Sustainability, Complex Systems, and Computer Science:
The Perfect Fit of Powerful Tools to Planetary-Scale (energy/pollution) Problems?

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1 Abstract

Sustainability problems are phenomena of resource use and pollution resulting from large-scale human behaviour. They are generally caused by some form of consumption (mobility, purchasing, construction), which is connected to energy-intensive industrial processes. Meanwhile, *Complex Systems* also involve large-scale systems. This field uses tools from Statistical Physics, network science, and Computer Science to characterize systemic dynamics, especially micro- to macro- relationships. Thus, these two fields form a perfect match of urgent phenomena to tools for understanding the most salient features, in a world with increasing problems but also more 'big data' sets for analysis. Meanwhile, Computer Science can allow us to come up with intelligent, practical, real-world solutions using their results.

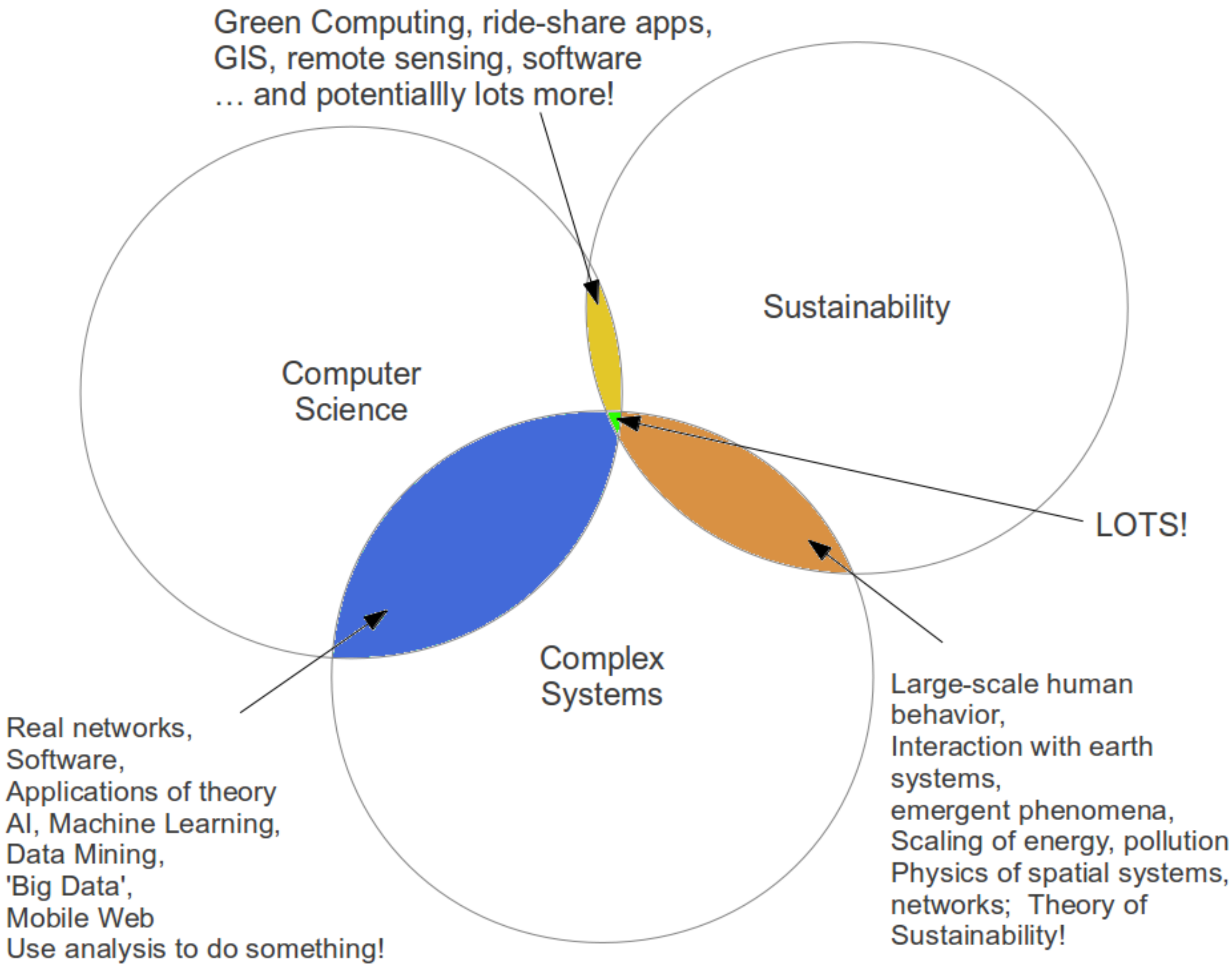
Here we investigate several areas (mostly mobility, but also urban scaling, and large-scale consumption) to look at ways to: A. Begin to understand crucial system dynamics, B. do something about it. Several projects, relevant papers, and project proposals are discussed, and tied together as perhaps a new direction for a kind of 21st Century (Complex) Sustainability Science.

Contents

2 Introduction: Definitions

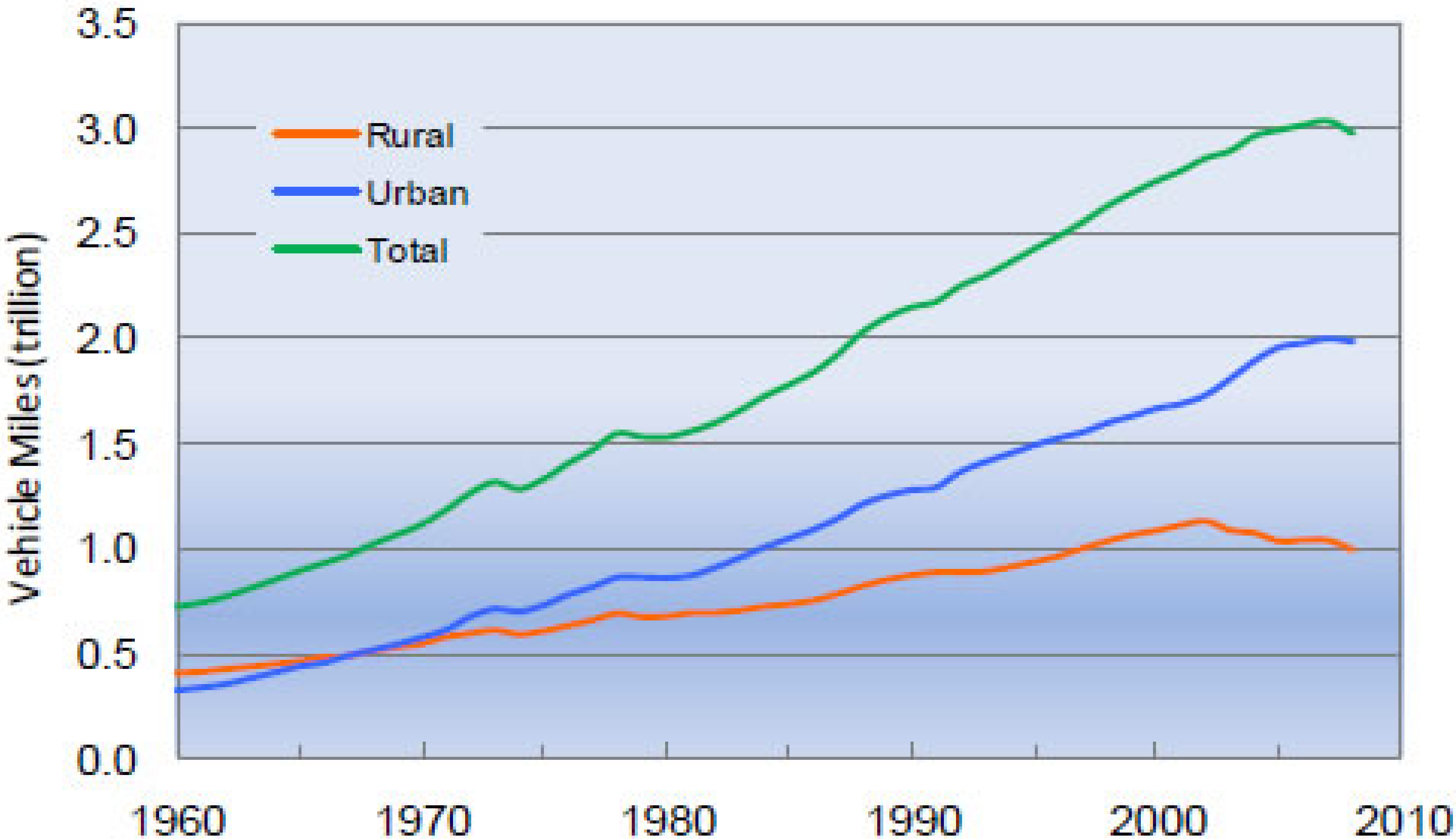
- 'Energy' = energy and/or CO2, a heuristic proxy for pollution (and other aspects of large-scale thermodynamic processes)
  - (debatable, but captures major features)
  - interested in large-scale effects, avoid 're-arranging deck-chairs'.
  - The climate/earth will 'judge' us by large-scale effects, not details.
- 'Sustainability' = ability of human and earth systems to co-exist and continue.
  - Some phenomena not global, scale plays intrinsic role.
  - Major unprecedented problems at largest scale (climate change, fossil fuel dependence).
- 'Complex systems' =
  - self-organizing systems,
  - 'many' parts,
- 'Complex Networks' =
  - Complex Systems of Networks
  - Network measures (Graph Theory) apply

