New Challenges and Opportunities for Old Physics Departments

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Main Points

- Computation has expanded the types of problems of interest to physicists. Many of these problems are interesting to students.
- The concepts and tools of physics are increasingly important in the other sciences and engineering and in many areas of social science.
- We can now reach majors in the other sciences and engineering as well as non-majors.
- The analytical skills of physics majors and other students are weaker than in the past.

$\Longrightarrow$ Need to change what and how we teach.

Nature of Physics Departments in the Golden Years

- Departments were well funded, due to prestige gained from development of nuclear weapons.
- The nature of the curriculum was influenced by research in particle and nuclear physics. Courses in thermal and solid state physics were not common and courses on complex systems and statistical physics didn't exist.
- Physicists were mainly rewarded for their ability to obtain research funding and lead research groups, not for their teaching.

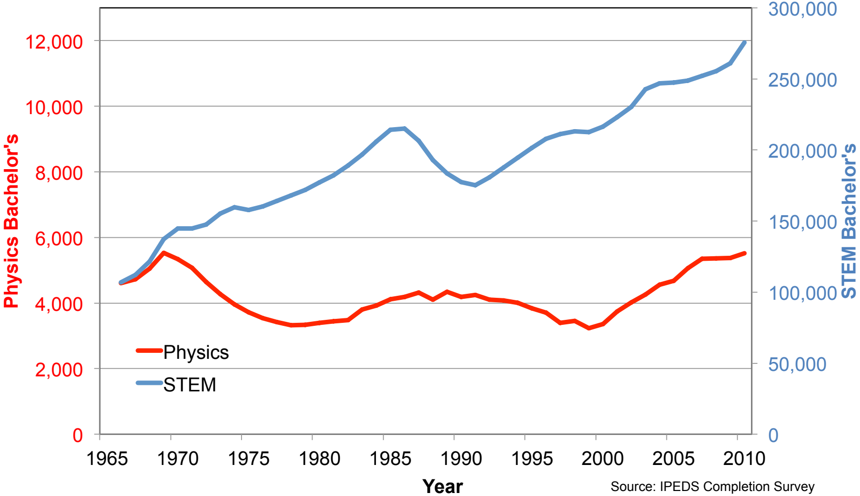
Societal Challenges

If physics research is to be well funded, it has to meet some of these challenges:

- Global climate change.
- Clean, efficient, and secure energy sources.
- Cost of health care and education.
- Sustainable food supply.
- Terrorism and nuclear proliferation.
- Poor infrastructure.
- High unemployment, growing income disparity. Where are the future jobs?

How Can Physics Departments Meet These Challenges?

- Increase the number of physics majors.



AY 2010/11 produced more physics B.A./B.S. degrees and more physics Ph.D. degrees than in any other year in U.S.

Challenges We Can Control

- Broaden our areas of research.
- Educate and collaborate with workers in other fields where the approach of physicists is useful.
- Offer courses for majors and non-majors in areas related to societal challenges.
- Use computers to reduce the barrier to studying physics – the fear of mathematics.

Our tools affect the way we think

- Several examples of approaches and models used by physicists to illustrate how computation changes how we think and the problems that we can study.

- Ideal Bose gas – a new approach to an old problem initiated by an undergraduate.
- Model of earthquakes.
- Model of wealth distribution.

The last two examples illustrate the limitations of analytical methods.

Ideal Bose Gas
Analytical Approach

$$\overline{N}(T,\mu) = \sum_{\vec{k}} \frac{1}{e^{\beta(\epsilon_k-\mu)}-1} \qquad (\beta = 1/kT).$$

Convert sum to an integral in thermodynamic limit:

$$\overline{N}(T,\mu) = \int \frac{g(\epsilon)\,d\epsilon}{e^{\beta(\epsilon-\mu)}-1} \quad (g(\epsilon) = \text{density of states}).$$

$$\rho = \frac{\overline{N}}{V} = \frac{(2m)^{3/2}}{4\pi\hbar^3}\int_0^\infty \frac{\epsilon^{1/2}d\epsilon}{e^{\beta(\epsilon-\mu)}-1}.$$

- Find chemical potential μ that yields density ρ.
- Integral cannot be done analytically except at $\mu = 0$.

