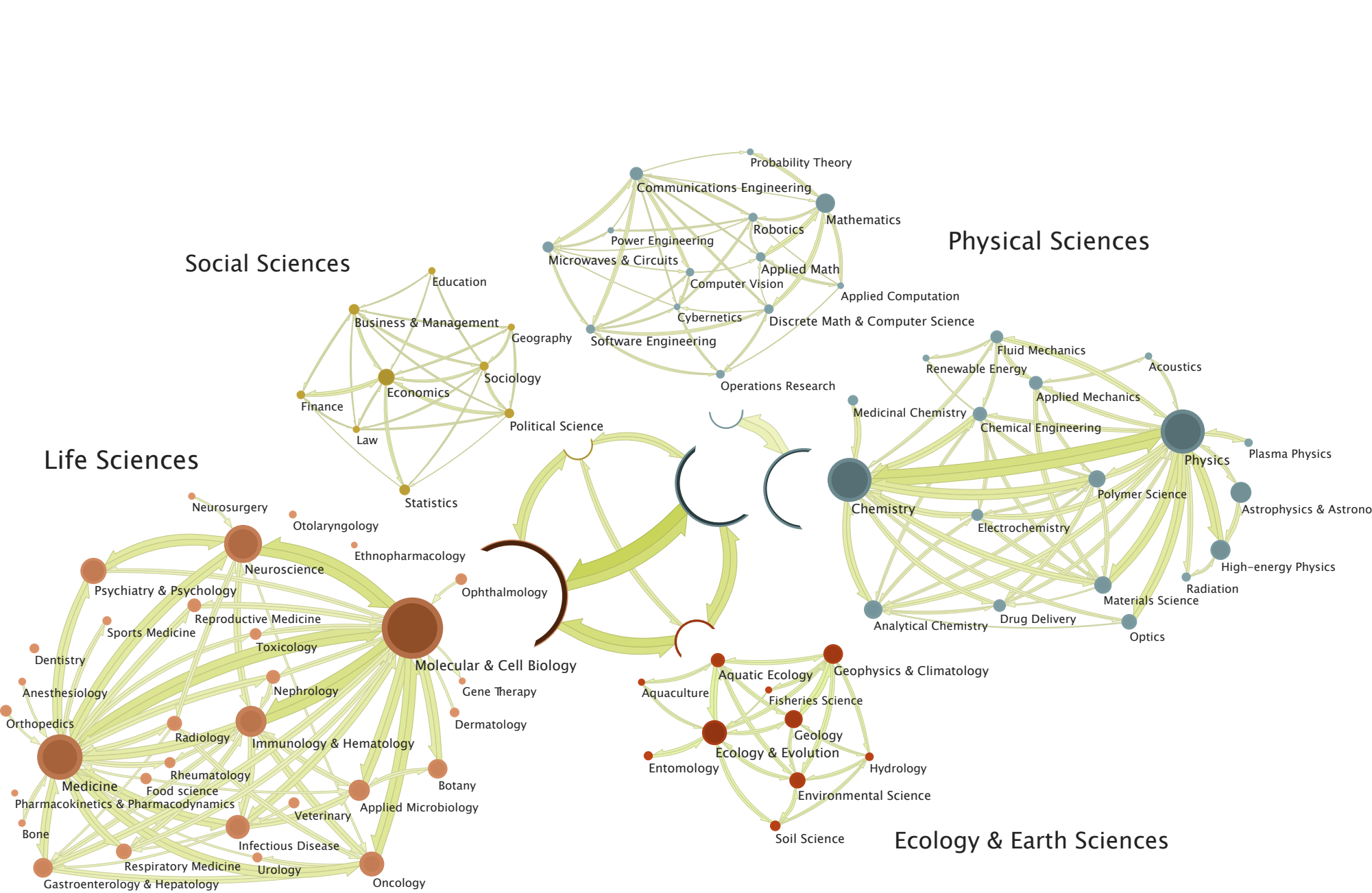
Mapping change

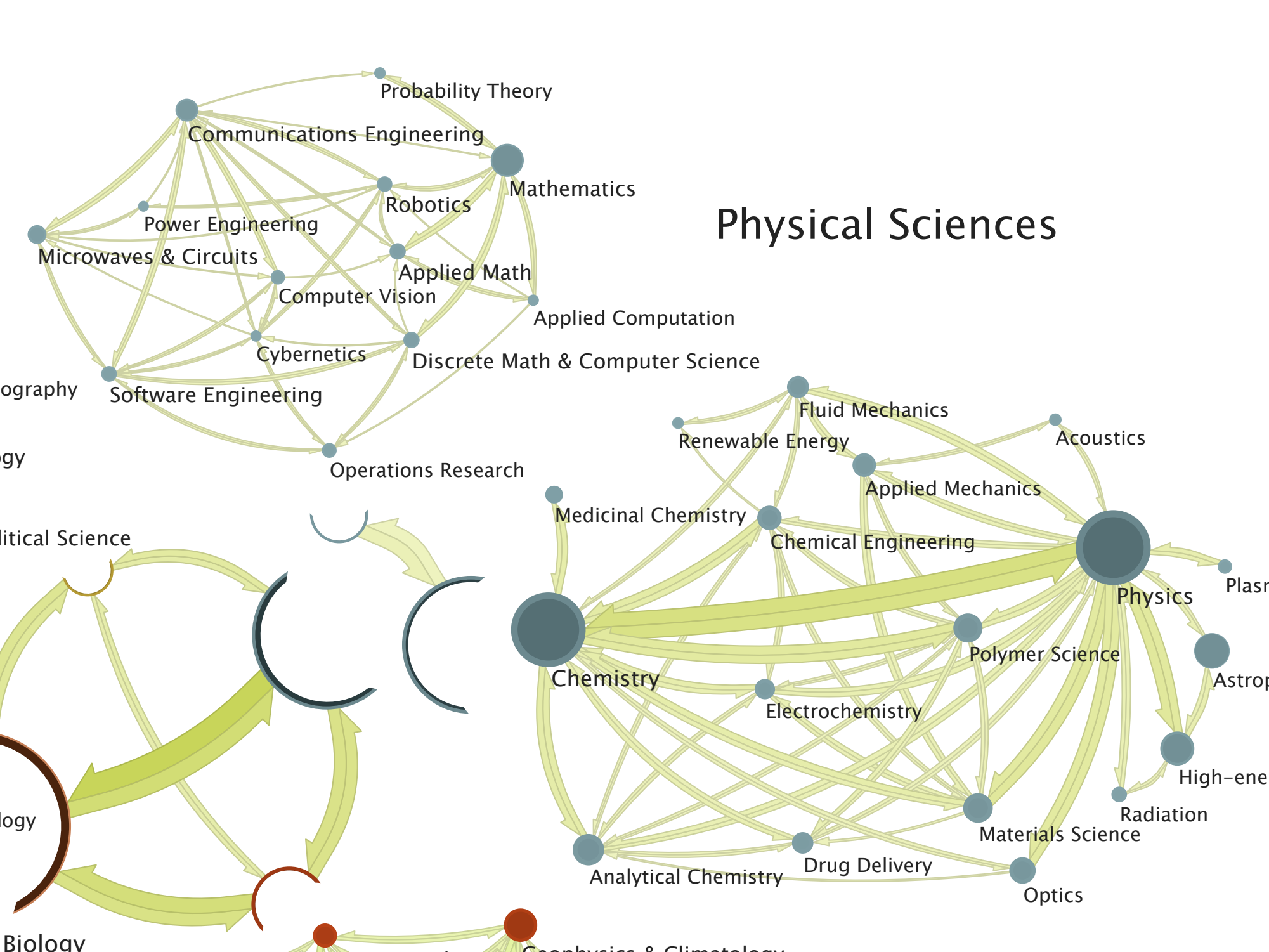
in large integrated systems

Martin Rosvall

Alcides V. Esquivel, Atieh Mirshahvalad,
Daniel Edler, and Carl Bergstrom



Rosvall & Bergstrom (2011)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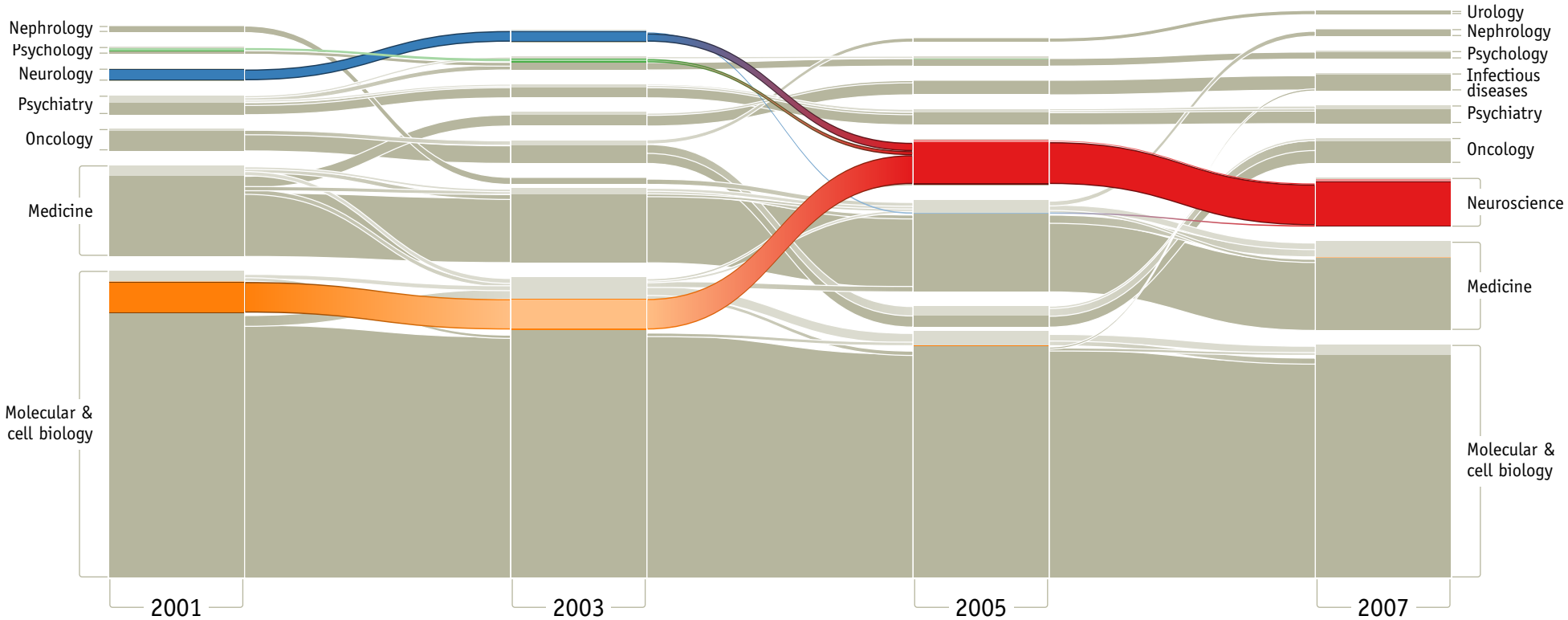
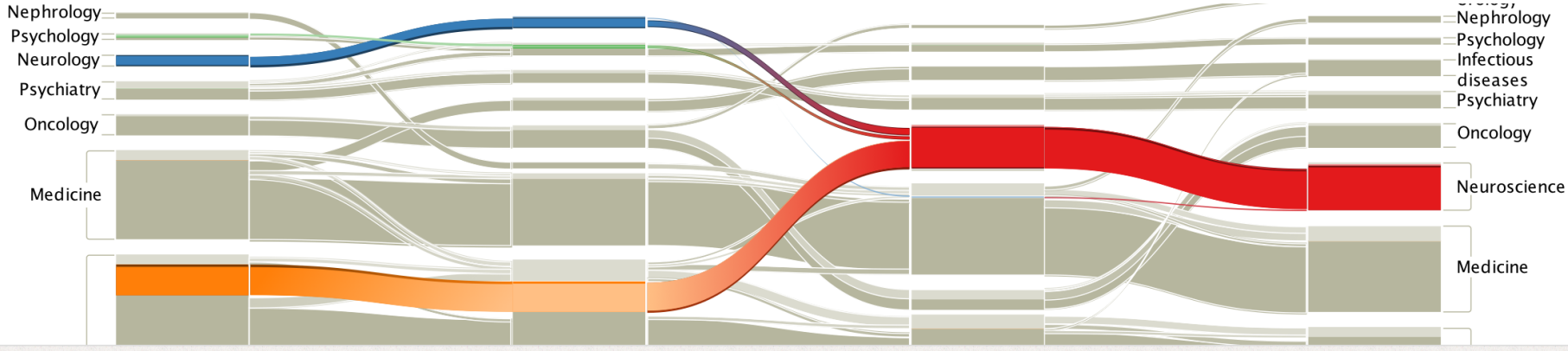
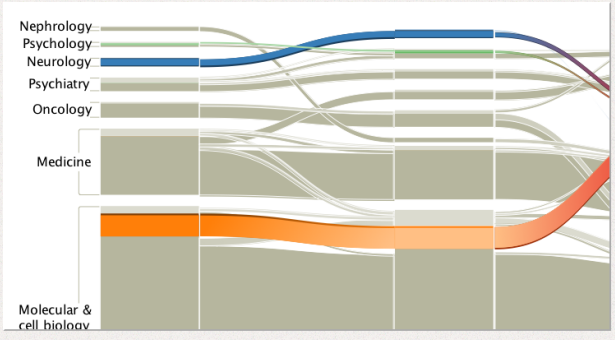


Rosvall & Bergstrom (2010)

Reveal structural change in complex networks



Apps »



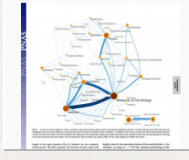
Code »

```
using infomath::plogp;
for (unsigned int i = 0; i < numNodes; ++i)
{
enter_log_enter += plogp(m_moduleFlowData[i].enterFl
exit_log_exit += plogp(m_moduleFlowData[i].exitFlow)
flow_log_flow += plogp(m_moduleFlowData[i].exitFlow
enterFlow += m_moduleFlowData[i].enterFlow;
}
enterFlow += exitNetworkFlow;
enterFlow_log_enterFlow = plogp(enterFlow);
```

Publications »

Maps of information flow reveal community structure in complex networks

Martin Rosvall and Carl T. Bergstrom
PNAS **105**, 1118 (2008). [arXiv:0707.0609]



To comprehend the multipartite organization of large-scale biological and social systems, we introduce a new information-theoretic approach to reveal community structure in

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Who are we, what do we do, and why do we do it?

About mapequation.org

> *The best maps convey a great deal of information but require minimal bandwidth: the best maps are also good compressions.*
>
> — M. Rosvall and C. T. Bergstrom, Maps of random walks on complex networks reveal community structure, PNAS 105, 1118 (2008)

What do we do?

We develop mathematics, algorithms and software to *simplify* and *highlight* important structures in complex systems.

What are our goals?

To *navigate* and *understand big data* like we navigate and understand the real world by maps.

Who are we?

We are researchers and developers at Umeå University with a background in physics.

How to cite the software?