3 Research Domain Intersections

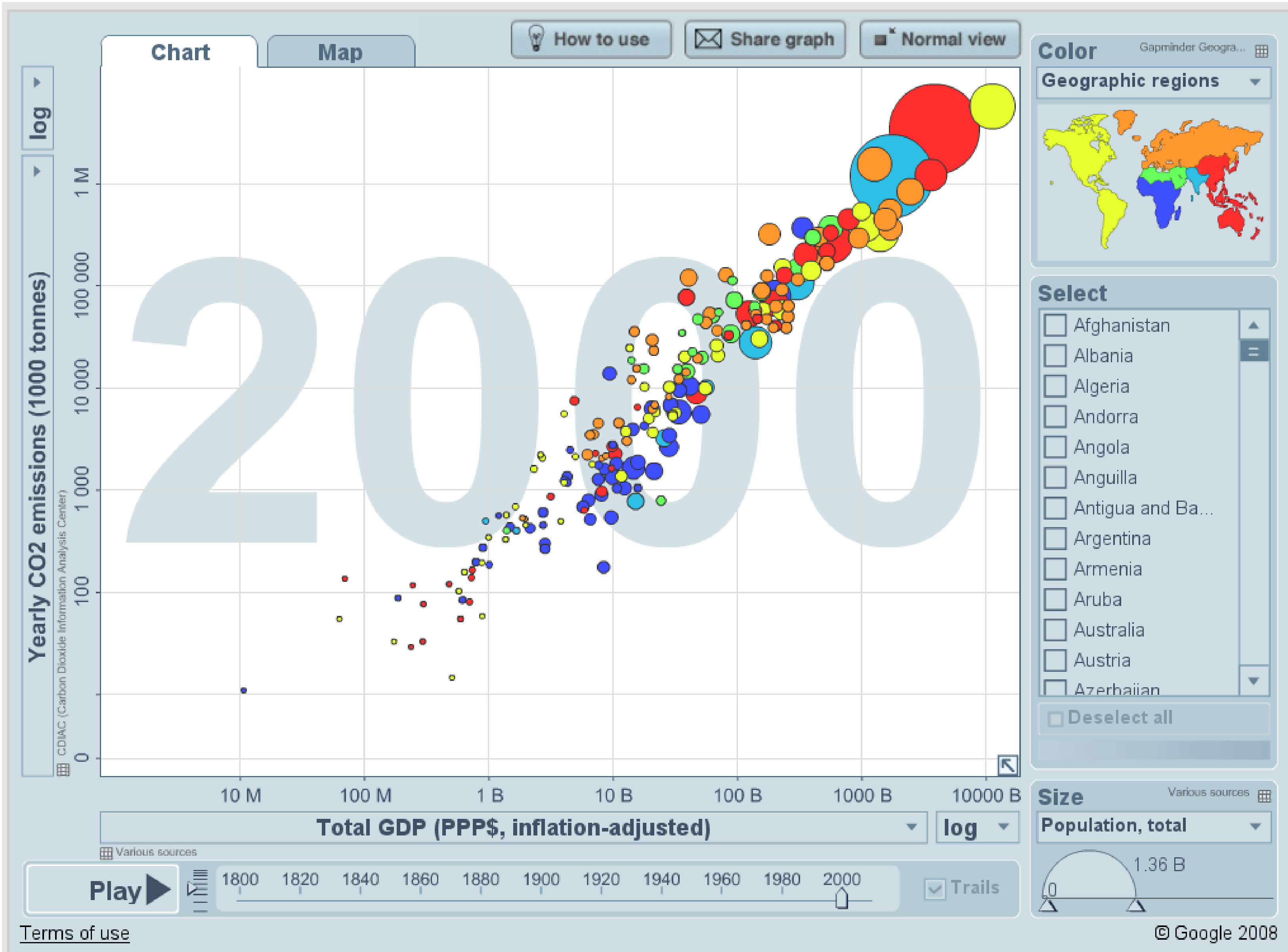


In terms of publications and projects, *Sustainability* does not have much to do with Complex Systems, and even less with Computer Science. Will this change?

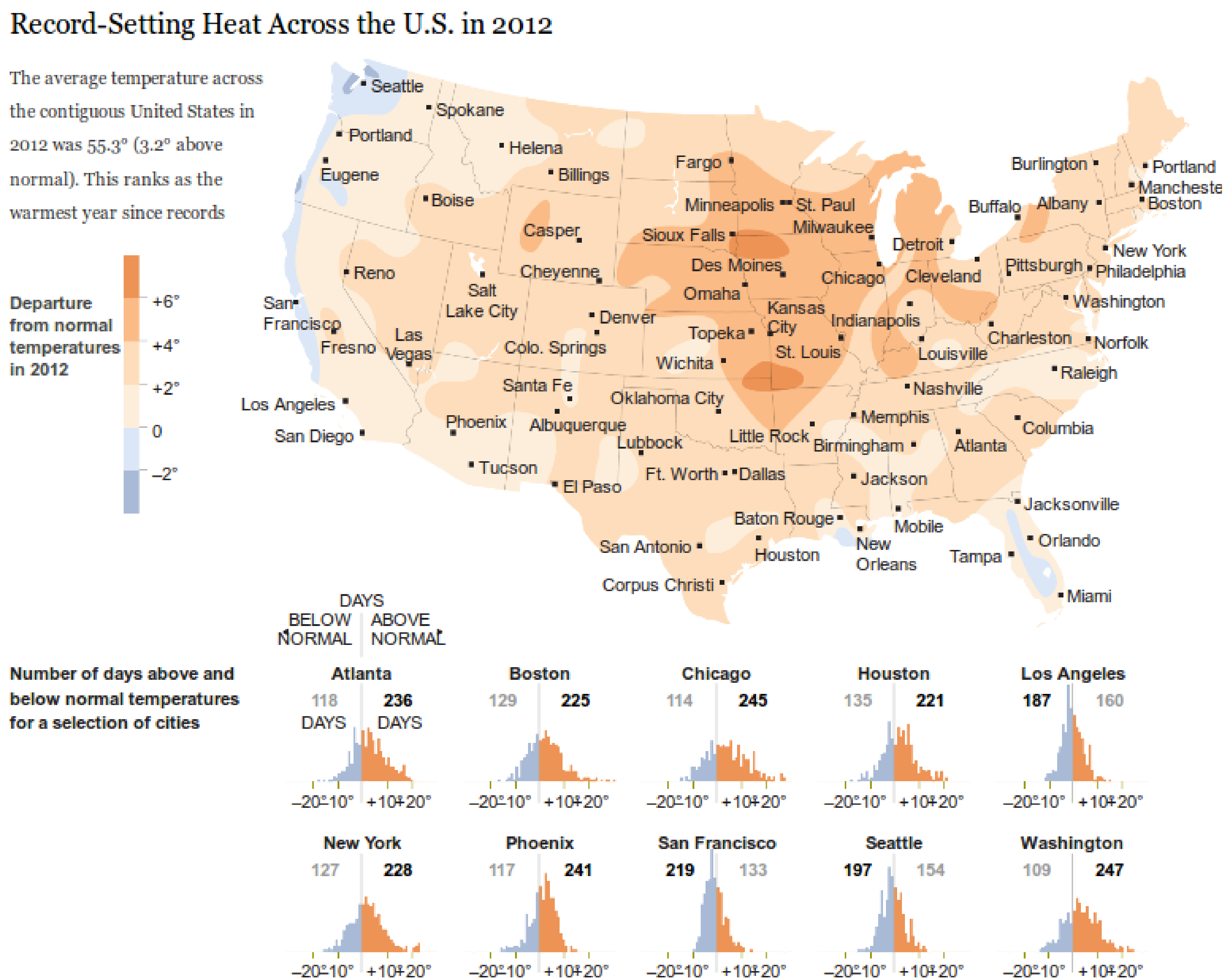
4 Sustainability Phenomena / Problems



(Very) large-scale behavior:
Vehicle Miles Travelled in the USA from 1960-2008 (US Federal Highway Admin.)



(Very) large-scale behavior: Total tons CO2 emissions vs. GDP; (gapminder.org)
Both can been studied as network phenomena.



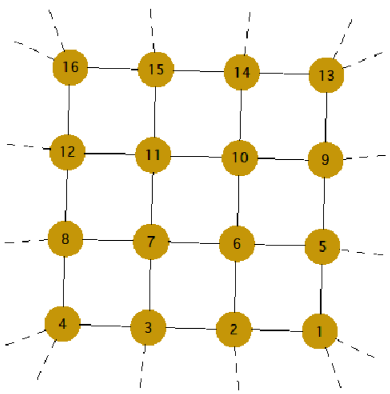
(Very) Large-scale effects: 2012 was the hottest summer to ever occur in the USA. (New York Times)

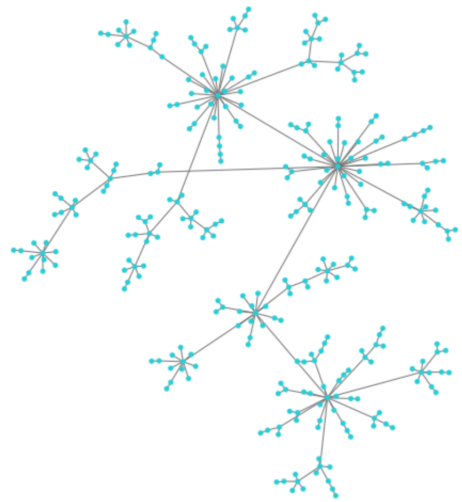
- Sustainability is messy! (from a rigorous Computer Science point of view)
- (often) inherently large-scale $\implies$ hard to capture features at linear scale
- urgent problems! Climate change, metabolic syndrome, species extinction, large-scale system failure?
- generally directly/indirectly by large-scale industrial processes from consumption $\rightarrow$ burning of fossil fuel (engines, plants, factories, furnaces)

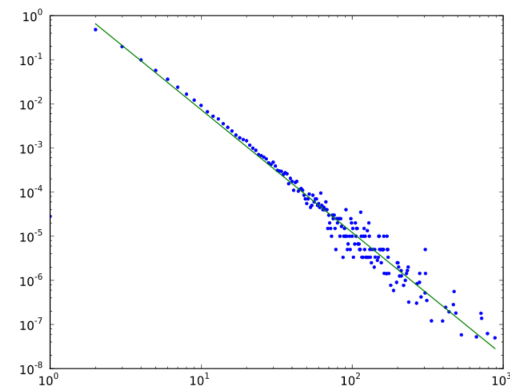
  I.e. modern world full of 'fires'. Identifying fires and (behavioral/systemic) causes interesting and potentially very useful.
- Post-industrial quality of life. Behavioral juggernaut? Unstoppable self-feeding social network automaton?
- Use technology to avoid/mitigate these problems?

