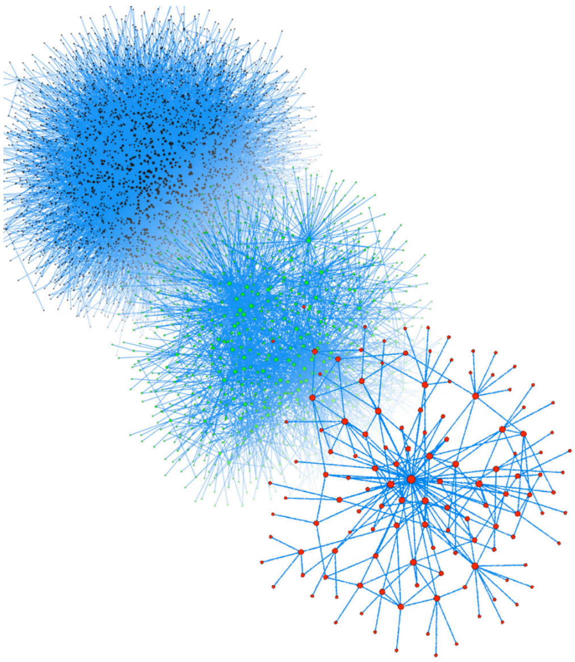
FINAL MMCOMNET WORKSHOP

MEASURING AND MODELLING
COMPLEX NETWORKS
ACROSS DOMAINS



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16th – 18th April 2008
Saïd Business School, University of Oxford.

UNIVERSITY OF OXFORD

TECHNISCHE UNIVERSITÄT DRESDEN

INSEAD

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

Final MMCOMNET WORKSHOP

MEASURING AND MODELLING COMPLEX NETWORKS ACROSS DOMAINS

16th – 18th April 2008
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16th April 2008 **Wednesday**	**Theoretical Approaches to Understanding Biological Networks** **SEMINAR ROOM B – Open Session**
12.30 – 14:00	Lunch for early arrivers
14:00 – 14:10	Welcome and Introduction of Participants Mark Fricker, University of Oxford.
14:10 – 14:30	The UK Fungal Network Fordyce Davidson, University of Dundee.
14:30 – 15:00	'*Mathematical modelling: a question of scale'* Fordyce Davidson, University of Dundee.
15:00 – 15:30	'*Geomycology: mineral-metal transformations by fungi'* Geoff Gadd, University of Dundee.
15:30 –16:00	Afternoon tea
16:00 – 16:30	'*Self-eating is important for mycelium growth'* Stefan Olsson, University of Copenhagen.
16:30 – 17:00	'*Network models for spread and control of soil-borne fungal plant pathogens*' Franco Neri, University of Cambridge.
17:00 – 17:45	Summary Session and Open Discussion

Social Event

19:30	**Evening Meal at Malmaison Hotel** **Sit down for meal at 20.00**

Thursday, 17th April 2008 – Open Sessions in Seminar Room B

AM - Seminar Room B
Theoretical Approaches to Understanding Biological Networks

9.00 – 9.30	*'Self-signalling and self fusion during hyphal network formation in Neurospora crassa'* Nick Read, University of Edinburgh.
9.30 – 10.00	*'Exploratory foraging and resource acquisition by a wood-decomposing fungus (*Phanerochaete velutina*)'* Peter Darrah, University of Oxford.
10.00 – 10.30	*'Regulation of hyphal orientation of fungi'* Neil Gow, University of Aberdeen.
10.30 – 11.00	Morning Coffee
11.00 – 11.30	*'Multiscale modelling of plant nutrient uptake'* Tiina Roose, University of Oxford.
11.30 – 12.00	*'Network automata and the functional dynamic network framework'* Jukka-Pekka Onnela, University of Oxford.
12.00 – 12.30	*'Transport efficiency and resilience in mycelial networks'* Mark Fricker, University of Oxford.

