Theory and Applications of Complex Networks: Advances and Challenges

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Acknowledgements

- ISCAS Special Sessions organized by NLCAS TC:
  G. Ron Chen, Ljiljana Trajkovic, Michael Tse, Maciej Ogorzalek, Chai Wah Wu, Mario di Bernardo, Jinhu Lu:
- 2007, New Orleans, USA
- 2008, Seattle, USA
- 2009, Taipei, Taiwan
- 2010, Paris, France
- 2011, Rio de Janeiro, Brazil
- 2012, Seoul, Korea
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- Jinhu Lu
- G. Ron Chen
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Invited lectures:

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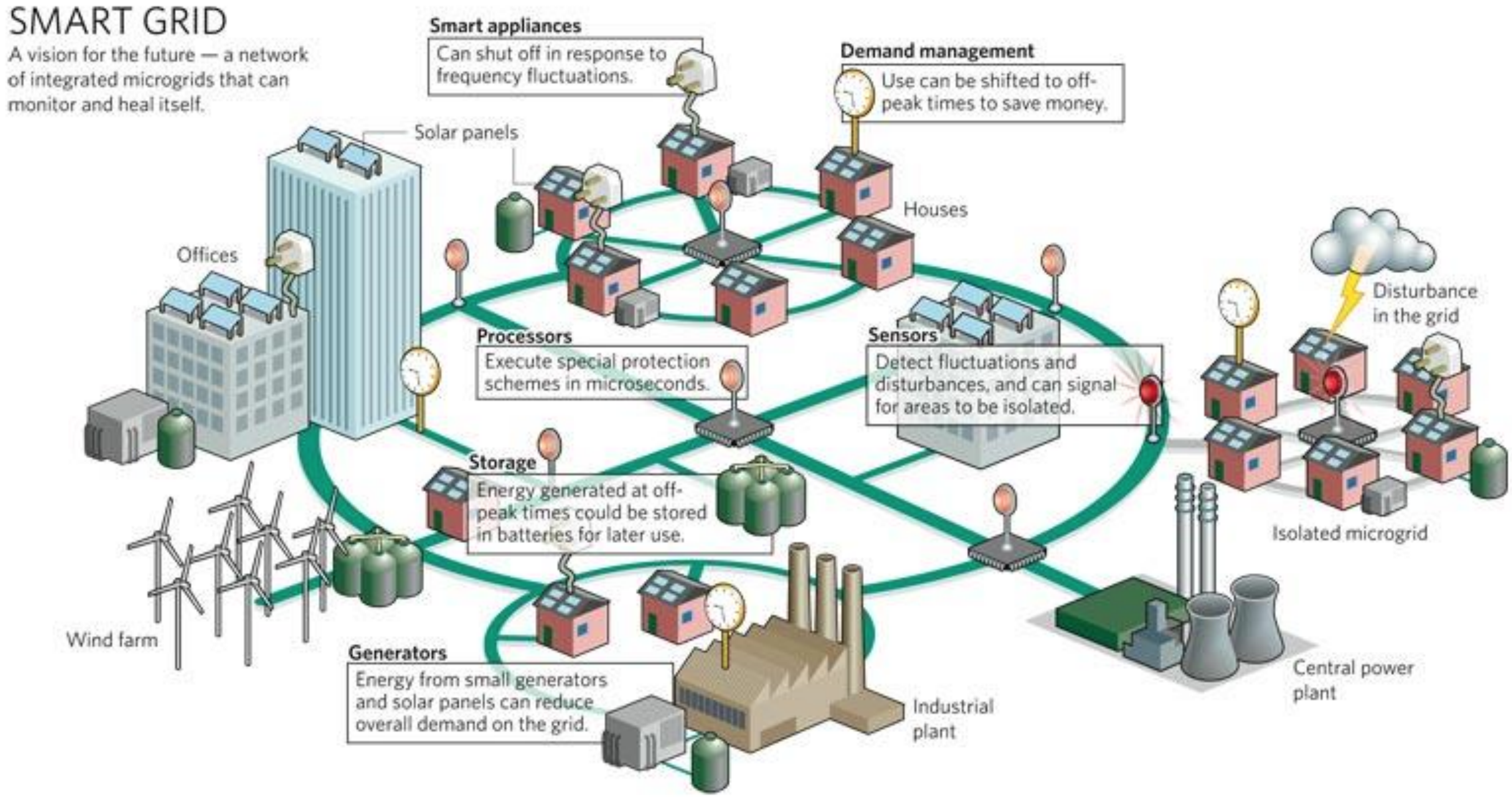
Outline

- Introduction
- Recent Theoretical Advances
- Recent Applications
- Conclusions

Complex networks are everywhere!

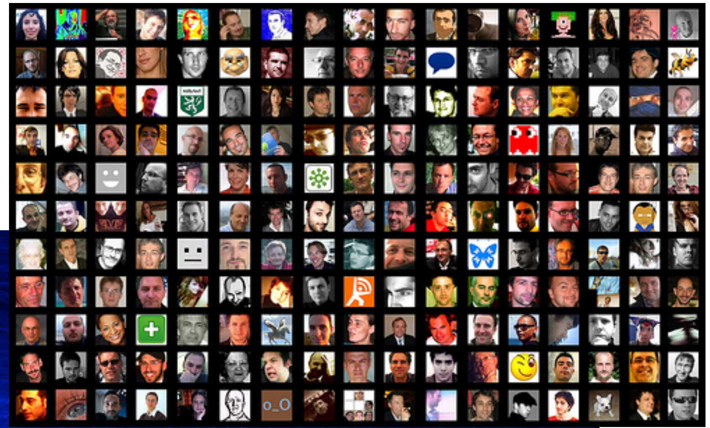
Smart Grids



SMART GRID
A vision for the future — a network of integrated microgrids that can monitor and heal itself.
Smart appliances
Can shut off in response to frequency fluctuations.
Demand management
Use can be shifted to off-peak times to save money.
Solar panels
Houses
Offices
Disturbance in the grid
Processors
Execute special protection schemes in microseconds.
Sensors
Detect fluctuations and disturbances, and can signal for areas to be isolated.
Storage
Energy generated at off-peak times could be stored in batteries for later use.
Isolated microgrid
Wind farm
Generators
Energy from small generators and solar panels can reduce overall demand on the grid.
Industrial plant
Central power plant

Transportation Networks

Social Networks



Financial Networks

Network Graphs

- Random Graphs
  - Nodes and edges are generated via a random process
  - Erdős and Rényi model (1960)
- Small World Graphs
  - Nodes and edges are generated so that most of the nodes are connected through a small number of nodes in between
  - Watts and Strogatz model (1998)
- Scale-Free Graphs
  - Graphs whose node degree distributions follow a power-law
  - Rich gets richer
  - Barabási and Albert model (1999)

Recent Theoretical Advances

For example:

- Controllability of complex networks
- Observability of complex networks
- Pinning Control of complex networks

