Multi-Level Science Models

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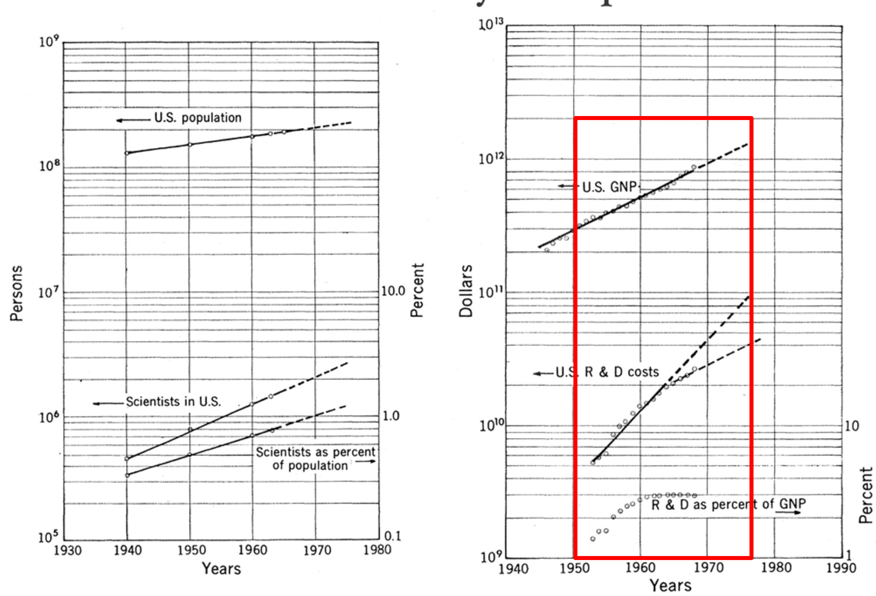
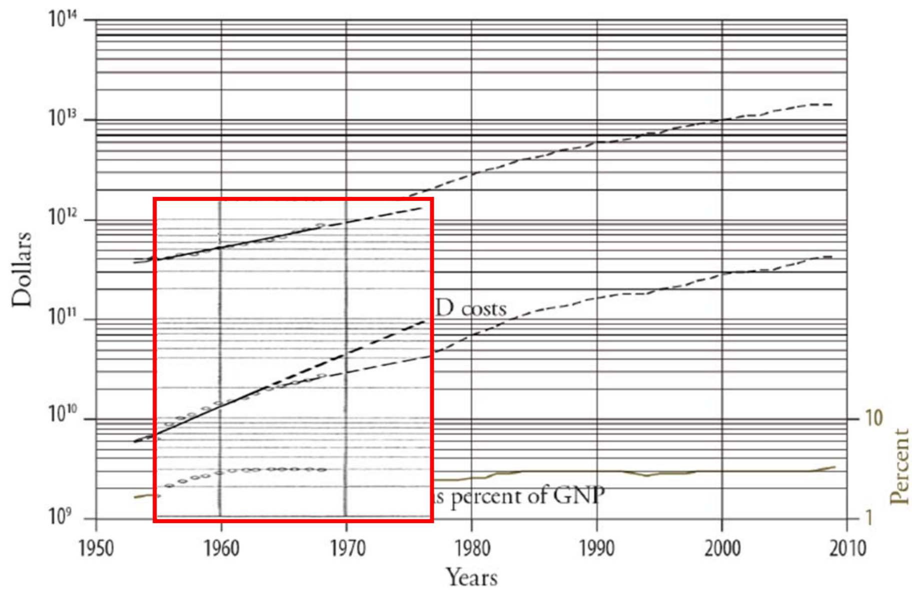
	Approx. Age *(in Years)*	Med. Diameter *(in Meters)*	Approx. Number *on Earth*
MACRO / GLOBAL *Supranational System*	4,500	> 10^6	1-100
MESO / LOCAL *Organization*	10,000	$10^2 - 10^6$	10,000,000
MICRO / INDIVIDUAL *Human*	500,000,000	0.5	7,000,000,000