AM - Seminar Room A
MMCOMNET Management Committee Closed Sessions

9.00 – 10.30
MMCOMNET Management Committee

12.30 – 14.00 Buffet lunch will be served in Seminar Room A

PM - Seminar Room B
MMCOMNET
Sustaining Local Economic Networks

	Welcome by Janet Smart
14.00 – 14.30	*'Reducing transaction errors in business networks'* Serguei Saavedra, University of Oxford.
14.30 – 15.00	*'Improving network robustness'* Alex Ng, University of Oxford.
15.00 – 15.30	*'Material and information flows in production networks'* Karsten Peters, University of Dresden.
15.30 – 16.00	Afternoon tea
16.00 – 16.30	*'Structure forming mechanisms in supply networks'* Janet Smart, University of Oxford.
16.30 – 17.00	Discussion and close

PM - Seminar Room A
Theoretical Approaches to Understanding Biological Networks

14.00 – 16.00
Fungal Network Meeting

16.00
Fungal Workshop End

17th April 2008
Thursday

MMCOMNET Evening reception at Saïd Business School

Entrance Hall and Lecture Theatre 4

Open Session

18.00 – 18.30	Welcome buffet in the Saïd Business School Entrance Hall and Network Gallery
18.30 – 19.00	Welcome by Felix Reed-Tsochas MMCOMNET Coordinator *'The mathematics of war'* Sean Gourley, University of Oxford
19.00 – 19.25	*'Fungi to run UK rail?'* Mark Fricker, University of Oxford
19.25 – 19.50	*'Connected or trapped? Firms and banks in credit networks'* Stefano Battiston, ETH Zurich
19.50 – 20.15	Questions
20.15	Networking reception and Network Gallery

MMCOMNET is a Specific Targeted Research Project (STREP) funded by the European Commission under the 6th Framework Programme (Contract No. 12999), with a total contribution of €1.5m over 3 years. The project is supported via the NEST Pathfinder Initiative on *Tackling Complexity in Science*. NEST (New and Emerging Science and Technology) activities aim to support unconventional and visionary research, with a view to helping European scientists to take a lead in pioneering new fields.

18th April 2008	**MMCOMNET – Presentation of results by project partners**
Friday	**SEMINAR ROOM A**

AM – Open Session

09:00 – 09:15	Welcome Felix Reed-Tsochas, University of Oxford
09:15 – 09:45	'*First order phase transition in Ising model on two connected Barabasi-Albert networks*' Janusz Holyst, Warsaw University of Technology.
09:45 – 10:15	'*Scaling of human behaviour in the World Wide Web*' Anna Chmiel, Warsaw University of Technology.
10:15 – 10:30	Open discussion
10:30 – 11:00	'*Scaling of distances in weighted complex networks'* Julian Sienkiewicz, Warsaw University of Technology.
11:00 – 11:30	Morning Coffee
11:30 – 12:30	*'Structure, Dynamics, and Visualization of Complex Economic Networks'* Stefano Battiston, ETH Zurich.
12:30 – 13:00	*'Summary of results on Innovation Networks'* Felix Reed-Tsochas, University of Oxford.
13:00 – 14:00	Lunch
14.00 – 15.30	Parallel meetings of MMCOMNET Project subgroups **Closed meeting for MMCOMNET Project Partners**
15:30 – 16:00	Afternoon
16.00 – 17.00	Discussion of opportunities for further research **Closed meeting for MMCOMNET Project Partners**
17:00 – 17:30	Conclusion and Workshop Close

WORKSHOP PARTICIPANTS

Dr Felix Reed-Tsochas (MMCOMNET Coordinator) is James Martin Lecturer in Complex Systems and Co-Director of the CABDyN Research Cluster at the Saïd Business School, University of Oxford. His research focuses on developing an interdisciplinary approach to the functional and dynamic properties of complex networks. Current interests include the dynamic properties of decentralised manufacturing networks, structural similarities between ecological and organisational networks, the flow of knowledge in high-tech innovation networks, diffusion in online networks, and modelling the interaction between technological change and social behaviour. He represents Oxford on the ONCE-CS and GIACS Coordination Action, which aim to bring together complexity research on a European level. Jointly with Neil Johnson, he is Series Editor for a book series on *Complex Systems and Interdisciplinary Science* published by World Scientific.

