Assessing Nanotechnology: Measuring Interdisciplinarity and Mapping Research Emphases

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Agenda

1. Measuring “nano” interdisciplinarity
2. Science Overlay Mapping
   - Locating bodies of research on a base map of science
   - Social/Intellectual Research Networks
3. Discussion

NSF SciSIP Project: Measuring & Tracking Research Knowledge Integration & Transfer

*Premise that Interdisciplinary research ("**IDR**") is vital & warrants study to understand & nurture*

1. Advance conceptualization and analytical algorithms for IDR indicators
2. Visually depict knowledge interchanges via multiple network representations (Maps)
3. Apply to **Nano** – to study the intellectual & social research networks, their evolution
4. For better tools to gauge such research endeavors

Initiative to measure Interdisciplinary research (IDR) driven by evaluation needs of the **National Academies Keck *Futures Initiative***

Their National Academies Committee defines IDR as a mode of research by teams or individuals that ***integrates***

- perspectives/concepts/theories and/or
- tools/techniques and/or
- information/data

from two or more bodies of specialized knowledge or research practice. Its purpose is to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single field of research practice.

Examples of *bodies of specialized knowledge or research practice* include: low temperature physics, molecular biology, developmental psychology, toxicology, operations research, and fluid mechanics.

THE NATIONAL ACADEMIES
KECK FUTURES INITIATIVE

Subject Categories ("SCs")

- WOS indexed journals are associated with 1 or more of ~244 Subject Categories based on
  - Journal-to-journal cross-citation patterns
  - Expert editorial judgment on which journals belong in a given SC (research field)
- We use as the essential categorization for
  - Interdisciplinarity metrics
  - Science overlay mapping
- These ISI SCs are the most widely used categorization of research fields [a particularly good fit for our notion of interdisciplinary "integration"]

Macro-disciplines

We group the **SCs** into “Macro-disciplines” 2 ways:

1. Using Principal Components Analysis on a general sample of 30,261 US-authored articles in WOS]
   - Choose a 21-factor solution for the 244 SCs
   - We can augment with the 4 Education-related SCs here (because of ROLE/REESE emphases)
2. Based on factor analyses of the SC x SC co-citation matrix for all Science Citation Index journals (2006); for all SCI + SSCI journals (2007). We now prefer these:
   - **175 SC science base map (14 factors)**
   - 221 SC science + social science base map (18 factors)

The Macro-disciplines are named by us. These are the labels in the science overlay maps.

ISSI Workshop on Measuring & Mapping Interdisciplinarity (July, 2009)
Considerations: Assessment rather than just "Measures" of IDR:

1. **Cognitive** and Social aspects
2. **Classification-based** and Network approaches

Heuristics of diversity

(Stirling, 1998; 2007)
(Rafols and Meyer, 2009)

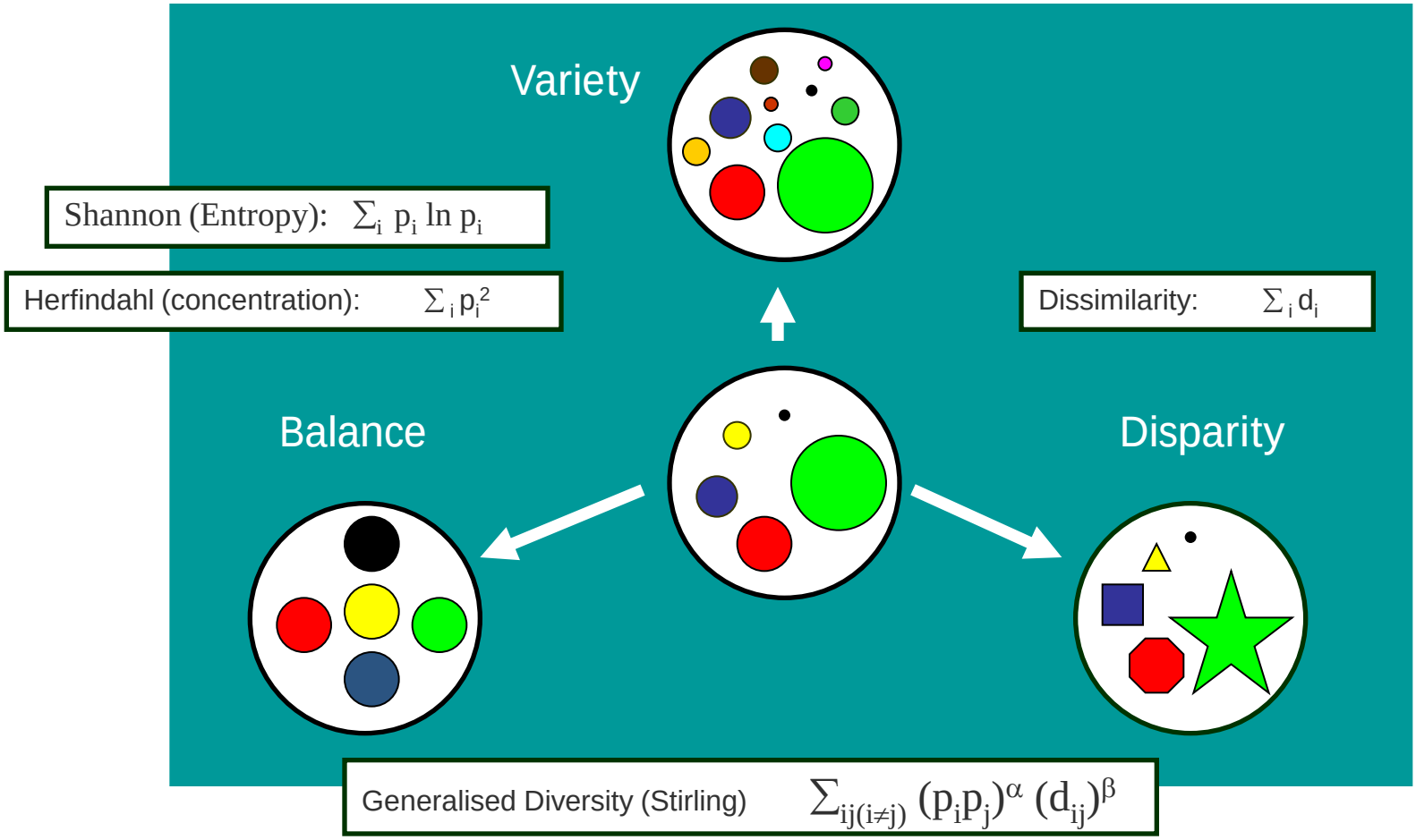
Diversity:

'attribute of a system whose elements may be apportioned into categories'

Characteristics:

Variety: Number of distinctive categories
Balance: Evenness of the distribution
Disparity: Degree to which the categories are different.

[** Shannon & Herfindahl do not include Disparity]



Integration Score

$$I = 1 - \left[\frac{\left[\sum \left(f_i \times f_j \times COS\left(SC_i - SC_j \right) \right) \right]}{\sum \left(f_i \times f_j \right)} \right]$$

Porter et al. (2007)

where $i = row$; $j = column$; $f = frequency$

"cos (SCi – SCj)" measures the association between two SCs, based on a national co-citation sample from Web of Science. It reflects the relative tendency of two particular SCs to be co-cited.

****equivalently,**

$$I = 1 - \sum_{i,j} p_i p_j s_{ij}$$

Rafols and Meyer (2009)

where p_i is the proportion of references citing the SC i in a given paper. The summation is taken over the cells of the SC x SC matrix. s_{ij} is the cosine measure of similarity between SCs i and j

[This measure is basically 1 – Stirling D.]

Behavior of our Integration Score ("I")

A paper cites N references [considering only those to journals indexed by WOS), and associated with journals associated with 1 or more Subject Categories (SCs]. Integration varies:

1. As the # of Cited SCs increases (higher **Variety**), I increases
2. As the **Balance** among those Cited SCs increases, I increases
3. As the **Disparity** among those Cited SCs increases [less tendency for them to be co-cited by national samples of articles], I increases

Ranges from:

0 (stand alone research that cites work from a single SC) to

1 (highly Integrative research drawing from multiple, ~unrelated SCs)

Why does interdisciplinarity matter for nano?