Science and Society in Equilibrium



Science and Society in Equilibrium - Joseph P. Martino - 1969



Atlas of Knowledge: Anyone Can Map - Katy Börner - 2014

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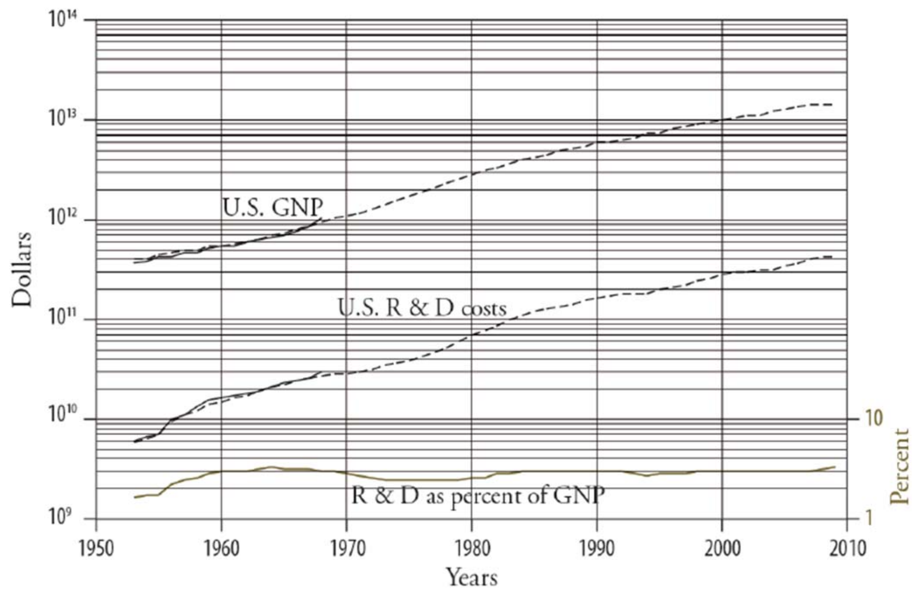

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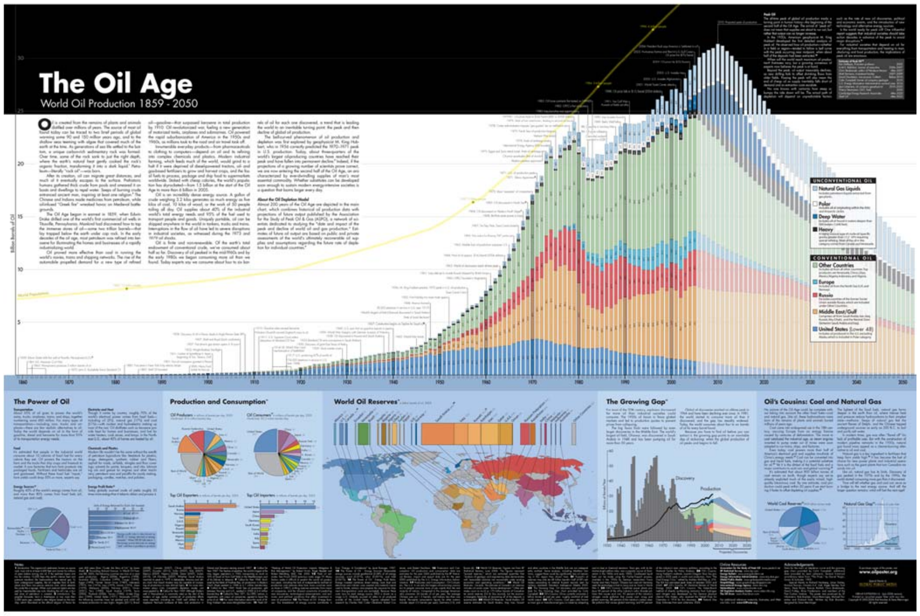

The Oil Age: World Oil Production 1859-2050 - Rob Bracken, Dave Menninger, Michael Poremba, Richard Katz - 2005

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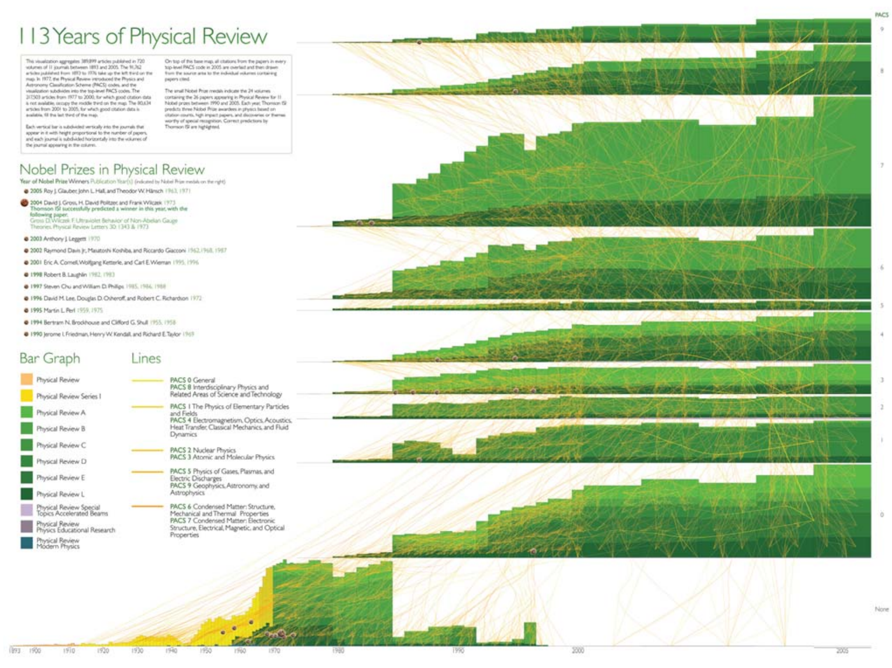