Dr Fordyce Davidson is a Senior Lecturer in Mathematics with research interests in the analysis and applications of differential equations. For over 14 years he has been involved in the mathematical modelling of fungal mycelia with particular interests in translocation and mycelial function in heterogeneous environments.

Professor Geoffrey M. Gadd is a microbiologist who works on the interactions of fungi, and other microorganisms, towards toxic metals, metalloids and radionuclides. This work has lead to an understanding of the processes underlying accumulation, detoxification and tolerance, as well as mechanisms that alter metal mobility and fate in the environment. The environmental and biotechnological significance of these phenomena continues to be a focus, particularly in biogeochemical studies on mineral formation and dissolution, and in the bioremediation of polluted soil and water.

Professor Stefan Olsson. In Copenhagen I have continued my interest in the fungal mycelium as a coordinated organism although my research has mainly been on biological control of fungi and fungal secondary metabolites. The different forms of programmed cell death as possible mechanisms for fungi to reuse resources has been in focus since these processes were first described in detail in animals and yeast. We described fungal apoptotic type metacaspase activity as well as a fungal PARP in 2002 and last year we finally got a grant for studying autophagy in a filamentous fungus.

Dr Franco M. Neri is currently a Postdoctoral Research Associate in the Epidemiology and Modelling Group of the Department of Plant Sciences, University of Cambridge. He has a background in Statistical Physics. His research interests are focused on the spread of epidemics on complex networks, and its applications to soil-borne plant diseases.

Professor Nick Read is currently Professor of Fungal Cell Biology at the Institute of Molecular Plant Sciences at Edinburgh University. His research interests include the regulation of hyphal growth and morphogenesis, especially in relation to: (1) hyphal fusion; (2) vesicle trafficking; and (3) calcium signalling. The focus of the research is on analysing living cells using a wide range of advanced imaging and measurement techniques in combination with vital fluorescent dyes and recombinant probes. Considerable emphasis is placed on interdisciplinary research.

Dr Peter Darrah is University Lecturer in Plant Sciences at the University of Oxford.

Professor Neil Gow. Neil's group has published over 200 research papers and reviews related to work on the growth, morphogenesis and pathogenesis of human fungal pathogens and other fungi. He has specific interests in the molecular genetics of cell wall biosynthesis in fungi and the directional growth responses of fungal cells as well as the virulence properties of medically important fungal species. In recent years he has focussed mainly on the genetics of glycosylation and the fungus-host interaction, and on chitin synthesis and hyphal orientation responses.

Dr Tiina Roose is currently Royal Society University Research Fellow. Previous posts include Postdoctoral Research Assistant with the Mathematical Institute, University of Oxford and Postdoctoral Fellow with the Harvard Medical School and Massachusetts General Hospital.

Dr David Smith is interested in complex networks, more from a methods rather than an application perspective. Recently, he has been studying the emergence of correlations in evolving networks through the development of a framework based upon master equations. He is also interested in Network Automata which are networks which build themselves using local microscopic rules.

Dr Jukka-Pekka Onnela is currently a Junior Research Fellow in Complex Systems at Wolfson College, University of Oxford, a member of the Oxford Physics Department, and Associate Fellow of the Oxford Saïd Business School. His current research focus is on large-scale social networks and collective phenomena in social systems. Recently he has studied the properties of social interaction networks constructed from the mobile phone calls of millions of individuals.

Dr Mark Fricker is a University Lecturer in Plant Science Tutorial Fellow, Pembroke College, Oxford. His research area is imaging signalling and transport in intact plant and fungal systems operating in their correct tissue context.

Serguei Saavedra is a Doctoral Candidate, Department of Engineering Science, University of Oxford. He is focused on the study of supply chain models applying different techniques such as Information Theory, Network Analysis, Q-analysis and agent-oriented simulation in order to establish measures that guide us to understand the performance of different supply networks.

