GSS: Towards a Research Program for Global Systems Science

Carlo Jaeger, Patrik Jansson,
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Conference Version, prepared for the
Second Open Global Systems Science Conference

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Contents

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1. Introduction: Global Systems and ICT

“The ATM changed banking practice but did not change how people saw themselves as human beings. The computer is said to be radical because, through its instant worldwide communications, it is changing us from locally aware beings to globally aware beings.“[1] This remark by Peter Denning – lead author of the seminal ACM report ”Computing as a Discipline“ – captures the reason why the evolution of computing has reached a point where it calls for and enables a science of global systems.

While most things in life can be captured by a crisp definition only in very provisional ways (try “time“, “headache“ or “definition”) a very provisional definition of global systems science (GSS) may be useful here: [2]

Global Systems Science

- studies global systems like the internet, the global city system, and more,
- develops evidence, concepts and doubts concerning such systems,
- helps practitioners dealing with them to reflect on their experiences and to assess possible consequences of their actions,
- and combines advanced computing technologies with conversations bridging the gap between science and society.

Rather than proposing an abstract definition of global systems, it is useful to consider some examples. A paradigmatic example of a global system is the internet. It “is unique among all computer systems in that it is built, operated, and used by a multitude of diverse economic interests, in varying relationships of collaboration and competition with each other.” [3] And for sure this multitude of interests cuts across nations to span the whole globe.

Other examples are:

- the energy, water and food supply systems
- the global financial system

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[1] Denning, P.J., Dunham, R. (2006) Innovation as Language Action. Communications of the ACM, 49, 47-52, p.49.

[2] The term Global Systems Science (GSS) originated at the Lawrence Hall of Science of the University of California, Berkeley. See: Sneider, C., Golden, R., Barrett, K. (1998) Global Systems Science. A New World View – Teacher’s Guide. Lawrence Hall of Science, Berkeley. The term was given a more policy oriented twist with a strong emphasis on ICT by Ralph Dum, scientific officer at the European Commission. He did so in a variety of discussions and unpublished notes, as did Ulf Dahlsten, former director at the European Commission, when he underlined the key importance of world market governance and therefore of economic modelling for GSS.

[3] Papadimitriou, C.H. (2001) Algorithms, Games, and the Internet. Proceedings of the thirty-third annual ACM symposium on Theory of computing, 749-753, ACM, New York, p.749.

- the global city system
- the agents, resources and mechanisms involved in climate policy
- the web of military forces and relations
- globally spreading diseases
- the scientific community

GSS provides evidence about global systems, for example about the network structure of the world economy.[4] This is essential to track, understand and shape how shocks propagate through the global economic system, or how the shift from "the West" towards South-East Asia and other areas may influence global institutional structures like the international monetary system.[5] Producing evidence is equally important in view of other global systems, from the dynamics of social networks to the worldwide interdependence of cities.

As important as evidence are concepts that help to structure problems, identify phenomena and organize actions. An example is the concept of "price of anarchy", developed in studies on computer networks, including the internet.[6] It is of great relevance for the study of global systems in general, as are related concepts of coordination games, network topologies and more.

In the world of computing, an important resource to achieve coordination under "anarchic" conditions is the culture shared by computer occupations, famously summarized in the internet meme: "We reject: kings, presidents, and voting. We believe in: rough consensus and running code." The concept of occupational groups is another example of a promising conceptual tool in GSS. It is essential to analyse their role in domains ranging from the dynamics of the global urban system[7] to the future of education.[8]

A key feature of GSS is the combination between computational tools and methods and conversations involving both researchers and practitioners. Why bother about such conversations? Because they can help us keep in mind that computation is but one of many facets of the human condition.[9]

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[4] Vitali S, Glattfelder JB, Battiston S (2011) The Network of Global Corporate Control. PLoS ONE 6(10): e25995.
[5] Zhou Xiaochuan (2009) Reforming the International Monetary System. BIS Review. Bank of International Settlements. www.bis.org/review/r090402c.pdf.
[6] Roughgarden, T., Tardos, E. (2007). Introduction to the Inefficiency of Equilibria, in: Nisan, N. et al. (eds.) Algorithmic Game Theory. Cambridge University Press.
[7] King, K., Mellander, C., Stolarick, K. (2010) What You Do, Not Who You Work For. Martin Prosperity Institute, Toronto.
[8] Maclean, R., Lai, A. (2011) The Future of Technical and Vocational Education and Training: Global challenges and possibilities. Int. J. of Training Research. 9, special issue 1-2.
[9] See www.terrybisson.com/page6/page6.html.

In the following we plant a few seeds for a research program of global systems science. They come in two kinds. First, we discuss global challenges that call for GSS and where GSS holds the promise of making useful contributions in the coming years (as opposed to problems where greater patience will be required). Second, we discuss the role of ICT in this endeavour, again with an emphasis on the near future (as opposed to the long-term development of the industry).

2. Policy Challenges Driving GSS

2.1 The Energy Nexus

The history of humankind is characterized by a long-term increase of per capita energy use. In modern times, this increase accelerated drastically thanks to the use of fossil fuels. Globalization as we know it would have been impossible without this expansion of energy use. There is a positive feedback here as the use of fossil fuels in turn accelerates globalization by expanding trade routes, leading to sophisticated worldwide logistics and intensifying global interdependencies.

Three key research questions arise. First, for how long can this increase in per capita energy use continue? Estimating the amount of fossil fuels that is available for future human use is notoriously difficult. Even more difficult is the assessment of the potential alternatives, from photovoltaics to nuclear fusion. And where an energy resource is available in principle, the costs of using it – including the energy costs to mobilize additional energy – need to be assessed as well. Moreover, the example of climate change has made it clear that limited availability of energy resources is by no means the only problem. Unintended consequences of energy use may be at least as important. Again, timing is critical. There is a need for robust estimates of how long it may take to detect such consequences, how long it may take for these consequences to have major impacts, and how long to develop either fixes for the resulting problems or alternative strategies. And to be robust, estimates must make the uncertainties involved much more explicit than is current practice.