If you are using the software at mapequation.org in one of your research articles or otherwise want to refer to it, please cite relevant publication or use the following format:

D. Edler and M. Rosvall (2013), The MapEquation software package, available online at http://www.mapequation.org.

People

Daniel Edler

Coding & ideas

Martin Rosvall

Ideas & coding

Collaborators

Carl Bergstrom, University of Washington
Jevin West, Umeå University & University of Washington

Inspiration

> *What a useful thing a pocket-map is!" I remarked. "That's anot*
> *thing we've learned from your Nation," said Mein Herr, "map-m*
> *But we've carried it much further than you. What do you consid*
> *largest map that would be really useful?" "About six inches to th*
> *mile." "Only six inches!" exclaimed Mein Herr. "We very soon go*
> *yards to the mile. Then we tried a hundred yards to the mile. Ar*
> *came the grandest idea of all! We actually made a map of the c*


Courtesy of Aaron Koblin

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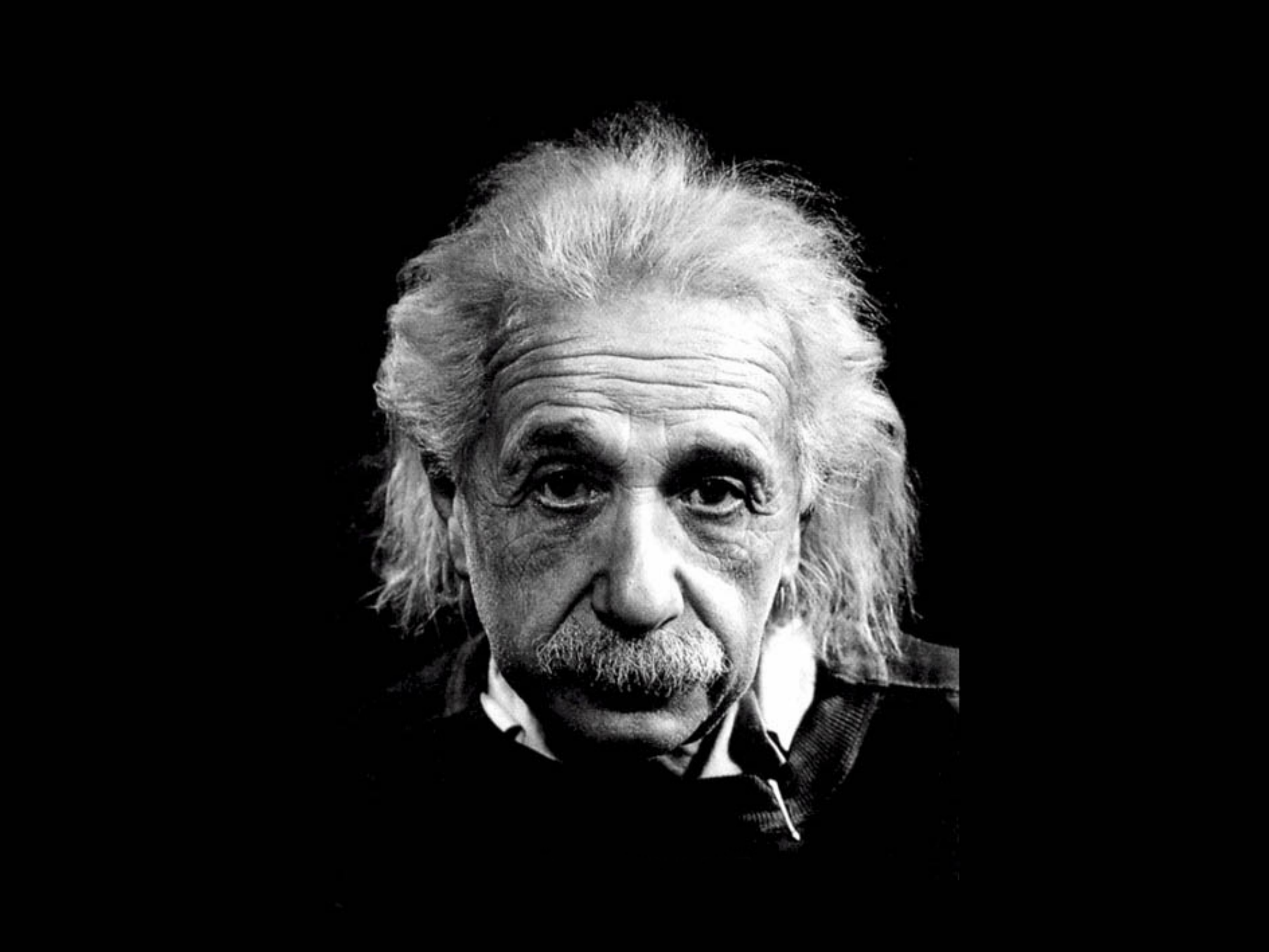

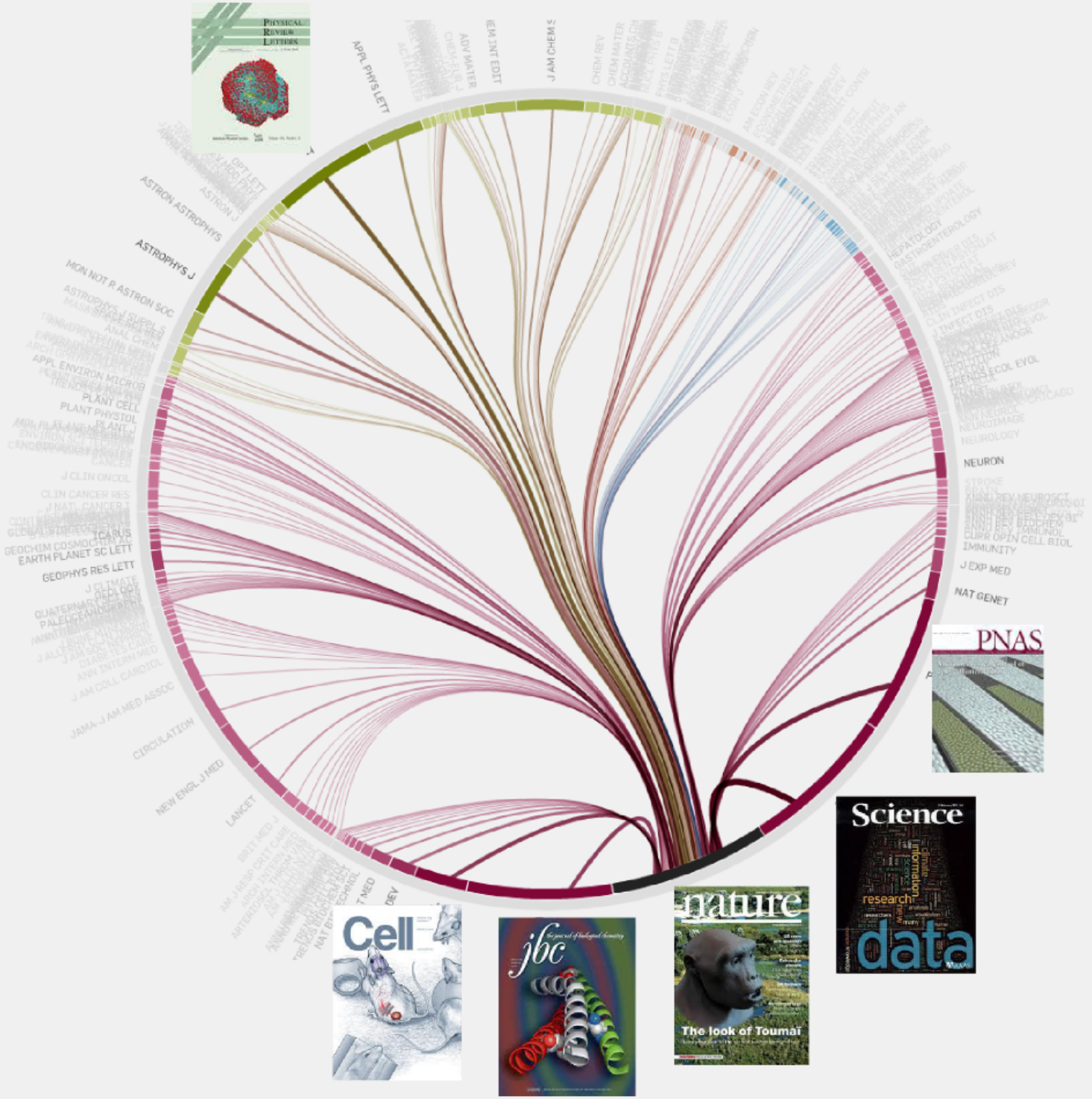
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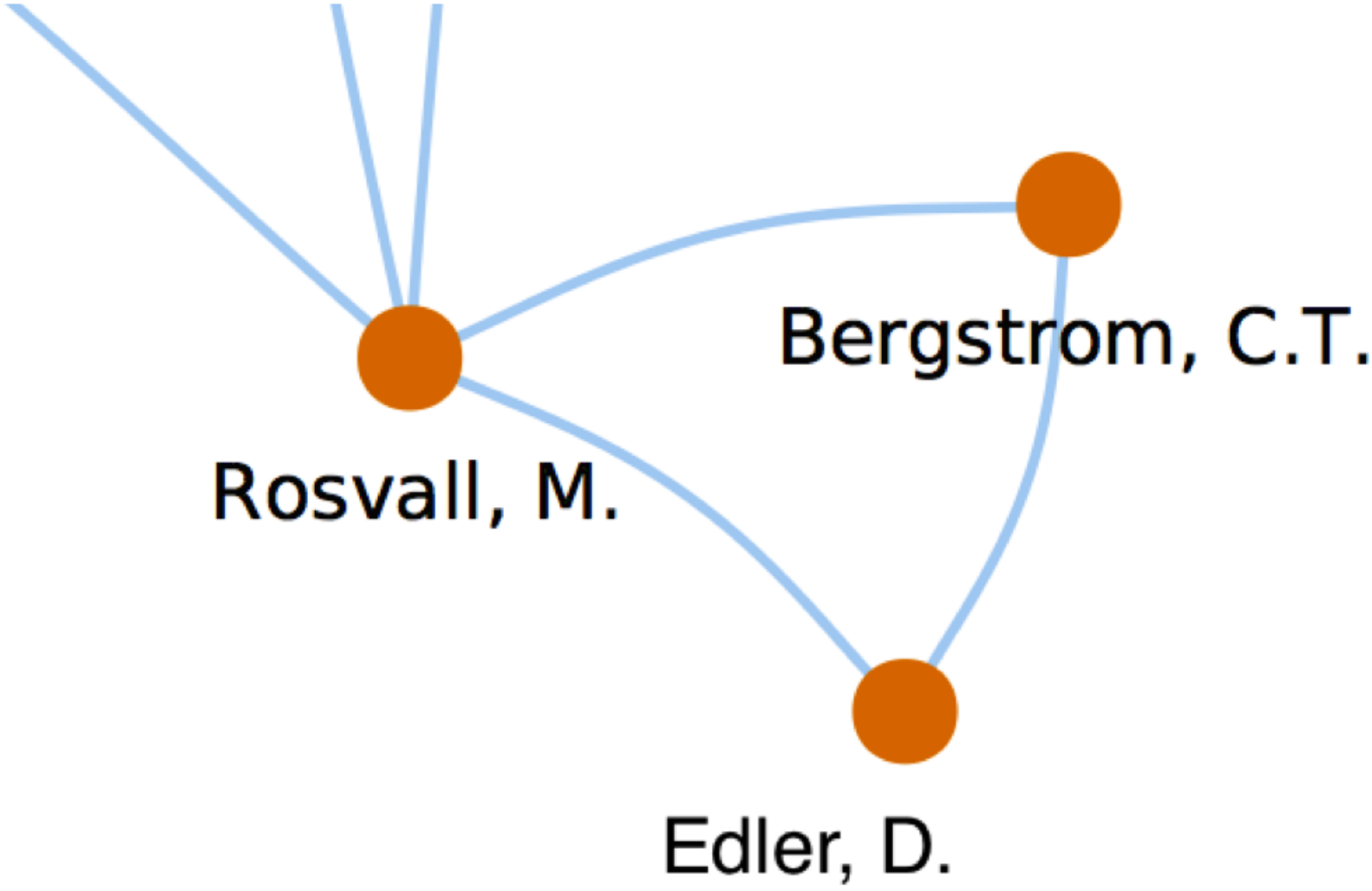
How are these systems organized?

How are these systems organized with respect to the flow?

Networks

Networks
describe flow
beyond nearest neighbors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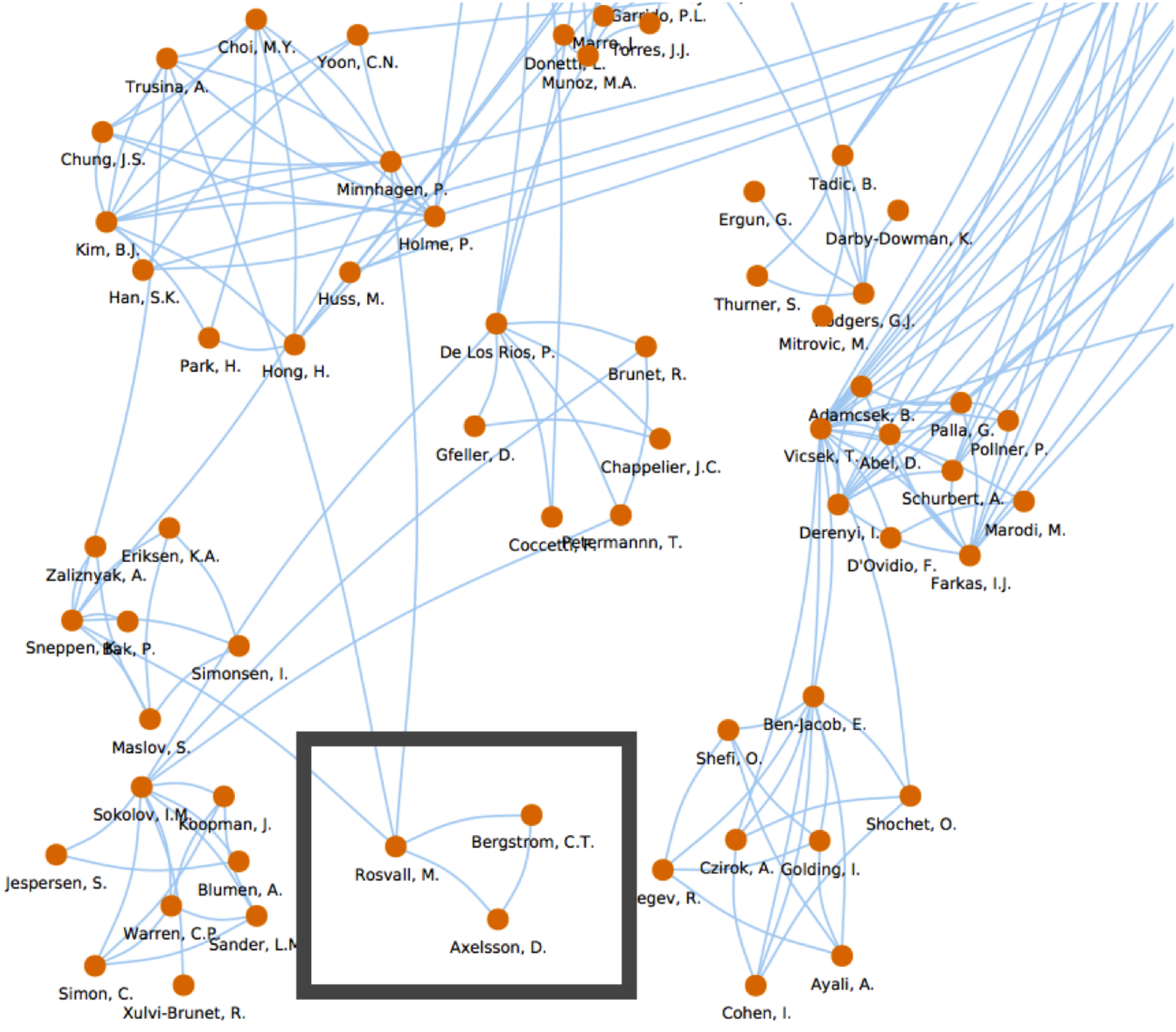
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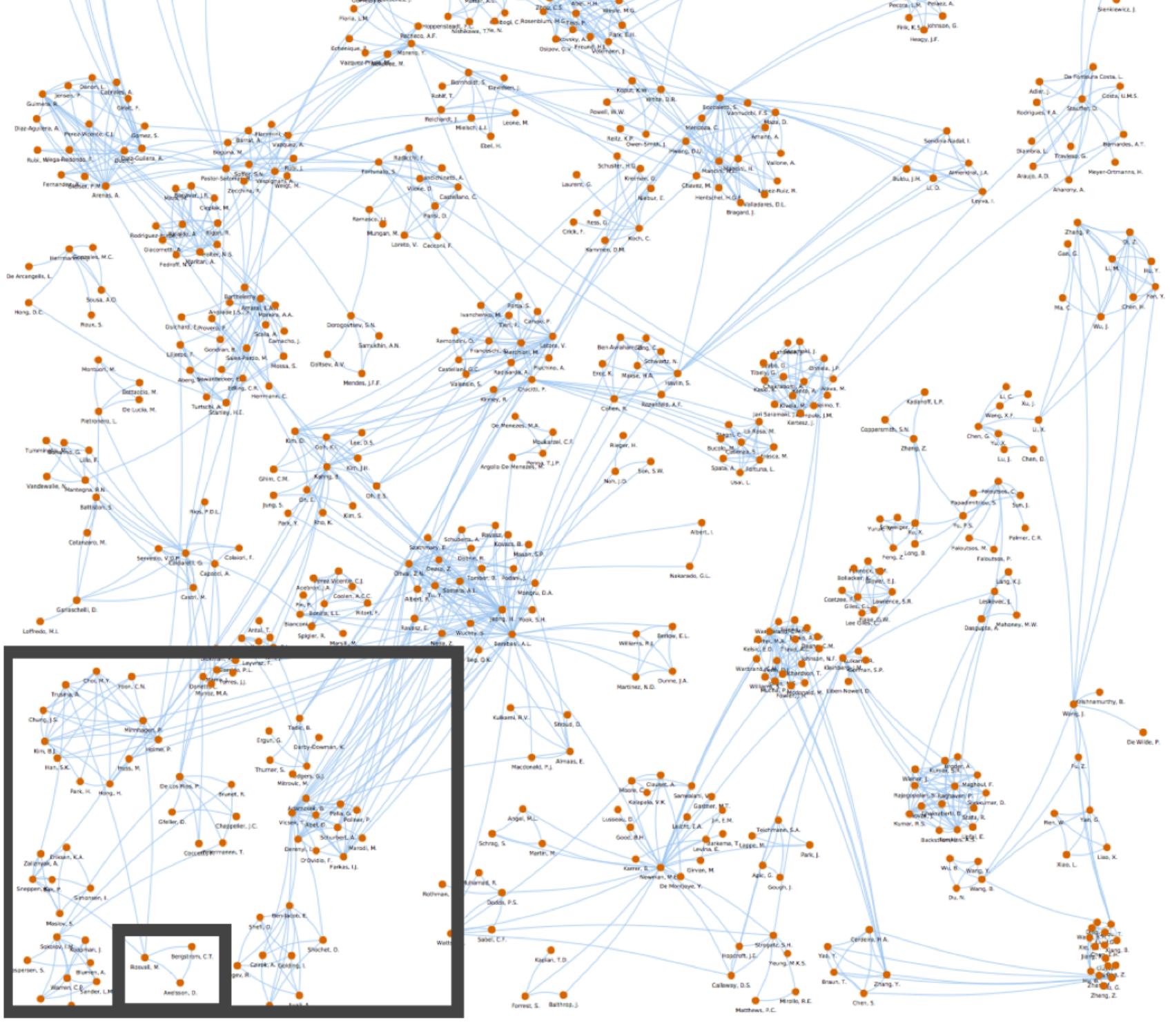