  (Efficiency, coordination, resource-sharing, cost-reducing)

5 Complex -Systems/ -Networks







Many large-scale systems can be seen as networks; A scale-free (Barabasi-Albert) network having power-law degree distribution created by self-organizing preferential attachment (aka 'Yule Process') - captures self-similarity of network [3]

- Why the line? (Fat tail)

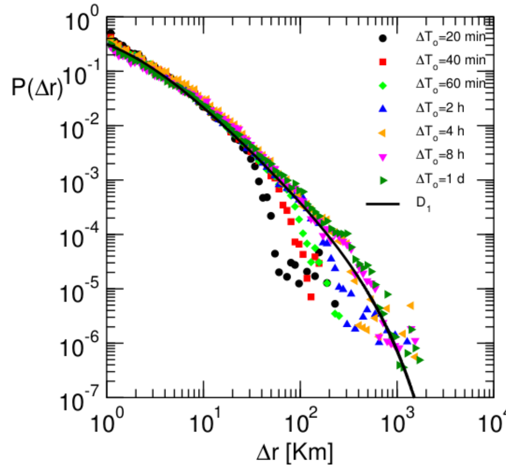
$$f(x) = Cx^{-\beta} \implies \log f(x) = -\beta \log x + \log C$$

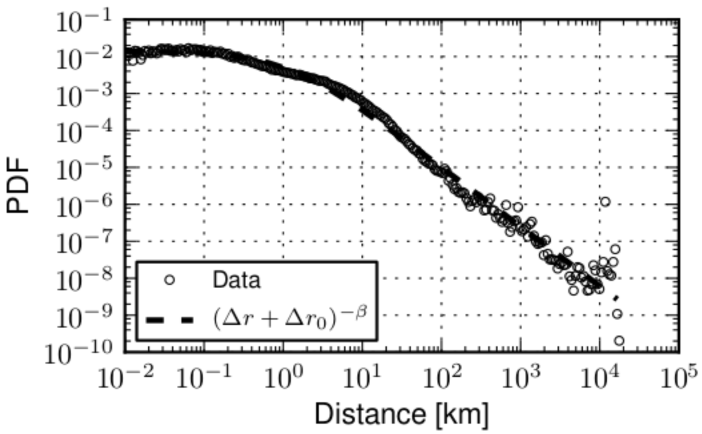
- Non-'physics' systems as particle systems - apply statistical physics, graph theory, statistics to real-world large-scale phenomena: Micro- to macro- emergence, phase transitions, large-scale system statistics (e.g. mobility patterns), network measures (degree distribution, assortativity, betweenness centrality, etc.).

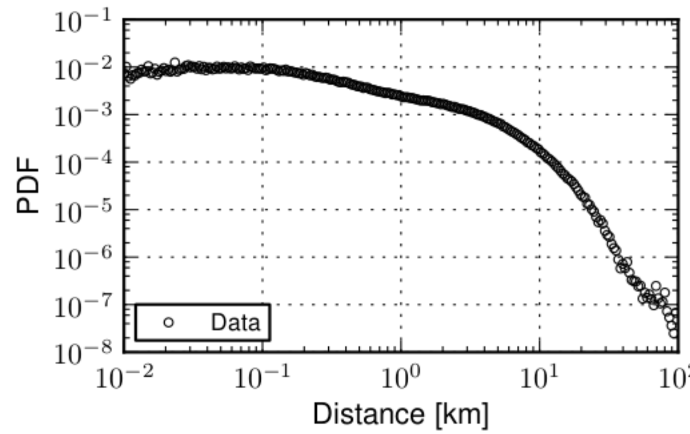
- Nice tools to study salient scaling phenomena. (E.g. Major sources of CO_2 and underlying system features.) [16, 1]

6 Part A: Some Recent Work in Complex Systems, Relevant to Sustainability

6.1 Mobility scaling

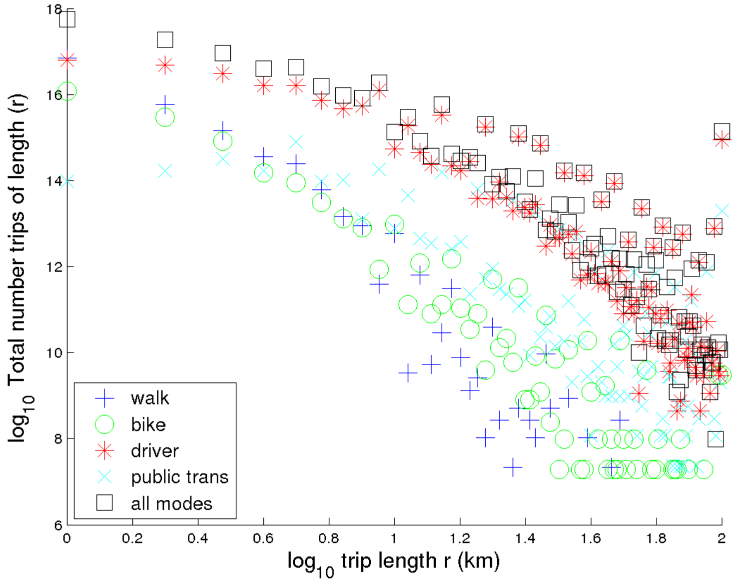


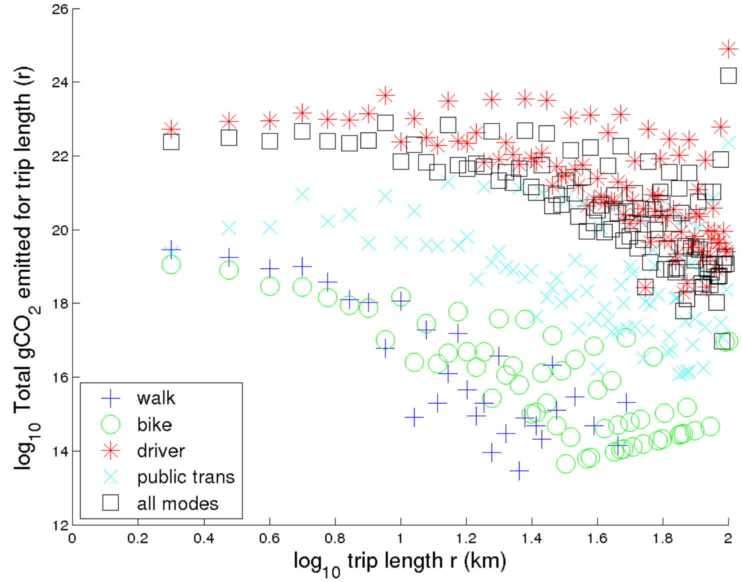




- Gonzalez, et al. 2008: Trip lengths follow a truncated power law: $p(\Delta r) = (\Delta r + \Delta r_0)^{-\beta} e^{-\Delta r/\kappa}$ $\beta \approx 1.75$ [10] Song, et al.: Mobility 93% predictable. [21]
- Noulas et al. 2012: Long-range trips $\rightarrow$ power law ($\beta \approx 1.50$) Short-range trips not power law. ($\beta \approx 4.67$) Bend in dist. defines natural edge of city. [18] (Decompose short trips $< 10^2$ km by mode?)
- Cho, et al. 2011: Social networks influence mobility patterns. [7]

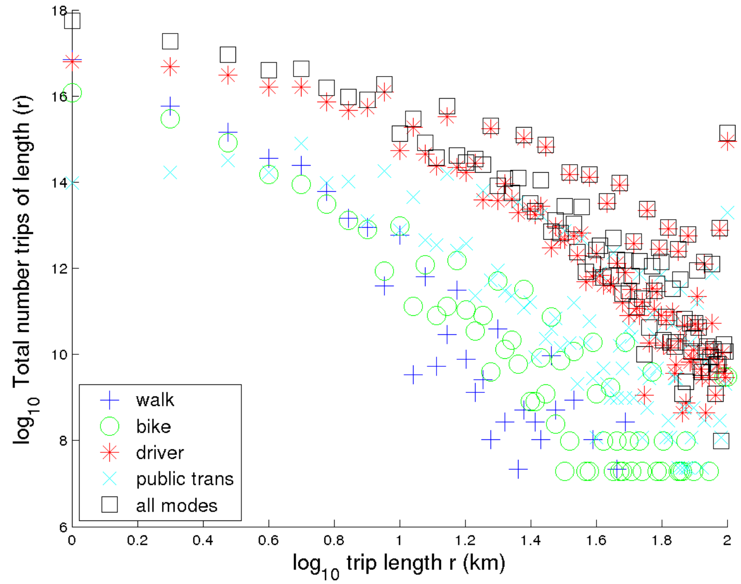
7 Current work (in progress) - Extending Trip Length Scaling to 'Energy'