This leads to the second question, namely what are the historical implications of a world where per capita energy use does not grow anymore.[10] So far, societies have tended to solve problems by developing increasingly complex structures based on increasing energy use; increased complexity then generated new problems, leading to positive feedback. In cases where energy became a limiting factor, complex structures became sclerotic or broke down (the decay of the Roman empire seems to be a case in point). GSS will have to look more deeply into these challenges than has been done so far.

The third question concerns alternative strategies. There is an urgent need to widen the array of strategies under discussion. In particular, there is a need for small-regret strategies that provide opportunities for reversal at low cost if unexpected difficulties arise. And there is a need for win-win strategies that reduce the dangerous geopolitical tensions involved in the present energy system.

[10] Tainter, J.A. (2011) Energy, Complexity, and Sustainability: A Historical Perspective. Environmental Innovation and Societal Transitions, 1, 89-95.

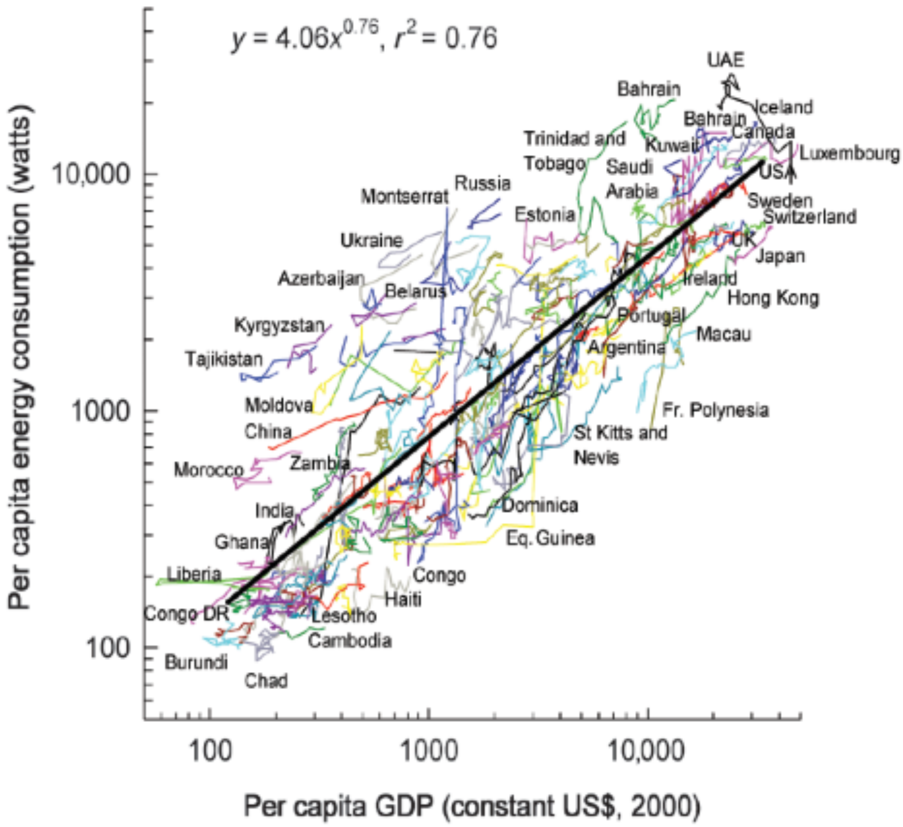

Figure 1: Energy use per capita and GDP per capita, 1980-2003 (coloured lines represent national trajectories)[11]

Fig. 1 shows the current scaling relation between energy use and GDP (for more about scaling relations see section 2.5, Urban Development). It gives a sense of how difficult it will be to tackle the global energy challenge in the coming decades.

2.2 Global Health

Health is a global challenge and disease is a global problem.[12] Health or well-being is also fundamentally a property of complex and ultimately global systems. The global dimension applies to individual health as well as to the health of populations, ecosystems or economies. Any understanding of health requires a complex adaptive systems (CAS) perspective that also includes values (social, economical, cultural, personal) and epistemologies (how do we know what we know, what are criteria of evidence, etc.).

All health challenges lie at the intersection of several global systems. These include various biological, ecological, social, technological, and economical systems. As part of a tightly interconnected world, processes at all levels intersect – although exactly how is in many

[11] Source: Brown, J.H., Burnside, W.R., Davidson, A.D., DeLong, J.R., Dunn, W.C., Hamilton, M.J., Mercado-Silva, N., Nekola, J.C., Okie, J., Woodruff, W.H., Zuo, W. (2011) Energetic Limits to Economic Growth, Bioscience, 61, 19-26.

[12] Jacobsen K.H. (2008) Introduction to Global Health. Jones and Bartlett, London.

cases not fully understood. But what we do know is that there are multiple complex interactions that play out at different spatial and temporal scales and involve various feed-back and feed-forward loops. Most research has been focused on small or local intersections and has missed important dimensions that are only visible at a global scale.

Global health researchers are currently collecting data that will allow us to understand some of these connections and causal links (the big data challenge). But these data will only be meaningful if we have a corresponding conceptual and theoretical framework that frames challenges, such as health as a truly global systems problem. To establish such a framework and test it in the context of specific health challenges at all levels of organization is one of the goals of global systems science.