Interdisciplinarity

- National Academies initiative – keys on ***integration*** of previously separate knowledge [not consensual, but supported at ISSI and "Philosophy of Interdisciplinarity" workshops this year.
- Most scientific breakthroughs occur at the "interstices" among established fields; high priority societal problems are not addressed within particular disciplines.

Nano – is it really interdisciplinary?

- An area where multiple disciplines converge? [c.f., Roco]
- Or an agglomeration of unrelated disciplines? [c.f., Schummer]

Our research

1. **What research areas are active in nano? What research areas comprise key knowledge sources?**
2. **To what extent is there integration of these ''disciplines'' within nano**

The GT Nano Datasets

- Two-stage, multi-component Boolean search
- 1991 through 2008 (part year)
- Nanotechnology publications: ~1.5 million publication records (508,000 from Web of Science)
- Others
  - 27,000+ patents granted (61 patent offices) [PatStat]
  - 6000+ US companies [corporate publications, patents, SBIR]
- Imported into text mining software (*VantagePoint*) for cleaning, analyses, and mapping
- Center for Nano in Society (Arizona State Univ.) subproject – toward "Real Time Technology Assessment; NC State Univ. Partnership for Innovation; GT SciSIP project – measuring & mapping research knowledge transfer (focused on nano)

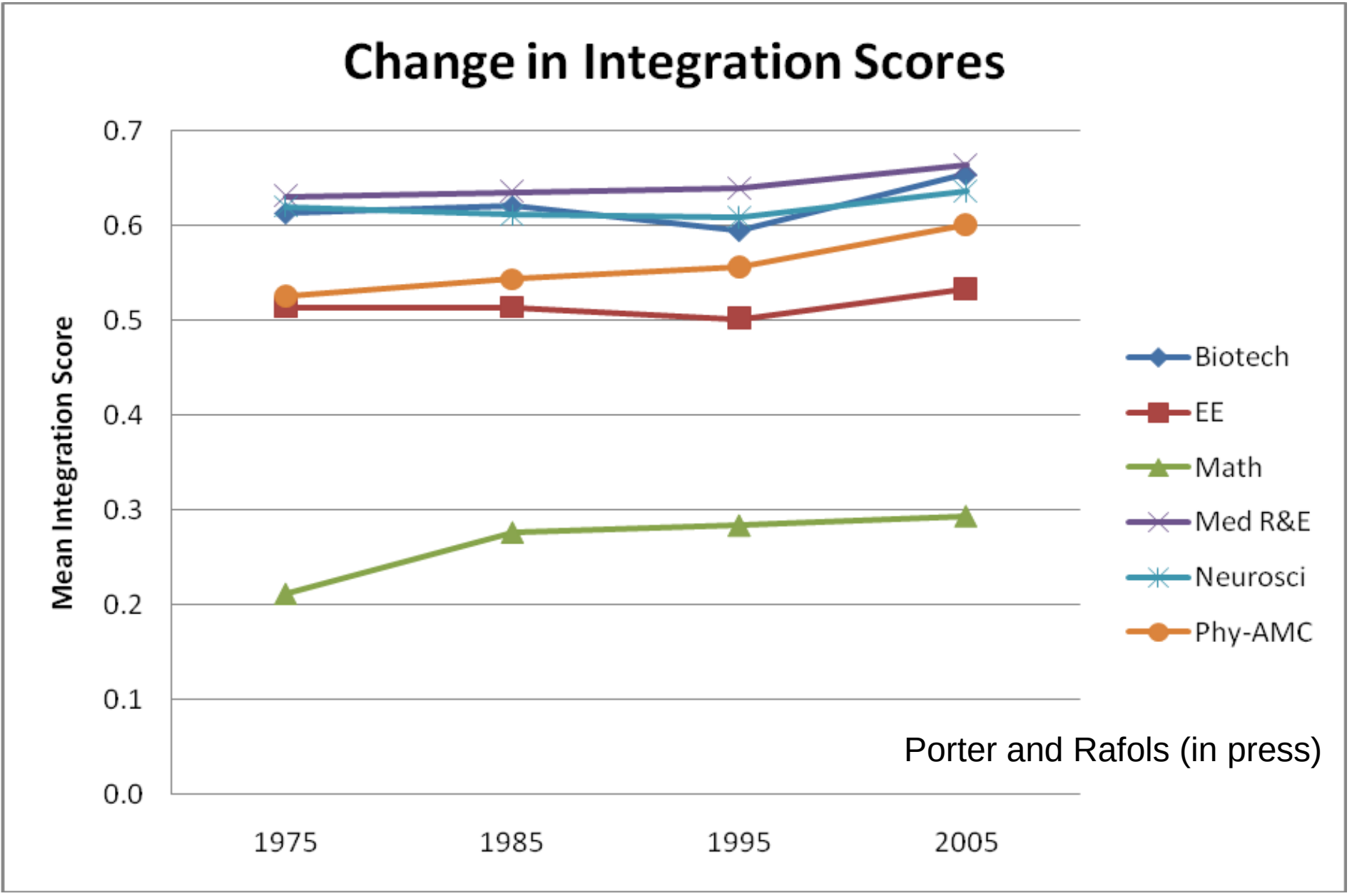
Leading Macro-Disciplines of Nano Publications & Citations, 2008 [SCI]

Macro-Disciplines	% of Publications	% that Cite
Materials Sciences	63	91
Chemistry	23	78
Physics	10	54
Biomedical Sciences	9	64
Engineering Sciences	8	40
Clinical Medicine	3	18
Computer Science	3	19
Agricultural Sciences	3	18
Environmental Science & Technology	2	14
Industrial Engineering/Management Sciences (including Mathematics)	1	32

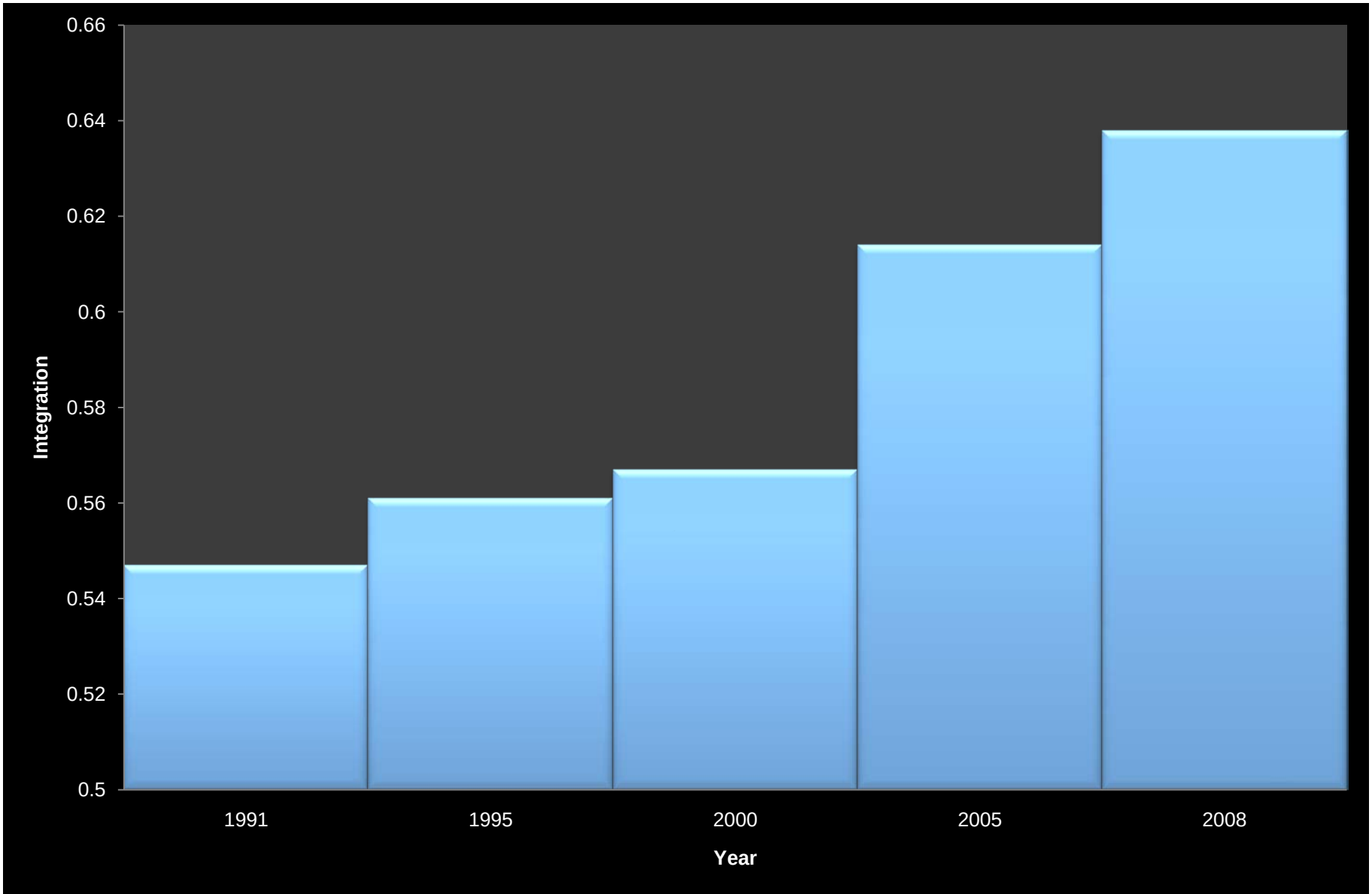
Percentage of Articles in each Macro-Discipline (rows) Citing at least one source in a given Macro-Discipline (columns)