113 Years of Physical Review - Bruce W. Herr II, Russell Duhon, Katy Borner, Elisha Hardy, Shashikant Penumarthy - 2007

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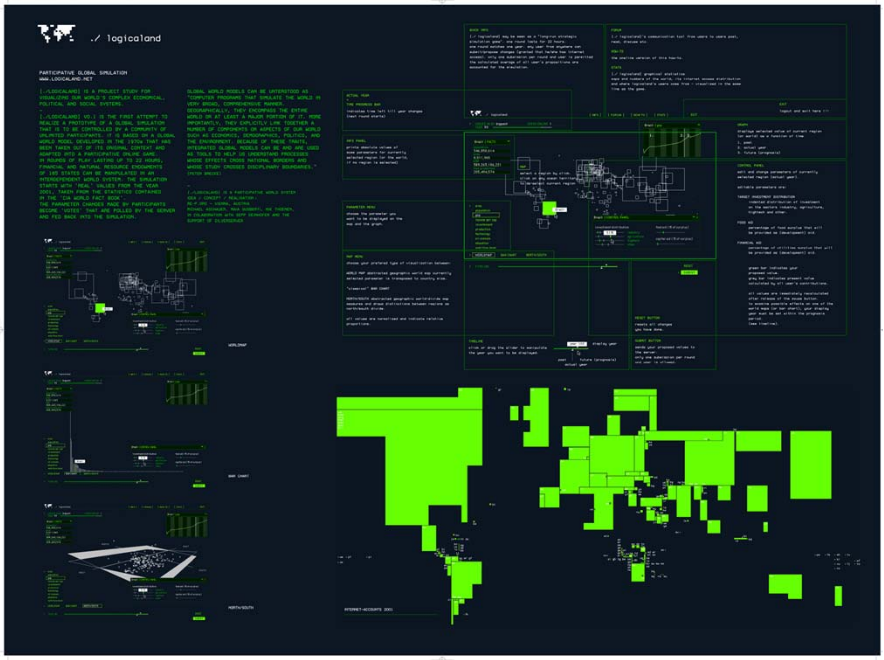

Logicland Participative Global Simulation - Michael Ashauer, Maia Gusberti, Nik Thoenen - 2002

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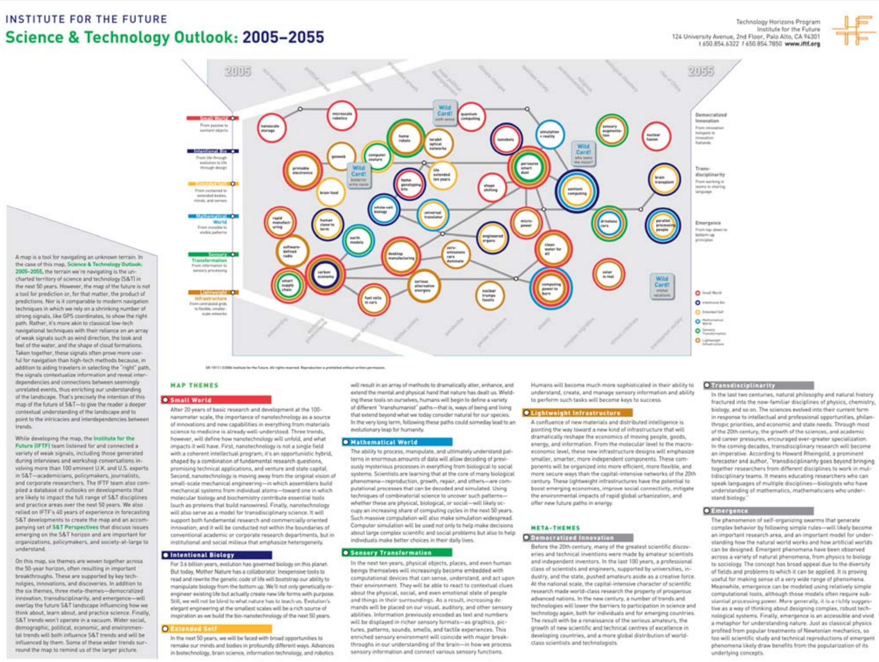