A global systems perspective applies to all dimensions of health:

- Individual Health: While traditional biomedicine is exploring genomic, physiological and behavioural components of health as complex adaptive systems it is becoming increasingly clear that global systems dynamics play a major role in determining individual health outcomes. Examples include shifts in the distribution of infectious disease agents due to global climate change, exposure to new diseases and environmental pollutants due to climate change and global economic activities, increased risks to the food supply, etc.
- Population Health: Many health issues also affect populations. And in today's world the population structure has reached a global scale. The ongoing danger of pandemics, the effects of demographic changes, mental health related illnesses and the patterns of global migrations affect health at the population level.
- Ecosystem Health: Another important aspect of global health is the state of the supporting ecosystems. These provide a variety of ecosystems services that are increasingly threatened by various aspects of globalization. Ongoing changes to ecosystems will, through various links and connections of integrated complex systems, affect all other dimensions of health. A global systems science perspective is essential to study, understand, and manage health at all levels.

Evolutionary dynamics are a central part of global systems and complex adaptive systems approaches to global health. All systems respond to external and internal challenges, either by regulatory dynamics that maintain an adaptive equilibrium or by transformative dynamics that change the system state, either in an adaptive or chaotic way. Currently many of our complex global systems are operating far away from their equilibrium points and are observing positive or feed-forward feedbacks that make it increasingly difficult to predict their behaviour (not unlike the financial system). In order to maintain or manage global health challenges we therefore need a better understanding of the dynamical properties of closely connected global systems.

Approaching health as a global systems problem is only possible if it is done in the context of big data and new forms of information and computing technology. Current trends in monitoring systems level properties and markers of systems health need to be expanded and most importantly these various data streams need to be integrated in real time to allow for adequate representations of system states in order to enable informed decision making. Global systems health is thus at its core also a computing challenge. This includes present and future as well as historical data (which increasingly become available). The historical dimension is especially valuable, as it will also allow us to study the effects of phase transitions in systems behaviour. Complex systems change their dynamics when they go through scale dependent phase transitions. It is therefore crucial to get access to as many case studies of such phase traditions as possible. Health data, financial data as well as data about the history of science are among those that allow us to study the consequences of phase transitions in complex and now global systems.

One foundational question in the context of globalization is what happens to knowledge systems after they pass through patterns of expansion finally reaching a truly global dimension. How are the dynamics of these systems affected by such transitions? What are the consequences for our understanding of such systems as well as for their governance and organization? Western science as a specific type of a knowledge system has continuously expanded since its inception in its modern form during the period of the scientific revolution. It has passed form a mainly local organization with well established patterns of communication in the 16th and 17th century to a period of national organization during the 18th and 19th century (including its role within European colonial expansion), a period of mainly transatlantic interactions in the early 20th century (amplified by the exodus of Jewish scientists from Germany and neighbouring countries) to finally a truly Global enterprise. Western science has thus experienced a number of phase transitions, all of which are very well documented in the historical record of science. It is thus a prime case study for exploring the consequences of transitions in scale. To do that, we need to analyse the history and current practices of science as a big data problem, analysing a rich and vast documented historical record with novel computational approaches that allow us to identify patterns and processes and their transformations in the context of transitions in scale. To this end we will apply concepts from evolutionary theory and the theory of complex adaptive systems to the analysis of the historical patterns and processes of in the development of Western science. Treating science and it history as a case study for global systems science has two distinct advantages: (1) science is a complex social system with a long and well documented history and analysing science can thus lead to important insights into global systems dynamics and (2) effective governance of current global science is one of the main challenges of our global society as we depend on getting the right kind of results from investing increasingly scarce resources.

2.3 Financial Markets

Until the global financial crisis, competitive markets for insurance and finance were seen as the ideal institutional setting for managing risks. Competitive markets in this sense are markets where the influence of any individual agent on overall market dynamics is negligible, as are the specific relations between particular agents. The crisis on the American subprime market, however, would have been way too small to induce a global financial (and then broadly economic) crisis if markets actually had this kind of structure.

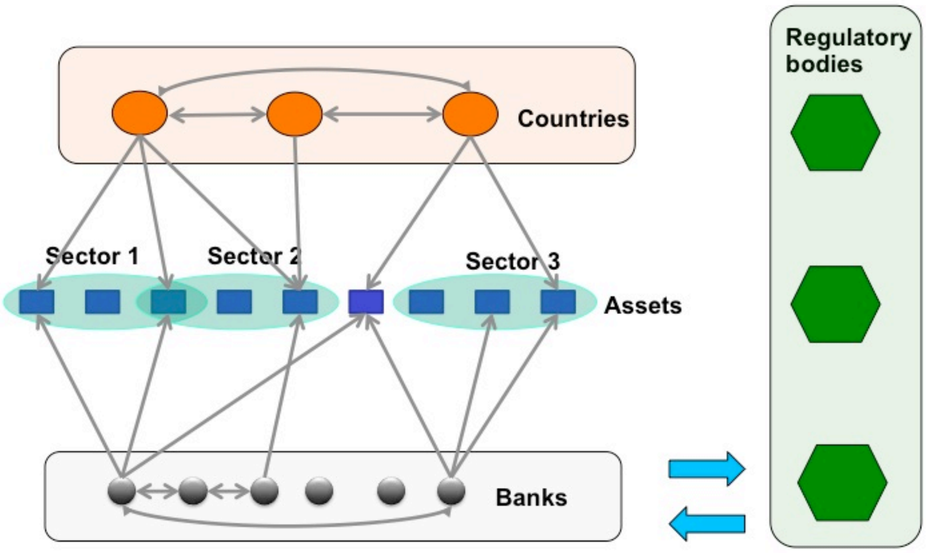

Figure 2: Network structure of the global financial system

GSS, therefore, will contribute to the understanding – and reduction – of risk cascades in the global financial system. To give an idea, consider a network of banks and governments dealing with different asset classes while interacting with a variety of regulatory bodies (Fig. 2).

For each actor we define a variable “financial stress”, assuming values between 0 (no stress) and 1 (bankruptcy). For the network we define an interdependency matrix where entry (i,j) indicates how vulnerable actor j is to the distress of actor i. The system dynamics then is represented by a transition function that yields tomorrow's distress vector as a function of today's distress vector and the interdependency matrix.