# Pubs	Macro-Disciplines: Publications \ Cited	Mtls Sci	Chemistry	Physics	Biomed Sci	Engr Sci	Clinical Med	Computer Sci	Agri Sci	Env Sci & Tech	Ind Engr/Mgt Sci (including Math)
19301	**Mtls Sci**	98	77	57	58	44	12	22	16	**12**	36
7020	**Chemistry**	91	96	53	77	33	19	13	20	**13**	29
2989	**Physics**	89	68	90	56	29	8	28	5	**6**	22
2647	**Biomed Sci**	51	83	24	94	19	47	6	34	**18**	12
2503	**Engr Sci**	95	74	48	54	81	11	19	24	**28**	32
973	**Clinical Med**	65	69	20	81	24	93	7	22	**12**	35
872	**Computer Sci**	89	47	63	36	34	5	75	3	**3**	21
793	**Agri Sci**	77	82	22	71	52	18	5	81	**38**	26
630	**Env Sci & Tech**	**71**	**75**	**26**	**62**	**64**	**20**	**5**	**46**	**92**	**19**
158	**Ind Engr/Mgt Sci (including Math)**	86	41	38	32	67	13	27	9	**11**	72

Benchmarking Integration Scores



Average Integration Scores for Samples of Nano Articles [Benchmark: 1985-2005, 6 SCs increased average of 0.03 – Here 1991-2008, increase of ~0.09]



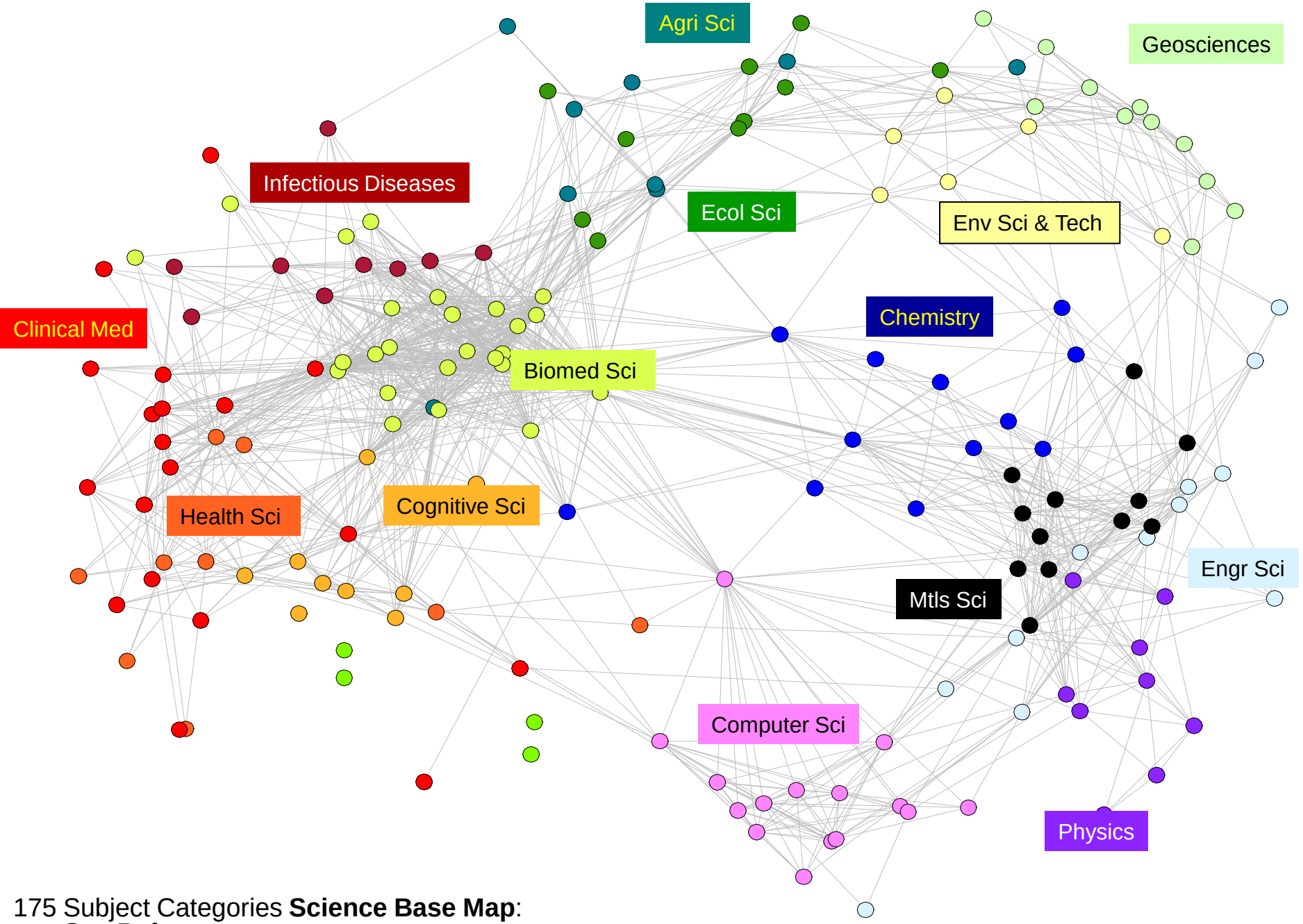
Science Mapping

- Based on Bibliometrics
- Since the 1970's
- But usually local – e.g., research networking in a specific research arena
- Recently, mapping "all" of science – Klavans, Boyack, Borner; Chen; Leydesdorff, Rafols, Meyer, Porter
- ~Robust to different data and representations