Science & Technology Outlook: 2005-2055 - Alex Soojung-Kim Pang, David Pescovitz, Marina Gorbis, Jean Hagan - 2006

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Impact of Communication and Transportation Speeds

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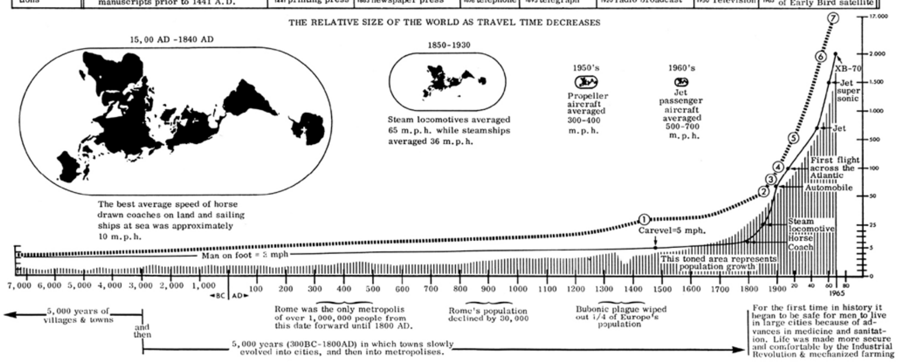
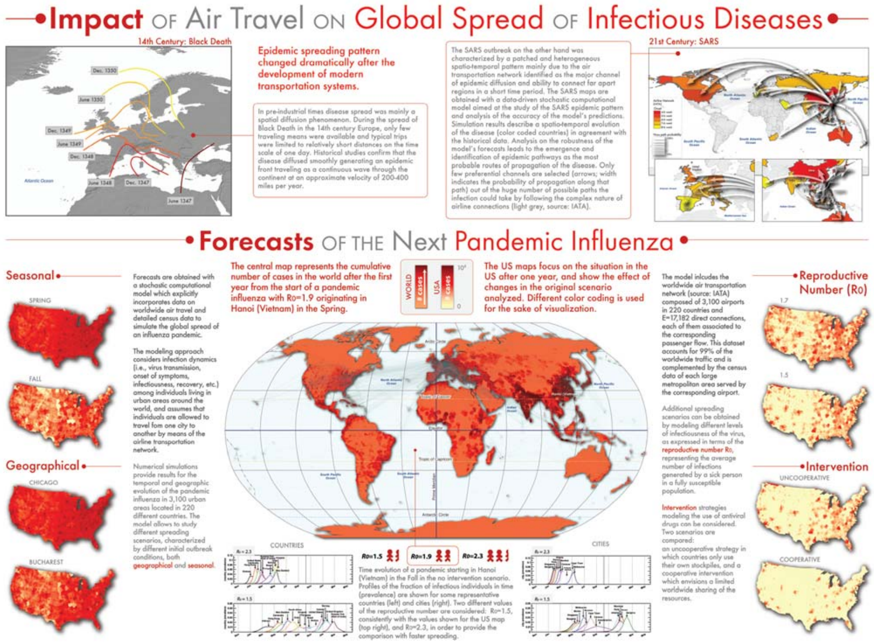
SHRINKING OF OUR PLANET BY MAN'S INCREASED TRAVEL AND COMMUNICATION SPEEDS AROUND THE GLOBE