Usual Textbook Argument for Bose Condensation

$$\rho = \frac{(2mkT)^{3/2}}{4\pi\hbar^3}\int_0^\infty \frac{x^{1/2}dx}{e^{x+\beta|\mu|}-1}.$$

- $\mu < 0$ for Bose systems.
- $|\mu|$ decreases as T is lowered.
- Integral maximum for $\mu = 0$. T_c is value of T at which $\mu = 0$.
- T_c is minimum value of T such that right-hand side equals ρ.
- For $T < T_c$, integral no longer includes all the particles.
- Finite fraction of particles in ground state for $T < T_c$.

Novel Numerical Approach

Tyson Price and Robert Swendsen

Do sum directly and see how N_0, the number of particles in the ground state, increases with N for $T < T_c$.

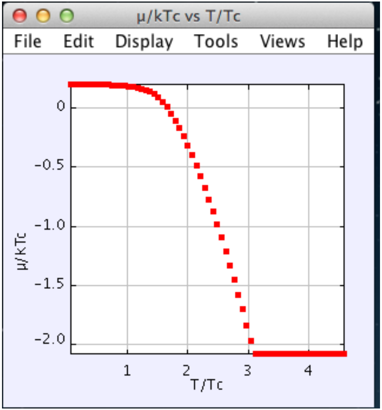
$$\overline{N} = \sum_{\vec{k}} \frac{1}{e^{\beta(\epsilon_k - \mu)} - 1} \qquad \vec{k} = \frac{2\pi}{L}(n_x, n_y, n_z).$$

$$\epsilon_k = \frac{\hbar^2 k^2}{2m} = \frac{\pi^2 \hbar^2}{2mL^2}(n_x^2 + n_y^2 + n_z^2).$$

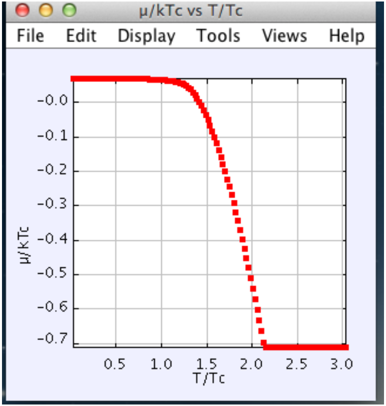
$$\overline{N}_0 = \frac{1}{e^{\beta(\epsilon_0 - \mu)} - 1}.$$

Dependence of μ on T

- Find $\overline{N}(\mu)$ for given T.
- Find $\mu(T)$ for given N.



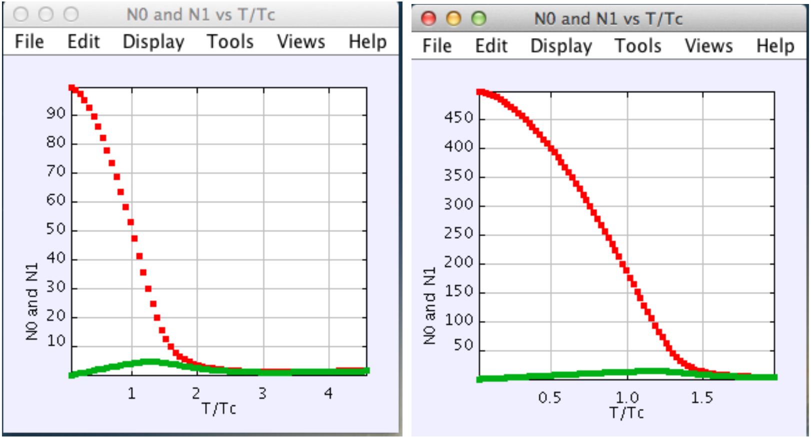
$N = 100$



$N = 500$

Nearly constant value of μ for $T < T_c$. Upper limit of μ equals lowest single-particle energy state.

Macroscopic Occupation of Lowest Energy State



(a) $N = 100$ (b) $N = 500$

Common student misconception: All particles in lowest energy state for $T < T_c$.

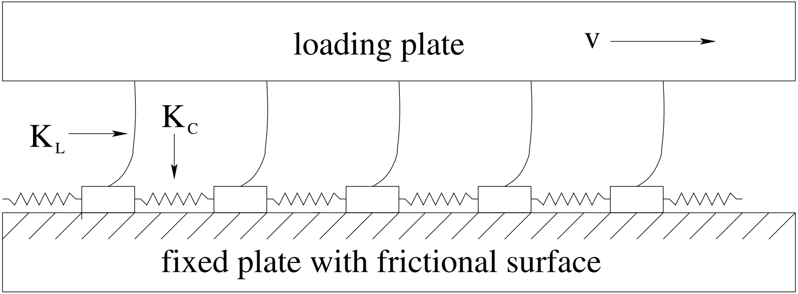
Gutenberg-Richter Scaling (1956)