Science Overlay & Citation Mapping

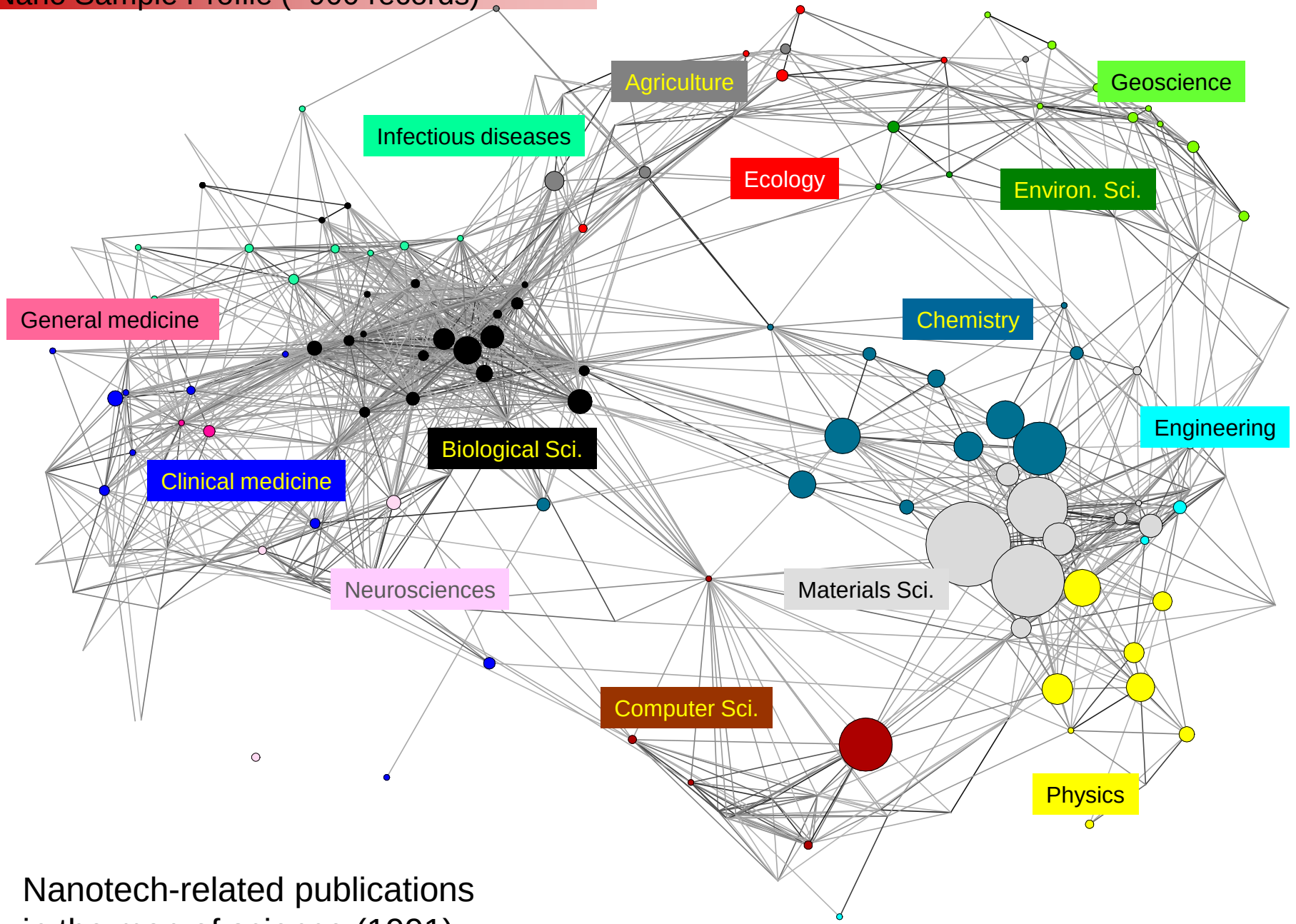
- Use the science map as a base upon which to locate a given body (or bodies) of research activity
- Convey research field engagement (or not)
- Show cross-disciplinary interchange

Based on Leydesdorff and Rafols (2009) and Rafols and Meyer (2009)



175 Subject Categories **Science Base Map**:
See References

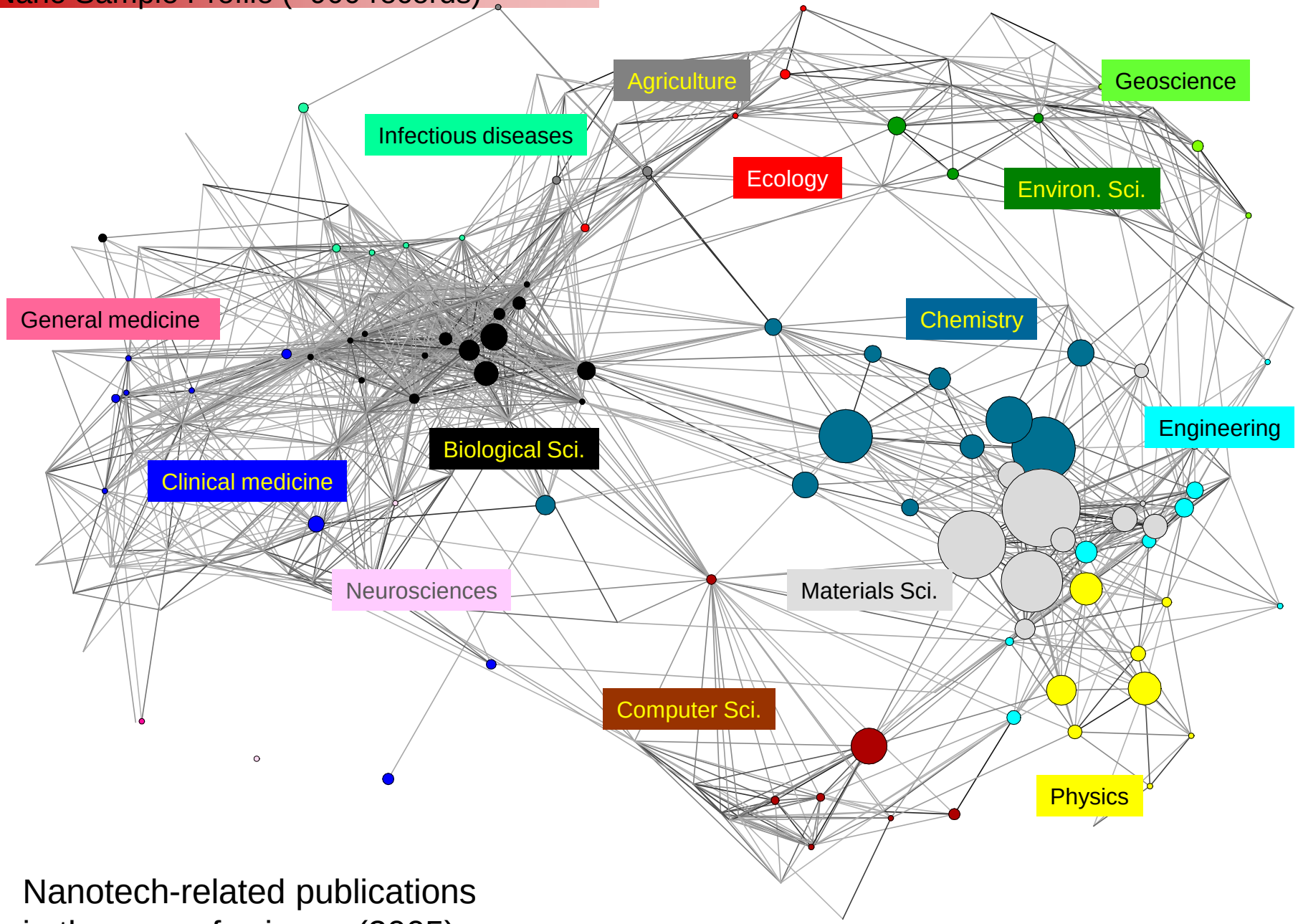
Nano Sample Profile (~900 records)



Nanotech-related publications
in the map of science (1991)