Given initial conditions, one can compute how overall distress will evolve through time. With data about specific shocks – like the subprime crisis – one can identify "dangerous liaisons" that put the system as a whole at risk.[13]

A peculiar kind of "dangerous liaisons", and therefore of systemic risk, arises where national currencies become global reserve currencies. Addressing the resulting problems, as well as ways to transform the present global financial system into a more sustainable one, will be a key task of GSS in the years to come.[14]

To analyse how the interdependence matrix and the transition function can be changed, and what effects such changes might have, one needs to recognize that no single actor controls this system. Rather, the evolution of the system can be analysed as a sequence of stage games played by a multitude of agents. The economy is then no more seen as simply addressing problems of scarcity, but rather as developing and transforming patterns of human coordination.

2.4 Climate Change

Over the past decades, an informal alliance of scientists and environmental activists has played a key role in "changing us from locally aware beings to globally aware beings".[15] Man-made climate change is now a major topic in the conversation of humankind.[16] By and large, there is a highly influential voice that warns against the threat of climate change as a global catastrophe, prefigured by scientific measurements of CO_2-concentrations, global temperature, average sea level and the like, as well as by local disasters like hurricanes, droughts and floods. To avoid that threat, drastic reductions of greenhouse gas reductions are advocated, starting immediately and achieving a near-zero emissions economy a few decades hence.

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13 Battiston, S., Gatti, D., Gallegati, M., Greenwald, B., Stiglitz, J. (2012) Liaisons dangerousness: increasing connectivity, risk sharing, and systemic risk, J. Econ. Dyn. Control 36, 1121–1141.
14 Jaeger, C., Haas, A., Töpfer, K. (2013) Sustainability, Finance, and a Proposal from China. IASS and GCF, Potsdam and Berlin.
15 See footnote 1.
16 "As civilized human beings, we are the inheritors, neither of an inquiry about ourselves and the world, nor of an accumulating body of information, but of a conversation, begun in the primeval forests and extended and made more articulate in the course of centuries. It is a conversation which goes on both in public and within each of ourselves." (Mike Oakeshott, 1959, The Voice of Poetry in the Conversation of Mankind. Bowes and Bowes, Cambridge.)

There is a second, hardly less influential voice, however, stressing that the reduction of emissions comes at the cost of reducing our prosperity in the years and decades to come. Arguments then have started as to how much prosperity we would need to forego, who would share how much of that burden, and how urgent and serious the threat of climate change is after all.

As a result, while the debate about climate change is generating a truly amazing amount of attention, effective action on global emissions reduction is badly missing. Attempts to scare ordinary people as well as policy makers into such action by stressing the magnitude of the threat looming in the future are clearly not very successful. It seems safe to conclude that "One can persuade people to tackle climate change only if those concerned with the dangers persuade ordinary people that action will not come at the expense of their prosperity."[17]

For this to happen, a third voice will need to emerge in the global conversation about climate change, a voice reframing the climate issue from a challenge of sharing burdens to one of sharing opportunities.[18] GSS can and shall contribute to that voice. In this endeavour, the following points deserve special attention:

- Out of the 7 billion people alive today, at least half are able to perform highly productive work if they get the opportunity to do so. This means having access to suitable jobs, including on-the-job training where required. With a time delay of a decade and more, formal training is essential, too – as long as the corresponding jobs exist. In fact, hardly more than 2 billion are active in reasonably competitive activity, while a large fraction of the global population is underemployed, i.e. working in extremely unproductive lines of activity or simply surviving outside the economic system. This matters because it shows that the world we live in is characterized by huge human resources that could be mobilized in the transition to a low-carbon economy and in the restoration of global ecosystems.
- This transition offers the opportunity for large additional investment, which can spur growth along with learning-by-doing. It is often overlooked that most technological progress is actually driven by practitioners reflecting on what they are doing, especially when familiarizing themselves with new equipment. This is the main channel through which technological innovations in production spread from their points of origin to the rest of the world. But it is actually also the main way innovations are generated in the first place. New ways of building planes, for example, are normally developed by people engaged in building planes or by

[17] p.772 in Wolf, M. (2012) Living With Limits: Growth, Resources, and Climate Change. Climate Policy. 12, 772-783.
[18] Jaeger, C., Hasselmann, K., Leipold, G., Mangalagiu, D., Tàbara, J.D. (2012) Reframing the problem of climate change: from zero sum game to win-win solutions. Earthscan, Abingdon.

researchers and inventors connected – if from a distance – to this activity. It will be investment in the low carbon economy that will generate the innovations needed to make that economy a prosperous one.

- Weather related disasters are widespread and on the rise, to some extent because of climate change, but much more because of demographic and economic changes that create new vulnerabilities. The suffering generated by these disasters should and can be a reason for social learning, increasing the awareness of environmental challenges, including, but not restricted to, climate change. This in turn means that improved disaster risk management can make a major contribution to mobilizing the resources needed for low-carbon investment. Given the nature of most weather related disaster, this will be especially relevant for the transformation of the built environment and the future of cities.

Each one of these points will need careful research at a global scale, driven by the kind of ideas nurtured, among others, by GSS researchers.

2.5 Urban Development

Urban studies have experienced a new push thanks to the discovery of remarkably robust scaling laws linking individual behaviour with the global urban system. The speed at which people walk in everyday life, e.g., shows a positive, but sub-linear ($0 < \beta < 1$) correlation with city size all over the world (Fig. 3). Similar correlations exist for energy use and carbon emissions. Other variables display linear – as with household water use – or super-linear – for economic output, measures of innovation, crime, and more – correlations.