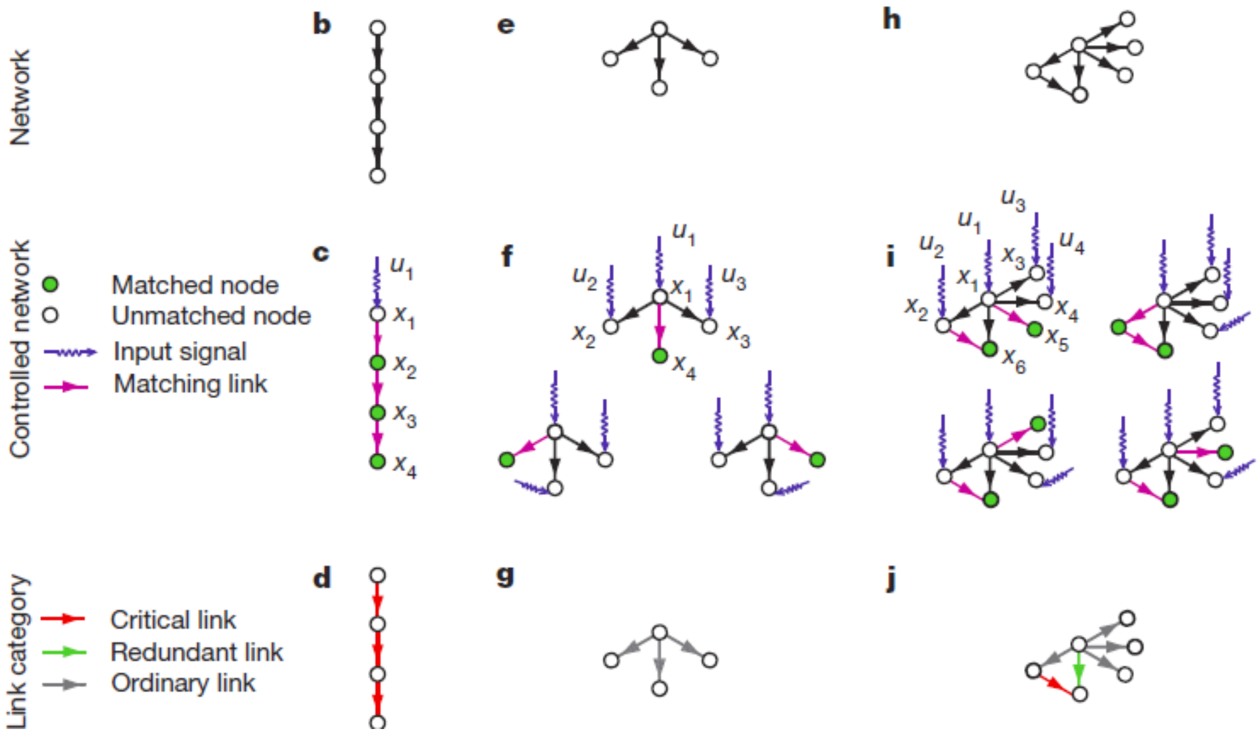
Controllability of Complex Networks

ARTICLE

doi:10.1038/nature10011

Controllability of complex networks

Yang-Yu Liu[1,2], Jean-Jacques Slotine[3,4] & Albert-László Barabási[1,2,5]

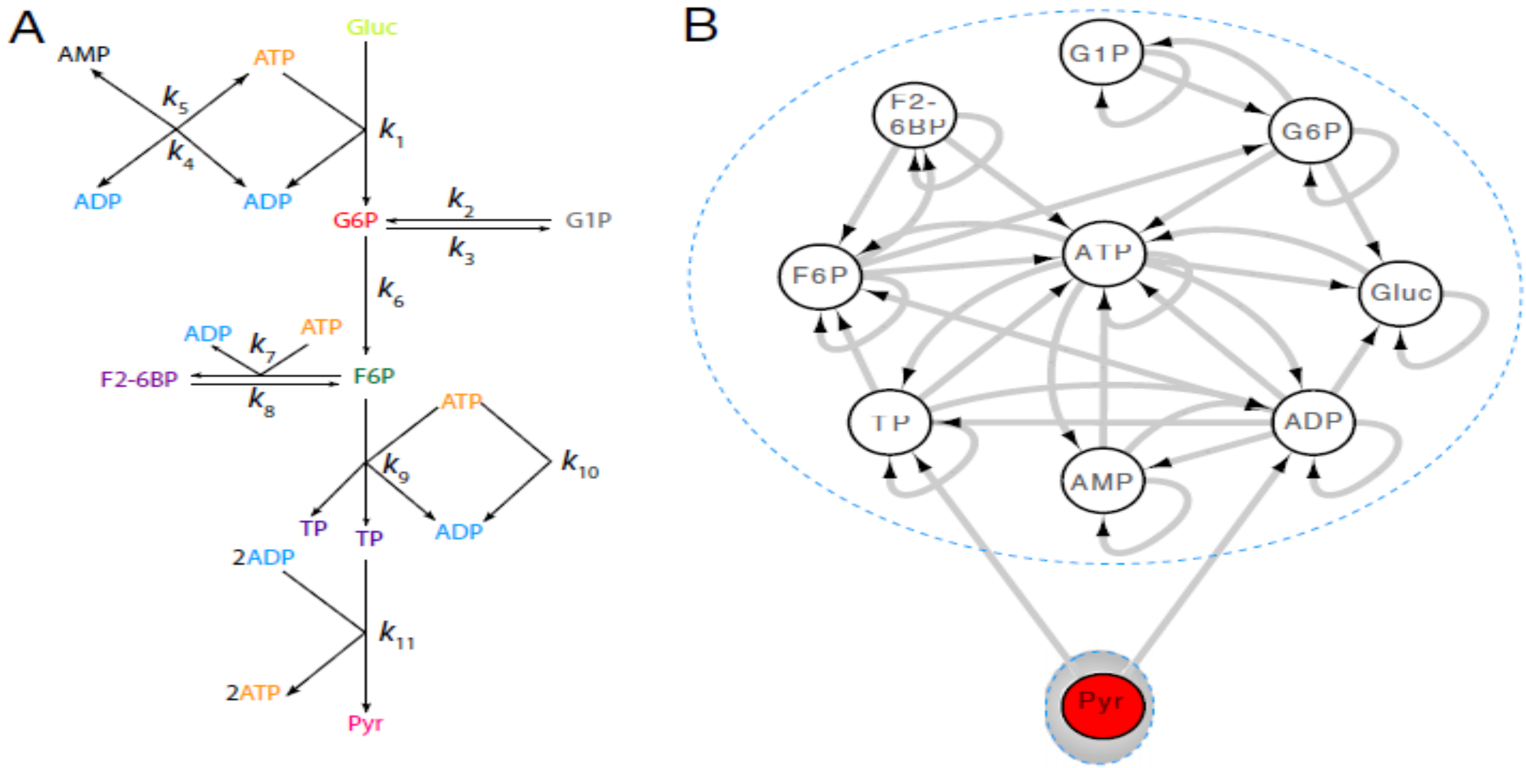


Observability of Complex Networks

Observability of complex systems

Yang-Yu Liu[a,b,c,d,e], Jean-Jacques Slotine[f,g,h], and Albert-László Barabási[a,b,c,d,e,i,1]

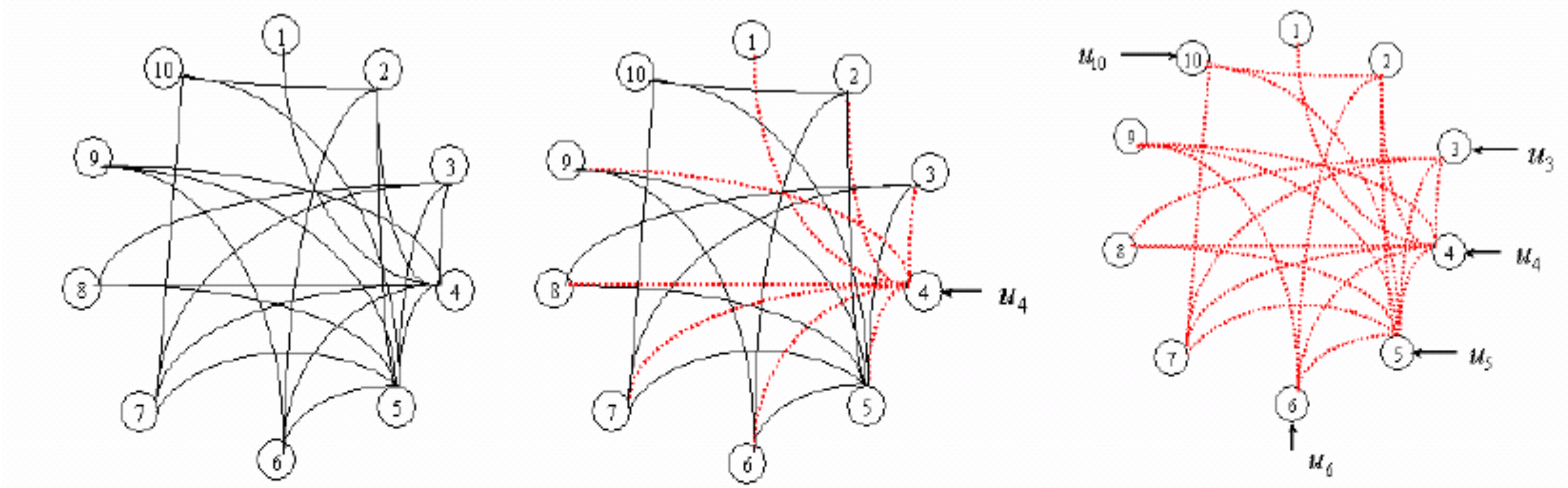
[a]Center for Complex Network Research and Departments of [b]Physics, [c]Computer Science, and [d]Biology, Northeastern University, Boston, MA 02115; [e]Center for Cancer Systems Biology, Dana-Farber Cancer Institute, Boston, MA 02115; [f]Nonlinear Systems Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139; Departments of [g]Mechanical Engineering and [h]Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139; and [i]Department of Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115