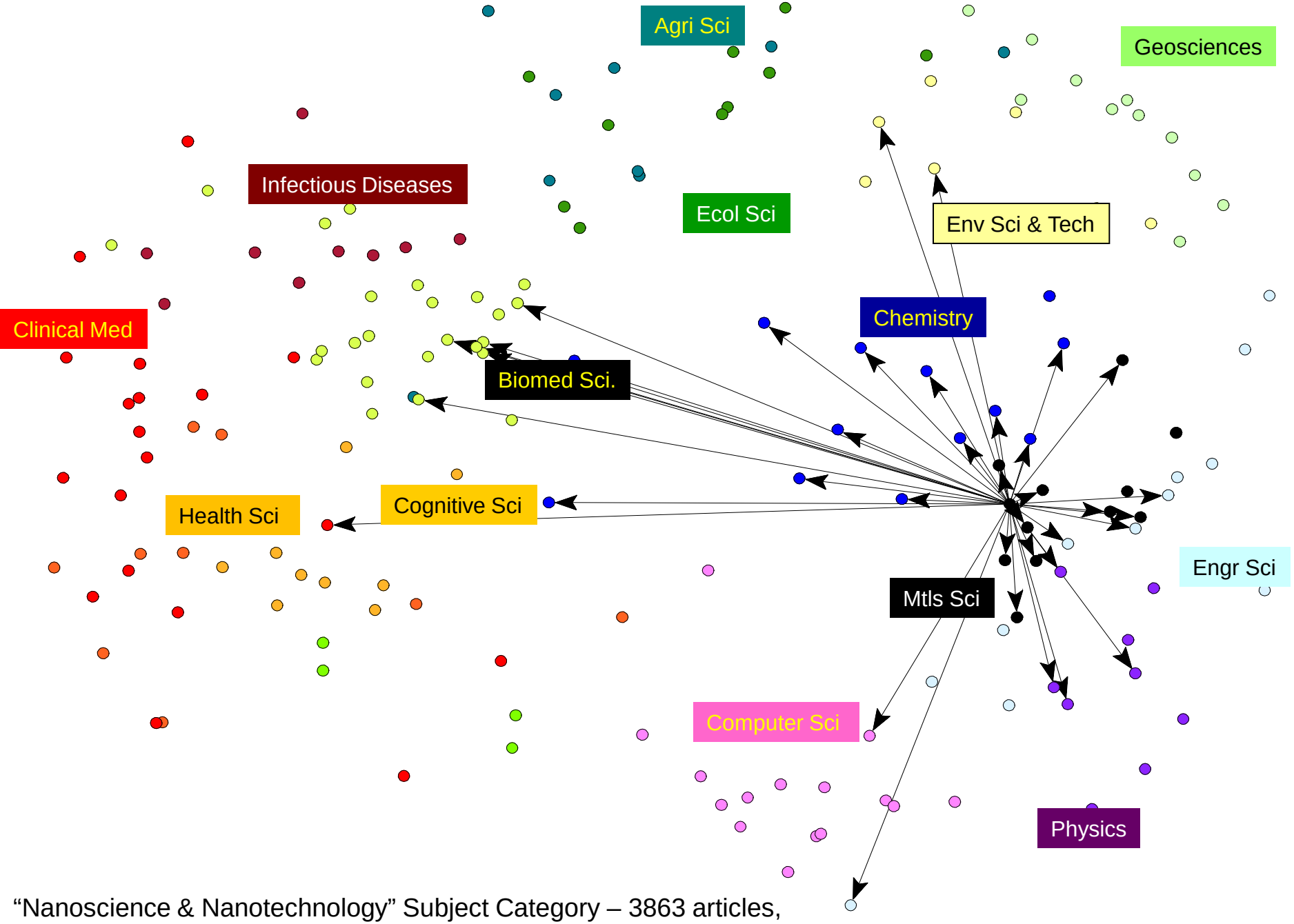
Pajek

Nano Sample Profile (~900 records)



Nanotech-related publications
in the map of science (2005)

Pajek



"Nanoscience & Nanotechnology" Subject Category – 3863 articles,
partial 2008 – showing Top 40 Cited SCs Overlay over base 175 SC Science Map

Summing Up

- How broadly does nano engage multiple disciplines (research areas)?
  - Very much
  - But the core is Materials Science
- To what extent does nano research integrate knowledge from multiple disciplines (research areas)?
  - Nano is not just an amalgam of ~disciplinary research "silos" – researchers draw from other subject categories
  - But citation is heaviest to nearby research areas
  - Integration scores are high & increasing – average of 0.64 here for 2008 vs. 0.63 for 5 benchmark SCs in 2005 [plus Math at 0.29]
  - To what degree is nano's interdisciplinarity a function of what is going on in the broader research enterprise, or something specific to it?
- This macro view should be complemented by micro probes
  - Whether component nano research fields are converging?
  - Require focus on particular applications
  - "Bottom-Up" analyses of specific research & what it integrates

Implications: We should

- Facilitate the diffusion and absorption of research across disciplines
- Assist researchers' ability to find knowledge in disparate areas
  - Attend to the language used to present essential nano research findings
  - Encourage exposure to, if not training in, ‘‘infometrics’’ tools and methods to better locate relevant research by using leading databases

Nano References

Nano Mapping

- Porter, A.L., and Youtie, J., Where Does Nanotechnology Belong in the Map of Science?, *Nature-Nanotechnology*, Vol. 4, 534-536, 2009.
- Porter, A.L., and Youtie, J., How Interdisciplinary is Nanotechnology?, *Journal of Nanoparticle Research*, Vol. 11, No. 5, 1023-1041; 2009.
- Subramanian, V., Houtie, J., Porter, A.L., and Shapira, P., Is there a shift to “active nanostructures”?, *Journal of Nanoparticle Research*, http://www.springerlink.com/content/ag2m127l6615w023/.
- Huang, L., Guo, Y., and Porter, A.L. (2010), Identifying Emerging Roles of Nanoparticles in Biosensors, *Journal of Business Chemistry,* to appear (Jan).
- Guo, Y., Huang, L., and Porter, A.L., Research Profiling: Nano-enhanced, Thin-film Solar Cells, *R&D Management*, submitted.
- Porter, A.L., Youtie, J., Shapira, P., and Schoeneck, D.J., Refining Search Terms for Nanotechnology, *Journal of Nanoparticle Research*, Vol. 10 (5), 715-728, 2008

Science Mapping References

Maps

Leydesdorff, L. and Rafols, I. (2009) A Global Map of Science Based on the ISI Subject Categories. Journal of the American Society for Information Science and Technology, 60(2), 348-362.

Rafols, I. and Leydesdorff, L. (2009). Content-based and Algorithmic Classifications of Journals: Perspectives on the Dynamics of Scientific Communication and Indexer Effects. Journal of the American Society for Information Science and Technology. DOI: 10.1002/asi.21086.

Overlay

Rafols, I., Porter, A. L. and Leydesdorff, L. (in preparation) Overlay science maps: a new tool for research evaluation.

Rafols, I. and Meyer, M. (2009) Diversity and Network Coherence as indicators of interdisciplinarity: case studies in bionanoscience. *Scientometrics*, DOI 10.1007/s11192-009-0041-y.

Interdisciplinary Metrics & Maps

Porter, A.L., and Rafols, I. (forthcoming) Is Science Becoming More Interdisciplinary? Measuring and mapping six research fields over time, *Scientometrics.* DOI: 10.1007/s11192-008-2197-2.

Kinesin Presentation

I. Rafols, _M. Meyer_, and A.L. Porter (2008) /Locating the sites of knowledge integration in nanotechnology, using diversity and coherence as indicators of interdisciplinarity. /Paper at the 10th International Conference on Science and Technology Indicators. Vienna, September 2008.

Resources

- **Science Base map data** are originally from Leydesdorff: //users.fmg.uva.nl/lleydesdorff/map06/texts/index.htm
- **Interactive Map of Science**: //users.fmg.uva.nl/lleydesdorff/map06/index.htm>.
- **How to make Map of Science with Pajek -USER-KIT** http://www.sussex.ac.uk/Units/spru/documents/MapScienceKit.zip
- **The text mining software used: www.theVantagePoint.com**
- **Our nano science overlay maps: http://www.nanopolicy.gatech.edu/**

Discussion

- If you're interested, we have a budding website and e-mail list to share ideas on interdisciplinary research metrics & maps – just let me know
- Also, another website and e-mail list on philosophy and/or interdisciplinarity
- Your thoughts??