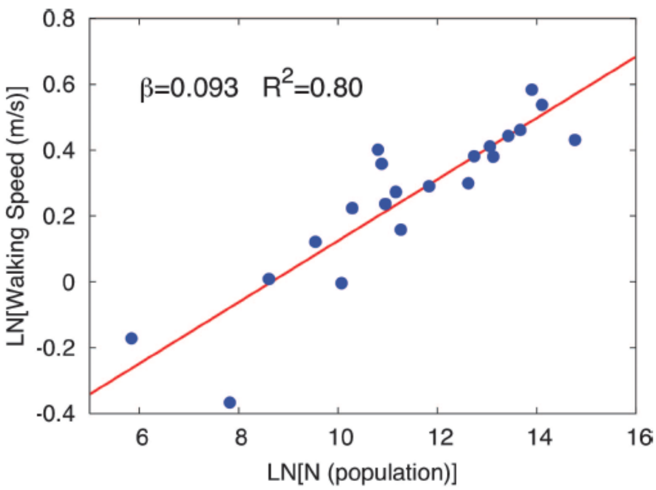

Figure 3: Walking speed in the global city system.[19]

[19] Source: Bettencourt, L.M.A., Lobo, J., Helbing, D., Kühnert, C., West, G.B. (2007) Growth, innovation, scaling, and the pace of life in cities. PNAS, 104, 7301-06.

These relations can be described by scaling laws of the form:

$$\mathbf{Y} = \mathbf{A} \cdot \mathbf{N}^{\beta} + \varepsilon$$

N is the population of a city, Y some variable of interest, the scaling constant A and the exponent beta are parameters, while epsilon is a random variable. This means that Y is a random variable, too. For its expected value we get:

$$\epsilon = \mathbf{0} \;\Rightarrow\; \mathbf{Log}[\mathbf{Y}] = \mathbf{Log}\left[\mathbf{A}\,\mathbf{N}^{\beta}\right] = \mathbf{Log}[\mathbf{A}] + \beta\,\mathbf{Log}[\mathbf{N}]$$

So far, most research on this kind of phenomena has focused on the value of the exponent. From a policy point of view, however, the random component and the scaling constant are of more immediate interest.

Consider a policy-maker who wants to develop a low-carbon city. At the level of a single city, neither the scaling constant nor the exponent can be influenced. What can be influenced are peculiarities that in the scaling law are lumped together in the random variable epsilon. If many cities move in the same direction by exploiting such peculiarities, they will eventually change the scaling constant for the system as a whole.

On the other hand, policy-makers may be able to influence the scaling constant for a subsystem of cities. National construction standards, e.g., can modify the scaling constant for energy use, carbon emissions, weather related damages, and more.

One of the tasks of global systems science, then, is to investigate possible typologies of cities, so as to understand how the scaling constants for the global city system can be broken down into scaling constants accessible to policy makers. In the same spirit, there is a need to investigate the distribution of the random component, too, so as to understand how it can be broken down into variables accessible to policy making.

This will lead to a greatly enhanced capability to monitor and influence urban dynamics. ICT will play an essential role in this process, through crowd sourcing of data, interactive models and databases, and a wealth of new technologies relating to single cities as well as to systems of cities all the way up to the global urban system.

The idea of smart cities, currently pursued by businesses and public authorities involved with urban development, clearly points in that direction. As a result, cities will become capable of much smarter learning than is currently the case. The complexity of innovation and social change can then be used to tackle global challenges that seem intractable today.[20]

[20] Lane, D., Pumain, D., van der Leeuw, S., West, G. (eds) (2009) Complexity Perspectives on Innovation and Social Change. Springer, Berlin.

3. Enabling Knowledge Technologies

3.1 High Performance Computing

Global Systems Science often requires detailed simulation of the system under consideration or a detailed analysis of data provided to understand such a system. Moreover, essential uncertainty analyses often require very large sets of simulation runs. In all these cases High Performance Computing (HPC) plays a role as a key enabling technology to achieve reasonable and reliable results.

Fortunately, suitable computing platforms are becoming available as we start seeing parallel architectures getting renewed attention. This is linked to the general purpose usage of parallel architectures, as found, for instance, in Graphical Processing Units (GPUs). The renewed attention on parallel architectures comes from the fact that engineers have reached a barrier as to how efficiently a Central Processing Unit (CPU) can compute. On the other hand, Moore's law still holds: the amount of transistors per silicon area is roughly doubling every 20 months. Thus, the number of parallel processing units found in new hardware, such as the graphics cards of a standard gaming PC, is growing exponentially, leaving an open problem to the software architects: how are we going to program these new highly parallel architectures?

Various approaches are materializing, for instance, in the form of toolkits, such as NVIDIA's CUDA programming platform or the open source programming platform OpenCL. But higher-level programming models are needed, as expressed, for instance, by Bill Dally, chief scientist at NVIDIA and senior vice president of NVIDIA Research:

"Making it easy to program a machine that requires 10 billion threads to use at full capacity is [also] a challenge. ... We need to move toward higher-level programming models where the programmer describes the algorithm with all available parallelism and locality exposed, and tools automate much of the process of efficiently mapping and tuning the program to a particular target machine."[21]

GSS, therefore, includes a research part that comes with the use of HPC. As HPC relies on very large scale systems based on millions of parts like processors, memory chips and disks, GSS has to master the handling of such systems. Research into the area of high-level parallel programming models is essential to develop, maintain, and manage tomorrow's high-performance parallel systems. This includes a number of issues:

[21] www.hpcwire.com/hpcwire/2013-04-15/future_challenges_of_large-scale_computing.html.

- First and foremost, the development of scalable models. Existing models were often developed with serial computers in mind. New models have to be developed that are scalable to the same extent as the HPC systems.
- Second, the development of scalable programming tools to be able to implement the scalable models on existing hardware. This includes programming languages, optimizing compilers, schedulers, debugging tools, performance analyses, and many more.
- Third, the development of new and scalable visualisation methods both for the results and for the increasingly complex models themselves.