Pinning Control of Complex Networks

- It is practically impossible to control every node in a large complex network
- Is it possible to control a small fraction of nodes (e.g., 5%) to achieve the same effect?
- Pinning control

Pinning Control: A Simple Example



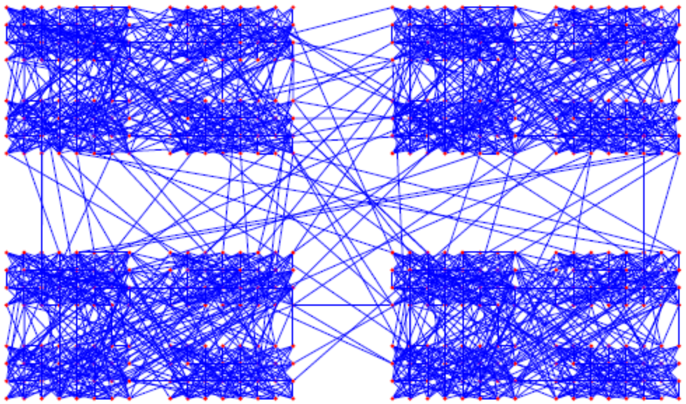
A network with 10-nodes

generated by the B-A scale-free model (N=10, m=$m0$=3)

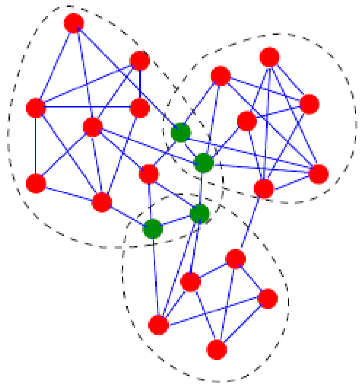
X. F. Wang, G. Chen, Physica A (2002)

X. Li, X. F. Wang, G. Chen, IEEE T-CAS (2003)

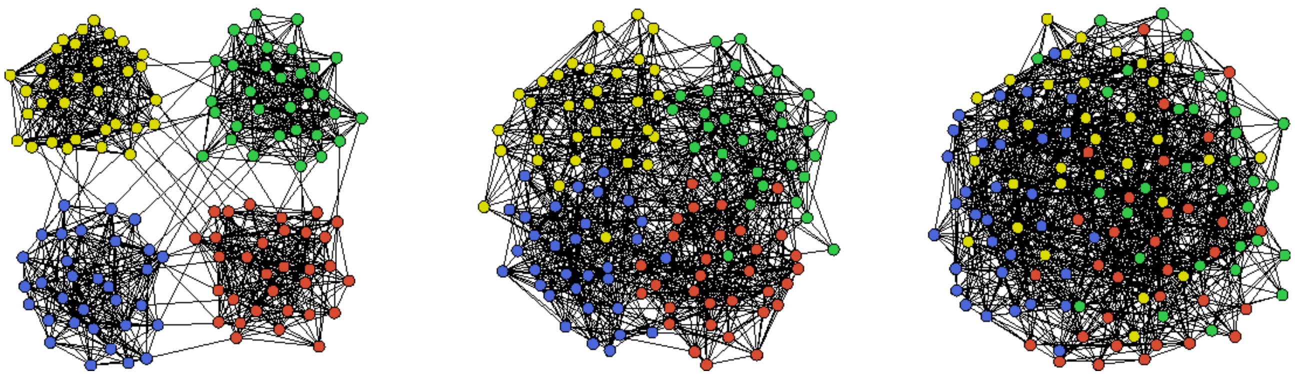
Detecting Community Structures: Challenges



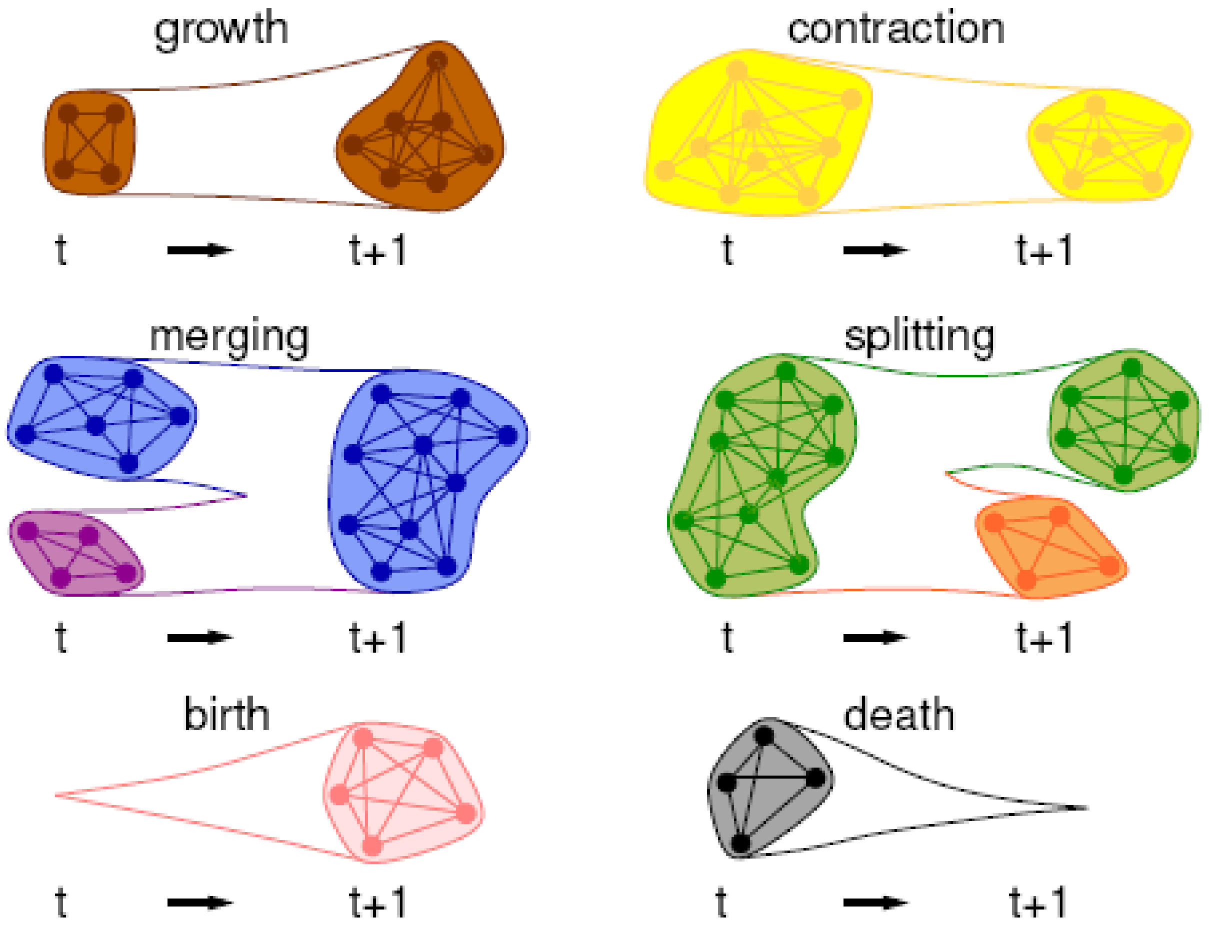
Hierarchical



Overlapping



Detecting Community Structures: Challenges



Two Fundamental Challenging Problems

- How many and which nodes should a network with fixed structure and coupling strength be pinned in order to reach network synchronization?
- How large the coupling strength should be applied to a network with fixed structure and pinning nodes in order to reach network synchronization?

- J. Zhou, J. Lu, J. Lü, Automatica, 44(4): 996−1003, 2008.
- H. Liu, J. Lu, J. Lü, D. Hill, Automatica, 45(8): 1799−1807, 2009.
- W. Yu, G. Chen, J. Lü, Automatica, 45(2): 429−435, 2009.