SC Issues

- Studies indicate ~50% disagreement on journal assignment
  - Researchers' views on what belongs in their field
  - Alternative categorizations
- But ~good news
  - Science maps show general pattern consistency
  - Disagreements are usually within a science neighborhood
  - So, both our Integration measure and maps are not overly sensitive to misclassifications
- For our analyses, recognize that we use SCs, thereby assigning articles to categories based on the journal in which they appear (not upon article content)

Dual, Complementary Methods

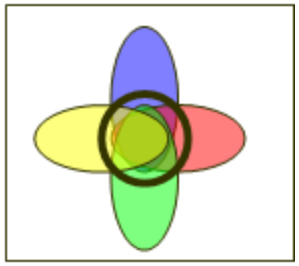
1) Science "Global" Overlay Maps: Show Diversity

- Breadth of Web of Science Subject Categories engaged

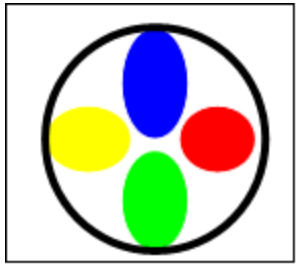
2) "Local" maps: Show coherence

- Based on bibliographic coupling – the extent to which articles cite the same references
- Rafols compared 2 Nanobio projects
  - Both reference a similar mix of Subject Categories (similar diversity)
  - But one shows as already reflecting a singular community (coherent) whereas the other is integrating two distinct research communities
- Case illustration: Kinesin research domain evolution (from Rafols)

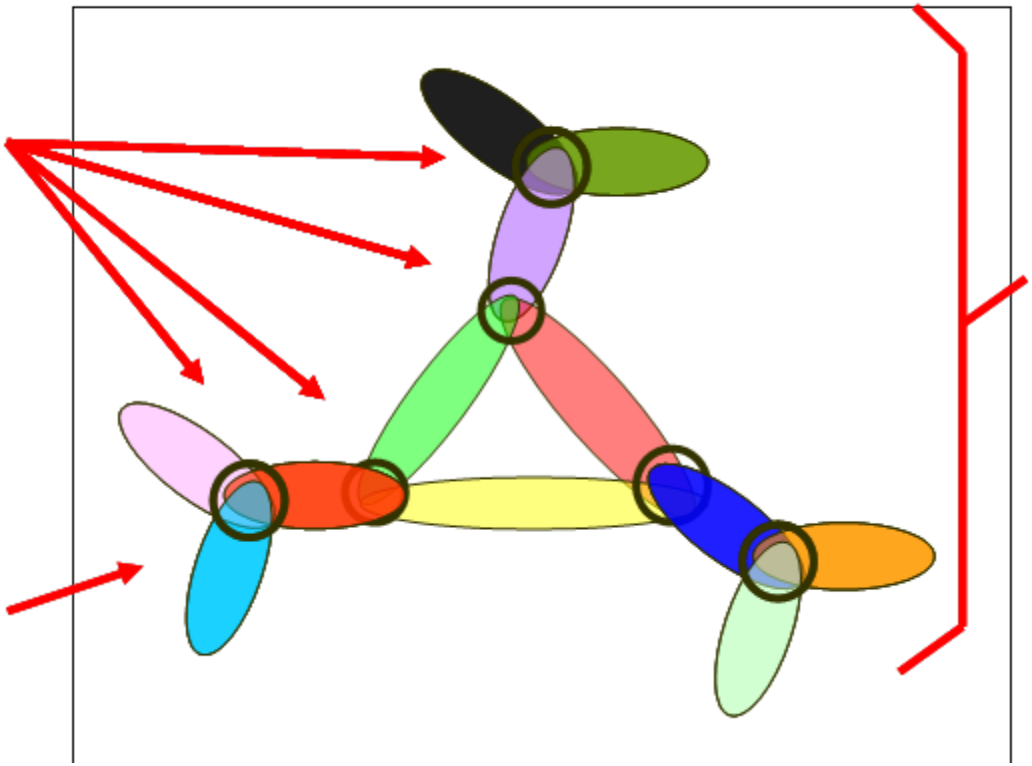
Tentative Conclusions: Modularization



Integration ——— Aggregation



Localised knowledge integration



Increasingly distributed yet articulated network

Diffusion to new topics

Specialization Formula:

$$S = \left[\frac{\left[\sum \left(f_i \times f_j \times COS\left(SC_i - SC_j \right) \right) \right]}{\sum \left(f_i \times f_j \right)} \right]$$

Where the Subject Categories (SCs 1--n) are those reflecting the journals in which the set of papers was published.

Note that Specialization only pertains to a set of papers – e.g., a researcher's work during a given time period.

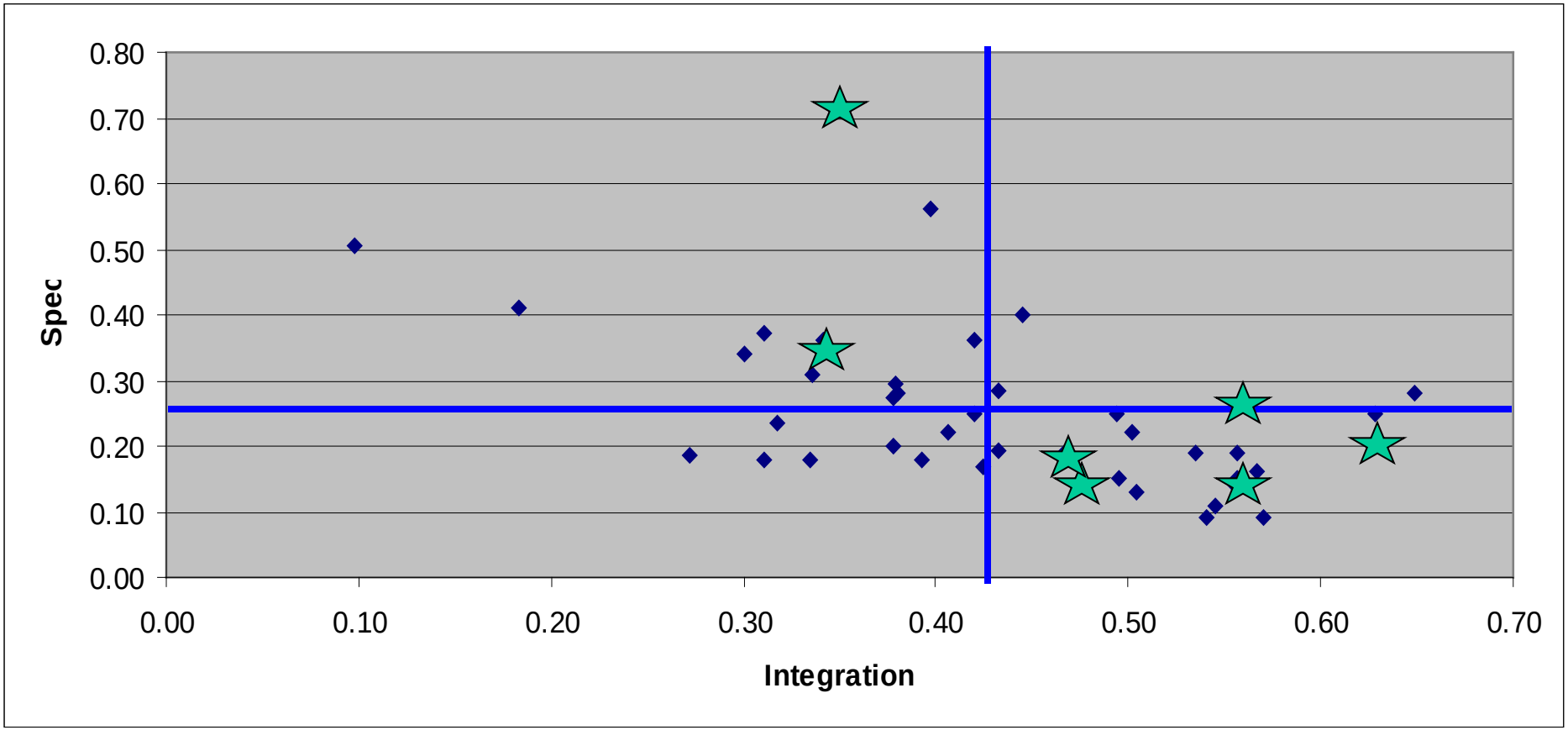
The cosine values for the SC x SC matrix derive from general samples (not from the body of research under study).