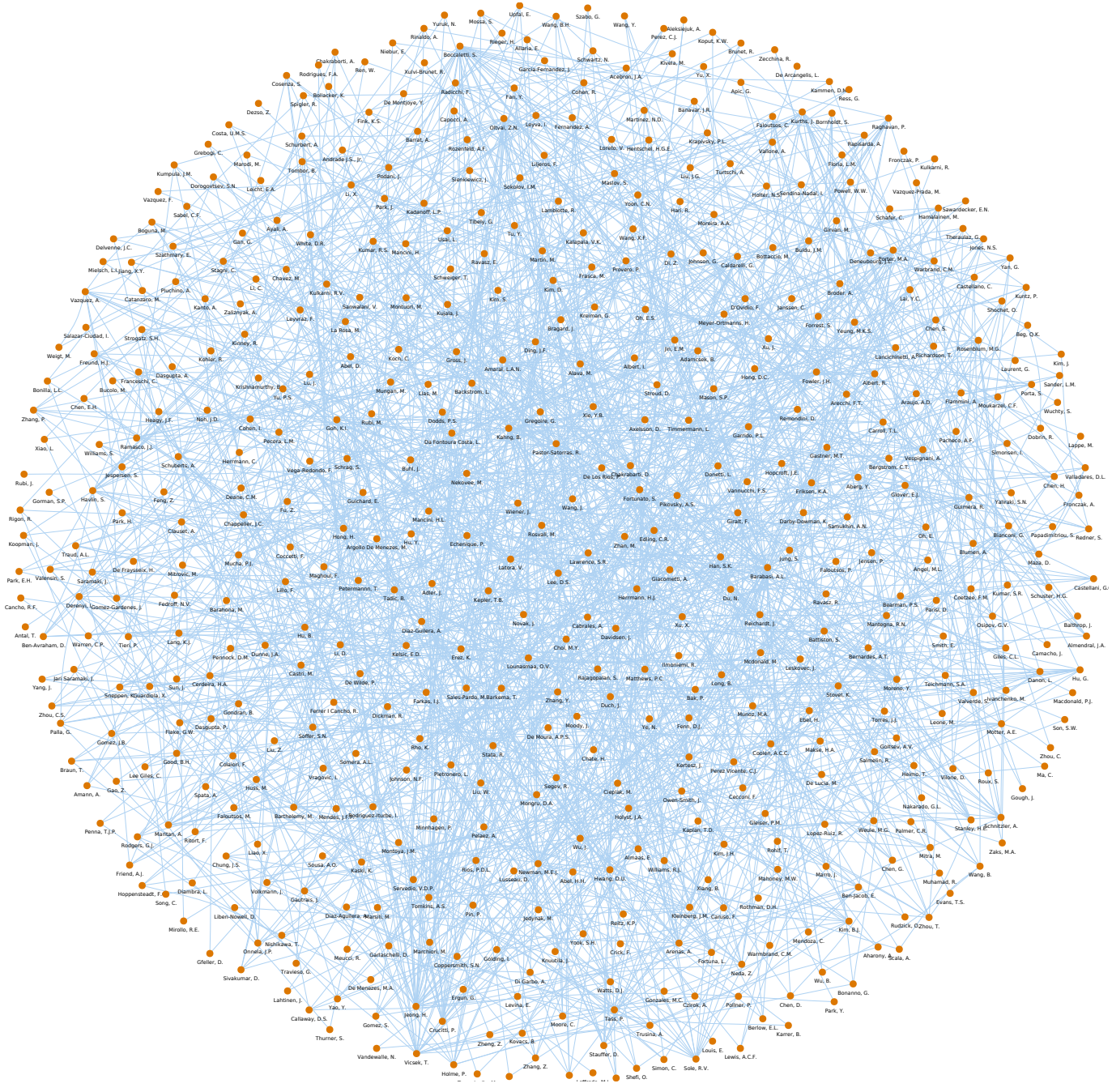
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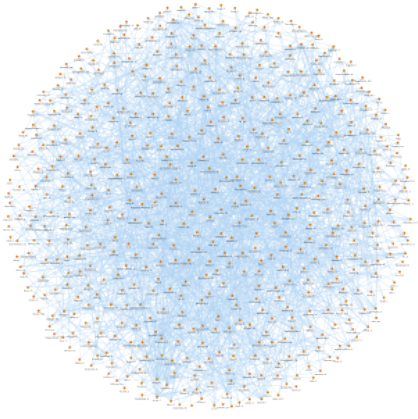
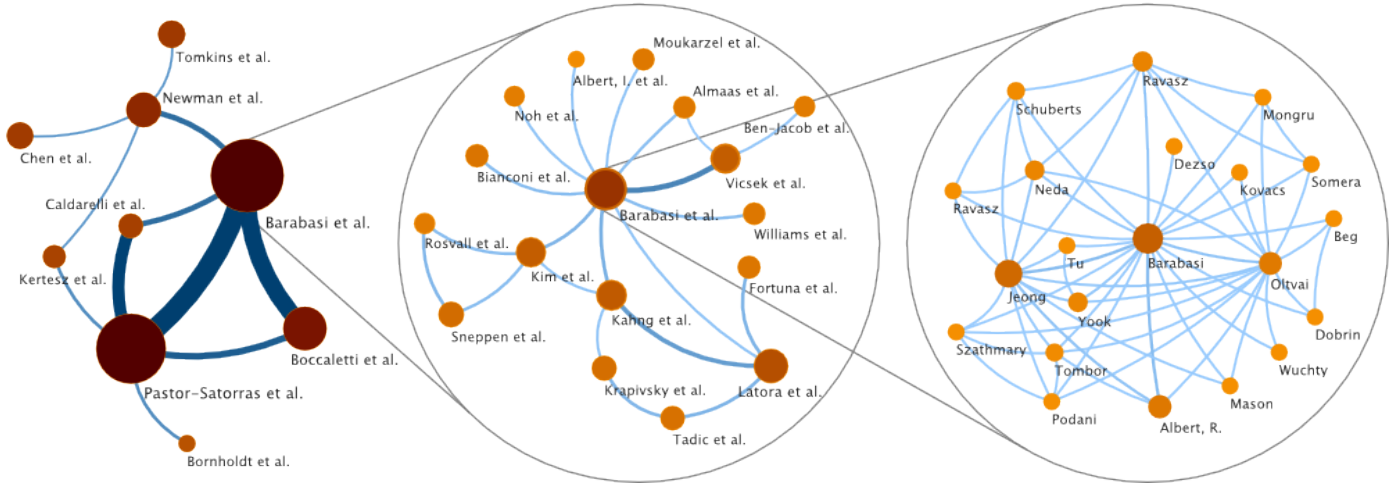


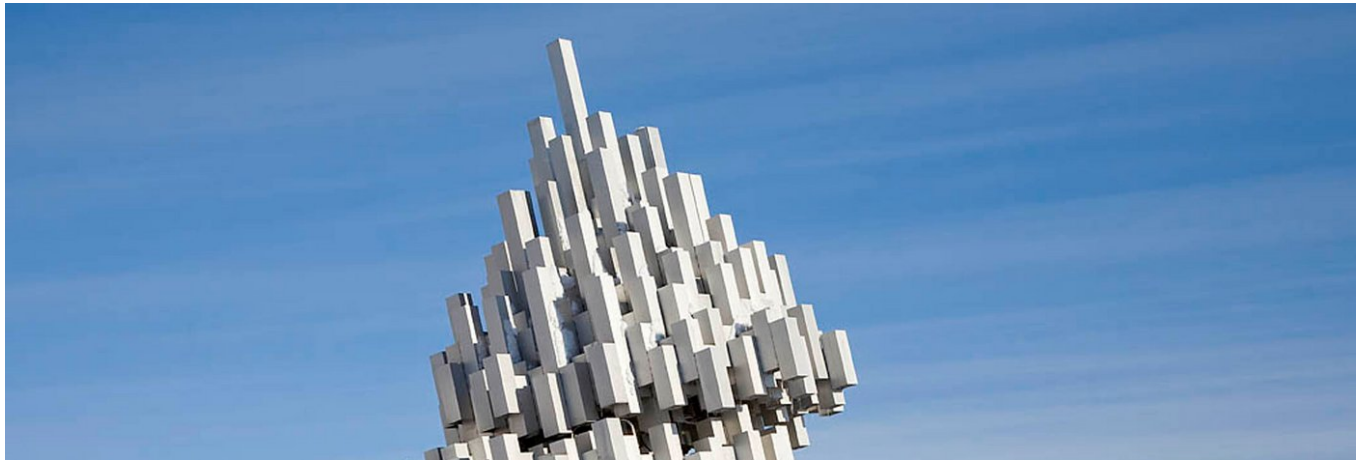

Tomkins et al.
Newman et al.
Chen et al.
Caldarelli et al.
Kertesz et al.
Barabasi et al.
Boccaletti et al.
Pastor-Satorras et al.
Bornholdt et al.
Moukarzel et al.
Albert, I. et al.
Almaas et al.
Noh et al.
Ben-Jacob et al.
Bianconi et al.
Vicsek et al.
Barabasi et al.
Williams et al.
Rosvall et al.
Kim et al.
Fortuna et al.
Kahng et al.
Sneppen et al.
Krapivsky et al.
Latora et al.
Tadic et al.
Ravasz
Schuberts
Mongru
Dezso
Neda
Kovacs
Somera
Ravasz
Beg
Tu
Barabasi
Oltvai
Jeong
Yook
Dobrin
Szathmary
Tombor
Wuchty
Mason
Podani
Albert, R.

Maps

Maps
depict regularities
in the dynamics on networks
using less information

Finding regularities $\Longleftrightarrow$ Compression

5.8MB (tiff) $\rightarrow$ 0.91MB (tiff + LZW)



5.8MB (tiff) $\rightarrow$ 2.8MB (tiff + LZW)

If we can find a good code
for describing flow on a network,
we will have solved the dual problem
of finding the important structures
with respect to that flow

We use a modular code structure
that can exploit regions in the network
in which units of flow tend to stay
for a relatively long time

Two-level partitions

How many modules are present? And which nodes are members of which modules?

Two-level partitions with the map equation

How many modules are present? And which nodes are members of which modules?

Maximal compression of flow with constraints:

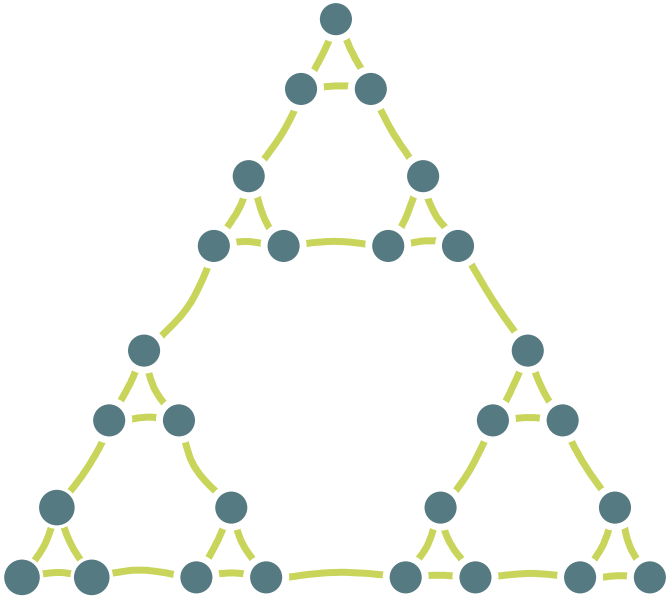
1. Modular code structure
2. No more than two levels
3. Each node can only belong to one module

Two-level partitions with the map equation

$$L(\mathsf{M}) = q_{\curvearrowright} H(\mathcal{Q}) + \sum_{i=1}^{m} p^{i}_{\circlearrowright} H(\mathcal{P}^{i})$$

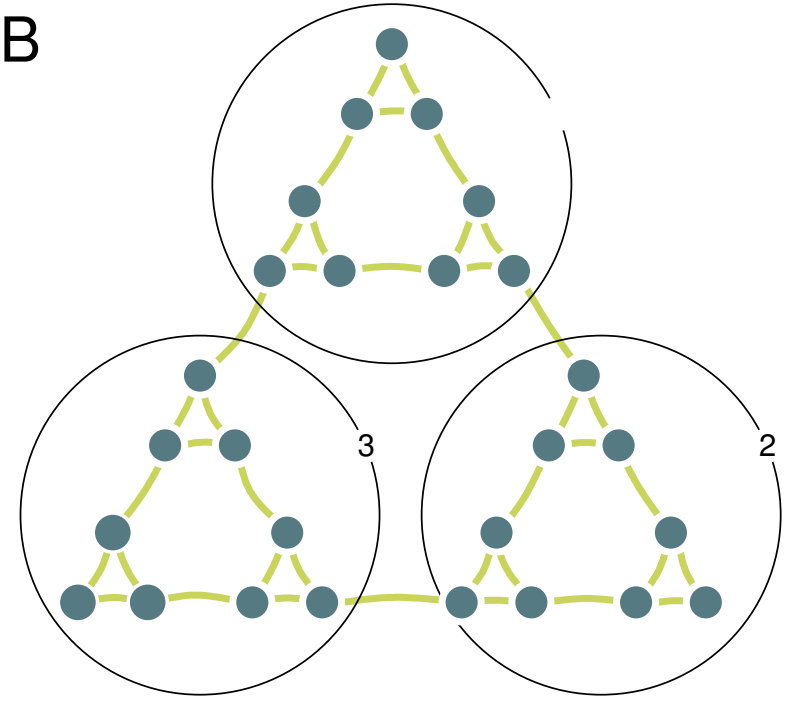
Two-level partitions with the map equation

A



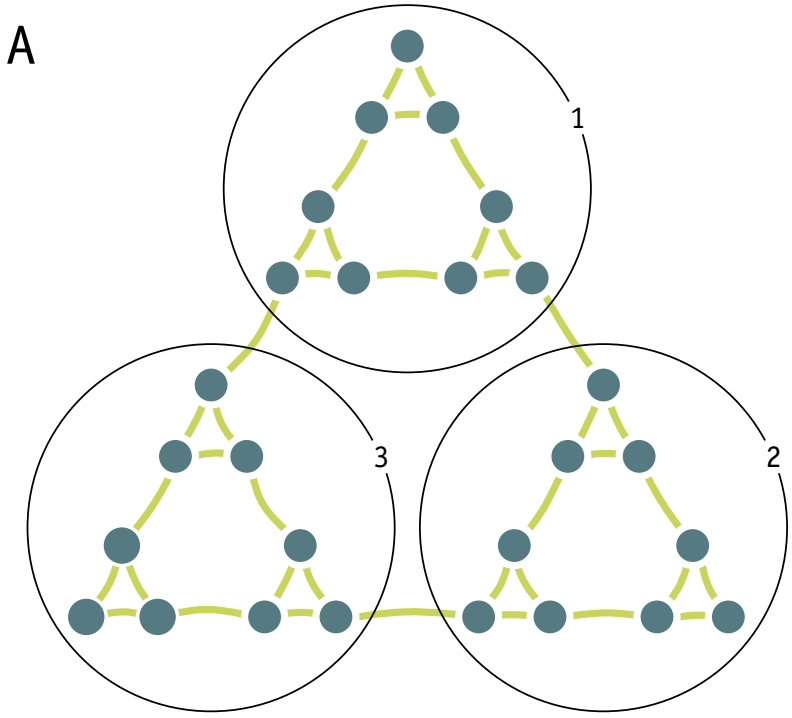
$$L(\mathsf{M}) = H(\mathcal{P}) = 4.75 \text{ bits.}$$