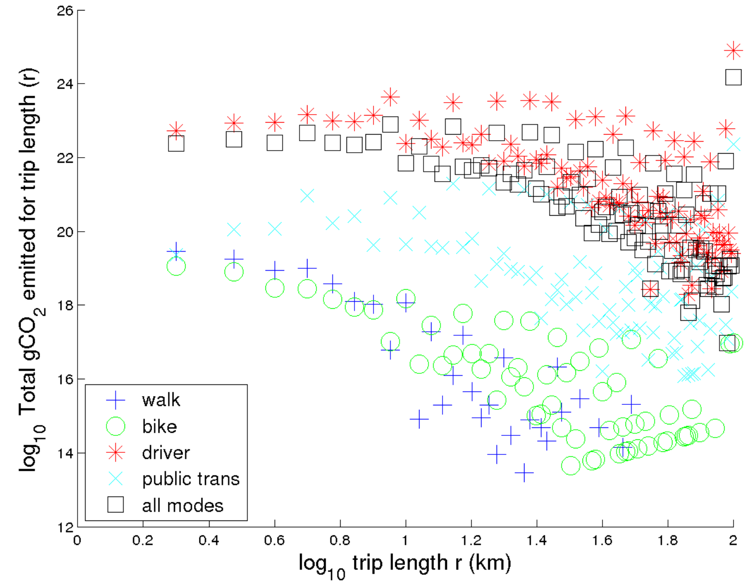




- Above works do not mention: A: Mode, or B: 'energy'.
- Mobility in Germany 2008, Trip length survey results ($\approx$ 200000 trips)
- Re-iterate Gonzalez, Noulas work to find trip-length distribution, convert to CO_2 emissions using available CO_2/km values.
- How do trip lengths scale, what is resulting 'energy'?
- We can derive the following equation: $\epsilon_m(\Delta r) = p(\Delta r|m) * t_m * \Delta r * c_m$,

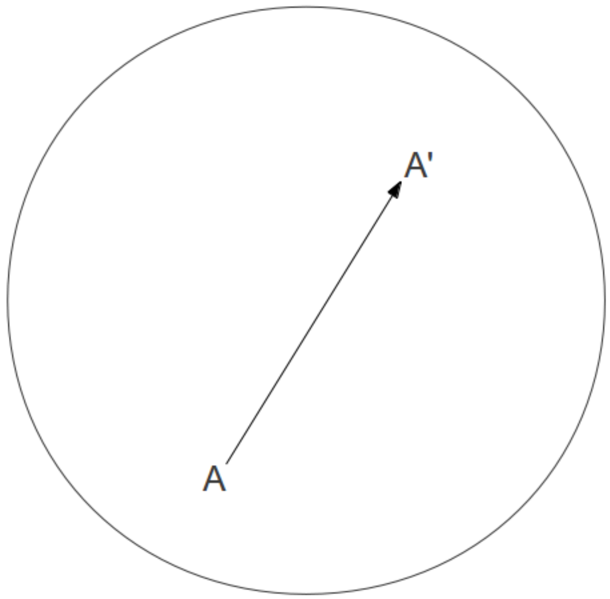
  Simply a re-scaling of $p(\Delta r|m)$ by positive values. If $p(\Delta r|m)$ follows a truncated power law, has meaning for system and for emissions.

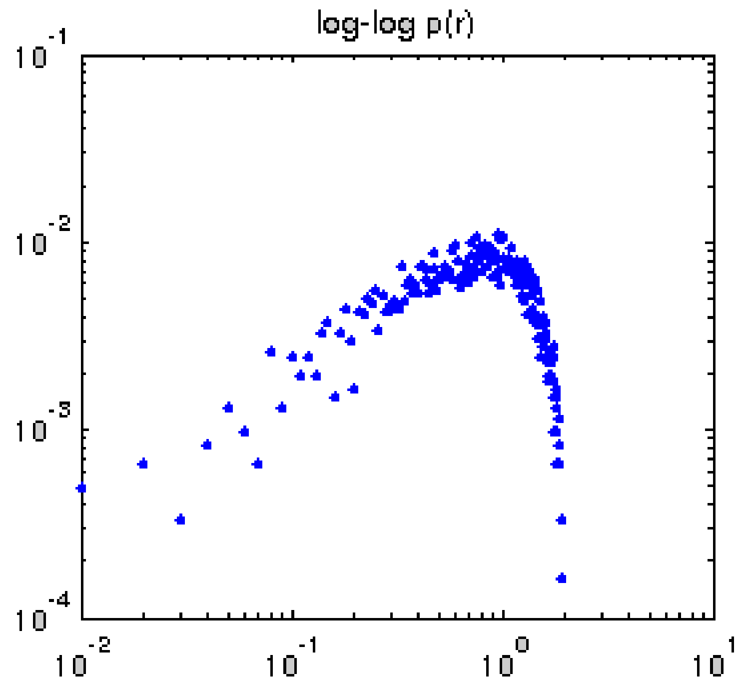




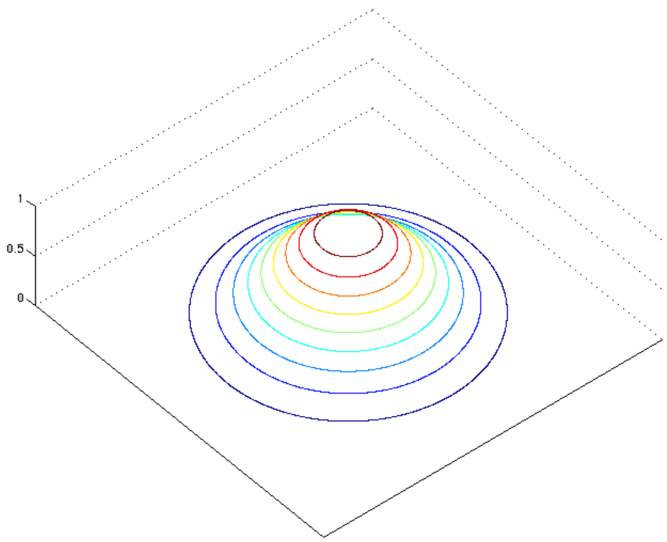
- Initial exponent results: Walk: 4.1; Bike: 3.3; Public Trans. 2.2; ... (more later)
- What does this curve say about our system? The possibility of a fat-tail becomes very significant here, since high-'energy' modes are those that make the longer trips.
- Connection between city growth and high-energy modes at the urban perimeter?
- Related to fundamental growth patterns of colonies of organisms or other phenomena?
- How to improve? - Represents extremely large amount of 'energy' in many modern societies.
- Elasticity of CO_2 to policy changes? (mode shift towards pedestrian, mode efficiency, etc.)

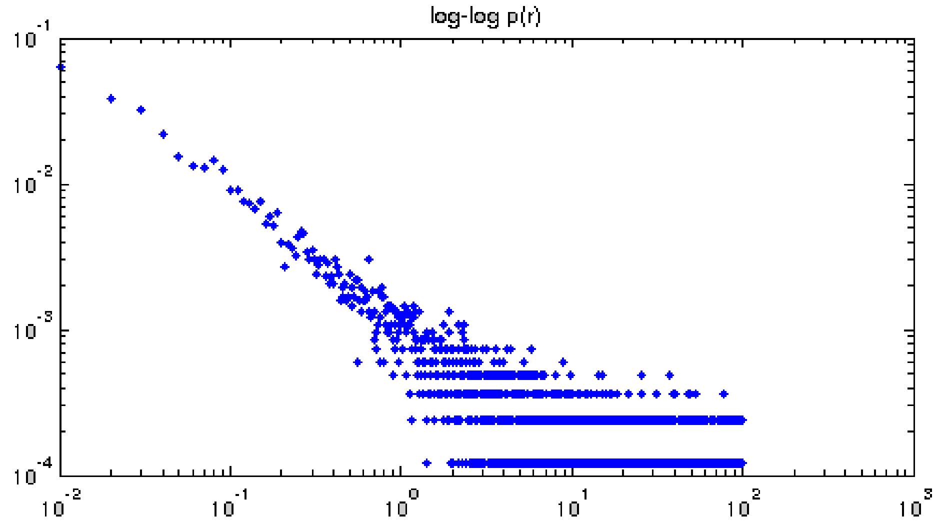
7.1 Some interesting early results - Theoretical Trip Length in a 'Circular City'





Monte Carlo simulation with origin and destination from uniform distrib. in circle:
Does not seem to generate power law trip length distribution.