Therefore, approaches like Scala – combining the power of languages like Java or C++ with the functional approach in view of producing scalable code – are especially relevant for GSS. The functional programming approach is essential because it captures the declarative properties that make it possible to express parallelism at a high level and also make it possible to generate efficient high-performance code from the high-level functional specifications.

Besides the research part, there is the very practical issue of the availability of computing resources. It is vital for GSS to keep a suitable HPC infrastructure but also to update such an infrastructure continuously to be able to harvest the potential of improved systems and turn it into improved GSS results.

Once HPC moves from well-defined problems in science and engineering towards the world of policy-making, mindless computing is an increasingly serious danger. In global policy areas like financial markets, climate policy and more, the evidence to be provided to policy-makers needs to be "reflexive evidence", i.e. evidence that comes with an assessment of its reliability, validity, and relevance. So far, HPC has rarely, if ever, been used in such a spirit. Nevertheless, it holds considerable promise in this regard, e.g. because of the possibility to explore large, complex sample spaces of parameter values and boundary conditions.

In GSS, the computational skills required to develop and use HPC must be combined with great skills in communication and in assessing the relevance of evidence for addressing specific practical issues. Therefore, GSS will systematically embed HPC work in dialogues with scholars from the humanities and with practitioners dealing with global systems.

3.2 Big Data

The near-canonical definition of “Big Data” identifies “3Vs”: information assets of high Volume, high Velocity and high Variety.[22] The increasing availability of such information assets has led to great hopes: “The benefits to society will be myriad as big data becomes part of the solution to pressing global problems like addressing climate change, eradicating disease and fostering good governance and economic development.”[23]

From a GSS perspective there are a few additional aspects: can you trust the data?, how do you handle privacy?, is the data open or proprietary? And most of all: do we gain or lose understanding?

One convenient definition of “high volume” is the moving target “more than you can store or process in one place” (tens of terabytes today). This means that computation on big data needs to be distributed over a network of computer nodes: we must take the computation to the data rather than the reverse. Cloud computing is a form of distributed computing where the compute nodes are abstracted away and where computing time often is sold as a commodity by the hour. Amazon's EC2 is a popular commercial service: there are also increasing open cloud initiatives.

An important challenge for GSS when it comes to big data is to sift through and analyse the "raw" data to extract and visualise meaningful aggregate results. This requires new research in algorithms, probability & statistics and optimization. Massive and complex multidimensional data also requires new approaches to visualisation and data representation.

One particularly useful technique which is a promising marriage of agent-based modelling and big data is synthetic populations. A synthetic population is generated for a particular purpose of study to statistically represent a real population (of a city, a region or a country). It has been very successful in addressing socially coupled systems in transport, public health and city planning. Advantages include anonymity, privacy and a direct connection to geo-spatial maps that helps in communicating results to policy-makers.

3.3 Programs, Tests, and Proofs

Global systems, if they fail, may fail big; it is for that reason that decision-makers dealing with such systems have an exceptional responsibility. Whenever policies are backed by

[22] www.gartner.com/it-glossary/big-data.
[23] Mayer-Schonberger, V., Cukier, C. (2013) Big Data: A Revolution that will transform how we live work and think. John Murray, London.

simulations, they rely on the results of a computation. Yet the fact of the matter is that those computations inevitably contain faults.

At present, most faults do not manifest themselves in a way that engenders practical problems. Which faults are benign, however, and which ones may seriously impact the result of a simulation, is largely unclear and can usually be said with certainty only in hindsight. A fundamental task of GSS, thus, is to provide methods for understanding the impact of faults. Specifically, metrics need to be defined to describe the magnitude of a fault, qualitative descriptions are necessary to capture its semantics, root causes need to be identified, and the dependencies between a fault and the healthy part of the system as well as among faults need to be researched.

Big data implies big faults. A large class of faults concerns the logic of the program under consideration; those require the investigation of formal languages. Yet other classes of faults exist that go beyond logic, ranging from the malicious tampering of a system over physical errors in the environment of the simulation to hardware faults in the computational architecture. Those faults can be transient, silent, non-reproducible, non-deterministic, or random, and are thus hard to detect. They are found in data, models, computations as well as networks, storage media, and computational units; and they may emerge at the interfaces of software and hardware components that by themselves may work just fine. They also are expected to dramatically increase in numbers.

For the future computers for global systems, exascale computers capable of a million trillion calculations per second, the “Mean Time to Failure” is projected to be so short that useful computations are seriously impaired. At the other end of the scale, and indirectly promoted by global systems themselves, one can observe already today that malicious intentions grow rapidly and that the financial, social, or personal incentives for manipulating simulations to one's own advantage only become larger. Both the kind of faults and their mere quantity defeat traditional concepts for resilience, reliability, and robustness. One has to fundamentally think over how computations for global systems possibly can be protected.

Understanding faults requires first and foremost that one knows of them. That knowledge does not exist today since the required infrastructure is completely lacking. At present, faults are hidden in regression tests, traces or log files, and even if one had access to those files, neither do standards and notations to describe them exist, nor concepts for evaluating and comparing them. Further, traditional recovery mechanisms cease to work.

Classical redundancy in space or time is too expensive - neither can one hold big data twice nor can one easily run a large simulation multiple times. Smarter ways are needed than those brute-force approaches, and redundancy must be made affordable with respect to energy costs and resources.

In principle, because of the Curry-Howard isomorphism it is always possible to prove program correctness with regard to well-defined specifications. It will be important to develop domain specific languages and type systems for GSS to facilitate specifications and correctness proofs, and an additional bonus will be a considerable amount of conceptual clarification. However, full formal proofs are feasible only to some extent. Still, some level of verification is of essence, and therefore a major task for GSS will be to develop suitable specification and testing routines to capture faults before they become failures.