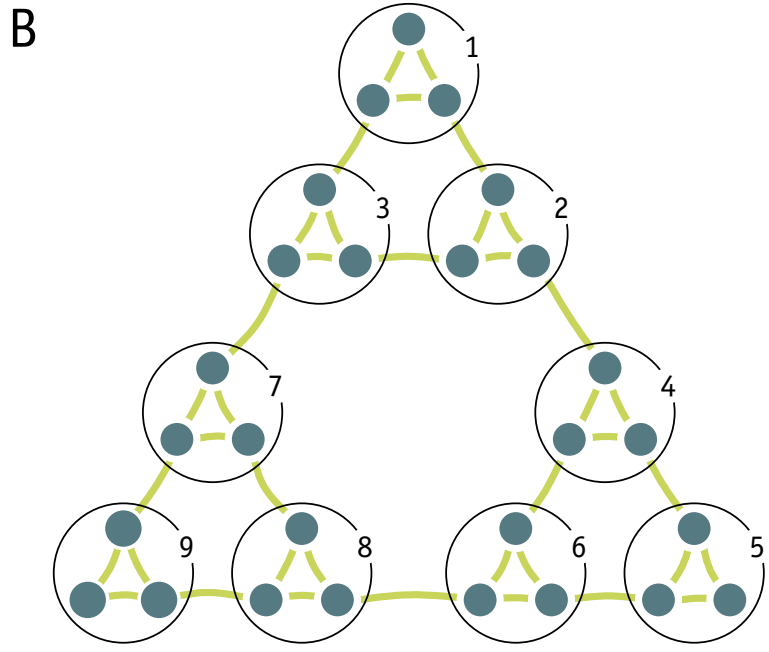
B



$$L(\mathsf{M}) = \underbrace{q_{\curvearrowleft} H(\mathcal{Q})}_{0.12 \text{ bits}} + \underbrace{\begin{cases} p^1_{\circlearrowleft} H(\mathcal{P}^1) \\ p^2_{\circlearrowleft} H(\mathcal{P}^2) \\ p^3_{\circlearrowleft} H(\mathcal{P}^3) \end{cases}}_{3.56 \text{ bits}} = 3.68 \text{ bits.}$$

Two-level partitions with the map equation





$$L(\mathsf{M}) = \underbrace{q_{\curvearrowleft} H(\mathcal{Q})}_{0.12 \text{ bits}} + \underbrace{\begin{cases} p^1_{\circlearrowleft} H(\mathcal{P}^1) \\ p^2_{\circlearrowleft} H(\mathcal{P}^2) \\ p^3_{\circlearrowleft} H(\mathcal{P}^3) \end{cases}}_{3.56 \text{ bits}} = 3.68 \text{ bits.}$$

$$L(\mathsf{M}) = \underbrace{q_{\curvearrowleft} H(\mathcal{Q})}_{0.97 \text{ bits}} + \underbrace{\begin{cases} p^1_{\circlearrowleft} H(\mathcal{P}^1) \\ p^2_{\circlearrowleft} H(\mathcal{P}^2) \\ p^3_{\circlearrowleft} H(\mathcal{P}^3) \\ p^4_{\circlearrowleft} H(\mathcal{P}^4) \\ p^5_{\circlearrowleft} H(\mathcal{P}^5) \\ p^6_{\circlearrowleft} H(\mathcal{P}^6) \\ p^7_{\circlearrowleft} H(\mathcal{P}^7) \\ p^8_{\circlearrowleft} H(\mathcal{P}^8) \\ p^9_{\circlearrowleft} H(\mathcal{P}^9) \end{cases}}_{2.60 \text{ bits}} = 3.57 \text{ bits.}$$

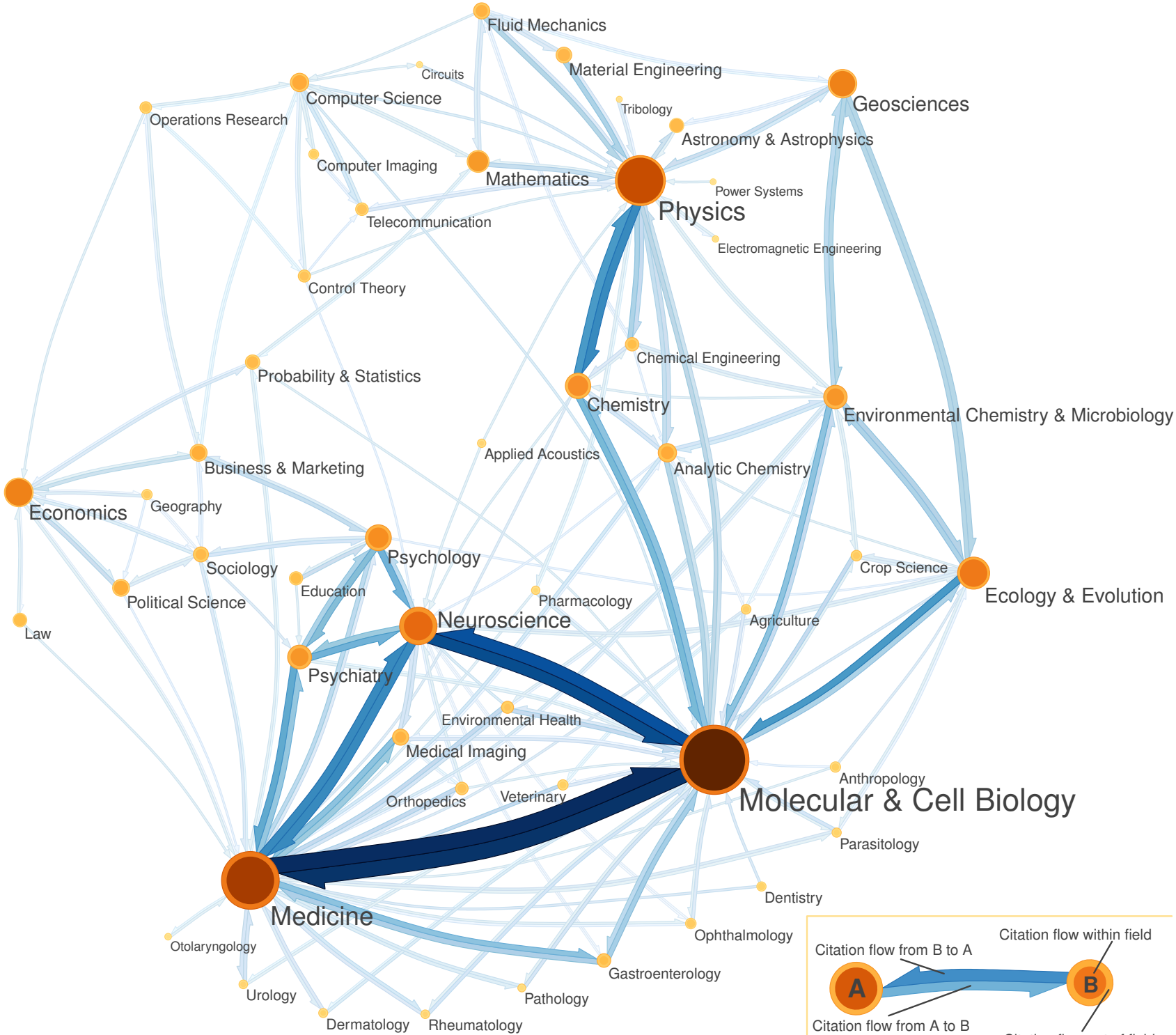
Science 2010

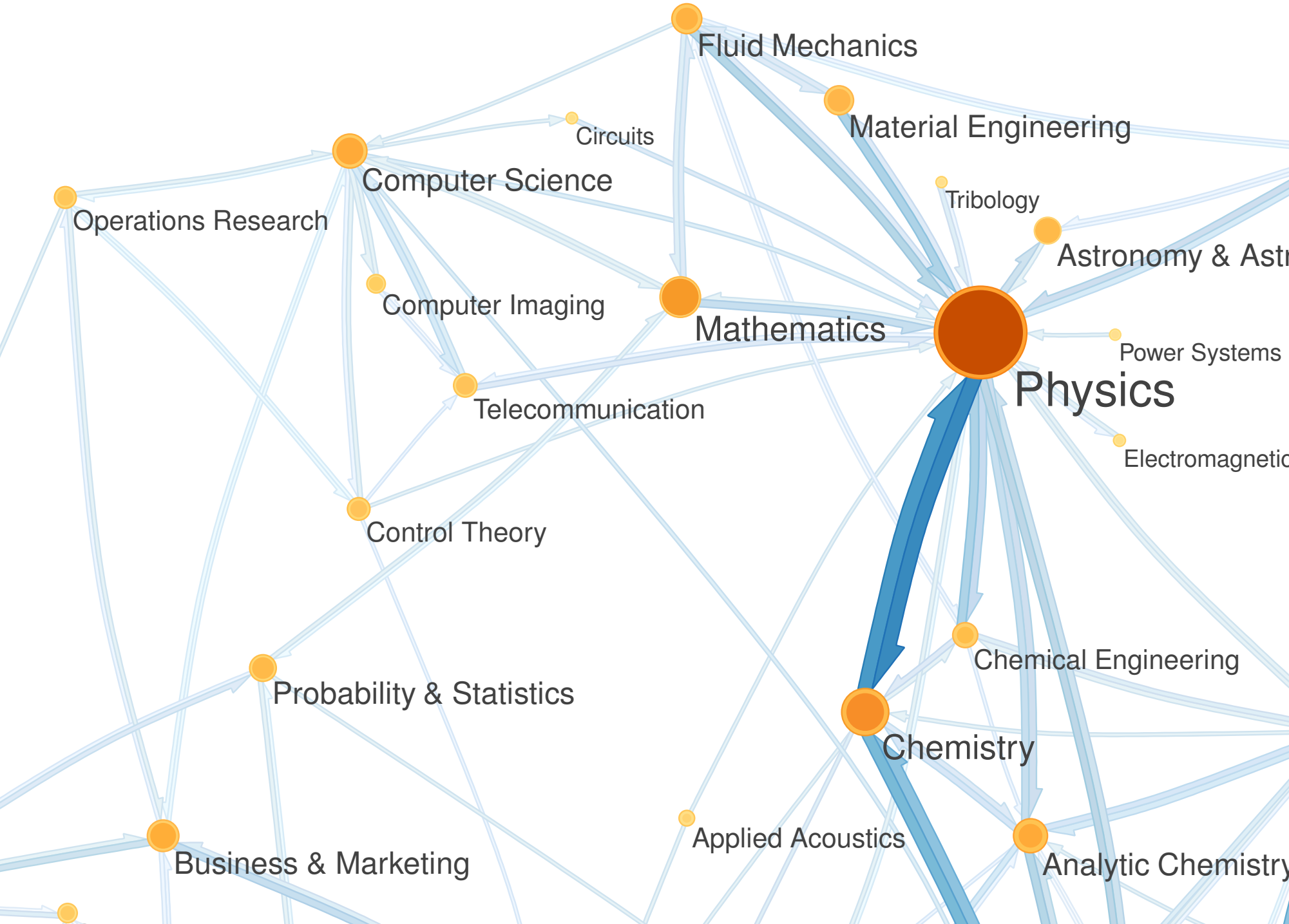
10,000 journals

1,000,000 articles

10,000,000 citations

Thomson Scientific Journal Citation Reports 2010


Fluid Mechanics
Material Engineering
Circuits
Computer Science
Geosciences
Operations Research
Tribology
Astronomy & Astrophysics
Computer Imaging
Mathematics
Power Systems
Physics
Telecommunication
Electromagnetic Engineering
Control Theory
Chemical Engineering
Probability & Statistics
Chemistry
Environmental Chemistry & Microbiology
Applied Acoustics
Business & Marketing
Analytic Chemistry
Economics
Geography
Psychology
Crop Science
Sociology
Education
Ecology & Evolution
Political Science
Pharmacology
Law
Neuroscience
Agriculture
Psychiatry
Environmental Health
Medical Imaging
Anthropology
Orthopedics
Veterinary
Molecular & Cell Biology
Parasitology
Dentistry
Medicine
Ophthalmology
Otolaryngology
Gastroenterology
Urology
Pathology
Dermatology
Rheumatology
Citation flow within field
Citation flow from B to A
A
B
Citation flow from A to B


Fluid Mechanics
Material Engineering
Circuits
Computer Science
Operations Research
Tribology
Astronomy & Astr
Computer Imaging
Mathematics
Power Systems
Physics
Telecommunication
Electromagnetic
Control Theory
Chemical Engineering
Probability & Statistics
Chemistry
Applied Acoustics
Analytic Chemistry
Business & Marketing

Multilevel partitions

Into how many hierarchical levels is a given network organized? How many modules are present at each level? And which nodes are members of which modules?

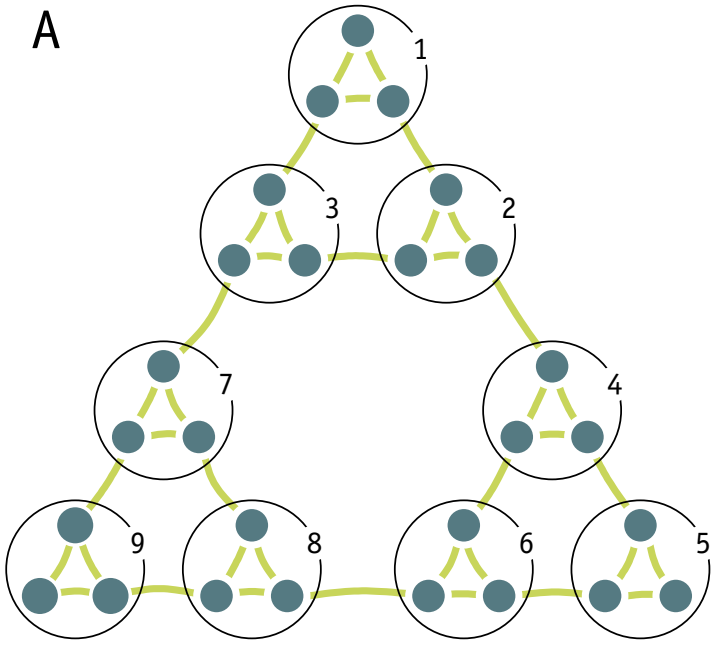
Multilevel partitions with the map equation

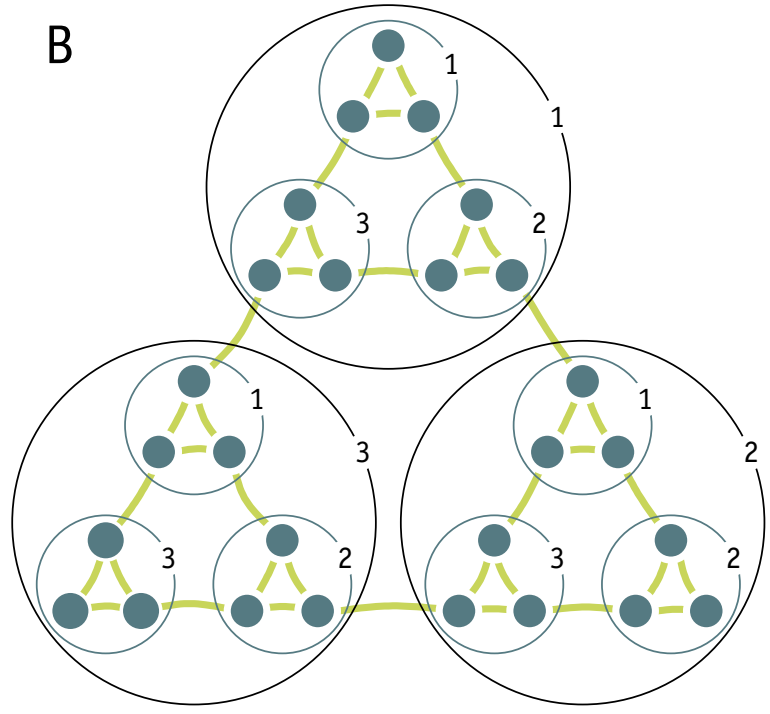
Into how many hierarchical levels is a given network organized? How many modules are present at each level? And which nodes are members of which modules?

