radius</td>
<td>$\frac{3}{8}$ (0.375)</td>
<td>$r_0$</td>
</tr>
<tr>
<td>Area of conductive tissue</td>
<td>$\frac{7}{8}$ (0.875)</td>
<td>$A_0^{CT}$</td>
</tr>
<tr>
<td>Tube radius</td>
<td>$\frac{1}{6}$ (0.0625)</td>
<td>$a_0$</td>
</tr>
<tr>
<td>Conductivity</td>
<td>1 (1.00)</td>
<td>$K_0$</td>
</tr>
<tr>
<td>Leaf-specific conductivity</td>
<td>$\frac{1}{4}$ (0.25)</td>
<td>$L_0$</td>
</tr>
<tr>
<td>Fluid flow rate</td>
<td>$Q_k$</td>
<td></td>
</tr>
<tr>
<td>Metabolic rate</td>
<td>$\frac{3}{4}$ (0.75)</td>
<td>$Q_0$</td>
</tr>
<tr>
<td>Pressure gradient</td>
<td>$-\frac{1}{4}$ (-0.25)</td>
<td>$\Delta P_0/l_0$</td>
</tr>
<tr>
<td>Fluid velocity</td>
<td>$-\frac{1}{3}$ (-0.125)</td>
<td>$u_0$</td>
</tr>
<tr>
<td>Branch resistance</td>
<td>$-\frac{3}{4}$ (-0.75)</td>
<td>$Z_0$</td>
</tr>
<tr>
<td>Tree height</td>
<td>$\frac{1}{4}$ (0.25)</td>
<td>$h$</td>
</tr>
<tr>
<td>Reproductive biomass</td>
<td>$\frac{3}{2}$ (0.75)</td>
<td></td>
</tr>
<tr>
<td>Total fluid volume</td>
<td>$\frac{25}{24}$ (1.0415)</td>
<td></td>
</tr>
</tbody>
</table>
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 $k$)*

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

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

Chemical energy
- Carbohydrates
- Fats
- Others

ATP
- Body's "energy currency"

Chemical waste
- Carbon dioxide
- Water

Heat

Metabolism
Growth

Incoming Metabolized Energy

↓

Maintenance (of Existing Cells)

+ 

New Growth (of New Cells)
\[ B = N_{\text{cells}} B_{\text{cell}} + E_{\text{cell}} \frac{dN_{\text{cell}}}{dt} \]

**IN TERMS OF MASS AT AGE t**

\[ \frac{dm}{dt} = am^{3/4} - bm \]

where

\[ a = \frac{B_0 m_c}{E_c} \]

\[ b = \frac{B_c}{E_c} \]

**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**

\[ M_0 = \text{MASS AT BIRTH} \quad (m = m_0 \text{ WHEN } t = 0) \]
SUB-LINEAR SCALING LEADS TO BOUNDED GROWTH
GROWTH CURVES OF ANIMALS

Guinea pig

\[ a = 0.200 \]
\[ M = 840 \]
\[ m_0 = 5 \]

Guppy

\[ a = 0.104 \]
\[ M = 0.15 \]
\[ m_0 = 0.008 \]

Hen

\[ a = 0.502 \]
\[ M = 2,050 \]
\[ m_0 = 43 \]

Cow

\[ a = 0.276 \]
\[ M = 442,000 \]
\[ m_0 = 33,333 \]
UNIVERSAL COLLAPSED GROWTH CURVE

RESCALED MASS VS. RESCALED AGE

Dimensionless mass ratio

\[ \left( \frac{m_t}{M} \right)^{1/4} \]

Dimensionless Time

\[ (at/4M^{1/4}) - \ln[1-(m_0/M)^{1/4}] \]
'in vivo' data
(patients)
NETWORK GEOMETRY AND DYNAMICS CONTROLS THE PACE OF LIFE AT ALL SCALES LEADING TO EMERGENT “UNIVERSAL” TIME SCALES