- Empirical observation: Number of earthquakes with moment (size) $\geq M$:

$$N_M \sim M^{-b} \quad \text{(cumulative distribution).}$$

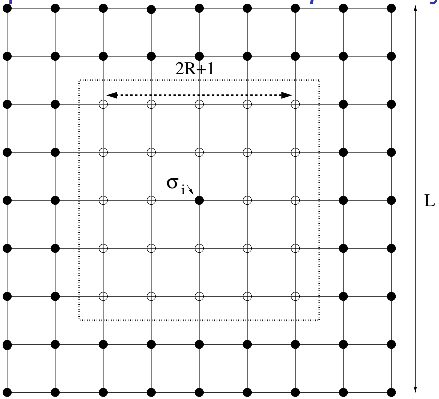
$$0.5 \lesssim b \lesssim 0.8.$$

Burridge-Knopoff model (1967)



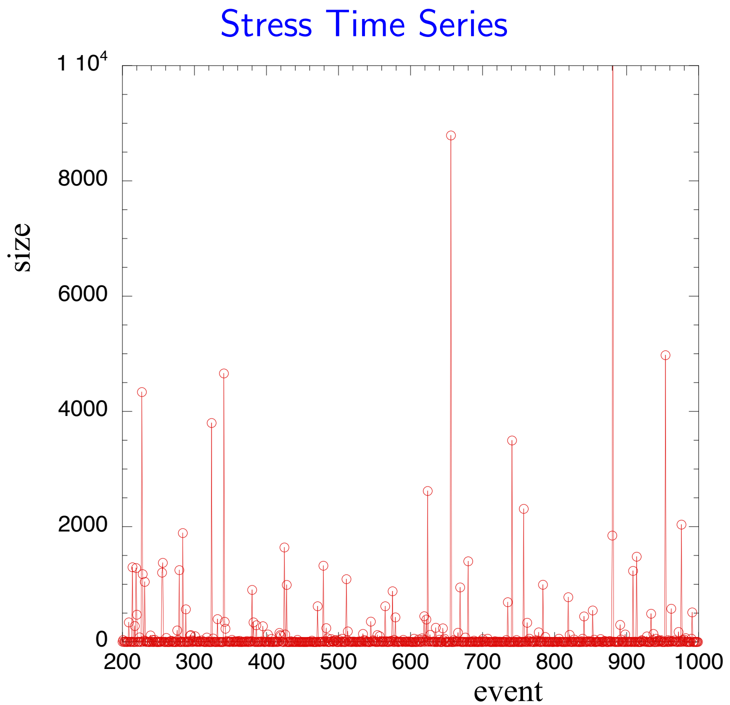
Olami-Feder-Christensen Cellular Automaton Model (1992)

Example of a *driven dissipative* system



- Stress σ_i on each site i. Each site has failure threshold σ_F and residual stress σ_R. Dissipation coefficient α. Initially distribute stress at random.

1. If $\sigma_i \geq \sigma_F$, reduce σ_i to σ_R and distribute stress $(1-\alpha)(\sigma_i - \sigma_R)$ to its neighbors.
2. Check neighbor sites and go to step 1.
3. Continue until $\sigma_i < \sigma_F$ for all i. Number of sites that fail constitute an earthquake of size s.
4. Reload the system: Find site with maximum stress and bring it to failure by adding $\sigma_F - \sigma_{\max}$ to all sites.



Stress Time Series
size
event
1 10^4
8000
6000
4000
2000
0
200
300
400
500
600
700
800
900
1000

Scaling of Events for Long-Range Stress Transfer

No scaling for short-range stress transfer.

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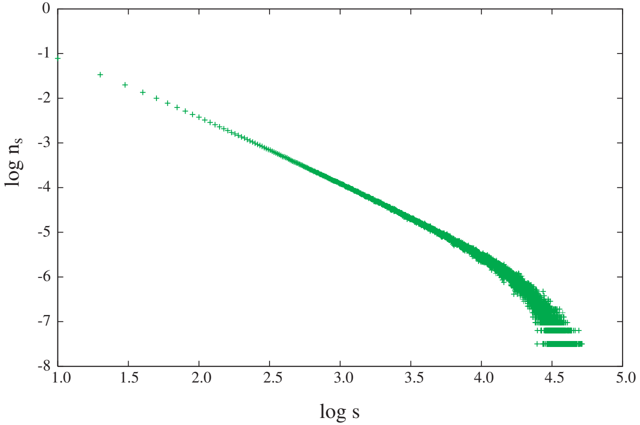
Long-range stress transfer:

$$n_s \propto s^{-3/2} \qquad (b = 5/2).$$

n_s, number of events (earthquakes) of size s.