3.4 Global Risk Assessments

The global challenges discussed in part two mostly concern global risks, and this seems to be a core problem of globalization in our times: it comes with risks that we don't really know how to handle. In fact, we don't really know how to assess them, which is why global risk assessments are a key methodological challenge for GSS.

The state of the art in global risk assessment is very much given by the annual assessments produced by the World Economic Forum.[24] For the 2013 report, a team of researchers familiar with discussions about global risks defined a list of 50 global risks and asked several thousand people with a reputation as risk experts to grade those risks. Five grades were offered, once for the likelihood of each risk, and once for the impact in case the risk should materialize. A separate survey produced similar gradings for the resilience of different countries in the face of different risks. The result can help decision-makers to prioritize the use of resources, including awareness, in view of different risks.

This approach is a coarse, and therefore feasible approximation to what has been developed over centuries as the canonical theory of rational risk management.[25] Risk is understood as a measurable quantity, the product of two other measurable quantities, namely probability and utility. The younger notion of resilience is presently used in many different ways, but usually to highlight the capability of some system to maintain desirable properties in the face of various exogenous shocks. Desirability is a close cousin of utility, and the mentioned maintenance may be more or less probable.

[24] Howell, L. (2013) Global Risks 2013. World Economic Forum, Geneva.
[25] Jaeger, C., O. Renn, E. A. Rosa, and T. Webler (2001) Risk, Uncertainty, and Rational Action. Earthscan, London.

The canonical understanding of risk can accommodate subjective probabilities, with two major implications for computer modelling and risk governance.[26] First, the well-known distinction between risk and uncertainty often boils down to one between objective and subjective probabilities. In the absence of objective probabilities, true uncertainty may be said to prevail. However, people take most decisions under this kind of condition, treating some consequences of their decisions as more likely than others – in other words, implying something like subjective probabilities.

Second, if sometimes – perhaps quite often – objective probabilities are illusionary, then an "objective" ranking of risks is illusionary, too. This is even more so because if a risk materializes, it will affect different people very differently, too. As a result, the idea of a single actor – say some international institution – successfully managing global risk all by itself, becomes a dangerous illusion. What is called for is the patient development of governance structures enabling a plurality of actors to address the risks they are faced with.[27]

When assessing global risks, therefore, it is important to clarify how the same possibility looks from the perspective of different actors. It is perhaps not a surprising, but in fact a very important hypothesis to expect actual risk governance to result in avoiding primarily those risks that are considered serious by influential – powerful, rich, knowledgeable, etc. – actors. This must be expected to hold quite often amongst the people presently alive.

The same hypothesis holds when comparing people presently alive with people not yet born: future actors have hardly as much influence on present decisions than those alive now. This leads to a key problem of the global civilization we live in: the tendency to postpone risks so that they are all but ignored by the decision-makers creating them.[28] This pattern has shaped the history of nuclear armament, of climate change, of biodiversity, and it is shaping the development of the international monetary system. In fact, postponing risks in this way may well amplify them.

Studying this pattern of accumulating future risks as well as ways to overcome it is one of the most fundamental tasks of GSS. The canonical view of rational risk management may well be transformed in this endeavour, e.g. by treating individual judgments of risk impact and likelihood as embedded in evolving structures of social norms geared to complex networks of actors.

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[26] Kennedy, M., O'Hagan, A. (2001) Bayesian calibration of computer models (with discussion). Journal of the Royal Statistical Society, Series B. 63, 425-464.
[27] Renn, O. (2008) Risk Governance: Coping with Uncertainty in a Complex World. Earthscan, London.
[28] van der Leeuw, S. (2012): Global Systems Dynamics and Policy: Lessons from the distant past. Complexity Economics, 1, 33-60.

3.5 Narratives of Hope

Most important decisions are made in conditions of ontological uncertainty – that is, in situations where the future development of entities and their future relations are profoundly unknowable ahead of time. Acting, taking decisions in these circumstances, requires conviction. There is growing evidence that economic and other important decisions that require pictures of the future to be created are subject to the forces (in urgent need of good understanding) that produce narrative conviction and narrative truth.[29]

Aggregate behaviour is subject to the convergence and sudden co-ordination of shared narratives about the future. Whereas the state of the world changes rather slowly the state of narratives about it can alter very sharply and is strongly subject to social interaction and influence. Recent events in financial markets have demonstrated this proposition forcibly.

Today, due to the large quantities of "big data" produced by the digital revolution, we can come to a better understanding of these dynamics. The new data sources (especially sources of text data) can be rigorously investigated using language technology and algorithms, in order to capture historical shifts in narrative sentiment which appear to warn about possible future patterns.

Narratives are not just means of creating personal conviction, they can also help structure the exploration and communication of complex and uncertain issues, such as the scope and limits of modelling, or the unintended consequences of political actions. Narratives can help us follow a process from its beginning to the possible outcomes without losing "the big picture". Supplemented with a wide range of ICT tools, ranging from mundane pie charts to advanced virtual reality representations, narratives can convey a basic, intuitive understanding that informs stakeholder dialogues.

Unfortunately, in their unreflected stage, narratives can also hinder clear thinking.[30] Wittgenstein used to say "A picture held us captive". Analysis of the role narratives play in building models and interpreting their results, critical investigation of the narrative kernels informing our visions of a sustainable future, sensitivity to ethical issues and foreign points of view, all this can help us "using the picture" rather than being obsessed by it.

At the same time, advances in ICT provide the key to an exciting prospect that of actively engaging the public in the process of creation of collective narratives and of the needed

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[29] The idea of narrative truth is close to the idea of fictionalism in the philosophy of mathematics; see e.g. Balaguer, M. (2009) Fictionalism, Theft, and the Story of Mathematics. Philosophia Mathematica, 17, 131-162.