THE PACE OF LIFE SYSTEMATICALLY SLOWS WITH INCREASING SIZE
ALL RATES $\sim M^{-1/4}$

METABOLISM
GROWTH
EVOLUTION
LONGEVITY
DIFFUSION
FLUXES

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

LIFESPANS
TURNOVER TIMES
TIMES TO MATURITY
CIRCULATION TIMES

.............
TEMPERATURE DEPENDENCE

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

\[ B = \sum_i P_i \]

\[ P_i \sim (\text{CONCENTRATIONS}) \times (\text{FLUXES}) \times (\text{KINETICS}) \]

\[ (\text{CONCENTRATIONS}) \times (\text{FLUXES}) \sim \text{NETWORK} \sim M^{3/4} \]

\[ (\text{KINETICS}) \sim \text{BOLTZMANN-ARRENHIUS} \sim e^{-E/kT} \]

\[ E = \text{AVERAGE ACTIVATION ENERGY FOR RATE-LIMITING PROCESS IN RESPIRATORY COMPLEX} \]

\[ (\text{PRODUCTION OF ATP}) \sim 0.7 \text{ eV} \sim 2 \times 10^{-20} \text{ cal} \]
ALL RATES $\sim M^{-1/4}$

METABOLISM
GROWTH
EVOLUTION
LONGEVITY
DIFFUSION
FLUXES

..................

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

LIFESPANS
TURNOVER TIMES
TIMES TO MATURITY
CIRCULATION TIMES

..................
TEMPERATURE
REACTION RATES GOVERNED BY STATISCAL PHYSICS (BOLTZMANN-ARRENHIUS)

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

METABOLISM
GROWTH
EVOLUTION
LONGLEVITY
DIFFUSION
FLUXES

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

LIFESPANS
TURNOVER TIMES
TIMES TO MATURITY
CIRCULATION TIMES

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

IF THE MASS AND TEMPERATURE DEPENDENCIES ARE ACCOUNTED FOR THEN:

\[
\text{(TIMES)} \times M^{-1/4}e^{-E/kT} \quad \text{(RATES)} \times M^{1/4}e^{E/kT}
\]

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

\[
1/4 \text{ AND } E \sim 0.7 \text{ ev}
\]
Evolution: measuring nucleotide substitution rate (S)

8 substitutions in 2 million years

\[ S = \frac{8}{(2 \times 2)} = \frac{8}{4} = 2/\text{my} \]
Rates of molecular evolution
temperature dependence

Gillooly et al. 2005
Rates of molecular evolution

body size
dependence

Gillooly et al. 2005

A  mtDNA

\[ y = -0.23x + 26.56 \]
\[ r^2 = 0.74 \]
\[ n = 15 \]

B  rRNA

\[ y = -0.22x + 25.73 \]
\[ r^2 = 0.48 \]
\[ n = 22 \]

C  cyt-b

\[ y = -0.23x + 26.14 \]
\[ r^2 = 0.23 \]
\[ n = 14 \]

D  cyt-b, transversions

\[ y = -0.21x + 24.17 \]
\[ r^2 = 0.72 \]
\[ n = 14 \]
Rates of molecular evolution: size correction reconciles molecular clock with fossil dates

Gillooly et al. 2005
\[
\ln(LM^{-1/4}) = 6.50x - 15.91 \\
r^2 = 0.88
\]

\[
\ln(LM^{-1/4}) = 6.37x - 15.97 \\
r^2 = 0.71
\]
a) **DOMINATED BY** NON-LINEAR 1/4 - POWER SCALING

b) **EXTRAORDINARY ECONOMIES OF SCALE** (THE BIGGER YOU ARE, THE LESS YOU NEED PER “CAPITA”)

c) **PACE OF LIFE** SYSTEMATICALLY SLOWS WITH INCREASING SIZE;

d) **GROWTH IS SIGMOIDAL** REACHING A STABLE SIZE AT MATURITY

e) **NETWORKS**
SOCIO-ECONOMIC ENTROPY!!
MASSIVE INCREASE IN KNIFE CRIME SURVEYS
WE LIVE IN AN EXPONENTIALLY EXPANDING SOCIO-ECONOMIC UNIVERSE!!

1800 < 4% OF THE US POPULATION WAS URBAN

2018 > 80%

2006 > 50% WORLD’S POPULATION URBANISED

2050 > 75%
EQUIVALENT TO URBANISING OVER ONE MILLION PEOPLE EVERY WEEK FROM NOW TILL 2050

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

OR....... A SINGAPORE EVERY MONTH!
World population growth

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

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

* Projection
BRIDGE CAPITAL
Bridge funding, as its name implies, bridges the gap between your current financing and the next level of financing.

MEZZANINE CAPITAL
Mezzanine capital is also known as expansion capital, and is funding to help your company grow to the next level, purchase bigger and better equipment, or move to a larger facility.

STARTUP CAPITAL
Start-up, or working capital is the funding that will help you pay for equipment, rent, supplies, etc. for the first year or so of operation.