Maximal compression of flow with constraints:

1. Modular code structure
2. ~~No more than two levels~~
3. Each node can only belong to one module

Multilevel partitions with the map equation



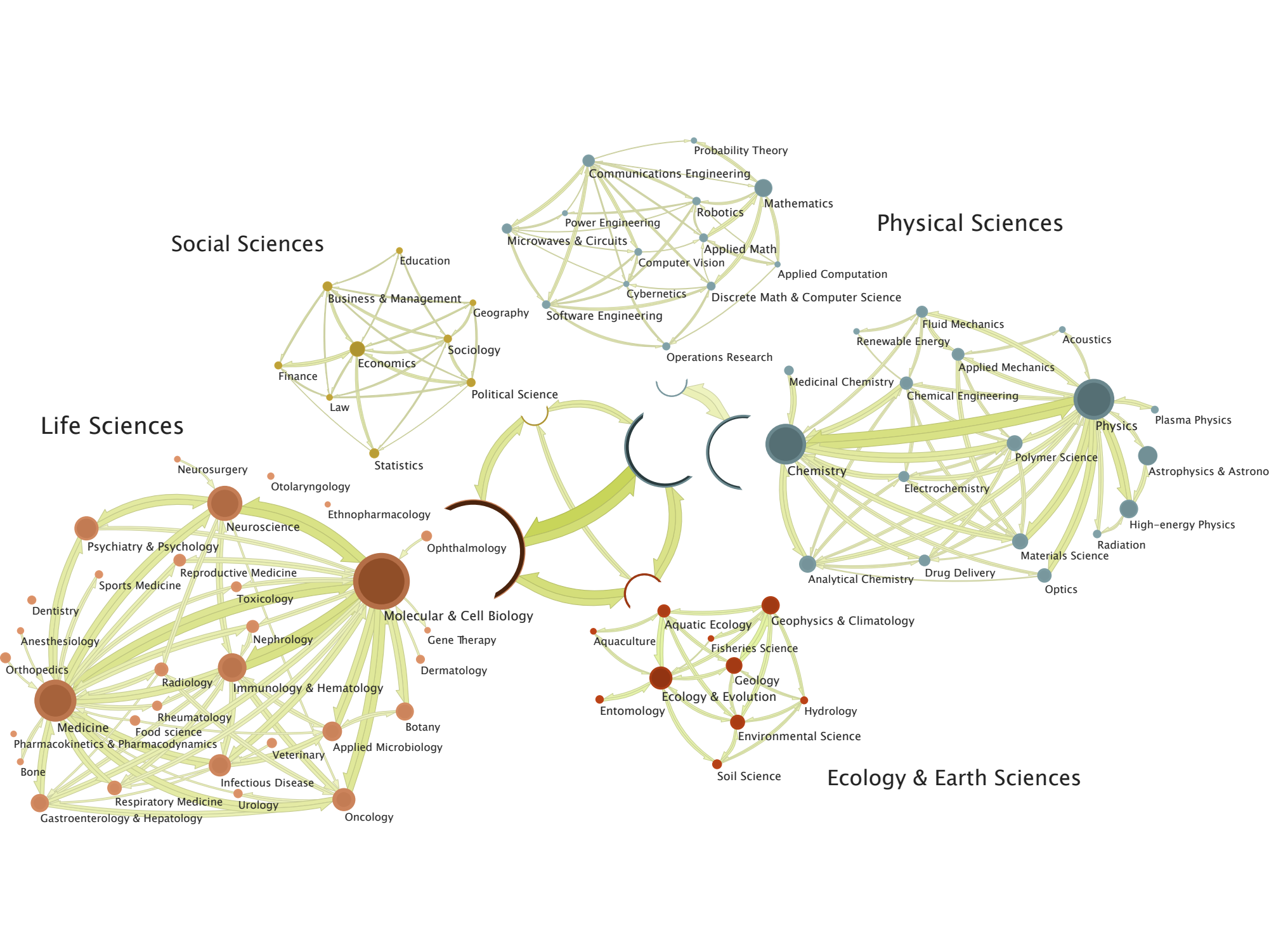


$$L(\mathsf{M}) = q_{\curvearrowleft} H(\mathcal{Q}) + \left\{ \begin{array}{l} p^1_{\circlearrowleft} H(\mathcal{P}^1) \\ p^2_{\circlearrowleft} H(\mathcal{P}^2) \\ p^3_{\circlearrowleft} H(\mathcal{P}^3) \\ p^4_{\circlearrowleft} H(\mathcal{P}^4) \\ p^5_{\circlearrowleft} H(\mathcal{P}^5) \\ p^6_{\circlearrowleft} H(\mathcal{P}^6) \\ p^7_{\circlearrowleft} H(\mathcal{P}^7) \\ p^8_{\circlearrowleft} H(\mathcal{P}^8) \\ p^9_{\circlearrowleft} H(\mathcal{P}^9) \end{array} \right. = 3.57 \text{ bits.}$$

$\underbrace{}_{0.97 \text{ bits}}$ $\underbrace{}_{2.60 \text{ bits}}$

$$L(\mathsf{M}) = q_{\curvearrowleft} H(\mathcal{Q}) + \left\{ \begin{array}{l} q^1_{\circlearrowleft} H(\mathcal{Q}^1) + \left\{ \begin{array}{l} p^{11}_{\circlearrowleft} H(\mathcal{P}^{11}) \\ p^{12}_{\circlearrowleft} H(\mathcal{P}^{12}) \\ p^{13}_{\circlearrowleft} H(\mathcal{P}^{13}) \end{array} \right. \\ q^2_{\circlearrowleft} H(\mathcal{Q}^2) + \left\{ \begin{array}{l} p^{21}_{\circlearrowleft} H(\mathcal{P}^{21}) \\ p^{22}_{\circlearrowleft} H(\mathcal{P}^{22}) \\ p^{23}_{\circlearrowleft} H(\mathcal{P}^{23}) \end{array} \right. \\ q^3_{\circlearrowleft} H(\mathcal{Q}^3) + \left\{ \begin{array}{l} p^{31}_{\circlearrowleft} H(\mathcal{P}^{31}) \\ p^{32}_{\circlearrowleft} H(\mathcal{P}^{32}) \\ p^{33}_{\circlearrowleft} H(\mathcal{P}^{33}) \end{array} \right. \end{array} \right. = 3.48 \text{ bits.}$$

$\underbrace{}_{0.12 \text{ bits}}$ $\underbrace{}_{0.76 \text{ bits}}$ $\underbrace{}_{2.60 \text{ bits}}$


Social Sciences
Physical Sciences
Life Sciences
Ecology & Earth Sciences
Probability Theory
Communications Engineering
Mathematics
Robotics
Power Engineering
Microwaves & Circuits
Applied Math
Computer Vision
Applied Computation
Cybernetics
Discrete Math & Computer Science
Software Engineering
Operations Research
Education
Business & Management
Geography
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Law
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Medicinal Chemistry
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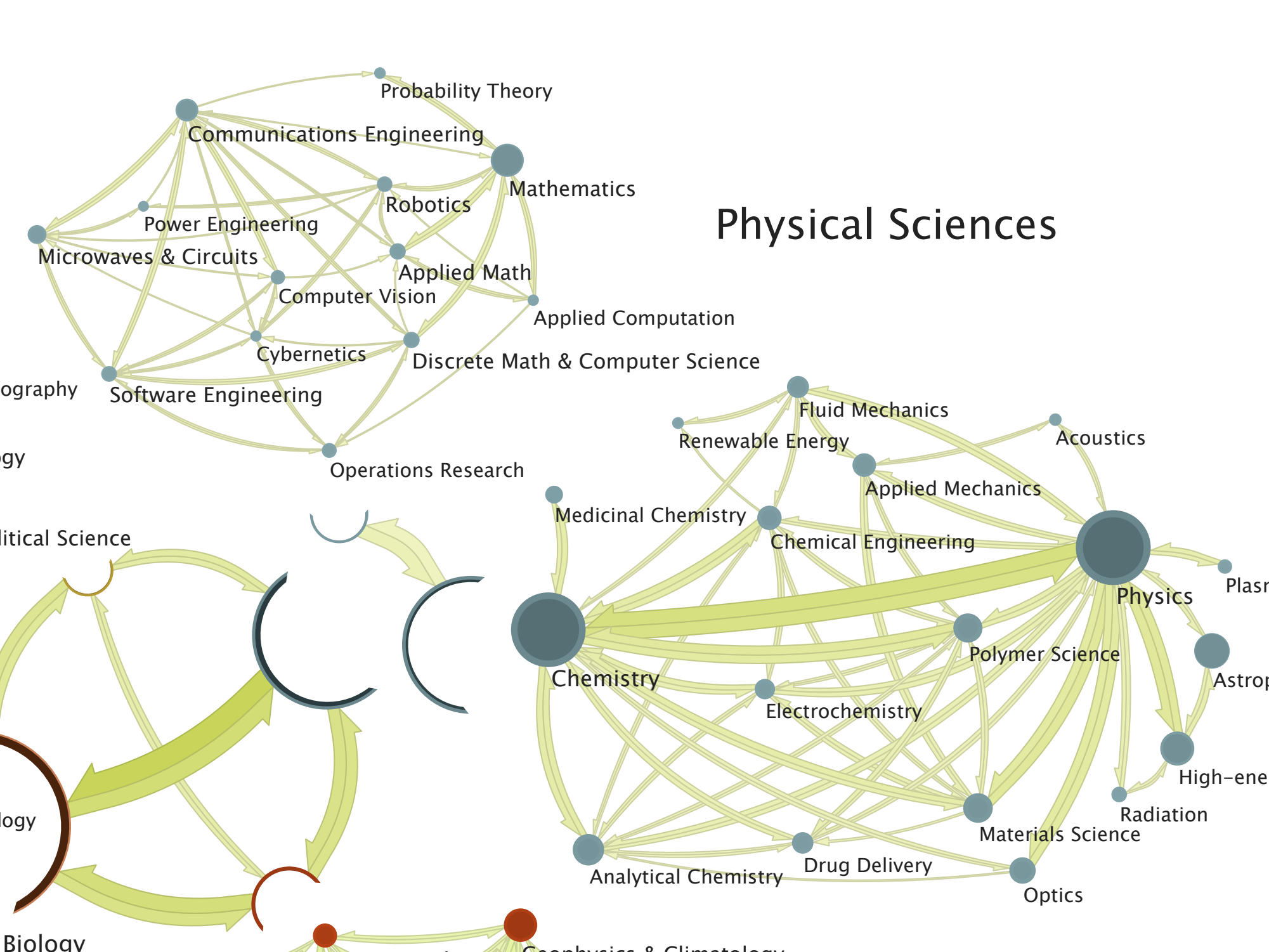
Physics
Plasma Physics
Polymer Science
Chemistry
Astrophysics & Astrono
Electrochemistry
High-energy Physics
Radiation
Materials Science
Analytical Chemistry
Drug Delivery
Optics
Neurosurgery
Otolaryngology
Ethnopharmacology
Neuroscience
Psychiatry & Psychology
Ophthalmology
Reproductive Medicine
Sports Medicine
Toxicology
Dentistry
Molecular & Cell Biology
Anesthesiology
Nephrology
Gene Therapy
Orthopedics
Dermatology
Radiology
Immunology & Hematology
Rheumatology
Botany
Medicine
Food science
Pharmacokinetics & Pharmacodynamics
Applied Microbiology
Veterinary
Bone
Infectious Disease
Respiratory Medicine
Urology
Gastroenterology & Hepatology
Oncology
Aquatic Ecology
Geophysics & Climatology
Aquaculture
Fisheries Science
Geology
Ecology & Evolution
Entomology
Hydrology
Environmental Science
Soil Science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Cybernetics
Discrete Math & Computer Science
ography
Software Engineering
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Fluid Mechanics
Renewable Energy
Acoustics
Applied Mechanics
Medicinal Chemistry
Chemical Engineering
Plasr
Physics
Polymer Science
Chemistry
Astrop
Electrochemistry
High-ene
Radiation
logy
Materials Science
Drug Delivery
Analytical Chemistry
Optics
Biology

Overlapping partitions

How many modules are present? Which nodes are members of which modules? And which nodes should belong to multiple modules and to what degree?

Overlapping partitions with the map equation

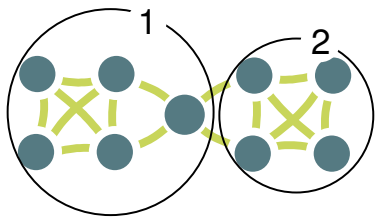
How many modules are present? Which nodes are members of which modules? And which nodes should belong to multiple modules and to what degree?

Maximal compression of flow with constraints:

1. Modular code structure
2. No more than two levels
3. ~~Each node can only belong to one module~~

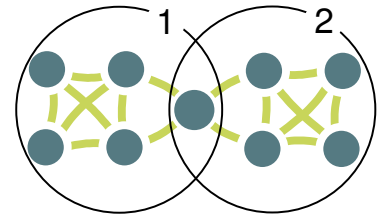
Overlapping partitions with the map equation

A

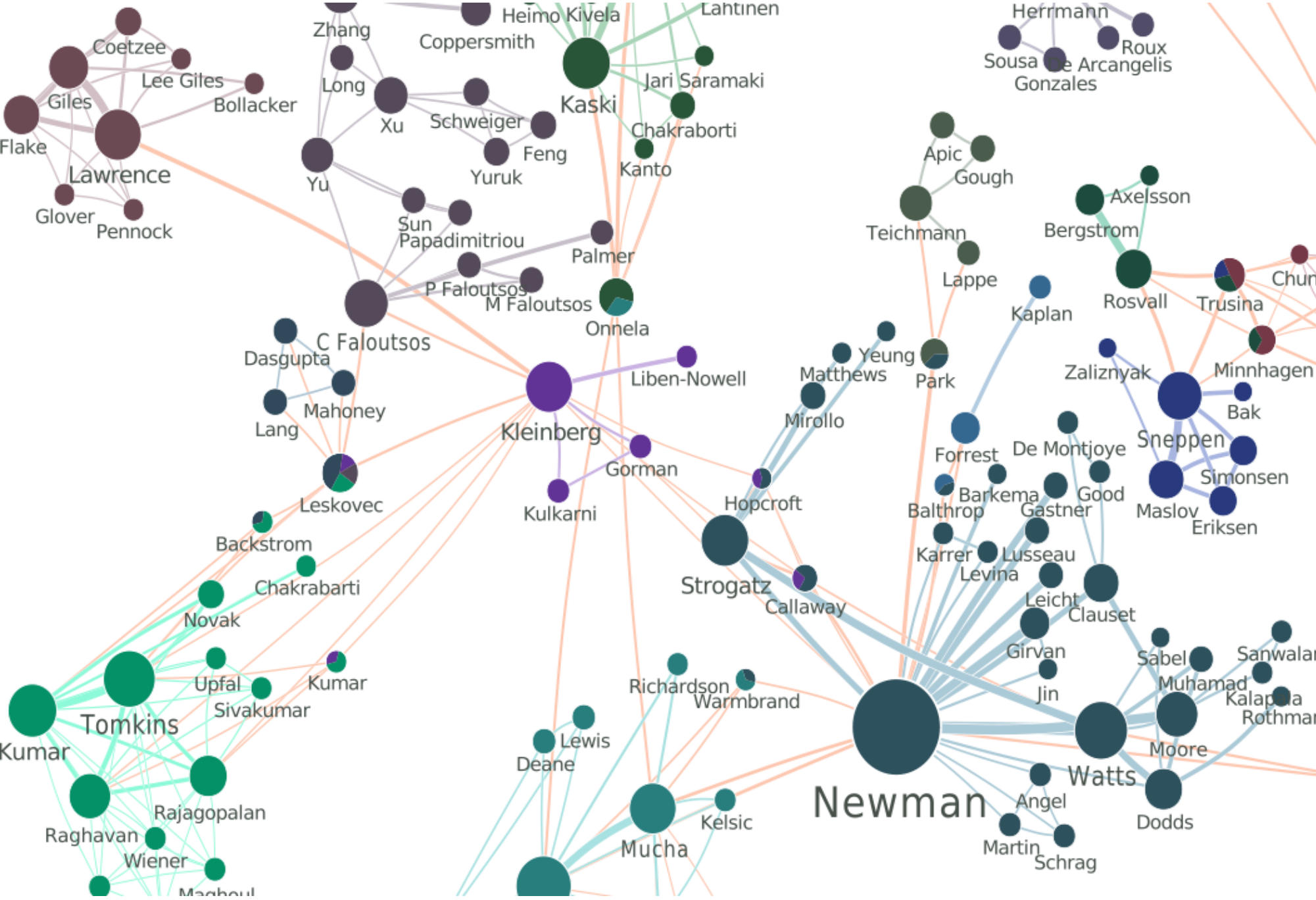


$$L(\mathsf{M}) = \underbrace{q_{\curvearrowleft} H(\mathcal{Q})}_{0.13 \text{ bits}} + \underbrace{\begin{Bmatrix} p^1_{\circlearrowleft} H(\mathcal{P}^1) \\ p^2_{\circlearrowleft} H(\mathcal{P}^2) \end{Bmatrix}}_{2.73 \text{ bits}} = 2.86 \text{ bits.}$$

B



$$L(\mathsf{M}) = \underbrace{q_{\curvearrowleft} H(\mathcal{Q})}_{0.063 \text{ bits}} + \underbrace{\begin{Bmatrix} p^1_{\circlearrowleft} H(\mathcal{P}^1) \\ p^2_{\circlearrowleft} H(\mathcal{P}^2) \end{Bmatrix}}_{2.61 \text{ bits}} = 2.67 \text{ bits.}$$