Application Examples

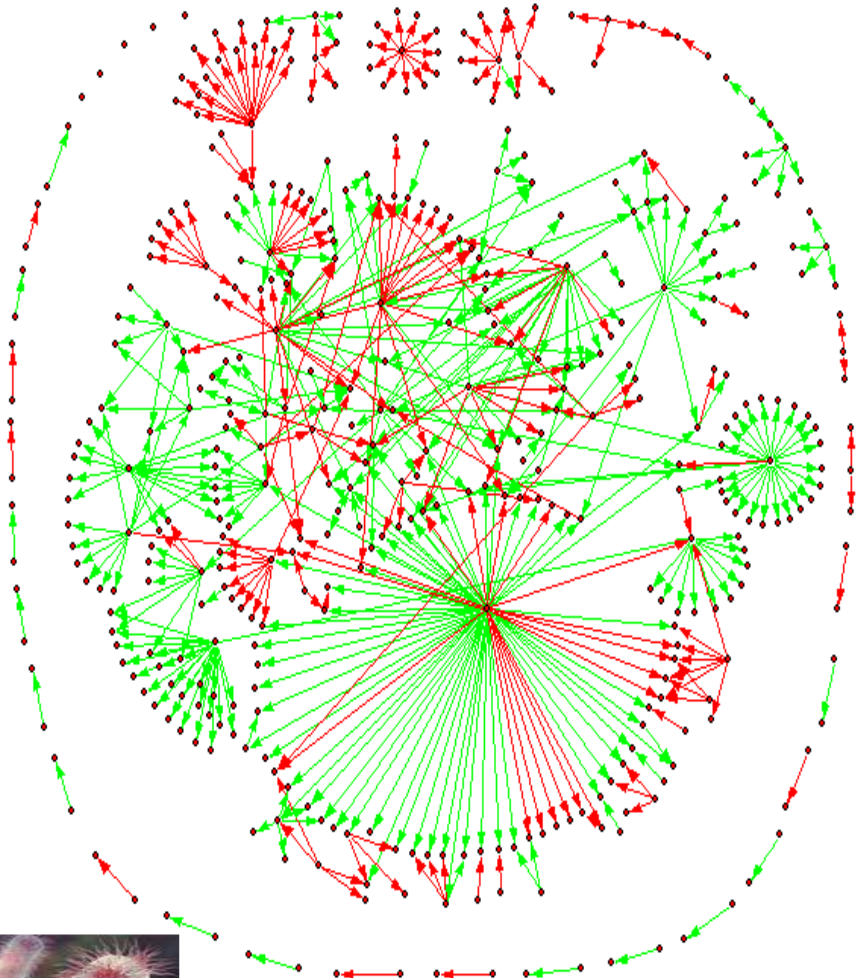
Numerous real-world applications:

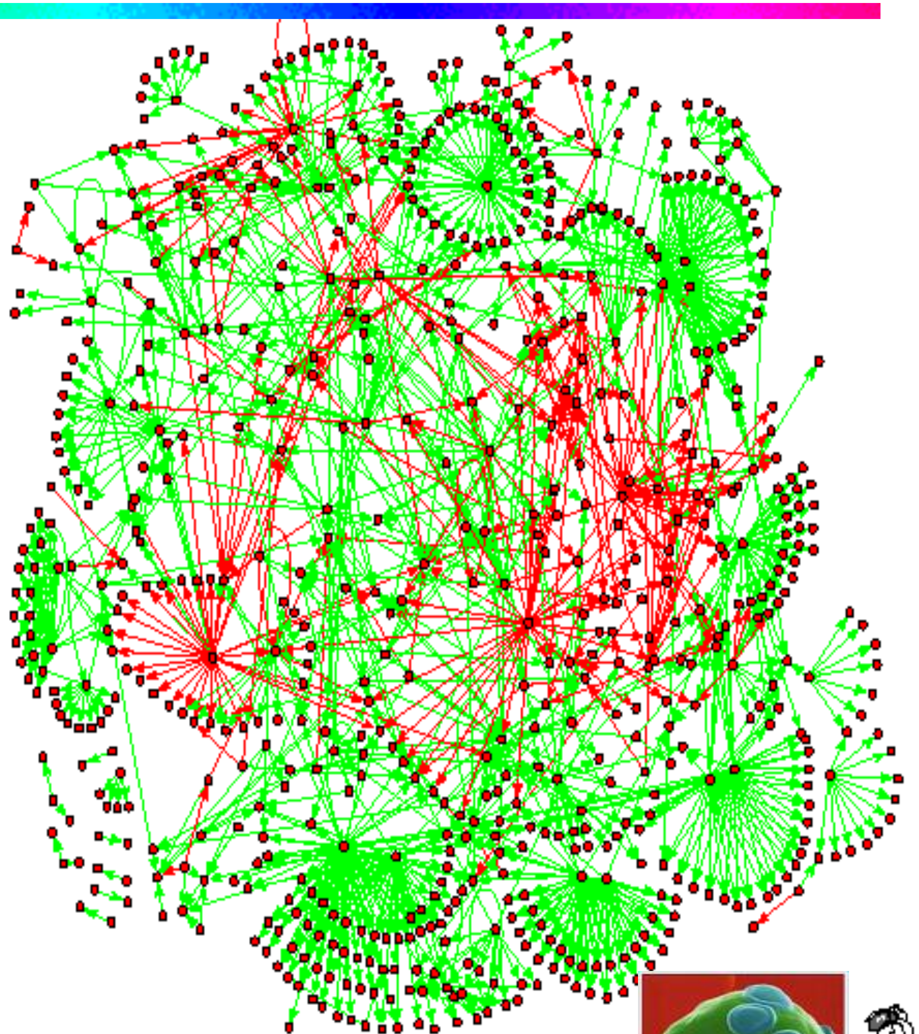
- Applications in Systems Biology

- Applications in Engineering Networks

- P. Wang, J. Lü, and M. J. Ogorzalek, "Global relative parameter sensitivities of the feed-forward loops in genetic networks," *Neurocomputing*, vol. 78, no. 1, pp. 155-165, Feb. 2012.