Alex Ng is a Doctoral Candidate with the Department of Engineering Science at the University of Oxford

Dr Karsten Peters is from the Institute for Transport and Economics, Faculty of Traffic Sciences "Friedrich List", TU Dresden.

Dr Janet Smart is Director of the BT Centre for Major Programme Management. She joined the Saïd Business School from the Department of Engineering Science at the University of Oxford, where she founded the Manufacturing Systems Group. She is also co-director of the CABDyN research cluster (Complex Agent-based Dynamic Networks). She has previously held faculty positions at the Universities of Cambridge and London and has published over 100 papers.

Sean Gourley is a researcher from Oxford University, Department of Physics. Recently he has been focused on flaws in the survey of Iraqi deaths published in the *Lancet.*

Dr Stefano Battiston is from the Eidgenössische Technische Hochschule Zürich, Department Management, Technology and Economics. He has a Physics background (Laurea Thesis in SISSA Trieste, Italy, and a PhD in Physics from Paris VII). He joined the scientific community of Complex Networks in 2001. This recent and innovative community has applied a number of methods inspired from Statistical Physics and Dynamical Systems to the characterization of real world complex networks. He has focused on the structure and dynamics of networks in socio-economic systems.

Professor Janusz Holyst is at Warsaw University of Technology, Faculty of Physics. His research field includes various issues of complex systems such as statistical physics of evolving networks, econophysics and sociophysics. He works also on deterministic chaos, time series analysis and noise level estimation.

Anna Chmiel is a PhD student at Warsaw University of Technology, Faculty of Physics. Her scientific interest is focused on economic complex networks, especially on networks of branches and companies in Poland.

Julian Sienkiewicz is a PhD student at Warsaw University of Technology, Faculty of Physics. His research includes investigation of complex network topology. He performed investigation of path lengths in urban transport networks and its dependence on node (stop) parameters.

WORKSHOP ABSTRACTS

Fordyce Davidson, Mathematical modelling: a question of scale

The study of the growth of filamentous fungi can be difficult through experimental means alone due to the heterogeneity of their natural growth habitat (e.g. soils) and the range of scales associated with growth and function (e.g. tip vesicle translocation through hyphal tip extension to colony expansion). Mathematical modelling provides a complimentary, powerful and efficient method of investigating fungal growth particularly in heterogeneous environments.

We outline the basic processes which go into the construction of mathematical models and discuss our model in the context of other work in this area. Model predictions are compared to experimentally- obtained data, and predictions regarding the complex interaction between the developing mycelium and its environment are made.

Geoff Gadd, Geomycology: mineral-metal transformations by fungi

In terrestrial environments, important mechanisms of fungal metal mobilization from minerals and soil components are acidification and ligand-promoted dissolution mediated by, e.g. organic acid anions. However, if oxalic acid is produced, metal oxalate minerals may result, and these may in turn form carbonates. Such processes can occur in the root region of plants growing on toxic metal minerals as well as in soil and rock-inhabiting fungal communities. Free-living and mycorrhizal fungi are capable of toxic metal mineral transformations and this can be related to fungal metal tolerance and the phosphorus status of the soil. In providing the plant host with phosphorus, fungal solubilization of inorganic phosphates (e.g. $Zn_3(PO_4)_2$) can result in release of associated toxic metals increasing metal toxicity. However, some mycobionts demonstrate the ability to re-precipitate released metals (Cu, Zn, Pb) within insoluble secondary mycogenic minerals making them chemically stable and unavailable for the plant host and soil biota. Such phenomena are components of geochemical cycles for metals but are also relevant to revegetation/reclamation of metal-polluted sites. Each of these component topics (i.e.. molecular biological and mineralogical processes; mineral dissolution/formation; metal speciation) requires an understanding of fungal growth, function and interactions with the environment at scales ranging from the nano- and sub-micron level through the micron level (e.g. thigmotropic responses of the hyphae to substratum structure), to the centimetre and >metre level (e.g. interactions between colonies, mycorrhizal symbioses, bioremediation strategies). A combined experimental-modelling approach has been very useful in understand such processes across these scales.

Stefan Olsson, Self-eating is important for mycelium growth.