[30] Salmon, C. (2010) Storytelling, bewitching the modern mind. Verso, London.

understanding to meet the global sustainability challenge. For example, the low-cost sensing technologies currently being developed enable citizens to directly assess the state of the environment; social networking tools allow effective data and opinion collection and real-time information sharing processes. In addition new models of interaction between citizens, authorities and scientists will have to be developed. Finally, the innovative integration of mobile technology, sensors, and socially-aware ICT can contribute to a shift towards a green and sustainable economy, which has been seen by many policy makers as one of the exit strategies from the current financial and economic crisis.

Scientific, technological and economic developments rely very much upon the existence of positive collective expectations in the widest sense. Indeed, narratives of hope are crucial in any system of governance as well in the governance of global systems.[31] The concept of sustainability will only become an effective guidance of action if it will be fleshed out with plausible narratives of hope.

In this vein, GSS will need to propose viable system options to deal with global challenges – including those options that entail disruptive changes in existing power arrangements and global inequalities. Only by securing that a large number of people can contribute to such a process of knowledge-building, and in ways that improve their own conditions and those of future generations, will GSS effectively support democratic decision-making.

It is natural to expect GSS to provide tools to for that purpose. It is, after all, in the nature of science to be an enabler of the many. Of course exceptional painters could use perspective to add depth to their creations before Leon Battista Alberti's mathematical treatise on perspective, but afterwards all painters could do it, and understand and communicate how they were doing it. The hope is that the science of global systems will eventually help us all add a quality perspective to the canvas of our lives.

[31] Moisi, D. (2009) The Geopolitics of Emotion: How cultures of Fear, Humiliation, and Hope are Reshaping the World. Doubleday, New York.

4. Conclusion: Reflective Practitioners

June 7, 1742, a German mathematician by the beautiful name of Goldbach – gold creek – wrote a letter to his Swiss colleague Euler, including the conjecture: "at least it seems that every number that is greater than 2 is the sum of three primes".[32] Simple as it looks, Goldbach's conjecture still stands as an unresolved problem in mathematics, more than two centuries later. Even if it should be resolved tomorrow, it is a wonderful example of a problem one has to learn to live with in order to perhaps solving it much later on.

Nowadays, globalization poses a problem of that class, with the difference that it is not only a few mathematicians, but humankind as a whole that has to learn to live with a problem that will take a long time to be solved. It may well be the first and foremost challenge for global systems science to share an awareness of how hard the problem of globalization has become. In fact, it cannot even be stated in a seemingly simple sentence like the one in Goldbach's letter.

Rather, a list of preliminary questions and conjectures must suffice to point to the problem. Examples of such questions are:

- What can different agents do to develop the internet and similar systems in ways that empower people all over the world?[33]
- What can different agents do to avoid global financial crises in the years and decades to come?
- What can different agents do to avoid mistakes triggering World War III in the decades to come?[34]
- What can different agents do to avoid dangerous climate change in the 21th century?
- What can different agents do to create an institutional setting in which humankind can develop a common will about what kind of world to bestow to future generations?

Examples of relevant conjectures are:

- The challenges of globalization arise because it involves a high-dimensional information flow that so far we are not able to handle in a reasonable manner; ICT can play a key role in learning to do so.

[32] In those days, 1 was looked at as a prime number. As Euler pointed out, Goldbach's original conjecture implies that every even number larger than 2 can be represented as the sum of two primes.
[33] Amichai-Hamburgera, Y., McKennab, K.Y.A., Tald, S.-A. (2008) E-empowerment: Empowerment by the Internet. Computers in Human Behavior, 24, 1776-1789.
[34] Mearsheimer, J.J. (2010): The Gathering Storm: China's Challenge to US Power in Asia. The Chinese Journal of International Politics, 3, 381–396.

- Increasing welfare and education together with improved global communication are leading to a widespread desire and request of empowerment for ordinary people in social life. ICT can play a key role in fulfilling that aspiration.
- Using algorithmic game theory to model iterated games in complex networks can lead to considerable progress in modelling and understanding global systems.
- ITC-supported occupational groups can play a vital role as carriers of global know-how and pathways of global decision-making.[35]

Of course, when living with an unsolved problem like the one of globalization it is essential to learn as much as possible. In the case of GSS, this means that it can only thrive in an on-going dialogue with practitioners. [36] Sometimes, this dialogue will be based on GSS providing indisputable evidence that helps practitioners to take and implement decisions relating to global cities. With regard to global problems, however, this is more likely to be the exception than the rule. Well-trained researchers working on such problems are likely to come to a rather broad spectrum of views and judgments, and there is little to be gained by blurring those differences in order to create the impression of a broad consensus. [37]

What is highly useful, however, is for researchers to offer their attention to practitioners, listening to how these organize their minds and actions with regard to a specific issue, and then making available to practitioners a range of relevant, not necessarily consistent, arguments. This leads to a governance style using pluralism as a resource and paying attention to the danger of closing ones mind instead of maintaining a learning stance.[38]

Such an approach is especially important for GSS as there is a second difference between Goldbach's conjecture and the core problem of global systems science. In the former case, the difficulties arise simply because we lack knowledge about something we would like to know. Sometimes, however, things are more subtle than that; questions can arise out of realising that we are maintaining illusions of unwarranted knowledge. As the saying goes: "It ain't so much the things we don't know that get us into trouble, it's the things we do know that just ain't so." With regard to globalization, this is the challenge to be addressed by GSS.

[35] For the importance of not relying simply on national identities in developing structures of global governance, see: Sen, A. (2006) Identity and Violence: the illusion of destiny. Norton, New York.
[36] Schön, D. (1983) The Reflective Practitioner: How professionals think in action. Temple Smith, London.
[37] Sarewitz, D. (2011) The Voice of Science: Let's Agree to Disagree. Nature, 478, 7.
[38] Meuleman, L. (2012) Cognitive dissonance in evidence-based sustainability policy? Reflections based on governance theory. Paper presented at the Conference on Evidence or Sustainable Development, Berlin 5 – 6 October 2012.

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