Genetic Regulatory Networks

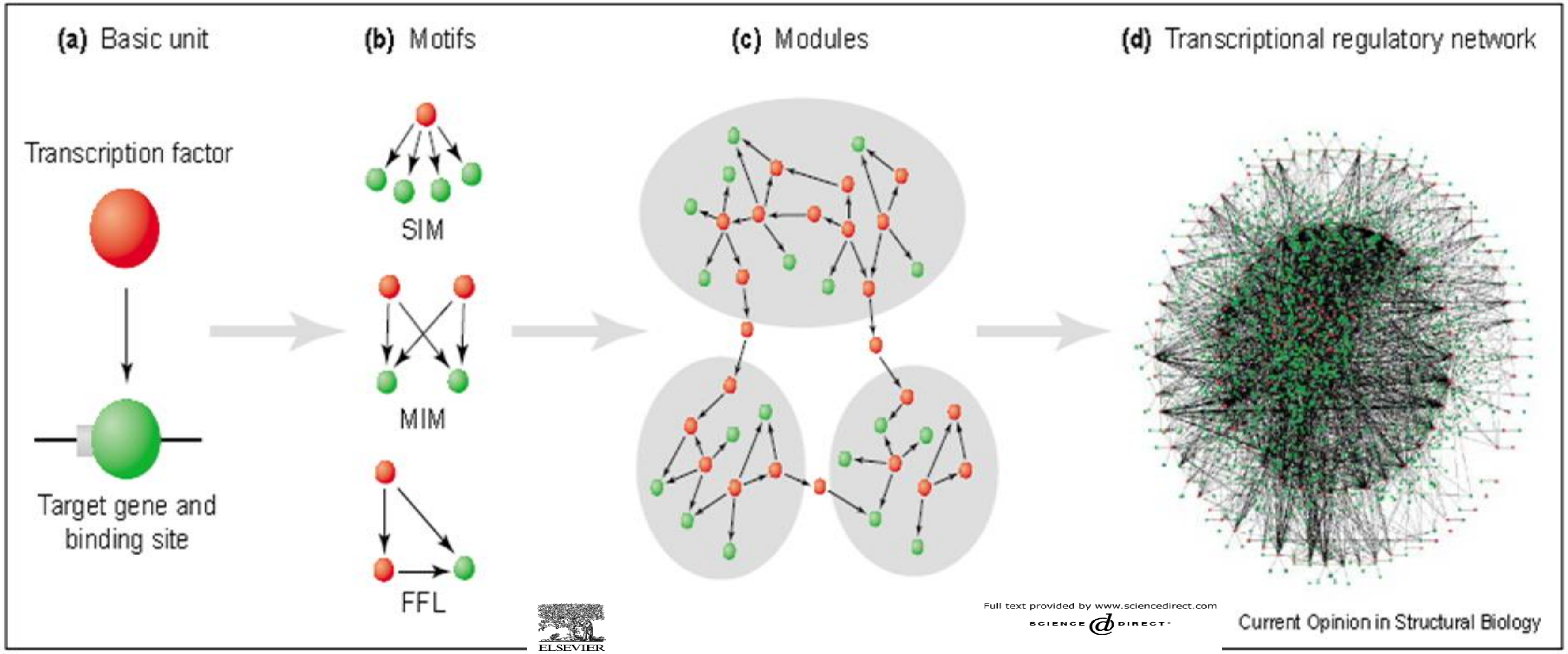




Bacterium: *E. coli*

Single-celled eukaryote: *S. cerevisiae*

Real-World GRNs Are Too Complex

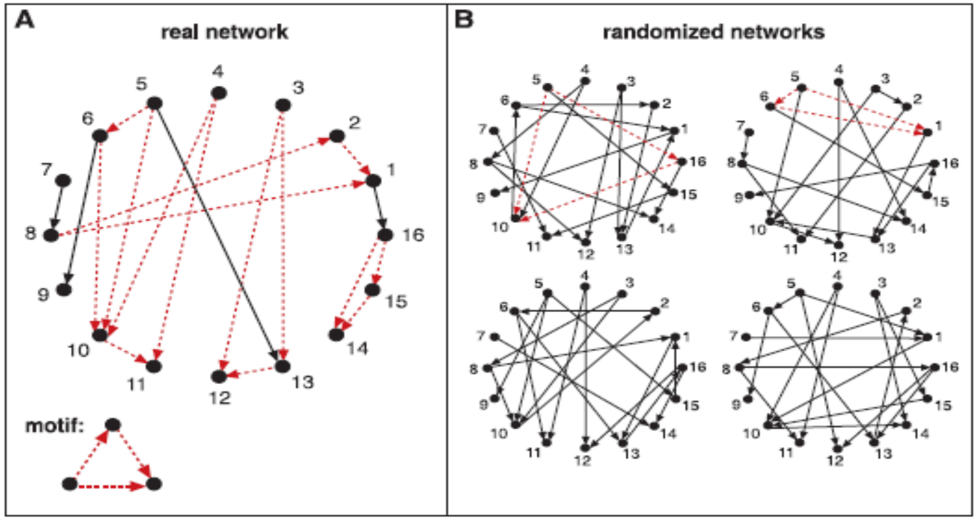


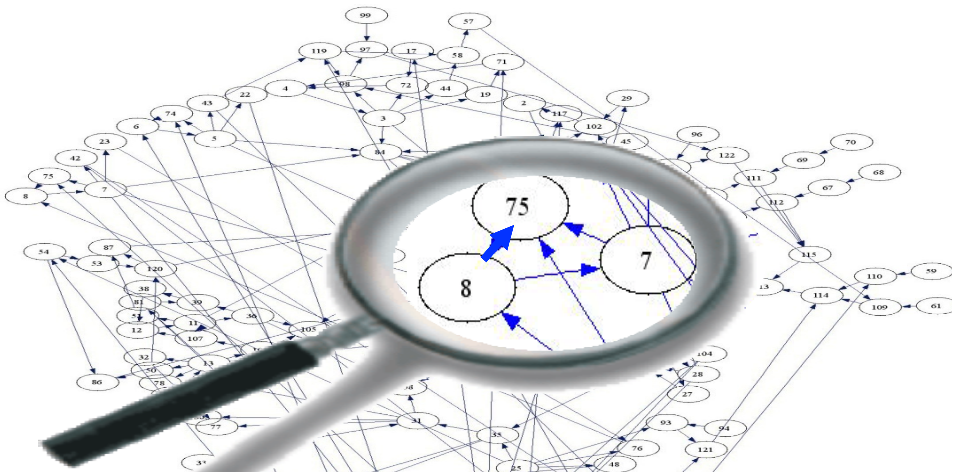
ELSEVIER
Structure and evolution of transcriptional regulatory networks
M Madan Babu[1,2*], Nicholas M Luscombe[3*], L Aravind[4], Mark Gerstein[3] and Sarah A Teichmann[1,5]

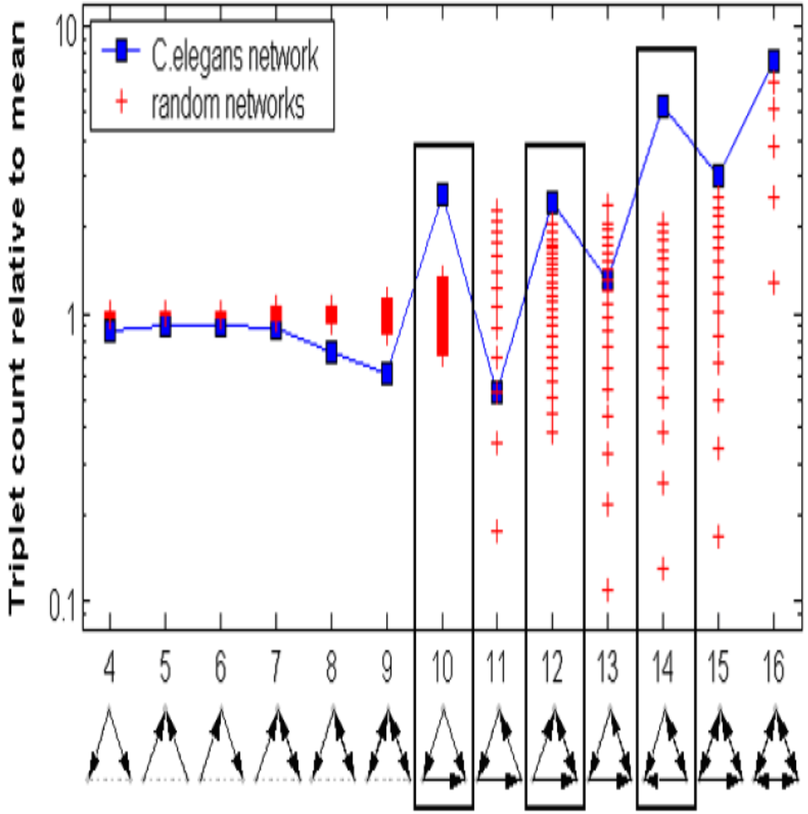
- Have hindered the understanding of real-world GRNs
- Complex GRNs have many simple building blocks
- Investigation of simple networks is a first step to understand real complex GRNs

