Theoretical foundations for statistical network analysis

Brief background / historical information

- **Why was the programme organized on this particular topic?**

Statistical network analysis has made significant strides in multiple application areas, generating papers in *Nature*, *Science* and other high-impact journals. However, the statistical theory underpinning use of networks to understand data was underdeveloped. Our programme aimed to advance this fundamental theory, by bringing together experts from combinatorics, probability and statistics.

- **What were the outstanding problems in the field?**

There was a need to develop and test mathematical models with the flexibility to depict heterogeneous networks, and the capacity to dovetail with existing combinatorics and probability frameworks for kernel-based models. Novel mathematical tools were also required to analyse multiplex networks (several networks with identical nodes), and dynamic networks (having evolutions in processes and over time).

How was the programme organised to address them?

Five workshops, an industry day, and a weekly seminar series (28 talks) targeted different aspects of the above problems.

Programme timeliness, scope and outline

- **Topics addressed and research areas involved**

1) *Statistical asymptotics*: including theoretical tools for describing network characteristics over growing network sizes (e.g. graphons, graphlets, graph limits), and methodological repercussions of these representations.
2) *Statistical models*: new structurally-rich and tractable mathematical models for network structure, e.g. nonparametric block models, and developments in algebraic statistics.
3) *Large-scale algorithms*: algorithms for datasets too large to be treated in their entirety.
4) *Dynamics in networks*: network spreading and percolation, probability, and applications e.g. epidemic modelling.

- **Brief summary of workshop and Satellite Meeting themes**

First Workshop: 11-15 July 2016: *Graph limits and statistics*
This workshop merged ideas from combinatorics, probability and statistical theory with methodology, starting from the notion of graph limits and nonparametric statistical models.

Second Workshop: 25-27 July 2016: *Bayesian methods for networks*
The Bayesian framework for construction of statistical network models and computational methods of inference was discussed - including exchangeable models of networks and relational data, and latent variable models of user preferences.

Third Workshop: 22-26 August 2016: *Network science and its applications*
Highlighted challenges for interpretation and validation of application-specific network models, aiming to draw bridges between methods employed across application areas.

Open for Business: 1 November 2016
Experts and stakeholders discussed network-related problems in industry and the public sector.

Satellite workshop: 21-22 November 2016: *Future directions in network mathematics*
Examined interplay of discrete mathematics, spectral methods, control, optimization and topology with mathematical statistics, aiming to anticipate future areas for cross-fertilisation.

Fourth Workshop: 12-16 December 2016: *Dynamic Networks*
Discussed traditional and emerging models for dynamic networks.

Scientific outcomes

- **Highlights**
  - Key developments in **heterogeneous network models**: e.g. Janson (arXiV:1608.01833v2), Roy (arXiV:1611.00843), Bianconi (arXiv:1703.05528); **dynamic models**: e.g. Newman (arXiv:1607.07570), Garavaglia (arXiv:1703.05943); **spreading on networks:** e.g. Bianconi (arXiv:1611.08750), Ball (arXiv:1611.04818), Avena et al (arXiv:1606.07639), and **network nonparametrics**, e.g. Maugis et al (arXiv:1705.05677), Bloem-Reddy et al (arXiv:1612.06404).
  - Lunch series and Women in Data Science event co-organised with concurrent *FOS* and *DLA* programmes.
  - George Pólya Combinatorics Prize won by Jozsef Balogh and Robert Morris.
  - Peter Bickel gave Rothschild Lecture: "From Small Data to Big Data and Back: Statistics and Data Science."

- **Collaborations**

Participants described plans to pursue new work in pathogen spreading and epidemic modelling, non-Euclidean metrics for covariance matrices, multiscale modelling of network structure, and topology in technological and social networks.

- **How the programme advance research in the field?**

94% of feedback rated international scientific quality as 80%+; the same percentage felt their participation would enable pursuit of new research directions. ~60% said the programme revealed new applications for their own work. We expect to see this reflected in the literature in due course.