Examples from extreme cases:

1. If a paper cites 20 references (all to journals indexed by WOS), and all were associated with journals in the same SC, I = 0.

2. If a paper cites just 2 references, each one associated with only a single SC but these SCs are never co-cited together, then cos = 0, the numerator is 0, and I = 1.

Specialization vs. Integration for the Publication Outputs of 43 Researchers [7 women starred]



Integration Scores for 22 Sample Subject Categories (based on samples of ~100 papers published in 2005 associated with each indicated SC)

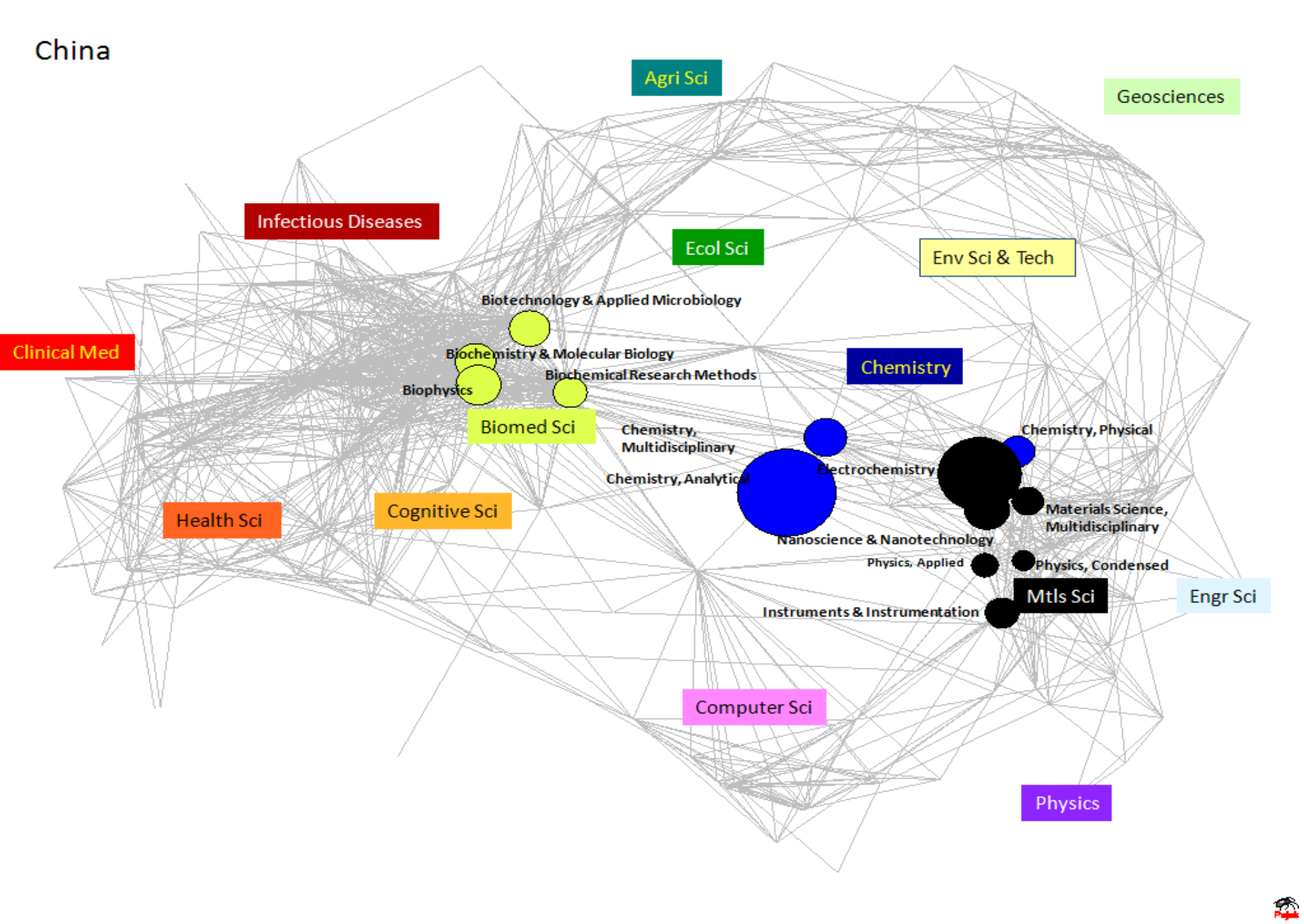
Subject Category	Integration (Mean)	Integration (SD)
Engineering, Biomedical	0.69	0.13
Materials Science, Biomaterials	0.68	0.11
Geriatrics & Gerontology	0.68	0.08
		0.11
Clinical Neurology	0.61	
Medicine, Research & Experimental	0.61	0.13
Engineering, Chemical	0.61	0.14
		0.13
Biochemistry & Molecular Biology	0.53	
Statistics & Probability	0.53	0.2
Engineering, Electrical & Electronic	0.52	0.19
Average	**0.61**	**0.13**
Standard Deviation	**0.05**	**0.03**

Trends in Nano Discovery:

Changing nano shares

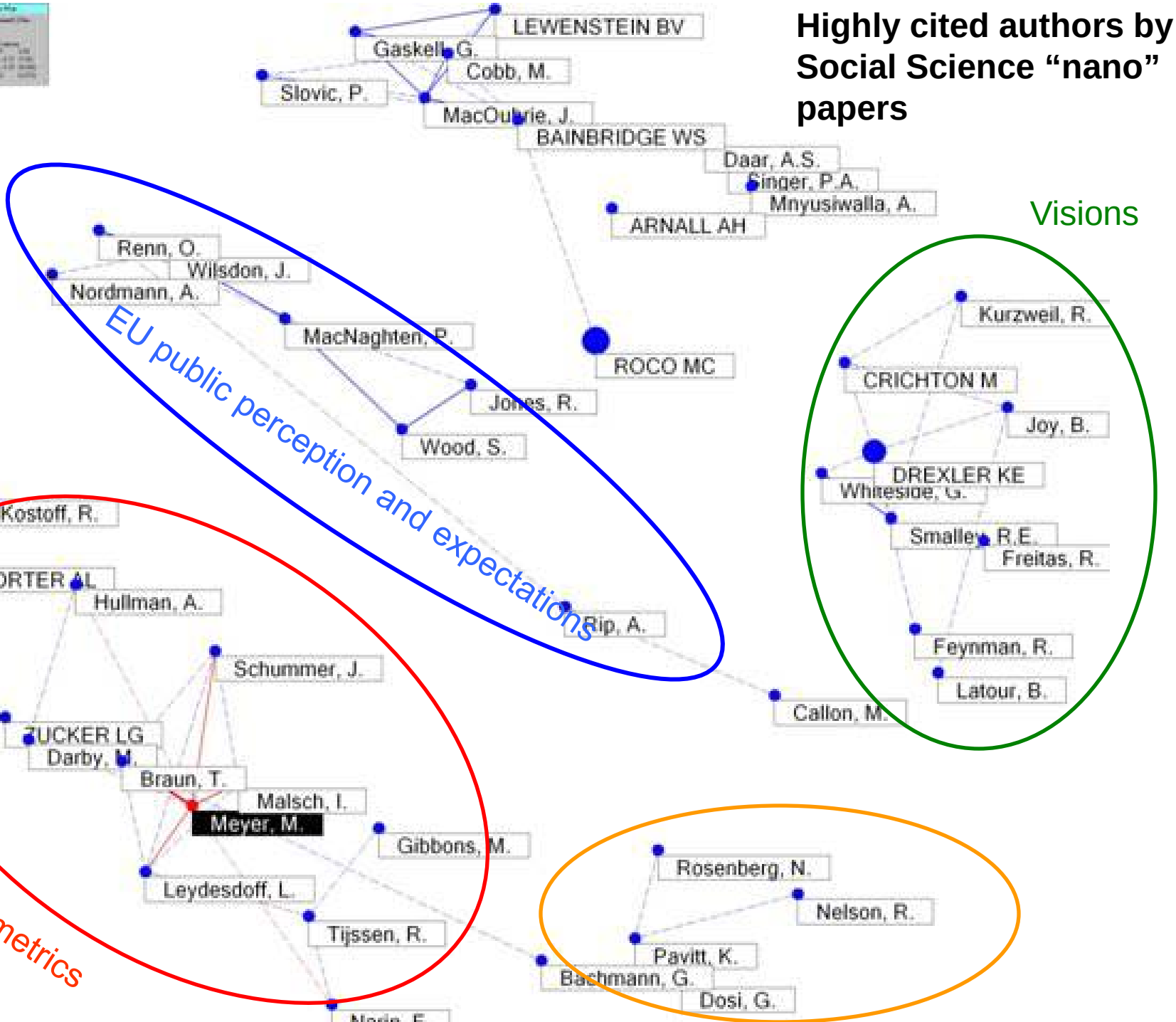
Subject Category	% of nano publications for year					% Change 1991-2008	2008 Rank
	1991	1995	2000	2005	2008		
Materials Science, Multidisciplinary	13.0	19.5	17.3	19.9	25.8	**+100%**	1
Physics, Applied	25.7	18.0	18.0	16.4	18.7	**-27%**	2
Chemistry, Physical	8.3	11.5	13.7	14.5	17.9	**+115%**	3
Physics, Condensed Matter	16.5	17.2	16.7	12.0	12.9	**-22%**	4
Nanoscience & Nanotechnology	n/a	n/a	n/a	n/a	12.6		5
Chemistry, Multidisciplinary	4.5	6.4	7.5	10.3	10.6	**+133%**	6
Polymer Science	4.7	5.2	5.2	6.5	6.2	**+32%**	7