Network Motif

Network motif： frequent patterns in real networks



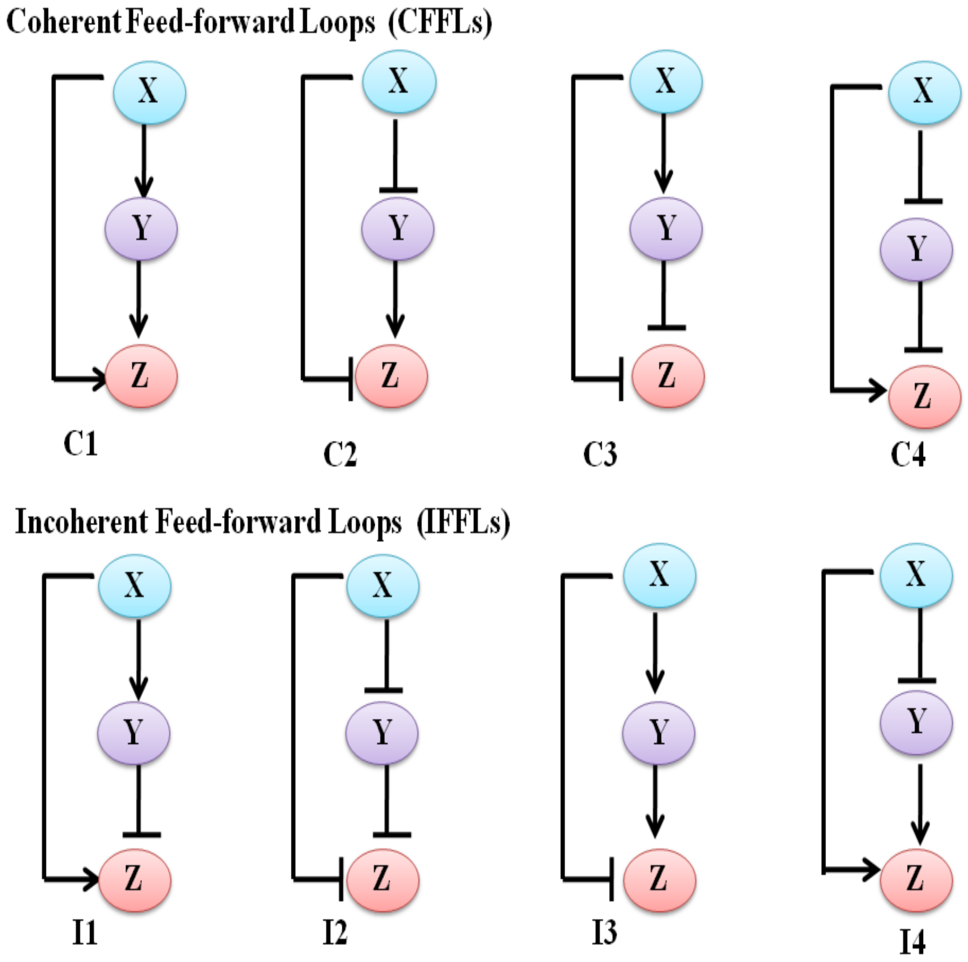




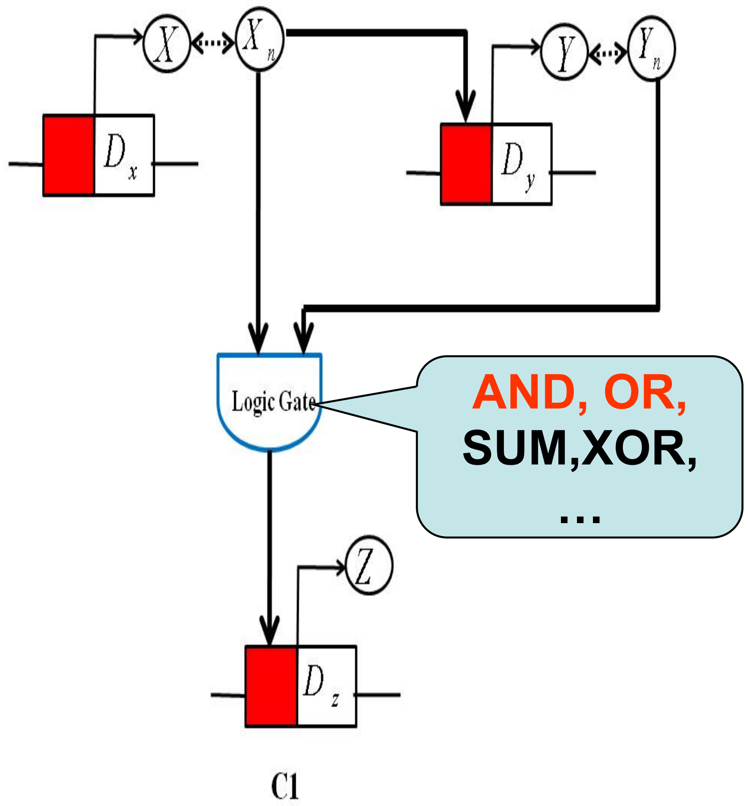
FFLs are the most important three-component network motifs

Science, 298 (2002) 824-827
Nat. Genet., 31 (2002) 64-68,

Eight Configurations of FFLs

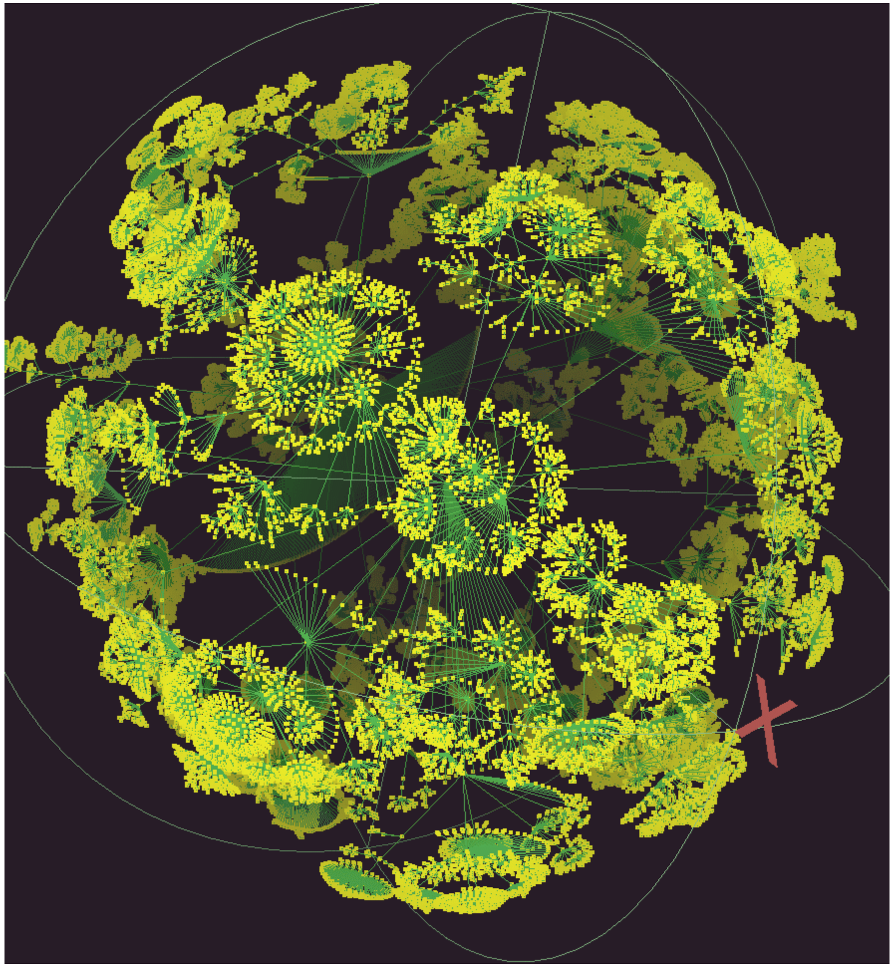


8 configurations



C1 detailed regulation

Applications in Engineering Networks



Internet Graphs

- Internet is a network of Autonomous Systems (AS):
  - groups of networks sharing the same routing policy
  - identified with Autonomous System Numbers
- Autonomous System Numbers: http://www.iana.org/assignments/as-numbers
- Internet topology on AS-level:
  - the arrangement of ASes and their interconnections
- Analyzing the Internet topology and finding properties of associated graphs rely on mining data and capturing information about Autonomous Systems (ASes)

Internet AS-Level Data

Source of data are routing tables:

- Route Views: http://www.routeviews.org
  - most participating ASes reside in North America
- RIPE (Réseaux IP européens): http://www.ripe.net/ris
  - most participating ASes reside in Europe