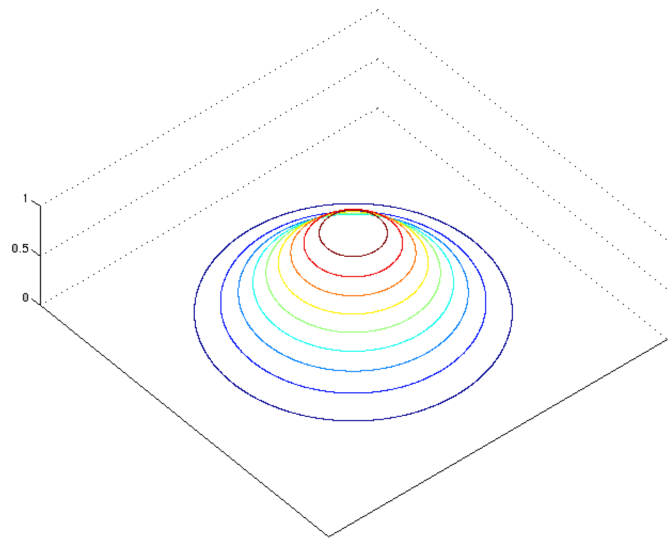


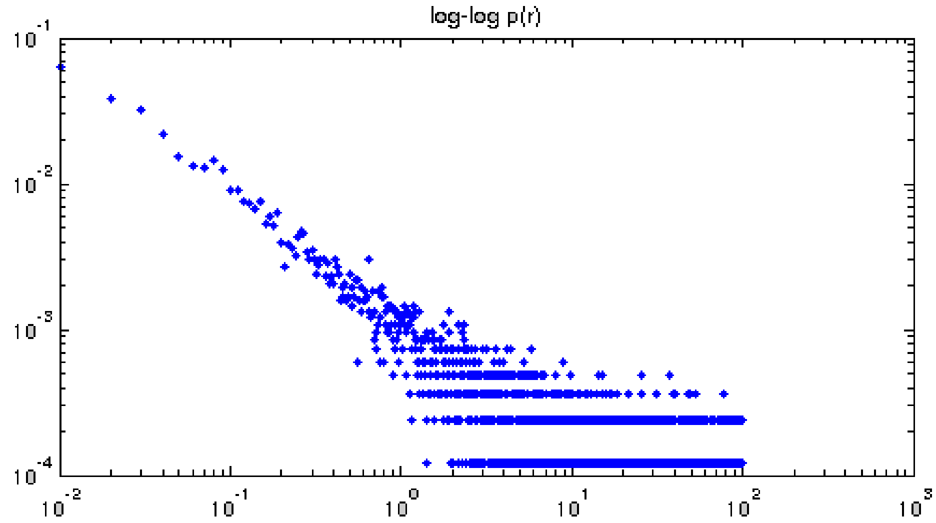


With added constraints:

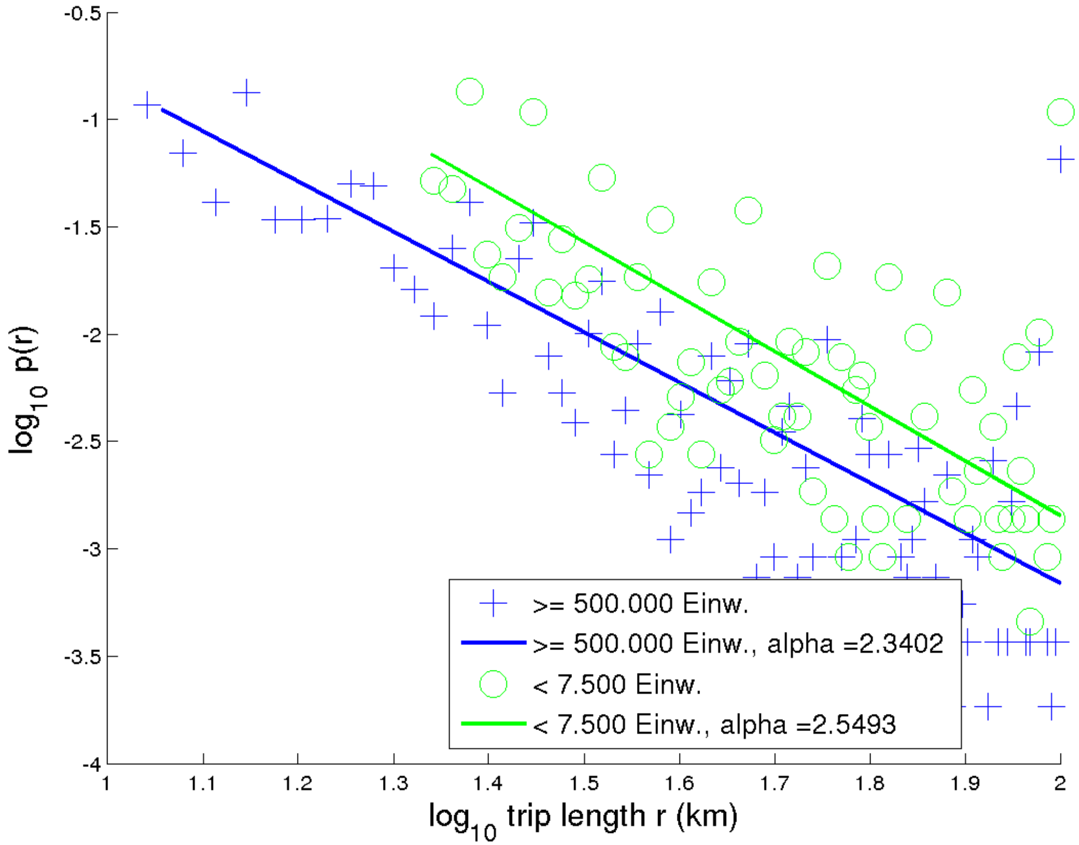
- Fixed identical total travel distance budget for all individuals - keep taking trips until used up.
- Gaussian origin-destination distribution
- Trip chaining

... trip length dist. resembles a power law?!





- What's going on? Realistic assumptions?
- Analytical result? Power law?
- How robust is trip length distribution to input parameters? multi-centered city, ellipse, modes, etc.
- Origins/destinations truncated to circular city. Using 2-D Gaussian, can we re-create empirical 'bent' power-law trip-length distribution $\Longrightarrow$ urban boundary? (Noulas, Gonzalez, above)
- If 'modes' are added, (i.e. means of mobility having characteristic velocity, energy distributions) what does 'energy' function look like?



Plotting trip lengths by size of urban area reveals compelling differences... and begs many questions.

Mode share? Energy function?

Relation between trip length and urban parameters.

What does this say about the city as a system? ... [COMMERCIAL BREAK]

7.2 Aside: Power law fitting with rigorous methods.

Many functions can look like power laws:

A. Clauset, C. R. Shalizi and M. E. J. Newman

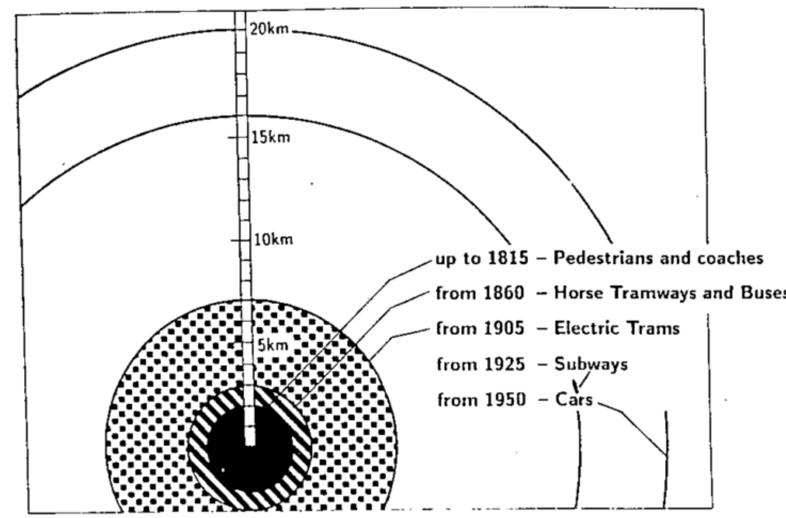
	name	distribution $p(x) = Cf(x)$ $f(x)$	C
continuous	power law	$x^{-\alpha}$	$(\alpha-1)x_{\min}^{\alpha-1}$
	power law with cutoff	$x^{-\alpha}\mathrm{e}^{-\lambda x}$	$\frac{\lambda^{1-\alpha}}{\Gamma(1-\alpha,\lambda x_{\min})}$
	exponential	$\mathrm{e}^{-\lambda x}$	$\lambda \mathrm{e}^{\lambda x_{\min}}$
	stretched exponential	$x^{\beta-1}\mathrm{e}^{-\lambda x^{\beta}}$	$\beta\lambda \mathrm{e}^{\lambda x_{\min}^{\beta}}$
	log-normal	$\frac{1}{x}\exp\left[-\frac{(\ln x-\mu)^2}{2\sigma^2}\right]$	$\sqrt{\frac{2}{\pi\sigma^2}}\left[\mathrm{erfc}\left(\frac{\ln x_{\min}-\mu}{\sqrt{2}\sigma}\right)\right]^{-1}$
discrete	power law	$x^{-\alpha}$	$1/\zeta(\alpha, x_{\min})$
	Yule distribution	$\frac{\Gamma(x)}{\Gamma(x+\alpha)}$	$(\alpha-1)\frac{\Gamma(x_{\min}+\alpha-1)}{\Gamma(x_{\min})}$
	exponential	$\mathrm{e}^{-\lambda x}$	$(1-\mathrm{e}^{-\lambda})\,\mathrm{e}^{\lambda x_{\min}}$
	Poisson	$\mu^x/x!$	$\left[\mathrm{e}^{\mu}-\sum_{k=0}^{x_{\min}-1}\frac{\mu^k}{k!}\right]^{-1}$

- Uses Kolmogorow-Smirnov MLE fitting statistics to find best xmin (start of 'tail') and goodness-of-fit.
- Adds significant rigor to power-law fitting (don't just take logs and fit a line!)
- Methods, code implemented for non-binned [8] and binned [23] data.
- Requires server for processing (many iterations).