When studying fungal mycelium growth and development it is customary to think in terms of nutrient uptake, growth in biomass, and especially when studying growth I heterogeneous environments, nutrient translocation. Newly taken up nutrients are not the only sources of nutrients to the advancing front of a mycelium. Old biomass can be recycled into new biomass. Autophagy, or self-eating, is a general process for recycling biomass to nutrients within an eukaryotic cell.

One of the key proteins in macroautophagy Atg8p is necessary for the formation of autophagosomes. In order to evaluate if internal recycling of nutrients is important for *F.*

graminearum we used homologous recombination and an *Agrobacterium*-mediated transformation technique to make *FgΔAtg8*-deletion strains.

The *FgΔAtg8*-deletion mutants have less extensive aerial mycelium but otherwise they grow as fast and dense and with similar colour as the wild type on standard media. In an infection assay on heads of wheat the *FgΔAtg8*-deletion mutants had a considerable reduced virulence in comparison with the wild type. A closer investigation of the aerial mycelium showed that it becomes filled with lipid droplets indicating starvation of some mineral nutrient and surplus of carbon/energy. The *FgΔAtg8*-deletion mutants have almost no ability to extend over inert plastic surfaces although the wild type does it to a great extent. Thus, virulence as well as formation of aerial hyphae and growth over inert surfaces is dependent on internal recycling of nutrients. These results highlight the importance of nutrient recycling within a mycelium for mycelium growth and development.

Franco Neri, Network models for spread and control of soil-borne fungal plant pathogens

We will review recent developments in the modelling and experimentation of the invasion of fungal plant pathogens in soil. Susceptible sites (hosts) in soil-borne epidemics can be identified as roots or plants in various spatial arrangements, analogous to networks. On these networks, infection of hosts occurs at small scales through mycelial spread between neighbouring sites, yet epidemics are observed at larger scales and involve cascading spread through a population of susceptible sites. The theory of percolation on networks, borrowed from statistical physics, proves to be a powerful framework to scale up from the small to the large scales. In particular, testable hypotheses related to invasion and persistence of epidemics can be formulated. For example, we will show how, using simple artificial experimental systems, it was demonstrated that thresholds for invasion of soil-borne fungal plant pathogens occur, and that these thresholds are consistent with those predicted by percolation theory for phase transitions on networks. We will also discuss how it is possible to analyse the efficiency of specific control strategies for diseases on those networks.

Nick Read, Self-signalling and self fusion during hyphal network formation in *Neurospora crassa*

Self fusion between genetically identical hyphae is a characteristic feature of the lifestyles of most filamentous fungi. Hyphal networking via hyphal fusion allows the fungal colony to act as a cooperative unit and single individual. It serves many useful functions including facilitating nutrient transport, water translocation and communication throughout the colony. Recently we discovered that hyphal fusion during colony establishment in the model *Neurospora crassa* involves the induction, homing and fusion of specialized hyphae called *conidial anastomosis tubes* (CATs). We have established the CAT system as a simple and experimentally amenable model in which to analyze self-signalling and self fusion in filamentous fungi. My talk will cover the following topics: (1) hyphal fusion in the mature colony and during colony initiation; (2) screening for mutants compromised in self-signalling and hyphal fusion; (3) use of laser tweezers as experimental tools to analyze cell-cell communication; and (4) the mechanistic basis of self-signalling.

Peter Darrah, 'Exploratory foraging and resource acquisition by a wood-decomposing fungus *(Phanerochaete velutina)'*

Saprotrophic fungi decomposing wood on the forest floor must acquire resources which are heterogeneously distributed in space and time. Discrete discs of cellulose and glass fibre were used to investigate the marginal responses of *Phanaerochate velutina* in a simple microcosm. The exploratory responses of the fungus to the baits are analysed. Mathematical simulations are used to explore the adaptive significance of the foraging behaviour.