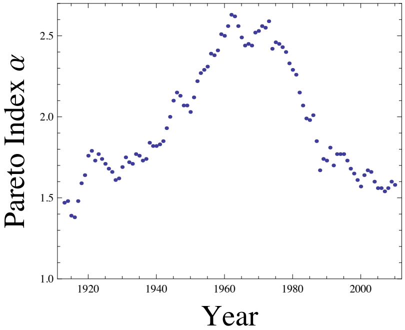


Pareto and Wealth Distributions

Vilfredo Pareto, b. 15 July 1848, observed that 80% of the land in Italy was owned by 20% of the population (1906). He also found that

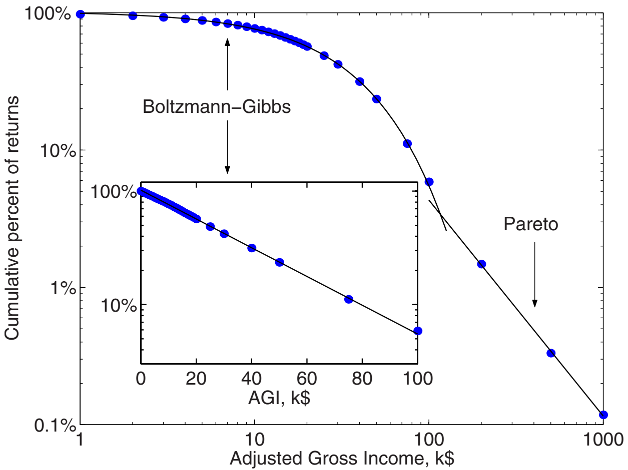
$$P(w) \propto w^{-\alpha} \quad (w \gtrsim w_c).$$

- $\alpha \approx 1.16$ for 80-20; $\alpha \approx 1.42$ for 70-30.
- Smaller $\alpha \implies$ more inequality.



Distribution of Wealth for Rich and Poor

$$P(w) \propto \begin{cases} e^{-w/\tilde{w}} & (w \lesssim w_c) \\ \propto w^{-\alpha} & (w \gtrsim w_c). \end{cases}$$



Cumulative probability distribution for U.S. Solid lines are fits.

Agent-Based Model

1. Choose at random a pair of particles i and j with energies w_i and w_j and let them "collide."
2. Particles i and j exchange energy according to

$$w_i \to r(w_i + w_j).$$
$$w_j \to (1 - r)(w_i + w_j).$$

r uniform random number between 0 and 1.
Total energy is conserved during the collision.

See the connection to statistical mechanics!

Yard Sale Model

A. S. Chakrabarti & B. K. Chakrabarti (2000)

$$w_i \to w_i \pm \tilde{\alpha} \min(w_i, w_j).$$

$$w_j \to w_j \mp \tilde{\alpha} \min(w_i, w_j).$$

$w_i = 1000$ at $t = 0$; $\tilde{\alpha} = 0.2$ and $N = 100$.

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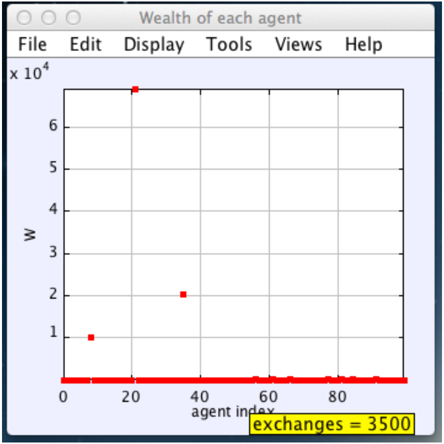

Does a Rising Tide Raise All Boats?

Arithmetic growth and the Yard Sale model

- What if we give each each agent the same amount after N exchanges?

