Statistical Mechanics of Money, Income, Debt, and Energy Consumption

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• Book *Classical Econophysics* (Routledge, 2009)

Outline: • Statistical mechanics of money
• Debt and financial instability
• Two-class structure of income distribution

INET funding 2013 • Global inequality in energy consumption
Boltzmann-Gibbs probability distribution of energy $\epsilon$

Collisions between atoms

$$\varepsilon_1' = \varepsilon_1 + \Delta \varepsilon$$

$$\varepsilon_2' = \varepsilon_2 - \Delta \varepsilon$$

Conservation of energy:

$$\varepsilon_1 + \varepsilon_2 = \varepsilon_1' + \varepsilon_2'$$

Detailed balance:

$$w_{12 \rightarrow 1'2'} P(\varepsilon_1) P(\varepsilon_2) = w_{1'2' \rightarrow 12} P(\varepsilon_1') P(\varepsilon_2')$$

Boltzmann-Gibbs probability distribution $P(\varepsilon) \propto \exp(-\varepsilon/T)$ of energy $\varepsilon$, where $T = \langle \varepsilon \rangle$ is temperature. It is universal – independent of model rules, provided the model belongs to the time-reversal symmetry class.

Boltzmann-Gibbs distribution maximizes entropy $S = -\sum \varepsilon P(\varepsilon) \ln P(\varepsilon)$ under the constraint of conservation law $\sum \varepsilon P(\varepsilon) \varepsilon = \text{const.}$

Economic transactions between agents

Conservation of money:

$$m_1 + m_2 = m_1' + m_2'$$

Detailed balance:

$$w_{12 \rightarrow 1'2'} P(m_1) P(m_2) = w_{1'2' \rightarrow 12} P(m_1') P(m_2')$$

Boltzmann-Gibbs probability distribution $P(m) \propto \exp(-m/T)$ of money $m$, where $T = \langle m \rangle$ is the money temperature.
Money distribution with debt

Debt per person is limited to 800 units.

Total debt in the system is limited via the Required Reserve Ratio (RRR):

\[ \text{Xi, Ding, Wang, Physica A 357, 543 (2005)} \]

- In practice, RRR is enforced inconsistently and does not limit total debt.
- Without a constraint on debt, the system does not have a stationary equilibrium.
- Free market itself does not have an intrinsic mechanism for limiting debt, and there is no such thing as the equilibrium debt.
Probability distribution of individual income

US Census data 1996 – histogram and points A


Distribution of income $r$ is exponential:

$$P(r) \propto e^{-r/T}$$
Income distribution in the USA, 1997

Two-class society

Upper Class
- Pareto power law
- 3% of population
- 16% of income
- Income > 120 k$: investments, capital

Lower Class
- Boltzmann-Gibbs exponential law
- 97% of population
- 84% of income
- Income < 120 k$: wages, salaries

“Thermal” bulk and “super-thermal” tail distribution
Income distribution in European Union, 2008

Income distribution is exponential for 97% of population.

Income distribution in the USA, 1983-2001

The rescaled exponential part does not change, but the power-law part changes significantly.
Lorenz curves and income inequality

Lorenz curve \((0<r<\infty)\):

\[
x(r) = \int_0^r P(r') \, dr'
\]

\[
y(r) = \int_0^r r' P(r') \, dr' / \langle r' \rangle
\]

For exponential distribution, \(G=1/2\) and the Lorenz curve is

\[
y = x + (1 - x) \ln(1 - x)
\]

With a tail, the Lorenz curve is

\[
y = (1 - f)[x + (1 - x) \ln(1 - x)] + f \Theta(x - 1),
\]

where \(f\) is the tail income, and Gini coefficient is \(G=(1+f)/2\).

A measure of inequality, the Gini coefficient is \(G = \frac{\text{Area(diagonal line - Lorenz curve)}}{\text{Area(Triangle beneath diagonal)}}\)

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Time evolution of income inequality in USA

Gini coefficient $G = (1+f)/2$

Income inequality peaks during speculative bubbles in financial markets

$$f = \frac{\langle r \rangle - T}{\langle r \rangle}$$

$f$ - fraction of income in the tail

$\langle r \rangle$ – average income in the whole system

$T$ – average income in the exponential part
The origin of two classes

- Different sources of income: salaries and wages for the lower class, and capital gains and investments for the upper class.