Analyzed Datasets

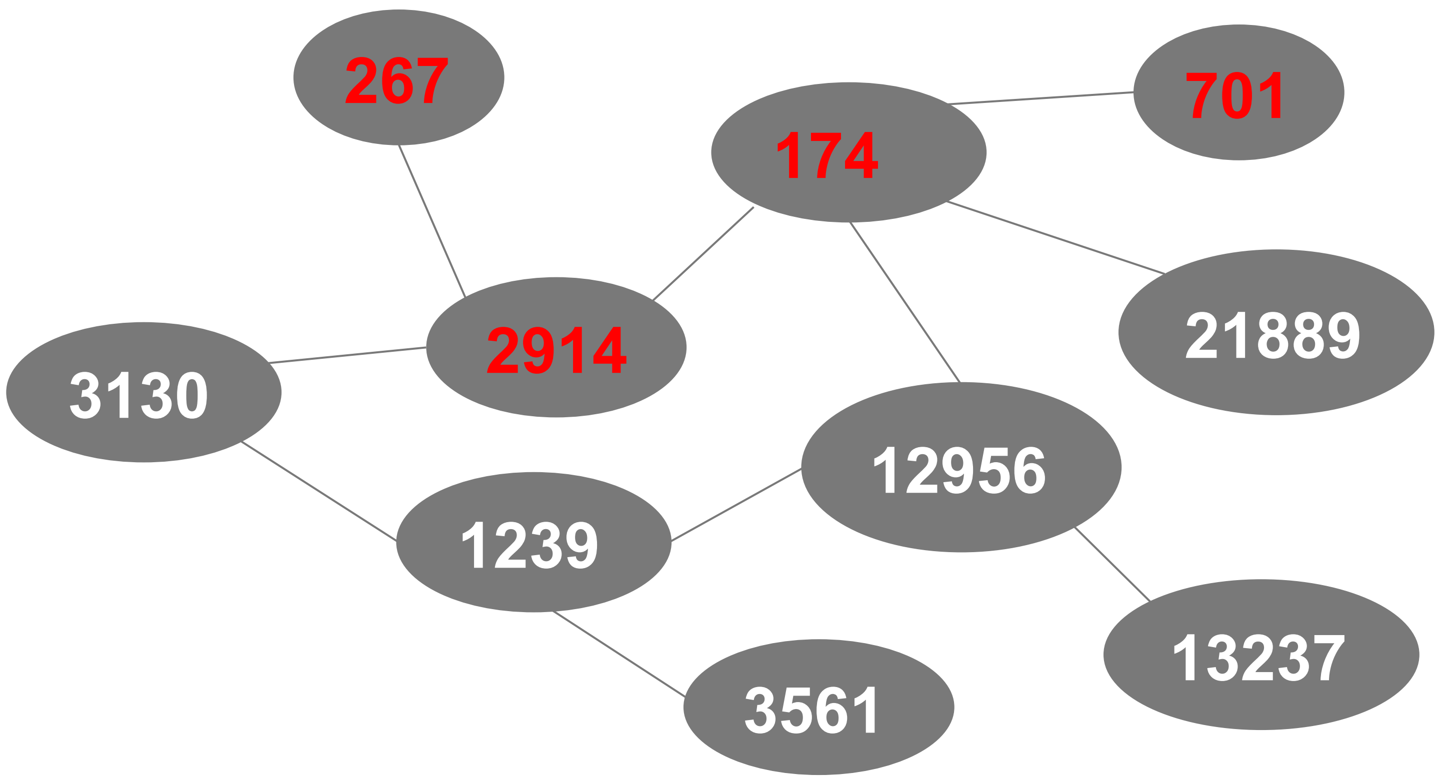
- Sample datasets:
  - Route Views:

    TABLE_DUMP| 1050122432| B| 204.42.253.253| 267| 3.0.0.0/8| 267 2914 174 701| IGP| 204.42.253.253| 0| 0| 267:2914 2914:420 2914:2000 2914:3000| NAG| |
  - RIPE:

    TABLE_DUMP| 1041811200| B| 212.20.151.234| 13129| 3.0.0.0/8| 13129 6461 7018 | IGP| 212.20.151.234| 0| 0| 6461:5997 13129:3010| NAG| |

Internet Topology at AS Level

- Datasets collected from Border Gateway Protocols (BGP) routing tables are used to infer the Internet topology at AS-level



Internet Topology

- The Internet topology is characterized by the presence of various power-laws observed when considering:
  - node degree vs. node rank
  - node degree frequency vs. degree
  - number of nodes within a number of hops vs. number of hops
  - eigenvalues of the adjacency matrix and the normalized Laplacian matrix vs. the order of the eigenvalues.

  - M. Faloutsos, P. Faloutsos, and C. Faloutsos, 1999
  - G. Siganos, M. Faloutsos, P. Faloutsos, and C. Faloutsos, 2003

Internet Matrices

- Adjacency matrix A(G):

$$A(i,j) = \begin{cases} 1 & if\ i\ and\ j\ are\ adjacent \\ 0 & otherwise, \end{cases}$$

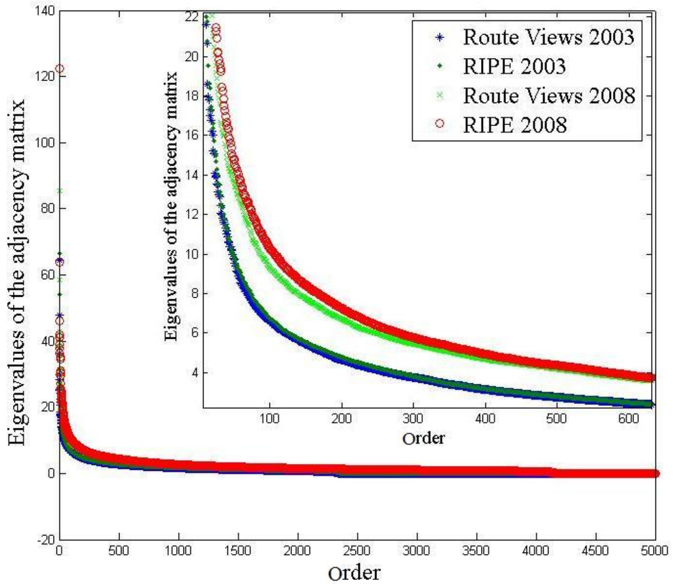
where i and j are the graph nodes

- Normalized Laplacian matrix NL(G):

$$NL(i,j) = \begin{cases} 1 & if\ i = j\ and\ d_i \neq 0 \\ -\frac{1}{\sqrt{d_i d_j}} & if\ i\ and\ j\ are\ adjacent \\ 0 & otherwise, \end{cases}$$

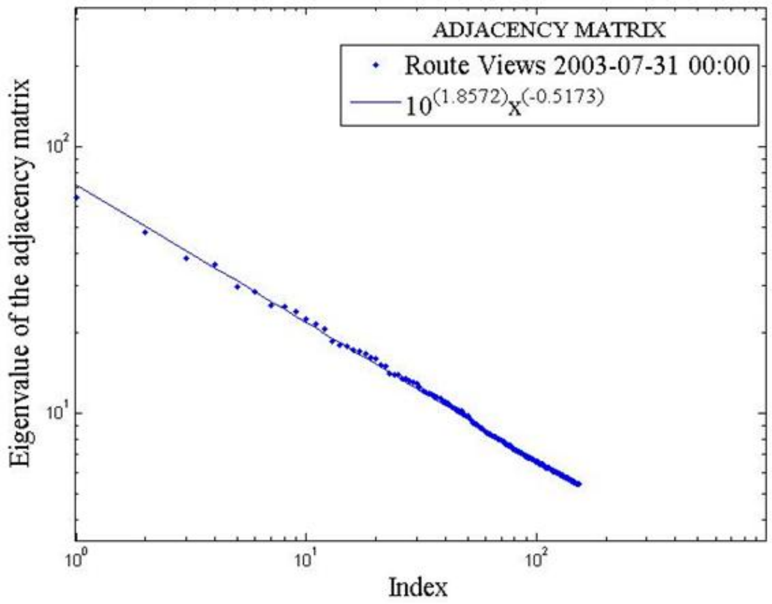
where d_i and d_j are degrees of node i and j, respectively