7.3 Cities - Scaling

Table 1. Scaling exponents for urban indicators vs. city size

Y	β	95% CI	Adj-R^2	Observations	Country–year
New patents	1.27	[1.25,1.29]	0.72	331	U.S. 2001
Inventors	1.25	[1.22,1.27]	0.76	331	U.S. 2001
Private R&D employment	1.34	[1.29,1.39]	0.92	266	U.S. 2002
"Supercreative" employment	1.15	[1.11,1.18]	0.89	287	U.S. 2003
R&D establishments	1.19	[1.14,1.22]	0.77	287	U.S. 1997
R&D employment	1.26	[1.18,1.43]	0.93	295	China 2002
Total wages	1.12	[1.09,1.13]	0.96	361	U.S. 2002
Total bank deposits	1.08	[1.03,1.11]	0.91	267	U.S. 1996
GDP	1.15	[1.06,1.23]	0.96	295	China 2002
GDP	1.26	[1.09,1.46]	0.64	196	EU 1999–2003
GDP	1.13	[1.03,1.23]	0.94	37	Germany 2003
Total electrical consumption	1.07	[1.03,1.11]	0.88	392	Germany 2002
New AIDS cases	1.23	[1.18,1.29]	0.76	93	U.S. 2002–2003
Serious crimes	1.16	[1.11, 1.18]	0.89	287	U.S. 2003
Total housing	1.00	[0.99,1.01]	0.99	316	U.S. 1990
Total employment	1.01	[0.99,1.02]	0.98	331	U.S. 2001
Household electrical consumption	1.00	[0.94,1.06]	0.88	377	Germany 2002
Household electrical consumption	1.05	[0.89,1.22]	0.91	295	China 2002
Household water consumption	1.01	[0.89,1.11]	0.96	295	China 2002
Gasoline stations	0.77	[0.74,0.81]	0.93	318	U.S. 2001
Gasoline sales	0.79	[0.73,0.80]	0.94	318	U.S. 2001
Length of electrical cables	0.87	[0.82,0.92]	0.75	380	Germany 2002
Road surface	0.83	[0.74,0.92]	0.87	29	Germany 2002

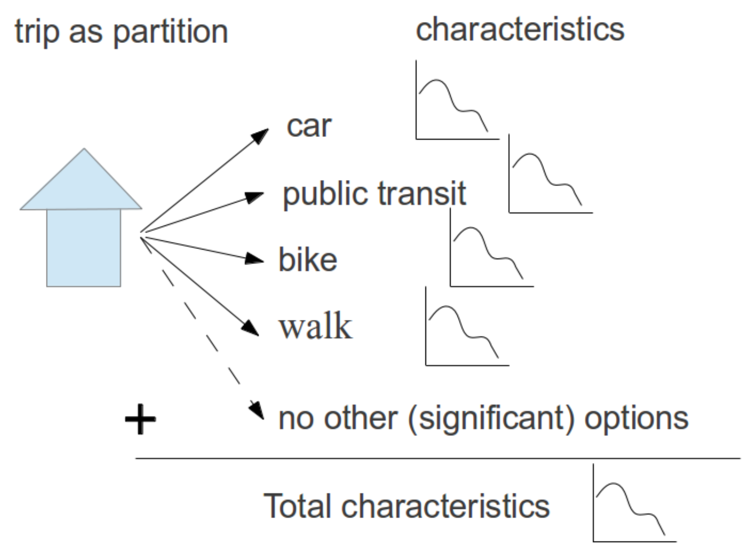


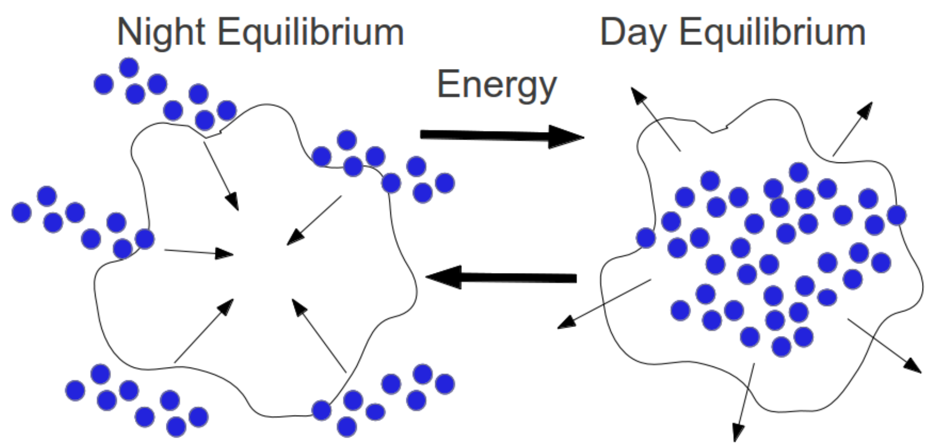
- 'Allometric' scaling of various urban parameters with population. (Bettencourt, et al., 2008) [6]

  'Why we have cities' - some things scale the way we would want/expect

- Marchetti's Constant: People travel ≈1 hour / day. (Germany: 1h 20m) The size of Berlin followed faster modes of transportation. Note that the faster the mode, the higher the 'energy'. Also note the key role mobility plays in city size. (Marchetti, 1994) [14]

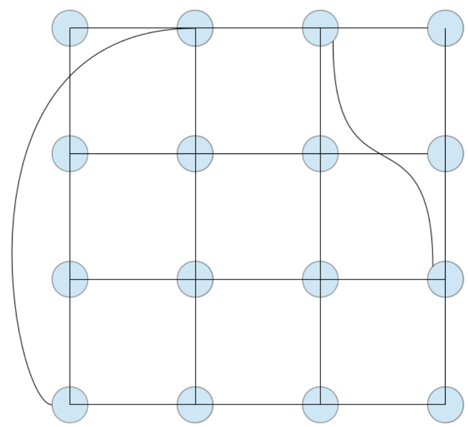
7.4 Thermodynamic model to relate mobility, city size, and other parameters?

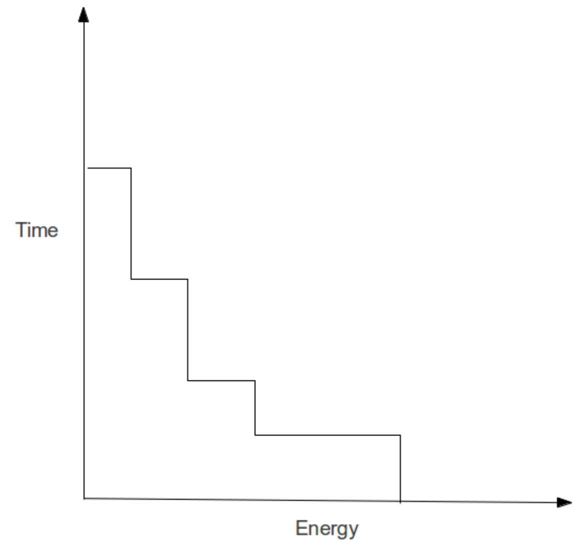




- Individuals partition selves into 'energy levels' of modes, having particular characteristics (speed, energy, trip length) - greatly reduces 'degrees of freedom' of large-scale city possibilities.
- In theory, free will; In practice mode share as predominant state given urban parameters. (Thought experiment: Probability no one drives tomorrow?)
- Note that the city moves between (roughly) two equilibrium states 'day' and 'night'. This transition requires a great deal of energy.
- Model (system of equations) to relate mode share, population, geographic size, energy share, trip lengths, velocities, travel time, infrastructure?

7.5 ...and/or a Small-World Network model to understand bandwidth between parts of the city.





Model a city mobility as a small-world network?

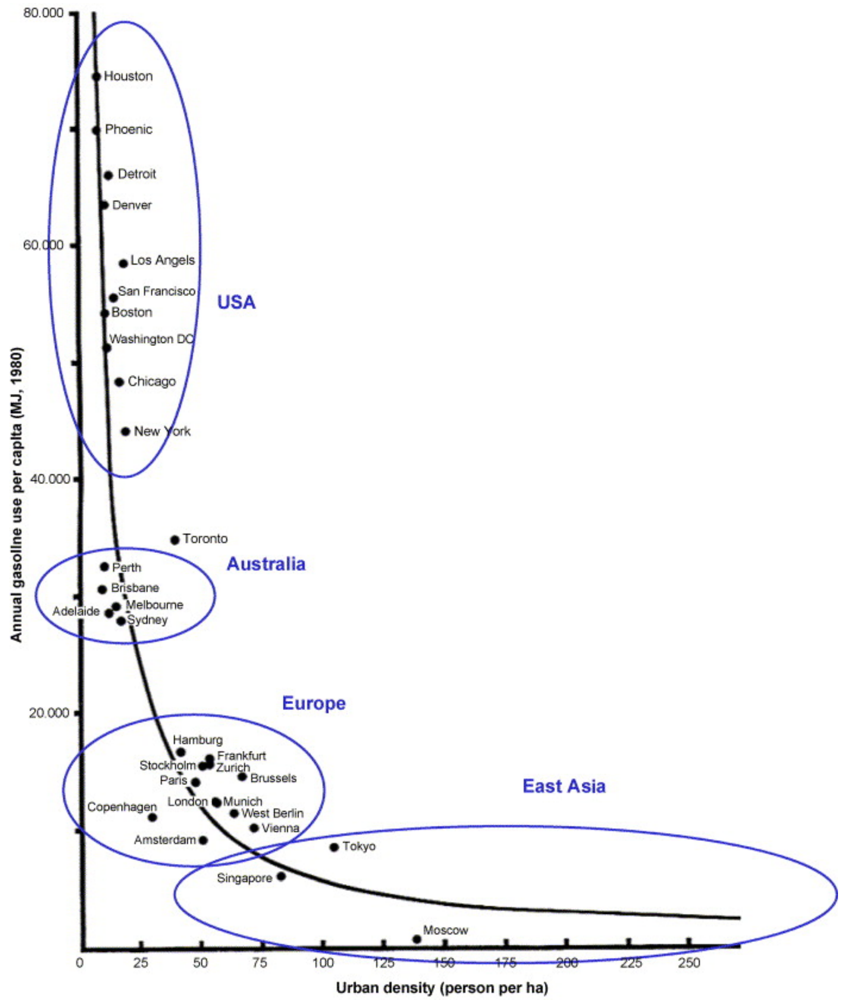
- Preserve bandwidth between grid-cells.
- Energy, time, and cost trade-offs between taking short and long hops: Pareto Front
- Useful theoretically...