Tiina Roose, Multiscale modelling of plant nutrient uptake

In this talk I will present a mathematical model for plant nutrient uptake from the soil. As a starting point I will consider the Nye-Tinker-Barber model for nutrient uptake by a single bare cylindrical root. I will then present some of the analysis of this model culminating with the derivation of the analytic formula for nutrient flux into the root. The basic "bald root" model is then extended to include root hairs and mycorrhizae, which have been found experimentally to be very important for the uptake of immobile nutrients. Again, analytic expressions for nutrient uptake can be derived. The simplicity and clarity of the analytical formulae for the solution of the single root models allows the extension of these models to more realistic branched roots. These root system models can be used to show that the volume averaging of the branching structure, a commonly used technique for translating results from single root scale to root system scale, can lead to large errors. The next step in developing the modelling is to include water movement and uptake. The water uptake model that we have developed shows that the water saturation can develop pseudo-steadystate wet and dry zones in the rooting region of the soil. The dry zone is shown to stop the movement of nutrient from the top of the soil to the groundwater.

David Smith, Network automata and the functional dynamic network framework

We introduce and define Network Automata, a generalization of Cellular Automata, which relates the topological evolution of a network to its structure. This framework is capable of replicating many familiar network models. We also introduce the Functional Dynamic Network framework for dealing with networks in which the topology evolves according to some specified microscopic rules and, simultaneously, there is a dynamic process taking place on the network that both depends on its structure but is also capable of modifying it. As such it is a generic framework for dealing with the types of systems in which network structure, dynamics, and function are interrelated. At the practical level, these frameworks allow for easy implementation of the microscopic rules involved in such systems. To demonstrate the Functional Dynamic Network in action, we develop a class of simple biologically inspired models of fungal growth.

Mark Fricker, Transport efficiency and resilience in mycelial networks

Transport networks are vital components of multicellular organisms, distributing nutrients and removing waste products. Animal cardiovascular and respiratory systems, and plant vasculature, are fractal-like branching trees whose architecture determines universal scaling laws in these organisms. In contrast, transport systems in multicellular fungi are not expected to fit into this conceptual framework, as they have evolved to explore the environment rather than ramify as a three-dimensional organism. Many fungi grow as a foraging mycelium, formed by the branching and fusion of threadlike hyphae. This process gives rise to a complex network that continuously adapts to its environment. However, the properties of the network and its dynamic behaviour have not yet been characterised. Using a range of woodland saprotrophic basidiomycetes, we have examined network development and its nutrient transport characteristics over a range of scales, using a combination of imaging, modelling, gene expression profiling and metabolomics.

We have found that fungal networks can display both a high transport capacity and high resilience to damage. These properties are enhanced as the network grows, while the relative amount of material used to build the network decreases. Thus, mycelia achieve the seemingly competing goals of efficient transport and resilience, with decreasing relative investment, by selective reinforcement and recycling of transport pathways. The fungal network demonstrates that indeterminate, decentralised systems can yield highly adaptive networks.

To test the predictions from the theoretical analysis of transport, we have mapped the distribution of non-metabolised, radiolabelled amino-acid and sugar analogues during mycelial development in spatially heterogenous resource environments using photon-counting scintillation imaging. These studies have revealed a number of novel phenomena, including a marked pulsatile transport component superimposed on a rapid underlying flux, preferential resource allocation to C-rich sinks, abrupt switching between different pre-existing transport routes and organization of the network into well demarcated domains differing in phase or frequency of oscillations. Furthermore, fusion between compatible individuals leads to rapid nutrient re-distribution and formation of a fully synchronised super-colony.

Overall the spatial organisation of these mycelial systems provide an almost unique opportunity for any eukaryotic system to directly correlate metabolite levels, nutrient fluxes, gene expression patterns and morphological development.