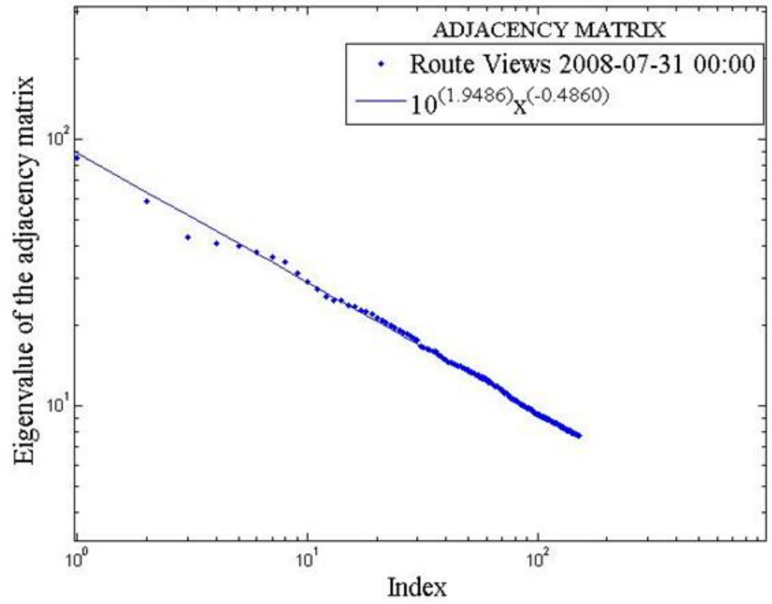
Eigenvalues of the Adjacency Matrix



order	Route Views 2003	Route Views 2008	RIPE 2003	RIPE 2008
1	64.30	85.43	66.65	122.28
2	47.75	58.56	54.19	63.94
3	38.15	42.77	38.24	46.14
4	36.23	40.85	36.14	41.98
5	29.88	39.69	31.21	41.08
6	28.50	37.85	27.38	38.93
7	25.47	36.21	26.41	37.94
8	25.06	34.66	25.06	36.47
9	24.13	31.58	23.86	35.08
10	22.51	29.34	23.32	34.47
11	21.61	27.40	22.02	30.97
12	20.69	25.69	21.77	30.54
13	18.58	25.00	20.75	29.68
14	17.94	24.82	19.55	27.03
15	17.78	23.89	18.67	25.74
16	17.31	23.69	18.42	25.35
17	16.99	22.81	17.85	24.83
18	16.75	22.46	17.44	24.30
19	16.22	22.04	17.24	24.06
20	16.01	21.36	16.63	24.00

Power Laws: Eigenvalues vs. Index



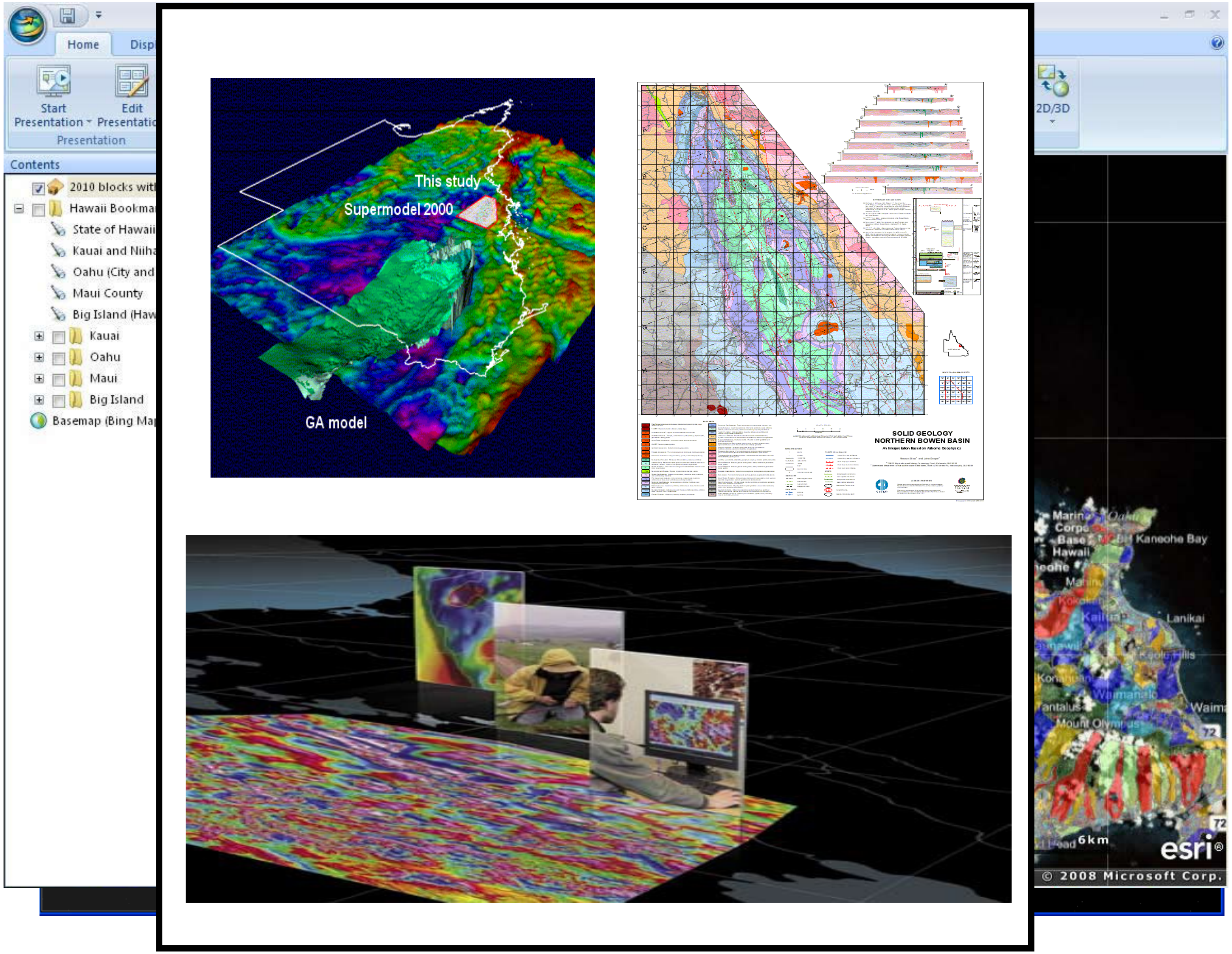


Adjacency matrix:

- Route Views 2003 datasets: ε= –0.5713 and r= –0.9990
- Route Views 2008 datasets: ε= –0.4860 and r= –0.9982

ε= power-law exponent; r= correlation coefficient

Typical Example



Conclusions:
Opportunities and Challenges

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Event

Network Science and Engineering: A Research Agenda

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David Clark, MIT
Mike Dahlin, University of Texas - Austin
Chip Elliott, BBN Technologies and GPO (ex-officio)
Joan Feigenbaum, Yale University
Stephanie Forrest, University of New Mexico
Mike Kearns, University of Pennsylvania
Ed Lazowska, University of Washington
Helen Nissenbaum, New York University
Larry Peterson, Princeton University
Jennifer Rexford, Princeton University
Scott Shenker, UC Berkeley/ICSI
John Wroclawski, USC/ISI
Ellen Zegura, Georgia Institute of Technology

nd Information
omputer Science

Network Science and Engineering (NetSE) Research Agenda

A Report of the Network Science and Engineering Council
Release Version 1.1

NetSE Research Agenda: Executive Summary

- Over the past forty years, the Internet has changed the way we live, work and play, and altered our notions of democracy, education, healthcare, entertainment and commerce
- The Internet has been a powerful engine for technological innovation and societal evolution
- However, and the Internet in particular, will need to improve:

  more secure, more accessible, more predictable, and more reliable

NetSE Research Agenda: Recommendations

- The funding agencies of the United States government must increase investment in research that will lead to a better Internet or risk a marginal future role
- Funding agencies should support a broad array of interdisciplinary research activities related to understanding the current Internet and designing future networks to include the Internet
- New mathematical tools and frameworks. Realizing better networks requires a foundational mathematical theory of network architecture and design

Network Science and Engineering: Fundamental Challenges

Science → Understand the complexity of large-scale networks → **Network science and engineering researchers**

- Understand emergent behaviors, local-global interactions, system failures and/or degradations
- Develop models that accurately predict and control network behaviors

Technology → Develop new architectures, exploiting new substrates → **Distributed systems and substrate researchers**

- Develop architectures for self-evolving, robust, manageable future networks
- Develop design principles for seamless mobility support
- Leverage optical and wireless substrates for reliability and performance
- Understand the fundamental potential and limitations of technology

Society → Enable new applications and new economies, while ensuring security and privacy → **Security, privacy, economics, AI, social science researchers**

- Design secure, survivable, persistent systems, especially when under attack
- Understand technical, economic and legal design trade-offs, enable privacy protection
- Explore AI-inspired and game-theoretic paradigms for resource and performance optimization

Emerging New Opportunities

- Big Data
- Cloud Computing
- Mobile Internet
- Social Networks

Thank You!

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