  E.g. How 'small world' is an 'ideal' city given mode share?
- ...empirically...

  E.g. How 'Small world' is city X? Does mode share match 'small-world-ness' of a particular city's infrastructure?
- ...and in terms of policy changes?

  E.g. We can't all suddenly walk to save energy, unless we quit our jobs.

7.6 Major Efforts/Opportunities Extending Complex Systems to Sustainability



A few groups/projects connecting Complex Systems and Sustainability:

- West, Bettencourt (Santa Fe), Dirk Helbing (ETHZ) and FutureICT)
- Newman, Kenworthy 1980s - large-scale view of density and fossil fuel consumption [17]
- Michael Batty (UK), Philip Ball, Carlo Ratti (MIT), others - Urban form, complexity [5] [2]

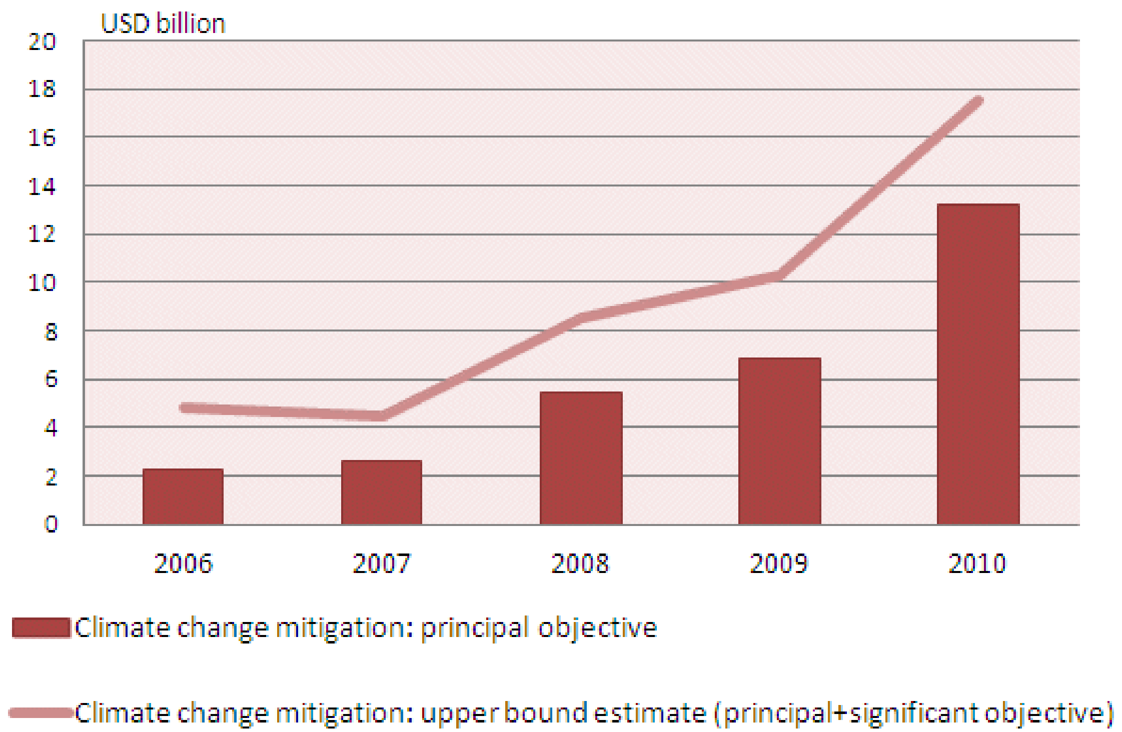
8 How to be happy when we are depressed. (and how can population growth be OK, and Computer Science might help?)

- Sustainability problems 'depressing' - feel powerless in system.
- However - 'Drive less, fly more.' Pedestrian lifestyle, etc. e.g. possible that quality of life can increase with less industrial consumption. (lower footprint - with fun!)
- Growing interest in perma-culture (also in US)
- Sigmoidal growth = resource shortage and saturation in a finite world: many non-linear negative implications.

  However, *super-linear growth of sharing and cooperation opportunities* ($O(n^2)$ edges in complete graph)
- Power of information. Intelligent automation, 'big data' processing, mobile web, data processing, communication very effective.

  Problems as algorithmic challenge. Sustainability just another application.
- Ebay, Craigslist, Amazon, Mitfahrgelegenheit, Couchsurfing. Net energy savings by re-selling/sharing through communication.
- Instantaneous communication, 'epidemics' of (perhaps sustainable) behaviors.
- Intelligent, secure, use of 'big (mobile) data' - personal information. (Already doing it, why not use it for 'positive change'?)
- Extension of (spatial) economies of scale through telecommunications, applications.

9 Part B: The longer term - What to Do? (Thoughts on Strategic Research directions [and funding...])



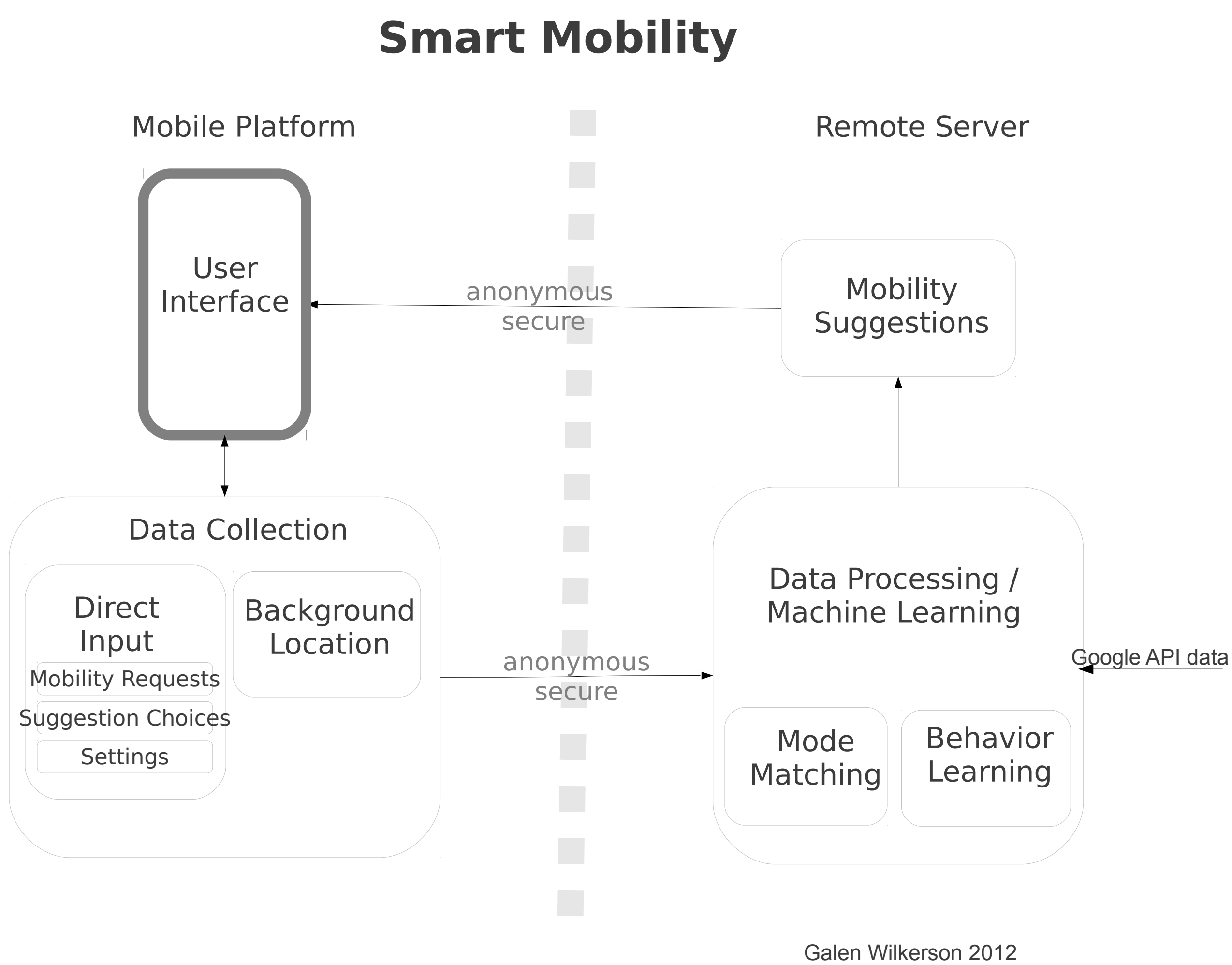
Sustainability funding is growing... (OECD)

- Climate-KIC (European Institute of Innovation and Technology (EIT)) - Innovation, Technology, Sustainability
- FuturICT (ETHZ - Helbing) - Innovation, Technology, Sustainability - 10 year EU 1 billion
- European Commission e.g. '...LIFE has co-financed some 2,750 projects for a total of EU 1.35 billion'
- World Bank - 'Climate change is core to our mission'
- Many others (Foundations, Governments, etc.)
- Energiewende...