- **Did the programme successfully bring different communities together, and are there research results or specific outputs that highlight this?**

Participants recognised that several communities were represented, particularly at workshops – and social events and discussion periods were successfully encouraged interaction. The cross-programme lunch was widely lauded.

- **What plans and direction have you identified for future investigations?**

Participant feedback suggests progress will be made in: network models with tuneable clustering; settings where latent space models perform differently than nonparametric graphon models; methods for network sampling and rapid detection of network structural change; theory of graphs with assumptions about edge-exchangeability; and methods for validating existing and new network structure models.

- **Are there notable impacts outside academia or to other areas of academia beyond mathematics?**

Several participants made adjoining academic and industrial visits, including to UK universities, the Alan Turing Institute, Nature and Deepmind. Since networks have wide applications, there will be impact beyond mathematics, in areas including biology and health, security, finance, artificial intelligence, and social and political science.

Multimedia activity:

- **Evidence of remote access to streamed lectures**

The entire programme (at INI and offsite) featured a total of 168 scientific talks, 139 of which were live-streamed and recorded for online access and archive. Slides from 48 presenters are available online.

Publications

- **Books**

Flandrin is developing a book on the theoretical grounds for signal recovering approaches.

- **Major publications**

In most instances, work is still on-going. However, Janson is preparing three papers on graph limits and random networks; two are available as pre-prints. Olhede and Wolfe are planning a review paper in Proceedings of the Royal Society A. A list of relevant papers produced during the after the programme by participants is given in the appendix.

- **Multimedia items**

Rothschild lecture: https://www.newton.ac.uk/seminar/20160817160017001

Photographs

Embedded event with the Cambridge Emmy Noether Society

Introductions at the satellite event at the Royal Society

Patrick Wolfe speaking at the opening workshop

Sofia Olhede talking about motifs at the opening workshop

Attendees at the second workshop

Attendees at the second workshop

Participants at the opening workshop

Participants at the second workshop

Participants at the third workshop

Participants at the closing workshop

Appendix :

List of publications authored and co-authored by participants, during and after programme
[Listed alphabetically by surname of first author]

A

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Yoann Altmann, Aurora Maccarone, Aongus McCarthy, Gregory Newstadt, Gerald S. Buller, Steve McLaughlin, Alfred Hero, Robust spectral unmixing of sparse multispectral Lidar waveforms using gamma Markov random fields, arXiv:1610.04107

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Amine Asselah, Bruno Schapira, Perla Sousi, Strong law of large numbers for the capacity of the Wiener sausage in dimension four, arXiv:1611.04576

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Luca Avena, Hakan Guldas, Remco van der Hofstad, Frank den Hollander, Mixing times of random walks on dynamic configuration models, arXiv:1606.07639

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Paul Balister, Béla Bollobás, Robert Morris, The sharp threshold for making squares, arXiv:1608.03857.

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Frank Ball, David Sirl, Evaluation of vaccination strategies for SIR epidemics on random networks incorporating household structure, arXiv:1611.04818

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József Balogh, Béla Bollobás, Bhargav Narayanan, Transference for the Erdős-Ko-Rado theorem, arXiv:1609.01001.

Jozsef Balogh, Hoi Nguyen, A general law of large permanent, arXiv:1701.00354

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Jozsef Balogh, Jozsef Solymosi, On the number of points in general position in the plane, arXiv:1704.05089

Jozsef Balogh, Sarka Petrickova, Adam Zsolt Wagner, Families in posets minimizing the number of comparable pairs, arXiv:1703.05427

József Balogh, Sean Eberhard, Bhargav Narayanan, Andrew Treglown, Adam Zsolt Wagner, An improved lower bound for Folkman's Theorem, arXiv:1703.02473

Taras Banakh, Adam Idzik, Oleg Pikhurko, Igor Protasov, Krzysztof Pszczoła, Isometric copies of directed trees in orientations of graphs, arXiv:1606.01973

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