Coetzee
Lee Giles
Giles
Bollacker
Flake
Lawrence
Glover
Pennock
Zhang
Heimo
Kivela
Lahtinen
Coppersmith
Long
Xu
Schweiger
Kaski
Jari Saramaki
Feng
Yuruk
Chakraborti
Yu
Kanto
Sun
Papadimitriou
Palmer
P Faloutsos
M Faloutsos
Onnela
C Faloutsos
Dasgupta
Liben-Nowell
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Lang
Kleinberg
Leskovec
Gorman
Kulkarni
Backstrom
Chakrabarti
Novak
Kumar
Upfal
Sivakumar
Tomkins
Kumar
Rajagopalan
Raghavan
Wiener
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Bergstrom
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Matthews
Park
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Hopcroft
Strogatz
Callaway
Forrest
De Montjoye
Barkema
Good
Balthrop
Gastner
Karrer
Lusseau
Levina
Leicht
Clauset
Girvan
Jin
Newman
Zaliznyak
Minnhagen
Bak
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Sabel
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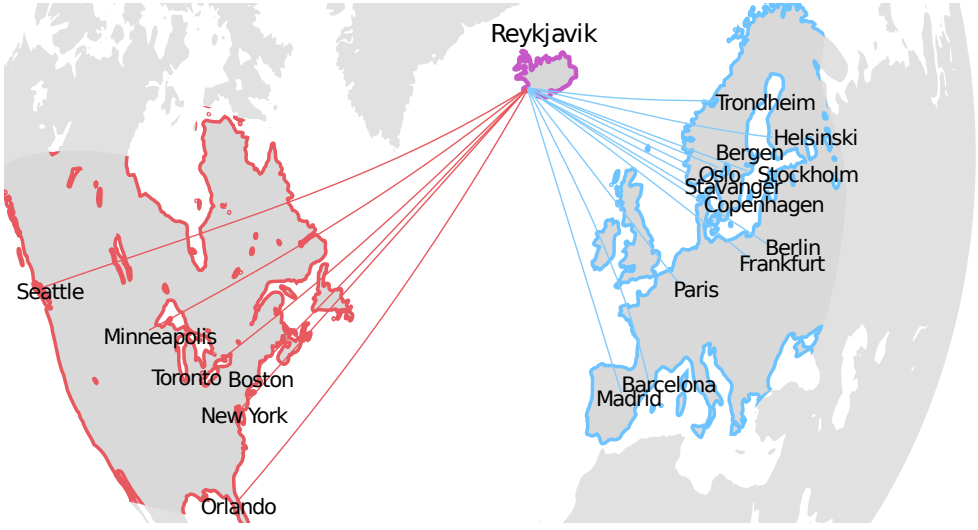
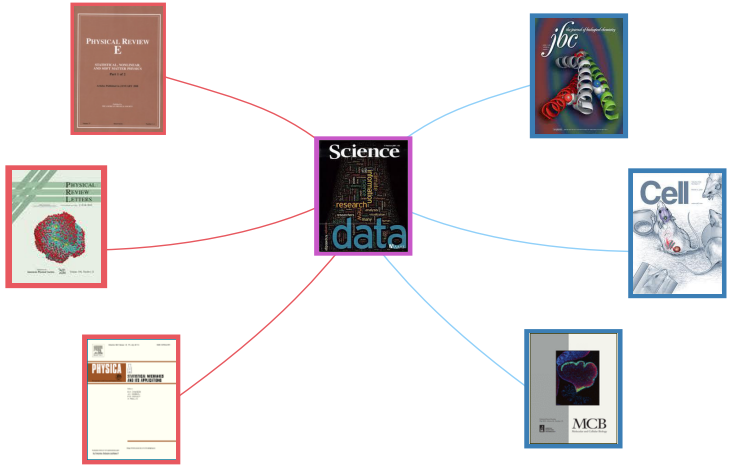
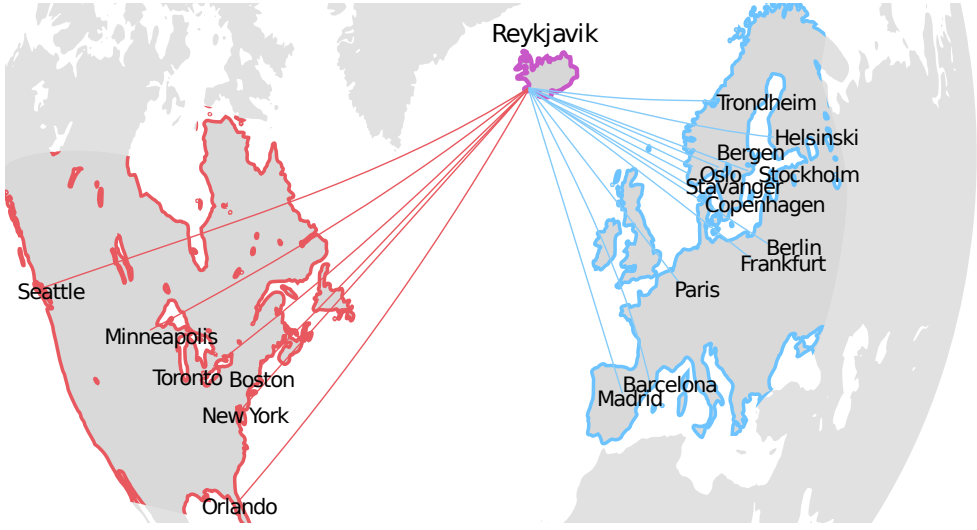
Moore
Watts
Dodds
Angel
Martin
Schrag

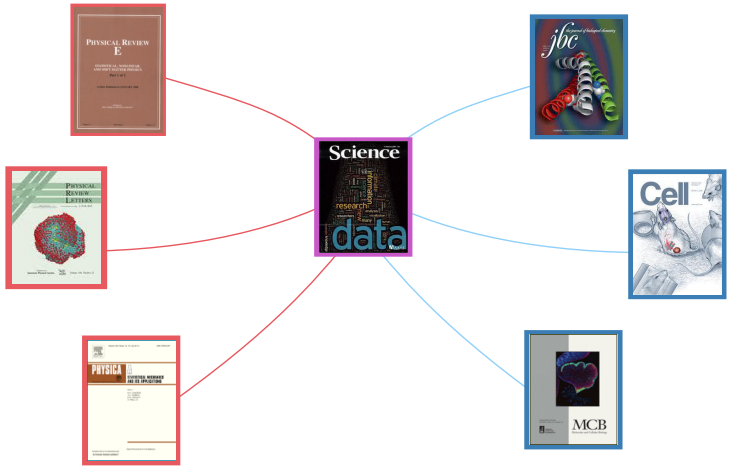
Memory networks capture real organization

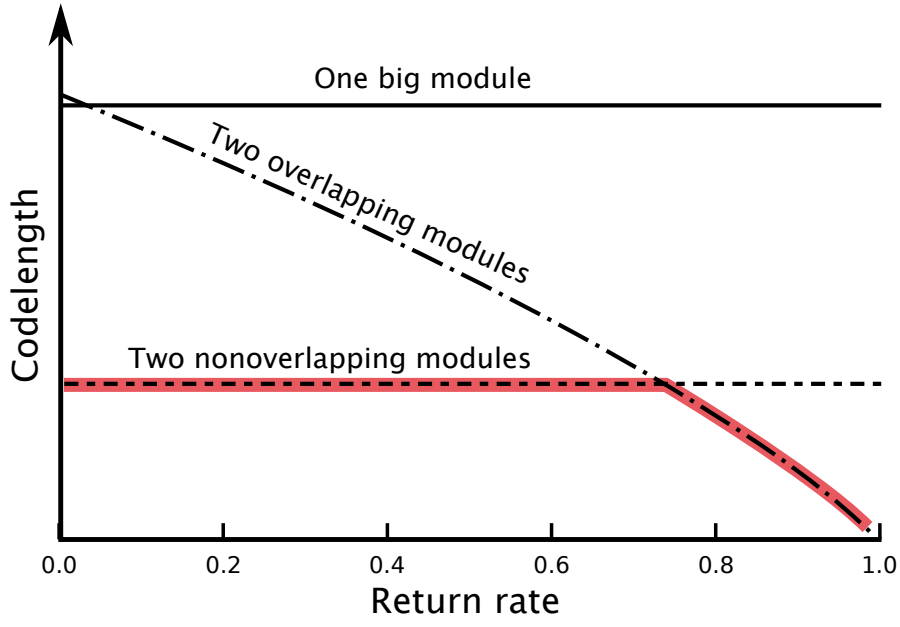




Memory networks capture real organization







Multilevel and overlapping partitions

Into how many hierarchical levels is a given network organized? How many modules are present at each level? Which nodes are members of which modules? And which nodes should belong to multiple modules and to what degree?

Multilevel and overlapping partitions with the map…

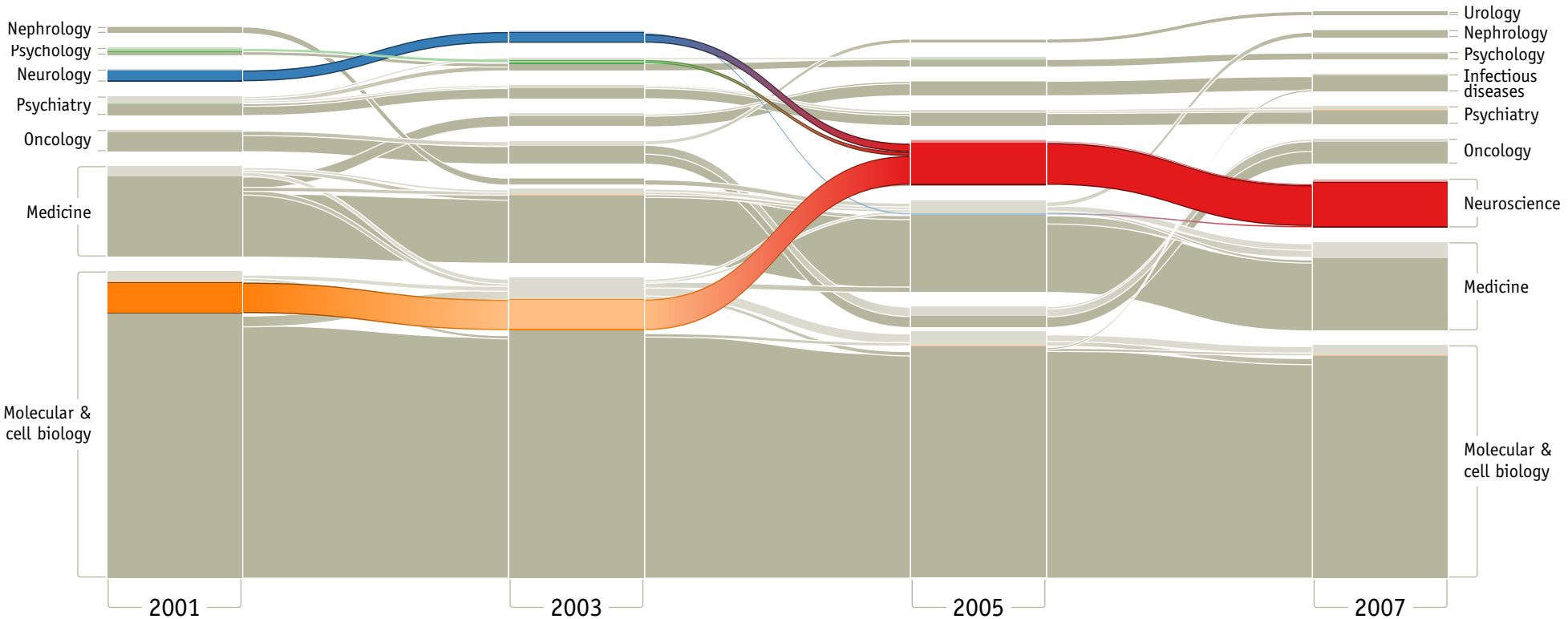
Into how many hierarchical levels is a given network organized? How many modules are present at each level? Which nodes are members of which modules? And which nodes should belong to multiple modules and to what degree?

Maximal compression of flow with constraints:

1. Modular code structure
2. ~~No more than two levels~~
3. ~~Each node can only belong to one module~~

CHANGE

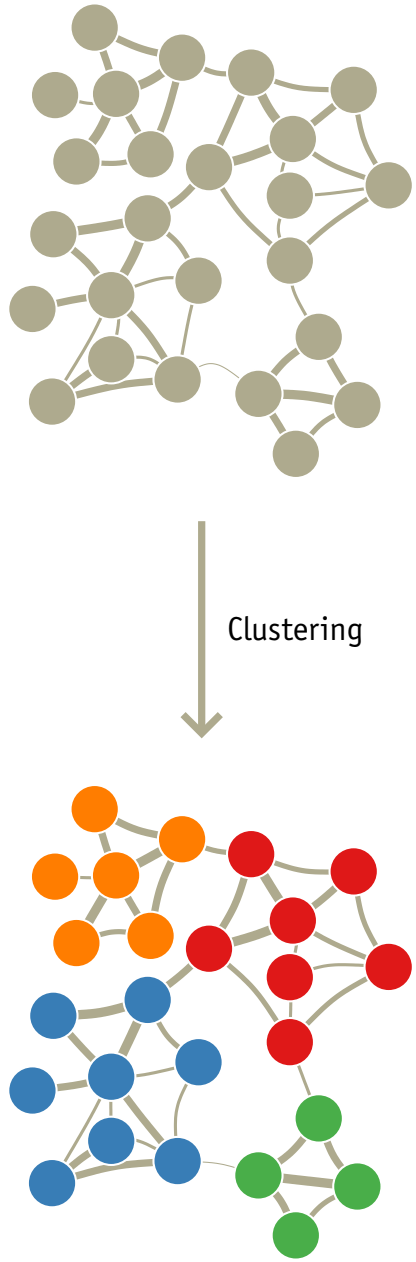
Mapping change in science



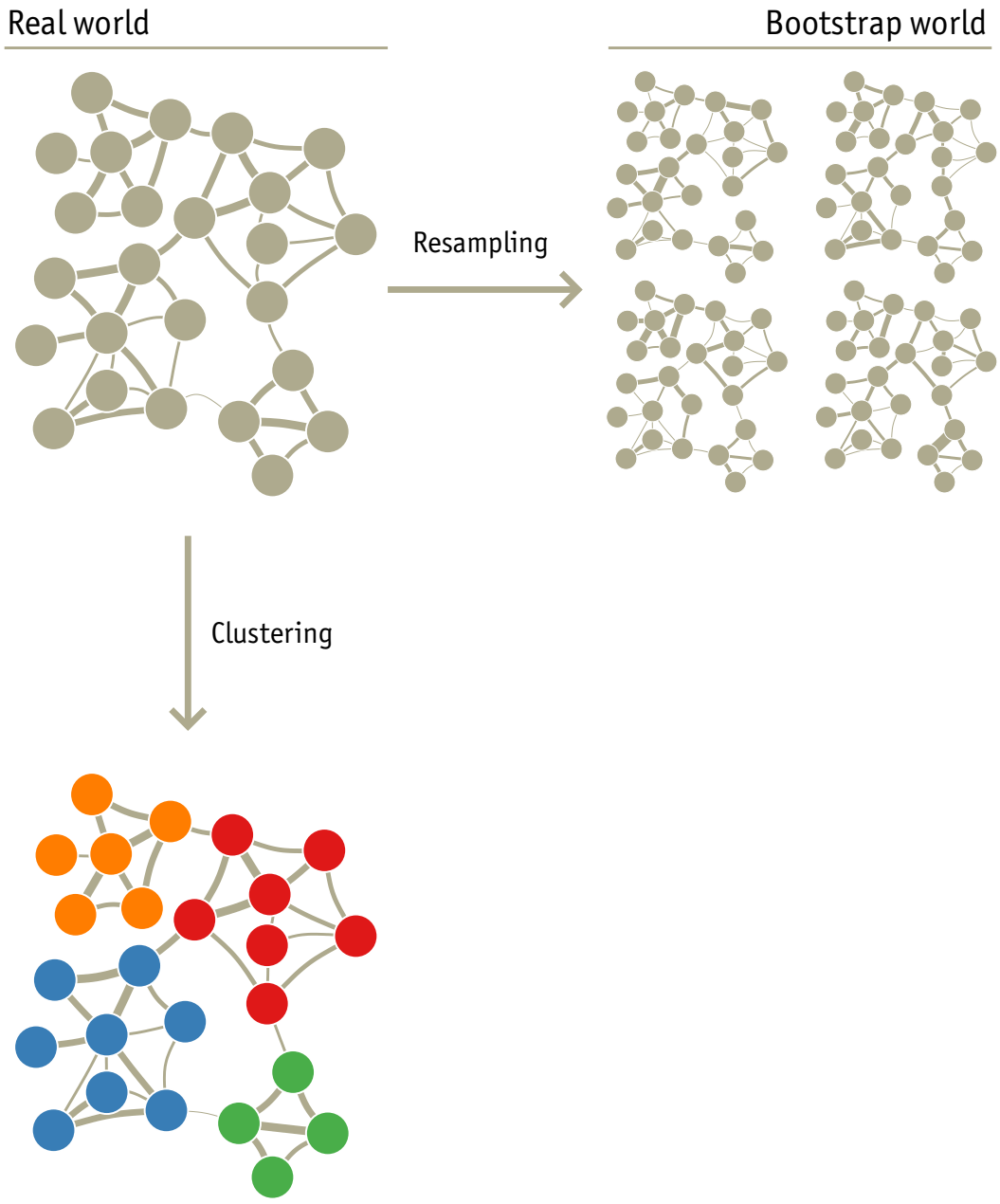
Rosvall & Bergstrom (2010)

What is real change
and what is mere noise?