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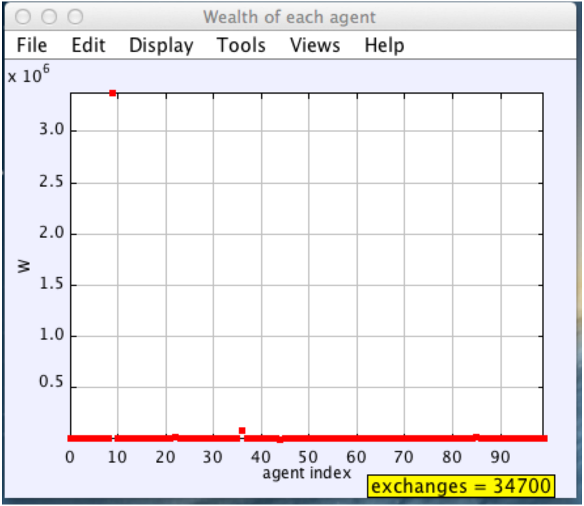


Geometrical Growth

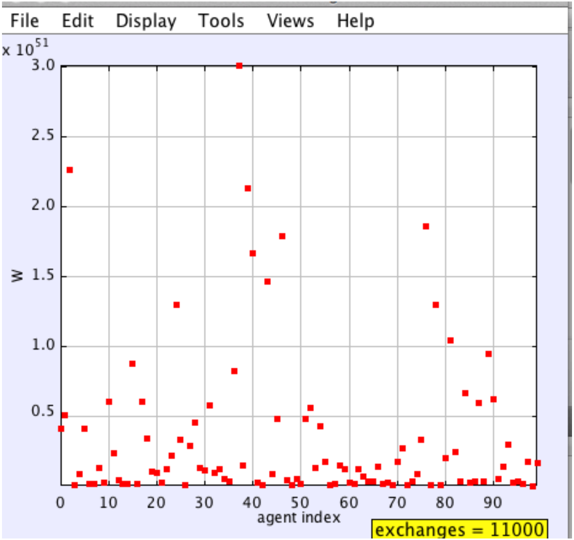
Wealth of society increases by a fixed percentage μ

Introduce parameter γ which determines how growth is distributed.

- $\gamma = 1$: expected return on investment.
- $\gamma < 1$: income redistribution (tax plus social programs).
- As γ increases, allocation of increased wealth weighted more toward agents with greater wealth.

Results of Exponential Growth

- For $\gamma < 1$, system is *ergodic*. Rank of each agent changes so that every agent has a chance to be the richest.



Effect of Increasing γ

$\gamma < 1$

- Economic mobility is nonzero and system is ergodic.
- Steady state wealth distribution reached after transient behavior and each agent's wealth grows as $e^{\mu t}$. As $\gamma \to 1^-$, bigger spread between rich and poor.

$\gamma > 1$

- System no longer ergodic. Growth in total wealth not indicative of growth of individual agent's wealth.
- Phase transition at $\gamma = 1$.

Models and the Real World
What is the use of simple models?

We can never have a totally realistic model of something as complicated as the economy.

- They force us to think quantitatively and expose implicit assumptions.
- Yield insight into mechanisms that might be universal.
- New paradigms suggest new questions and approaches.

Soapbox

- Computation is a third way of doing physics. In many cases insight comes from computation, not from traditional theoretical methods.
- Computation allows new possibilities in research and teaching.
- Computation allows us to reach more students.
- Physics departments should increase their efforts on reaching other science majors and non-science majors.
- Use open source software.
- Part of teaching is involving students in current research.
- AAPT/APS should hold more joint meetings.
- More physicists should run for political office!

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General

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Computational Physics Section of AJP

Jan Tobochnik and Harvey Gould, editors

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5. R. H. Swendsen, "Using computation to teach the properties of the van der Waals fluid," Am. J. Phys., to be published.
6. T. Price and R. H. Swendsen, "Numerical computation for teaching quantum statistics," manuscript in preparation.

Related Work

Posters PST2007–2009, Wednesday Morning

- Edit Yerushalmi, Elon Langbeheim, Shelly Livne, Samuel Safran, Ruth Chabay, and Nava Schulman, "Random and Structure 1, 2, 3."
- Elon Langbeheim, Shelly Livne, Edit Yerushalmi, and Samuel A. Safran, "Introductory physics going soft," Am. J. Phys. **80**, 51–60 (2012).

Remembering

- **Ken Wilson**, 1936–2013. From his 1982 Nobel Prize lecture: "... I found it very helpful to demand that ... a field theory should be soluble by computer, the same way an ordinary differential equation can be solved on a computer ... ."

  Wilson became interested in K-12 education and asked, "How can we tap into the natural love of learning exhibited by young children and change the education system in such a way as to sustain that love of learning throughout life?"
- **Sheng-keng Ma**, 1940–1983, is known for his work on critical phenomena and made important contributions to the Monte Carlo renormalization group method. He also wrote two textbooks:

Modern Theory of Critical Phenomena
Statistical Mechanics.