- Their income dynamics can be described by additive and multiplicative diffusion, correspondingly.

- From the social point of view, these can be the classes of employees and employers, as described by Karl Marx.

- Emergence of classes from the initially equal agents was simulated by Ian Wright “The Social Architecture of Capitalism” *Physica A* **346**, 589 (2005), see also the book “Classical Econophysics” (2009)
Diffusion model for income kinetics

Suppose income changes by small amounts $\Delta r$ over time $\Delta t$. Then $P(r,t)$ satisfies the Fokker-Planck equation for $0 < r < \infty$:

$$
\frac{\partial P}{\partial t} = \frac{\partial}{\partial r} \left( AP + \frac{\partial}{\partial r} (BP) \right), \quad A = -\left\langle \frac{\Delta r}{\Delta t} \right\rangle, \quad B = \left\langle \frac{(\Delta r)^2}{2\Delta t} \right\rangle.
$$

For a stationary distribution, $\partial_t P = 0$ and $\frac{\partial}{\partial r} (BP) = -AP$.

For the lower class, $\Delta r$ are independent of $r$ – additive diffusion, so $A$ and $B$ are constants. Then, $P(r) \propto \exp(-r/T)$, where $T = B/A$, – an exponential distribution.

For the upper class, $\Delta r \propto r$ – multiplicative diffusion, so $A = ar$ and $B = br^2$. Then, $P(r) \propto 1/r^{\alpha+1}$, where $\alpha = 1 + a/b$, – a power-law distribution.

For the upper class, income does change in percentages, as shown by Fujiwara, Souma, Aoyama, Kaizoji, and Aoki (2003) for the tax data in Japan. For the lower class, the data is not known yet.
Additive and multiplicative income diffusion

If the additive and multiplicative diffusion processes are present simultaneously, then
\[ A = A_0 + ar \] and \[ B = B_0 + br^2 = b(r_0^2 + r^2) \]. The stationary solution of the FP equation is

\[
P(r) = \frac{Ce^{-\frac{r_0}{T}\arctan\left(\frac{r}{r_0}\right)}}{\left[1 + (r/r_0)^2\right]^{1+a/2b}}
\]

It interpolates between the exponential and the power-law distributions and has 3 parameters:

- \( T = B_0/A_0 \) – temperature of the exponential part
- \( \alpha = 1 + a/b \) – power-law exponent of the upper tail
- \( r_0 \) – crossover income between the lower and upper parts.

Income distribution in Sweden

The data plot from Fredrik Liljeros and Martin Hällsten, Stockholm University

- Total incomes
- Work
- Capital
- Social transfers
Global inequality in energy consumption

Global distribution of energy consumption per person is roughly exponential.

Division of a limited resource + entropy maximization produce exponential distribution.

Physiological energy consumption of a human at rest is about 100 W
Global inequality in energy consumption

- Energy consumption evolves toward the exponential distribution.
- The distribution is getting smoother: The gap in energy consumption between developed and developing countries shrinks.
- Global inequality in energy consumption decreases.
Conclusions

• The probability distribution of money is stable and has an equilibrium only when a boundary condition, such as $m>0$, is imposed.
• When debt is permitted, the distribution of money becomes unstable, unless some sort of a limit on maximal debt is imposed.
• Income distribution in the USA has a two-class structure: exponential ("thermal") for the great majority (97-99%) of population and power-law ("superthermal") for the top 1-3% of population.
• The exponential part of the distribution is very stable and does not change in time, except for a slow increase of temperature $T$ (the average income).
• The power-law tail is not universal and was increasing significantly for the last 20 years. It peaked and crashed in 2000 and 2007 with the speculative bubbles in financial markets.
• The global distribution of energy consumption per person is highly unequal and roughly exponential. This inequality is important in dealing with the global energy problems.
• All papers at http://physics.umd.edu/~yakovenk/econophysics/