9.1 What to Do? I. Applications

Address problems revealed by understanding system (salient features, dynamics):

9.1.1 Example: Fully-anonymized and secure, automated, smart-mobility



- Mobility *not* 'transportation': mode-independent, focus on quality of service; 'driving while texting'
- Why?
  - Addresses exactly high-energy mobility at edge of city. cars as 'small buses' through intelligent information sharing
  - Would you run a car as a business? Only $\approx 25\%$ usage of capacity!
  - Addresses increasing real energy prices: energy harder to get, slow economy
  - Allows quality of life with privacy: human health and well-being
- Fully-anonymized, secure?
  - Establish *highly robust location-privacy* (along with standard user-anonymization) protocol for geotagging/location-based apps.
  - *establishes industry standard* for other providers to allow true location privacy.
  - e.g. I can calculate distances on server, but *cannot deduce location*.
- How?
  - Phone as 'electronic thumb' for mobility
  - automated? - machine learning/AI for clustering of users and real-time scheduling
  - location: people are very predictable - (Song, et. al.) [21]
  - location: similar people go to similar places; we can capture major features of mobility - (pentland et. al.) [9]
  - Rideshare comes for free with a good job done on other modes - market-share = economies of scale.
  - cloud computing for processing - parallel, scalable, mobile

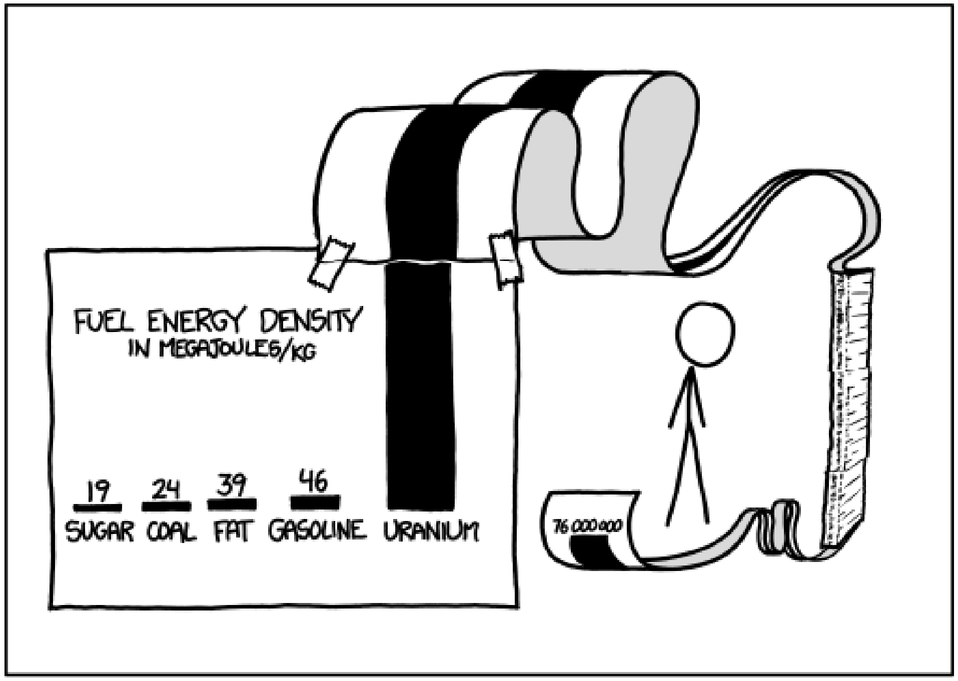
9.1.2 Example: Mobility analysis for cities?

- cities have limited budgets!
- identify major areas of energy consumption and inefficiencies
- Begin to see empirical data with geo-tagged Twitter, mobile phone data, (e.g. Orange) and others ...social networks of course!

9.1.3 Other areas: Consumption analysis for consumers - smart eco-footprinting feedback mechanisms, information sharing

- use trade network information (see Appendix: Product Space)
- avoid confusion of bio/local
- e.g. if I buy a computer locally, does it really matter?
- automated
- again, can also extend as country energy analysis (trade networks - see Appendix)

9.2 What to Do? II. Develop a (complexity-based) theory and science of sustainability!



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY.*

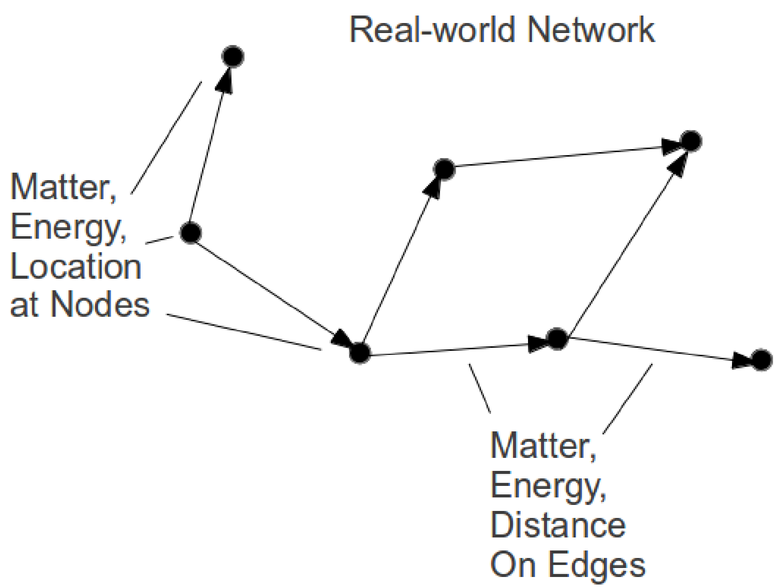
Log Scales (xkcd.org): log scale (orders of magnitude) as best perspective on large systems?

- illustrate salient features? - allows 'rigorous thinkers' to remove 'noise' and reduce dimensionality of problem
- capture system properties? (i.e. gets down to factors relating to large-scale behavior, consumption, emissions)
- communicate to policymakers - log scale measure communicates qualitative information 'automatically'?

- use new 'big data'!
- Not just economics or some other field, but interaction of a variety of 'parameters' - transcend fields
- 'complex systems' of sustainability. i.e. quality of life while cutting out energy? Does life look significant different when it is (much) more efficient? Where is energy embodied in quality of life?
- Look for 'fires', understand them, put them 'out'
- Climate as 'proof adversary' for large-scale behavior? e.g. Us: "We are being ecological...!" Climate: "nope, have some more climate change"
- Lots on climate modeling, not as much on human action and outputs
- Helbing, 2011: Urban sustainability by 'Reality Mining' [22]
- Muneepeerakul, 2012: - Scaling-based model of sustainability (phase space, uses Bettencourt exponents) [15]
- Liu 2007 - Complexity of Coupled Human and Natural Systems [13]

9.3 What to Do? III. Develop a (Physics) theory of spatial networks?

- Since all real networks are in some way related to physical world, matter and energy (can) come into play. physics? = Matter and energy
  - What happened to energy in modern complex -systems/-networks?
  - Too hard? Too dynamic? Too much variation?
  - Legacy of Prigogine, et. al.: Open, Non-equilibrium Thermodynamic Systems. [20, 19]



- Develop, understand a canon/ontology of spatial networks as they relate matter and energy.
  - location of nodes, distance along edges
  - matter at nodes, on edges
  - energy at nodes, along edges
  - growth, movement, matter/energy dynamics at nodes? etc.
- Starting points - review articles by Barthelemy, Newman, Barabasi [4, 16, 1]

Thank You

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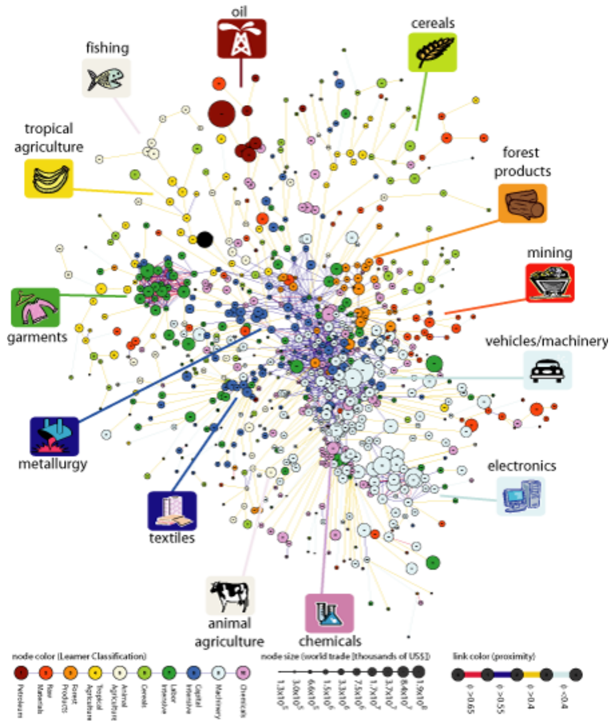
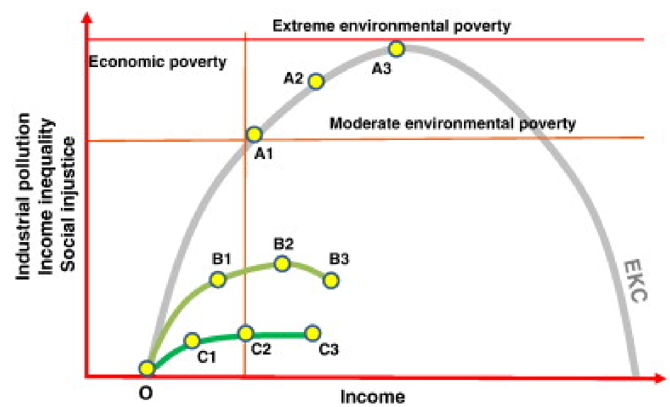
10 Appendix

10.1 Consumption - The Product Space





Hidalgo, Hausmann: Product Space - network from (basically) conditional probability of exports; relation of GDP to network complexity. [11, 12]

- What about 'energy'? A new way to think about product networks, economic complexity, and development, implies very large amounts of energy and emissions. How does econ. complexity relate to energy?
- Hidalgo and Hausmann look at diffusion through this network, energy required to diffuse would be very interesting.
- How does energy flow around the network?
- Energy/emissions has been studied with (older, Leontief) input-output models.
- investigate 'Kuznets curve' aka 'environmental leapfrogging' in context of product space - really possible?

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