SEED CAPITAL
Seed capital is the money you need to do your initial research and planning for your business.
FATE OF OUR PLANET IS
the fate of our cities
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.
Are Cities Approximate Scaled Versions of Each Other?

Do They Obey Power Law Scaling?

Do Exponents Manifest “Universality” (analogous to quarter powers in Biology)?
“What is the city but the people?”

William Shakespeare
NUMBER OF PETROL STATIONS VS. POPULATION

INFRASTRUCTURE

SUB-LINEAR SCALING

ECONOMY OF SCALE
SUPER-LINEAR SCALING

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

Supercreative employment per MSA in 2003, for the USA vs. metropolitan population.
INNOVATION MEASURED BY PATENTS

NUMBER OF PATENTS IN CITIES

POULATION
TOTAL CRIME (JAPAN)

Slope = 1.21  [1.08, 1.35]
RESTAURANTS IN THE NETHERLANDS

![Graph showing the relationship between the number of restaurants and population in the Netherlands.](image)

- **X-axis**: Population
- **Y-axis**: Number of restaurants

Log-log plot indicating a logarithmic relationship.
UNIVERSALITY OF URBAN SCALING
THE GOOD, THE BAD, THE UGLY
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

SAVES APPROXIMATELY 15% ON ALL INFRASTRUCTURE (ROADS, ELECTRICAL LINES, GAS STATIONS,........)
Universality of Social Networks
(clustering hierarchies)
UNIVERSALITY

Collapsed Income, GDP, Crime (binned), and Patents (binned)
UNIVERSALITY

SOCIAL CONNECTIVITY
(Cell Phone Data)
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:

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

\[ \beta = 0.093 \quad R^2 = 0.80 \]
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
\[
\frac{dN}{dt} = \left( \frac{R_1}{E_0} \right) \left[ N^\beta - \left( \frac{R_0}{R_1} \right) N \right]
\]

**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

SUB-LINEAR SCALING LEADS TO BOUNDED GROWTH
SUPER-LINEAR

SUPER-EXPONENTIAL UNBOUNDED GROWTH

COLLAPSE
UNBOUNDED GROWTH Requires Accelerating Cycles of Innovation to Avoid Collapse
Singularity is near

Years to reach 10 million customers (US)

Time

Registered genetic pairs (75% in last 2 yrs)

1.2 million

1982

1997

Telephone (40+ yrs)

Cable TV (25 yrs)

Fax (20 yrs)

Cellular phone (11 yrs)

PC (6 yrs)

VCR (8 yrs)

Internet (3 yrs)

The Spike

Damien Broderick
Population growth for New York City

Population growth of New York City MSA 1790-2003

New York MSA population

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

Time Before Present (years)

- Life
- Eukaryotic cells, multicellular organisms
- Cambrian Explosion (body plans)
- Class Mammalia
- Primates
- Superfamily Hominoidae
- 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
SUSTAINABLE???
COMPANIES SCALE SUB-LINEARLY ANALOGOUS TO ORGANISMS
GROWTH OF FIRMS
GROWTH OF FIRMS RELATIVE TO GDP
WALMART, 1970-1994

- Vertical axis: Deflated sales in millions of US$
- Horizontal axis: Year (1965 to 2010)
Our "natural" metabolic rate ~90 watts

Our social metabolic rate ~11,000 watts
We are equivalent to a 30,000 kg Gorilla
12 Elephants
PAST AND PRESENT PATRONS:

NATIONAL SCIENCE FOUNDATION

GENE & CLARE THAW CHARITABLE TRUST

BRYAN & JUNE ZWAN FOUNDATION

ROCKEFELLER FOUNDATION

McDONNELL FOUNDATION
In 1825, late in life, Goethe wrote a letter to his friend, the composer Leiter in which he reflected on character of life as it had come to be lived in their lifetime:

Everything nowadays is *ultra*, [he writes] *everything is being transcended continually in thought as well as in action. No one knows himself any longer; no one can grasp the element in which he lives and works or the materials that he handles. Pure simplicity is out of the question; of simplifiers we have enough. Young people are stirred up much too early in life and then carried away in the whirl of the times. Wealth and rapidity are what the world admires.... Railways, quick mails, steamships, and every possible kind of rapid communication are what the educated world seeks but *it only over-educates itself and thereby persists in its mediocrity*. It is, moreover, the result of universalization that a mediocre culture [then] becomes [the] common [culture]....
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)