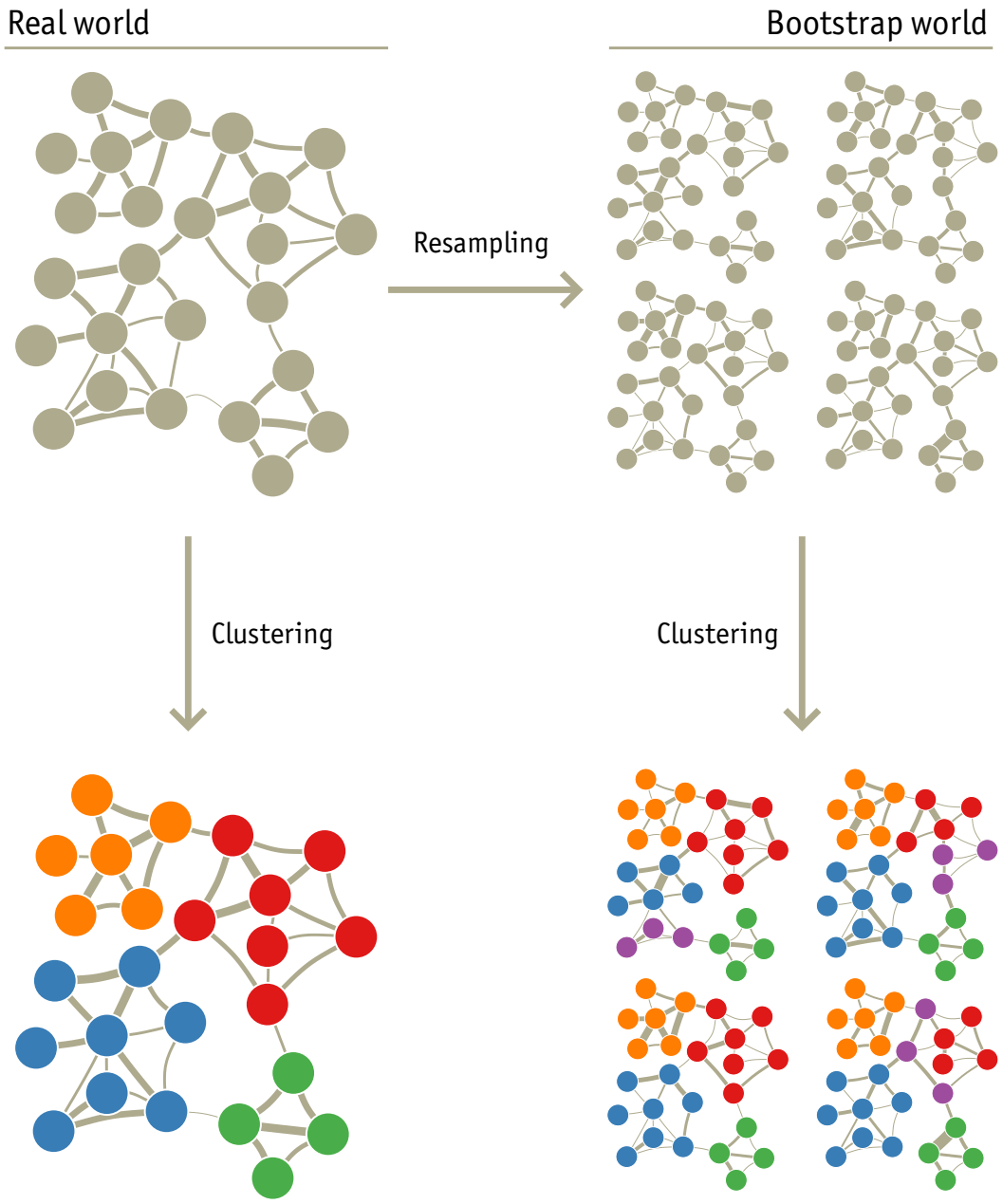
Significance clustering



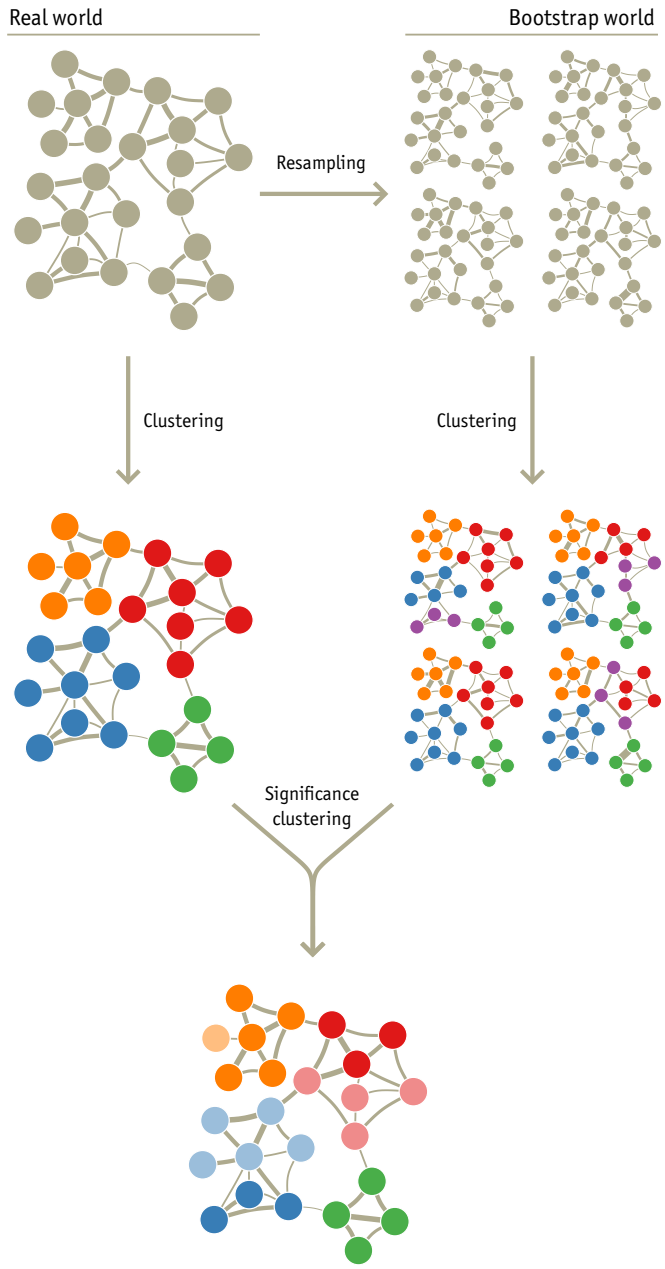
Significance clustering



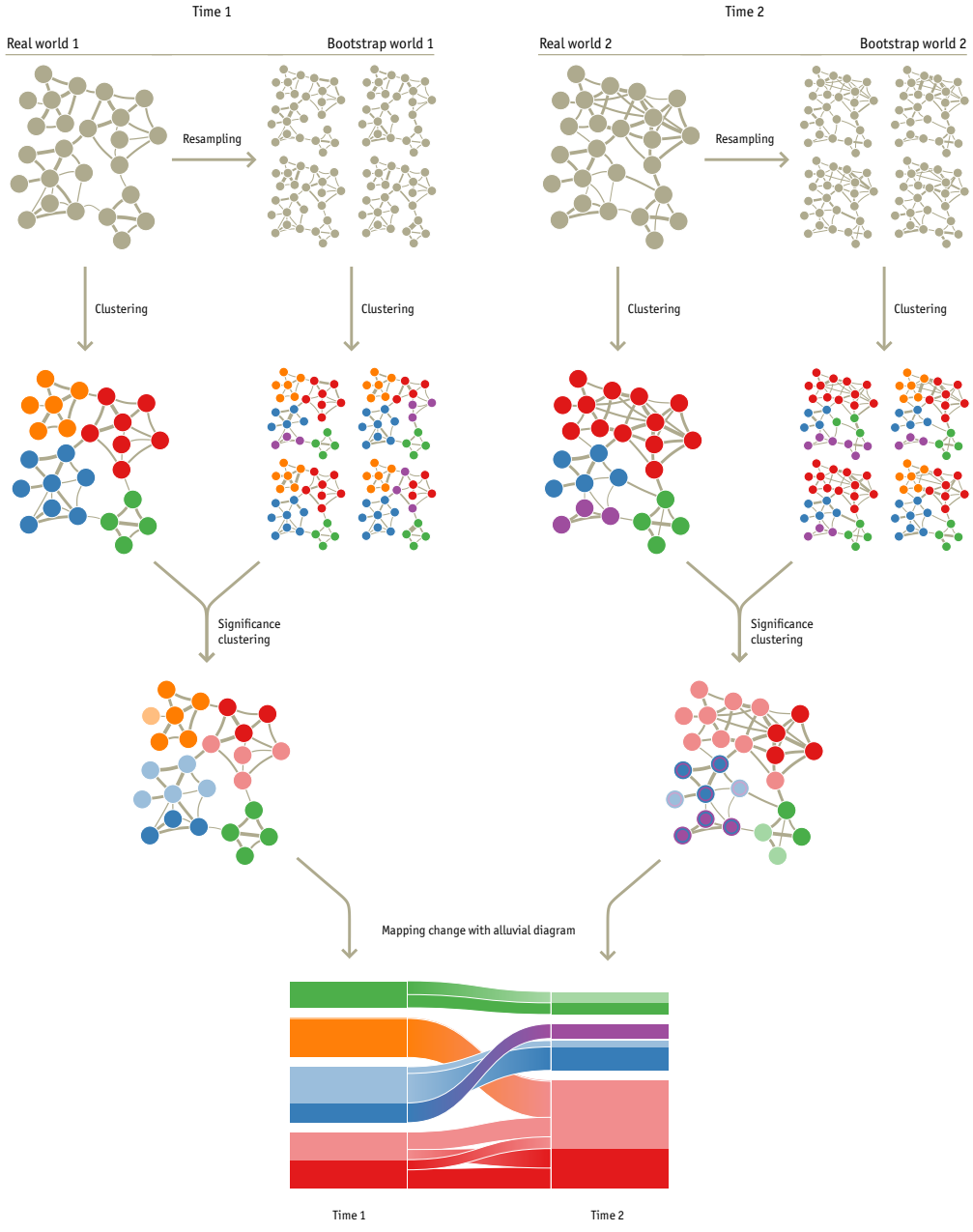
Significance clustering



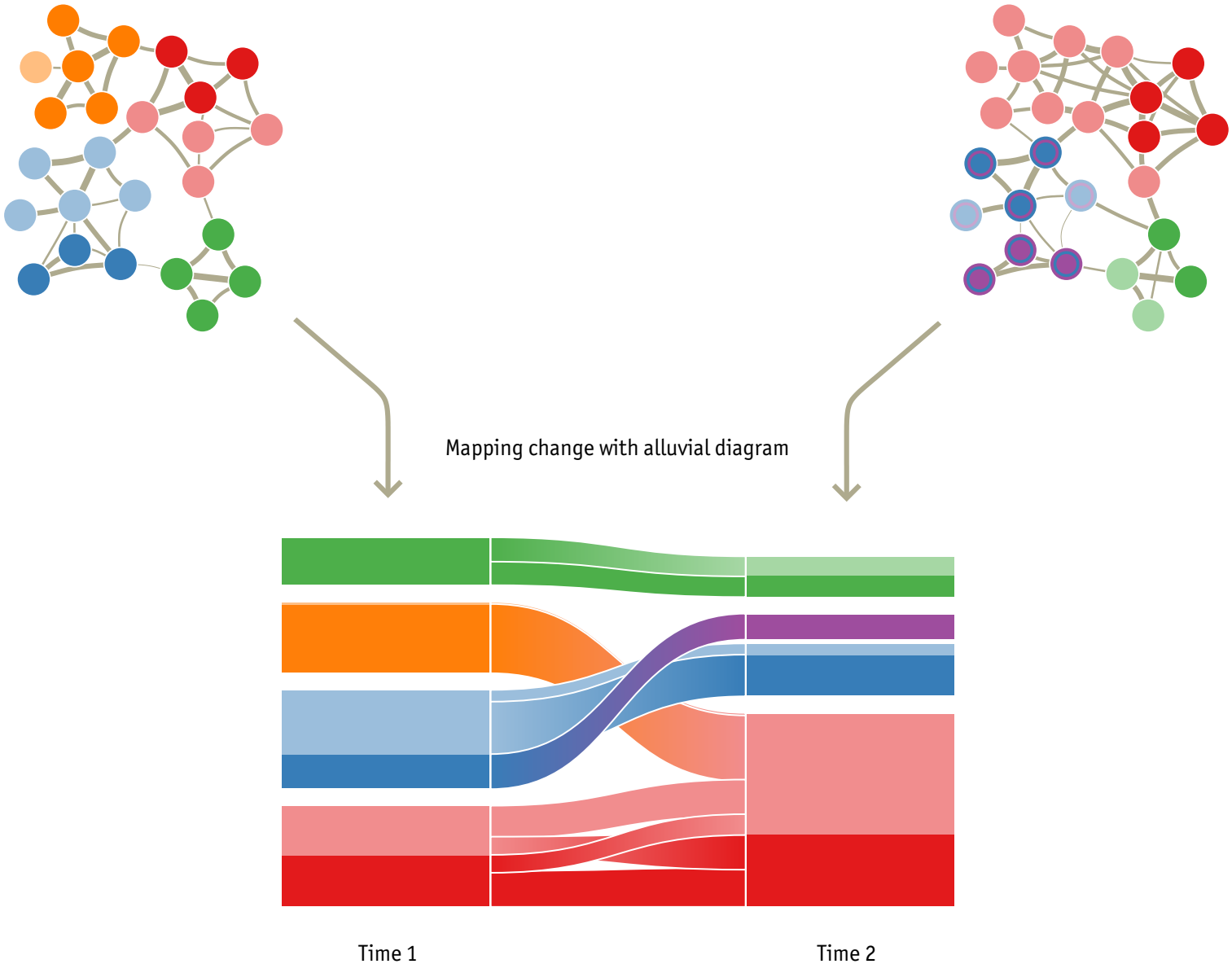
Significance clustering



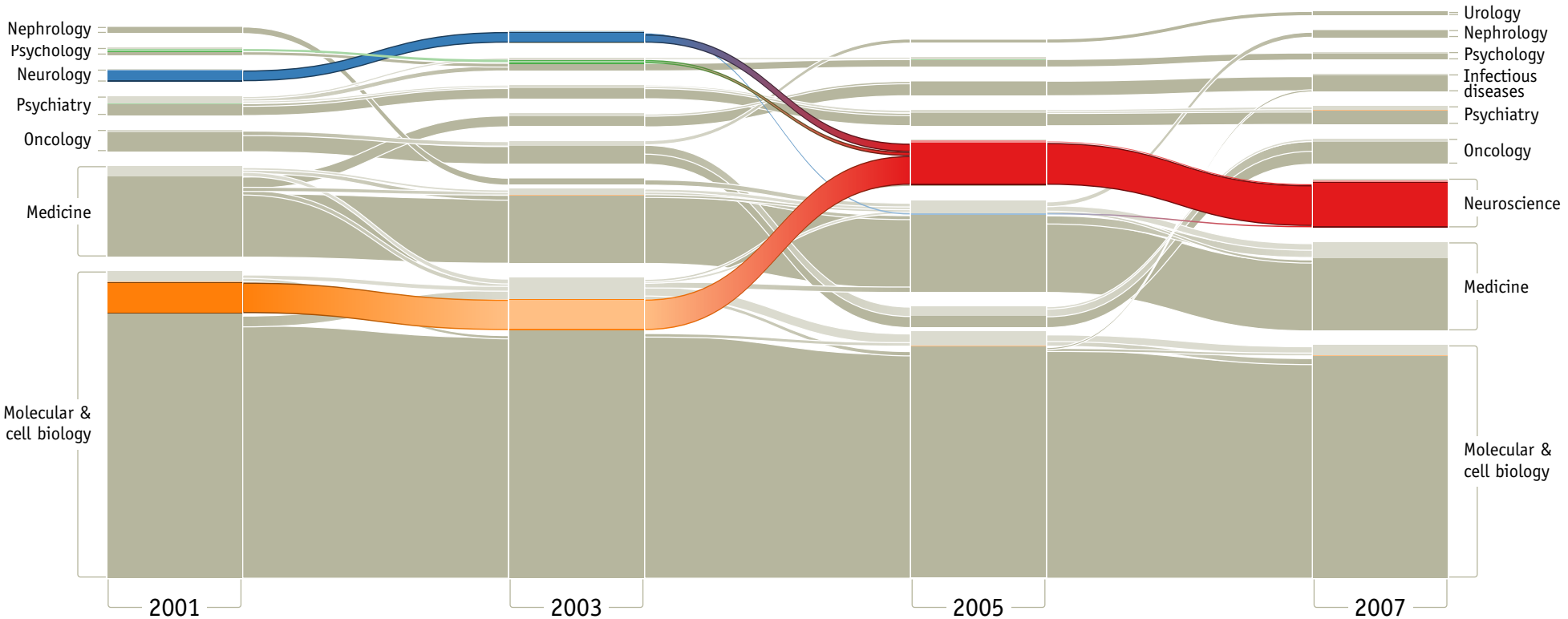
Mapping change



Mapping change

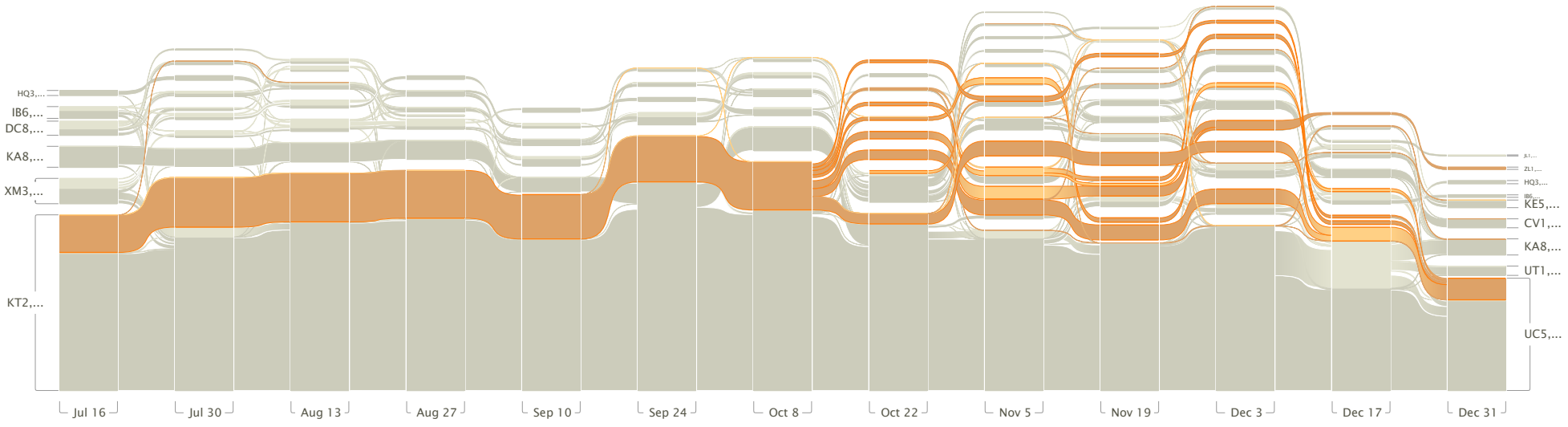


Mapping change in science

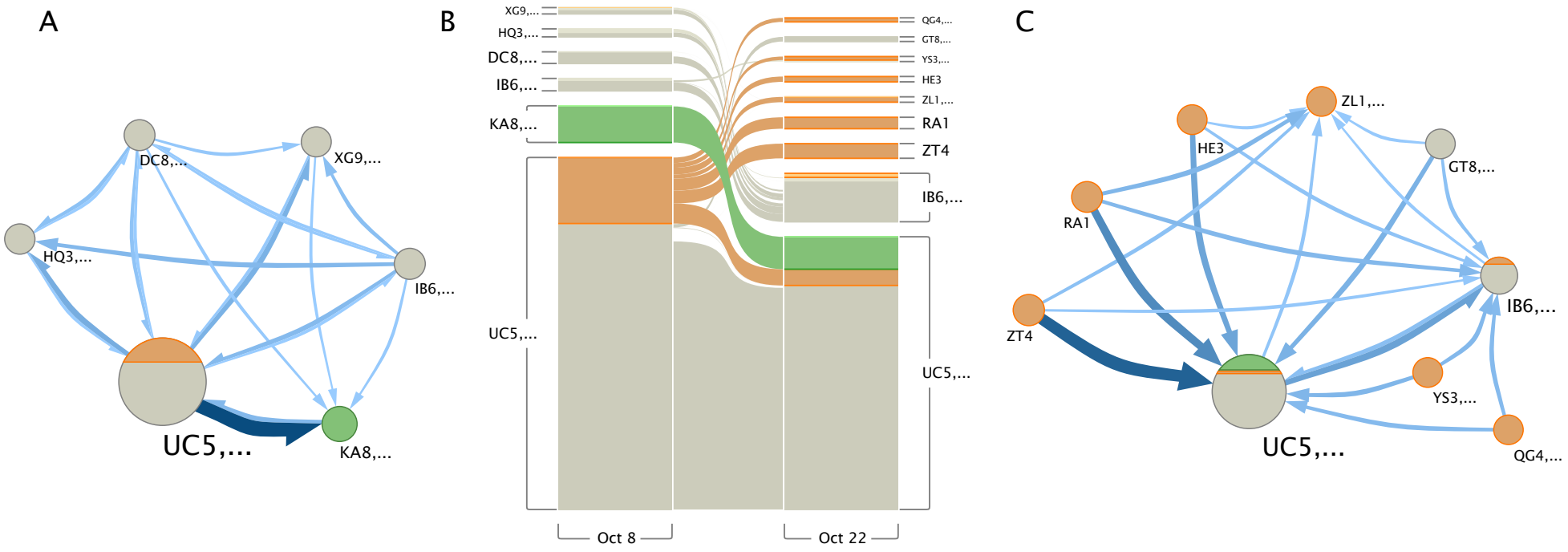


Rosvall & Bergstrom (2010)

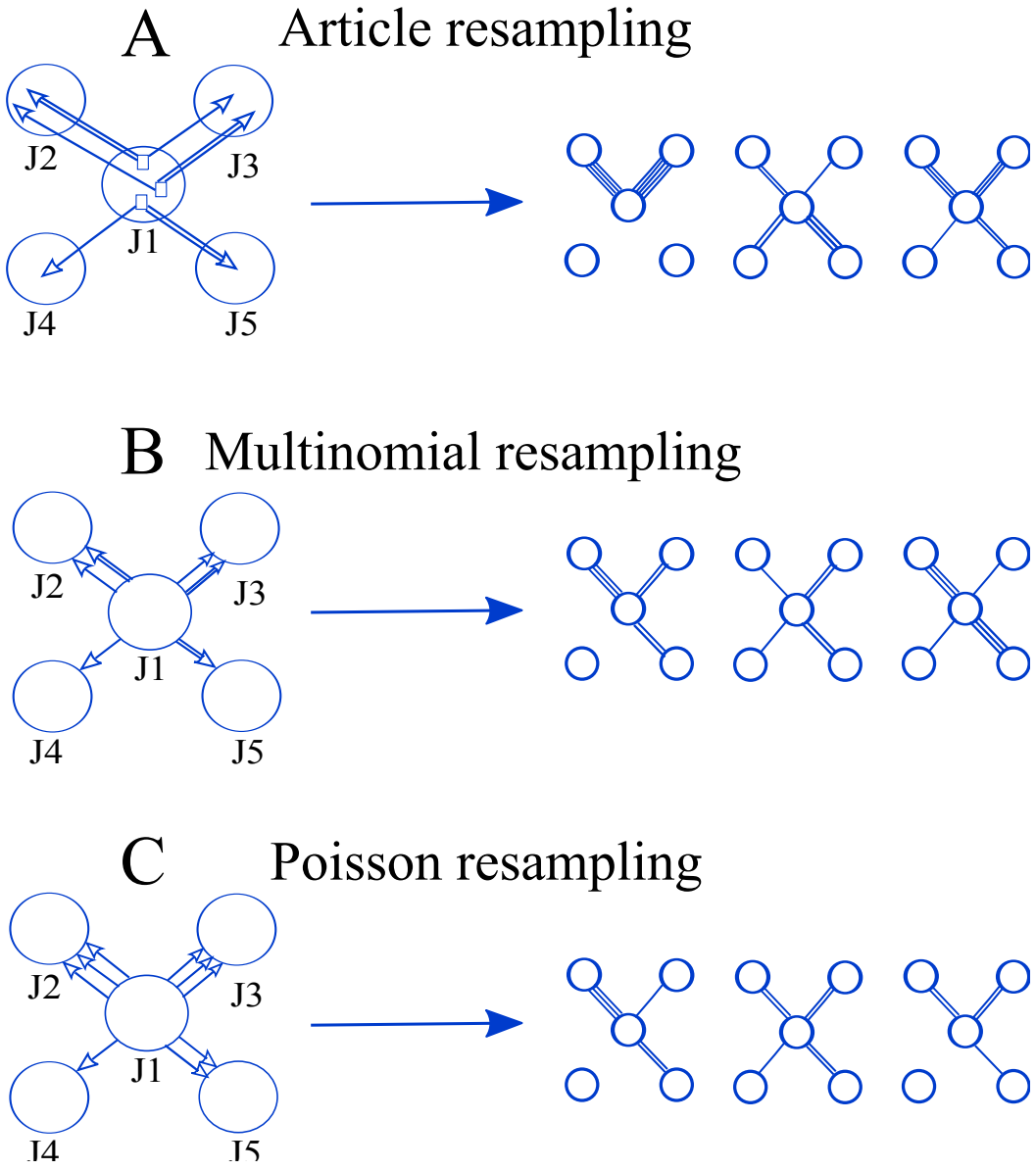
Mapping change in the federal funds market



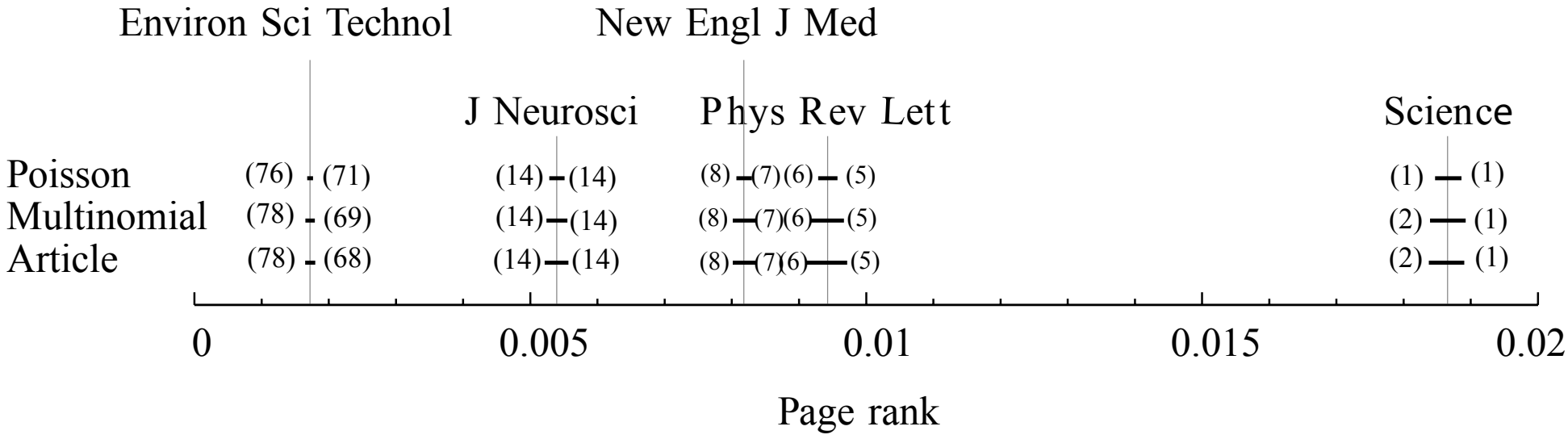
Mapping change in the federal funds market



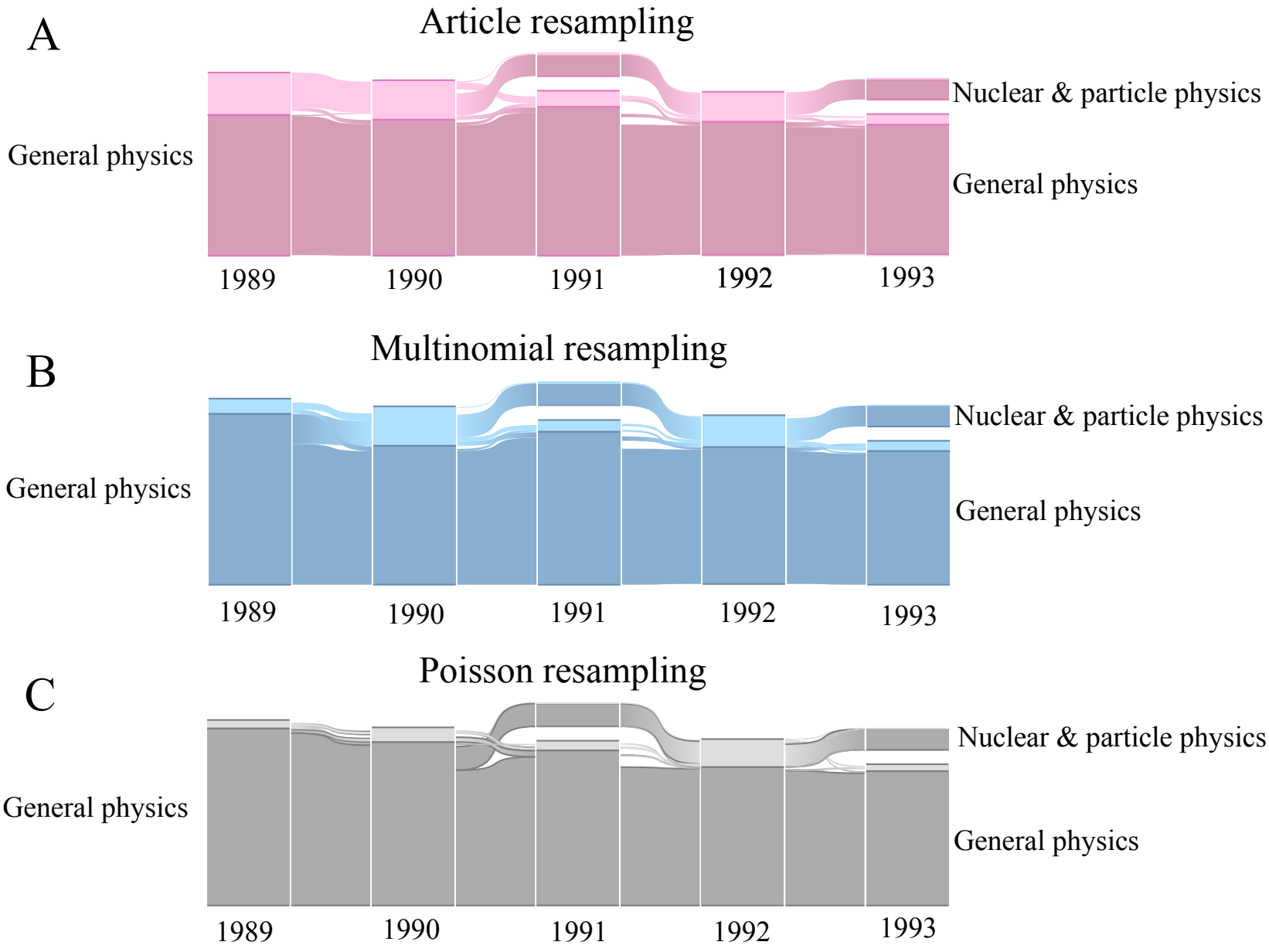
Resampling effects



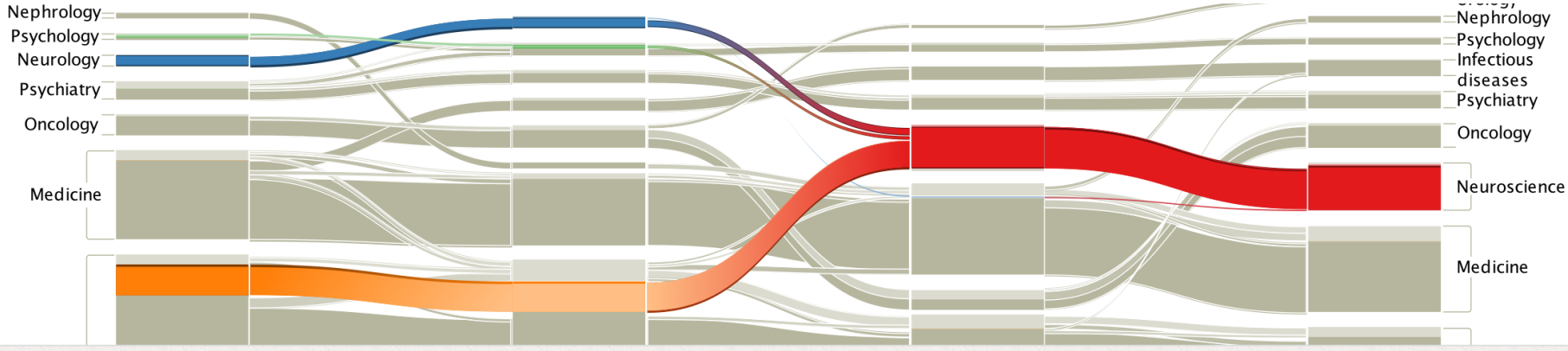
Resampling effects on ranking



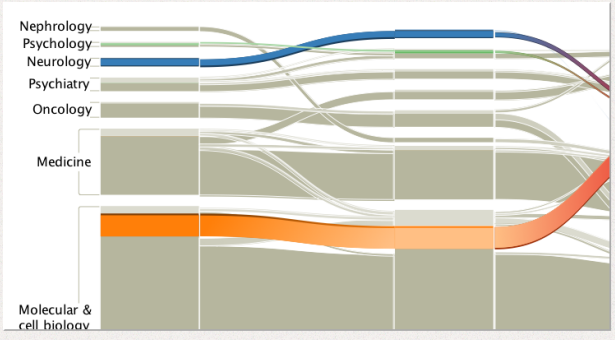
Resampling effects on clustering



Reveal structural change in complex networks



Apps »



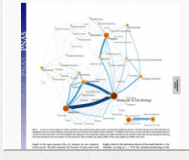
Code »

```
using infomath::plogp;
for (unsigned int i = 0; i < numNodes; ++i)
{
enter_log_enter += plogp(m_moduleFlowData[i].enterFl
exit_log_exit += plogp(m_moduleFlowData[i].exitFlow)
flow_log_flow += plogp(m_moduleFlowData[i].exitFlow
enterFlow += m_moduleFlowData[i].enterFlow;
}
enterFlow += exitNetworkFlow;
enterFlow_log_enterFlow = plogp(enterFlow);
```

Publications »

Maps of information flow reveal community structure in complex networks

Martin Rosvall and Carl T. Bergstrom
PNAS **105**, 1118 (2008). [arXiv:0707.0609]



To comprehend the multipartite organization of large-scale biological and social systems, we introduce a new information-theoretic approach to reveal community structure in

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