Karsten Peters, Material and Information Flows in Production Networks

Production and supply networks are complex networks of nonlinear dynamical elements designed to fulfill certain functional requirements. By using recently developed models we study the interaction and dynamics of production units exchanging material and information in such network structures. Whereas the directed flow of materials introduces a coupling between nearest neighbours in a supply network, the accompanying information network can involve even long range interactions. The stability and robustness under demand variations with respect to the topology of the underlying network structures is investigated. Surprisingly, even small changes in network topology can lead to different dynamics. Furthermore, for a fixed material flow network, the stability and dynamical behaviour of the system can be influenced significantly by changing the structure of the sub-network for information exchange. In particular, we have extended an existing dynamical input-output model in order to study weighted mixtures of pull ands push strategies, i.e., in situations where the production rate of individual manufacturers is determined by both the availability of commodities and the demand for the final products. Recent findings suggest that an adjustment of the corresponding production parameters allows one to minimise or even avoid an undesired amplification of demand and supply fluctuations along a supply chain (Bullwhip effect).These results can be used to optimize the structure of the material flow network and the information network in order to obtain more reliable, stable and robust supply networks.

Janusz Holyst, First order phase transition in Ising model on two connected Barabasi-Albert networks

We investigate the behavior of the Ising model on two connected Barbasi-Albert scale-free networks. We show that a first order temperature-driven phase transition occurs in such system. The transition between antiparalelly ordered networks to paralelly ordered networks is shown to be discontinuous. We calculate the critical temperature using several methods.

We use a mean-field approach that leads to a self-consistent equation for the average spin. If we consider two networks that interact (inter-network links number is proportional to intra-network links), we can treat the influence of the second network as external field hi. As result we receive a matrix equation which eigenvalues bring critical temperatures.

In connected B-A networks, Ising model is characterized by two phase transition in two different critical temperatures Tc- and Tc+. Below Tc- there are two possible phases: both networks ordered in with same spin and both networks ordered with opposite spins. At critical temperature Tc- the state with antiparallel spin ordering disappears, and between Tc- and Tc+ the system orders only parallely. At Tc+ and above the temperature is too high for network to remain ordered and it assumes paramagnetic state. As in regular Ising model, the transition at Tc+ is second order phase transition. The transition at Tc- turns out to be of first order. We have performed analytic calculations, numeric map iterations and Monte-Carlo simulations.

Anna Chmiel, Scaling of human behaviour in the World Wide Web

The cyberspace can be understood as a complex system of human actions, with one very popular kind of this activity corresponding to the information search in this virtual world. The set of web pages we choose, the browsing art, and the time we spend reading the contents reflects our pastime habits and interests in the real world.

To study this issue we used the data from Polish portals, and considered the behaviour of a user on a Web page. Our analysis is based on cookie statistic provided by Gemius company. For example the portal www.onet.pl consists of 515 sub pages which are visited by 4 millions cookie users during one day. We constructed a weighted network of sub pages defining link weights as the number of users moving from one sub page to another. The weights distribution is a power law with characteristic exponents $\gamma = 1.45 - 1.65$. We observed the traffic at the portal and we learnt about habits and patterns of behaviour of internauts by the analysis of network properties.

Our data contains also the information about the time spent by a user on various sub pages. We investigated the distribution of total time a user spent on the portal, and the distribution of times spent on one sub page. This distribution is a power law $p(t) \sim t^{-\gamma}$ ($\gamma = 1.19$ for the www.gazeta.pl and $\gamma = 1.31$ for the www.onet.pl) over two decades. We also examined also properties of partial time distribution. A partial time is the time the user stayed on one sub page normalized by the total time spent on the portal for this user. The distribution of partial times is a power law with $\gamma = 1.10$ for the www.gazeta.pl and $\gamma = 1.13$ for the www.onet.pl). On the other hand we observed an exponential distribution of numbers of different pages visited by a single user. We constructed a model explaining some of features observed at sub pages networks.

Julian Sienkiewicz, Scaling of distances in weighted complex networks

In our previous works we examined the internode distances in complex networks as a function of the product of nodes' degrees. We showed that in many commonly known models as Erdos=Renyi graphs or Barabasi-Albert evolving networks as well as in real-world examples that relation takes the form of a logarithmic law.

In the current work we extended our previous results, providing evidence that the described relation is a case of a more general law in which unweighted distances are substituted with weighted ones and degrees with nodes' strengths. The shape and character of the relation is strongly connected to the width of the weight distribution.