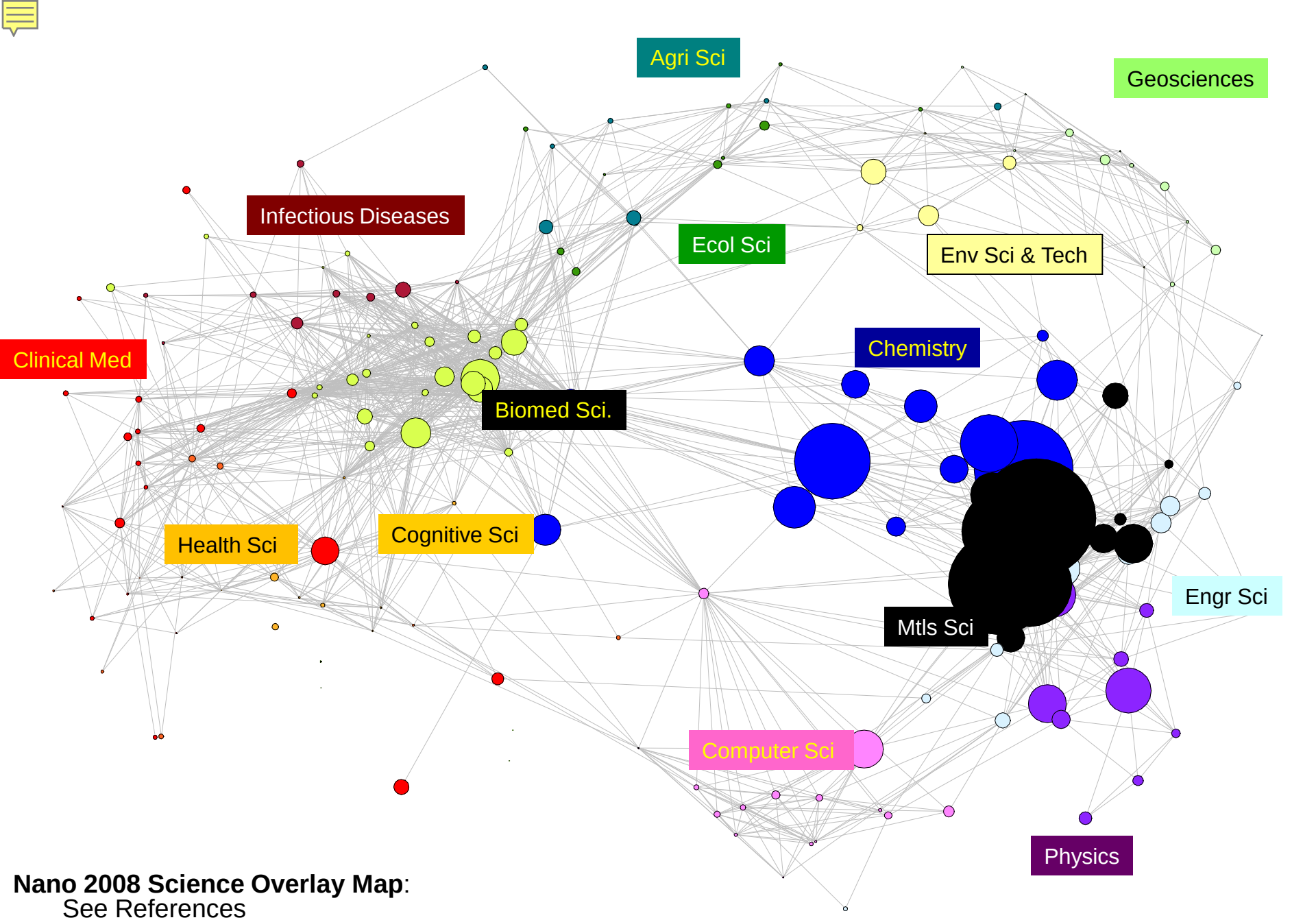
Source: Analysis by the Program in Research and Innovation Systems Analysis, Center for Nanotechnology and Society (CNS-ASU) at Georgia Tech. Bibliometric definition as in Porter et al. 2008. SCI nanoscience/nanotechnology publications, 508,000, 1991-2008 (part-year).



Locating China's "Nanoparticles in Biosensors" Research over the Base Map of Science

Highly cited authors by Social Science “nano” papers





Nano 2008 Science Overlay Map:
See References

VantagePoint Map Principles

- Nodes = entities mapped; larger implies more activity (but relative to full data set, so differences among a relatively homogeneous mapped set may not show up)
- Multi-Dimensional Scaling ("**MDS**") representations
  - Closer proximity suggests stronger relationship (association)
  - Accuracy is not guaranteed because of the dimensional reduction from N-D to 2-D
  - Position on X & Y axes has no inherent meaning
- Path-erasing Algorithm added to indicate relationship
  - Heavier links (lines) indicate stronger relationship
  - Absence of a link only means that relationship is less than the arbitrary threshold selected
  - In preparing maps, we vary threshold to show relationships most effectively

Sample WOS Abstract Record (excerpted)

[Retrieved Publications and/or Citing Articles]

AU Oliver-Hoyo, M
  Gerber, RW
TI From the research bench to the teaching laboratory: Gold nanoparticle layering
SO JOURNAL OF CHEMICAL EDUCATION
DT Article
C1 N Carolina State Univ, Dept Chem, Raleigh, NC 27695 USA.
AB …
CR BENTLEY AK, 2005, J CHEM EDUC, V82, P765
  BOLSTAD DB, 2002, J CHEM EDUC, V79, P1101
  HALE PS, 2005, J CHEM EDUC, V82, P775, …
NR 16
TC 1
PY 2007
VL 84
IS 7
BP 1174
EP 1176
SC Chemistry, Multidisciplinary; Education, Scientific Disciplines

Getting "SCs" = easy; Getting "Cited SCs" is more challenging

Sample Article with Integration score of 0.65 (High)
[Quantum dots area -- Title: Tunable optical properties…

Cited Journals	
account CHEM RES	PHSY REV LETT
ADV mat	PHYS CHEM CHEM PHYS
ANGEW CHEM INT ed	PHYS REV
ANNU REV PHYS CHEM	PHYS REV A
APPL PHYS LETT	PHYS REV A B
CHEM PHYS LETT	PHYS REV B
CHEM REV	PHYS REV LETT
J amer CHEM SOC	RECENT ADV DENSITY
J CHEM PHYS	REV MOD PHYS
nature	science