YEAR	500,000 BC	20,000 BC	300 BC	500 BC	1,500 AD	1900 AD	1925	1950	1965
Required time to travel around the globe	A few hundred thousand years	A few thousand years	A few hundred years	A few tens of years	A few years	A few months	A few weeks	A few days	A few hours
Means of transportation	Human on foot (over, ice bridges)	On foot and by canoe	Canoe with small sail or paddles or relays of runners	Large sail boats with oars, pack animals, and horse chariots	Big sailing ships (with compass), horse teame, and coaches	Steam boats and railroads (Suez and Panama Canals)	Steamships, transcontinental railways, autos, and airplanes	Steamships, railways, auto jet and rocket aircraft	Atomic steamship, high speed railway auto, and rocket-jet aircraft
Distance per day(land)	15 miles	15-20 miles	20 miles	15-25 miles	20-25 miles	Rail 300-900 miles	400-900 miles	Rail 500-1,500	Rail 1000-2000
Distance per day (sea or air)		20 by sea	40 miles by sea	135 miles by sea	175 miles by sea	250 miles by sea	3,000-6000 air	6000-9500 air	408,000 air
Potential state size	None	A small valley in the vicinity of a small lake	Small part of a continent	Large area of a continent with coastal colonies	Great parts of a continent with trans-oceanic colonies	Large parts of a continent with transoceanic colonies	Full continents & Transocean Commonwealths	The Globe	The globe and more

Communications	Word of mouth, drums, smoke, relay runners, and hand printed manuscripts prior to 1441 A.D.	① The Gutenberg 1441 printing press	② The rapid print Web 1863 newspaper press	③ The Bell 1876 telephone	④ The Marconi 1895 telegraph	⑤ First commercial 1920 radio broadcast	⑥ National 1950 Television	⑦ 1965 Transcontinental T.V. with the introduction of Early Bird satellite



Shrinking of Our Planet - R. Buckminster Fuller, John McHale - 1965



Impact of Air Travel on Global Spread of Infectious Diseases - Vittoria Colizza, Alessandro Vespignani - 2007

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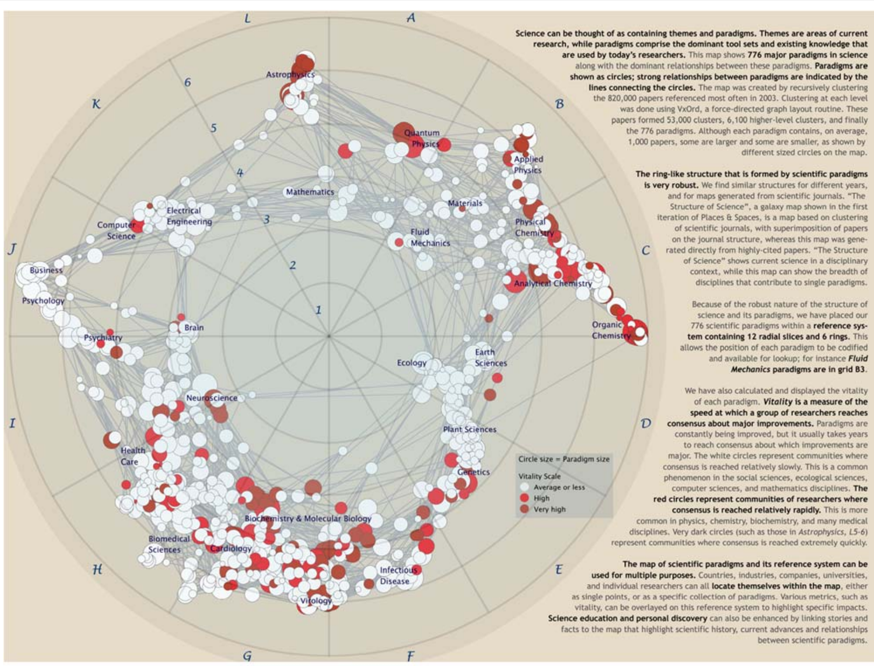

Map of Scientific Paradigms - Kevin W. Boyack, Richard Klavans - 2006

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Model Types

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MACRO / GLOBAL *Supranational System*		4,500	$> 10^6$	1-100
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Part I: Foundations

1 An Introduction to Modeling Science: Basic Model Types, Key Definitions, and a General Framework for the Comparison of Process Models Borner, Boyack, Milojevic & Morris

2 Mathematical Approaches to Modeling Science from an Algorithmic-Historiography Perspective by Lucio-Arias & Scharnhorst

Part II: Exemplary Model Types

3 Knowledge Epidemics and Population Dynamics Models for Describing Idea Diffusion by Vitanov & Ausloos

4 Agent-Based Models of Science by Payette

5 Evolutionary Game Theory and Complex Networks of Scientific Information by Hanauske

Part III: Exemplary Model Applications

6 Dynamic Scientific Co-Authorship Networks by Mali, Kronegger, Doreian & Ferligoj

7 Citation Networks by Radicchi, Fortunato & Vespignani

Part IV: Outlook

8 Science Policy and the Challenges for Modeling Science by van den Besselaar, Borner & Scharnhorst

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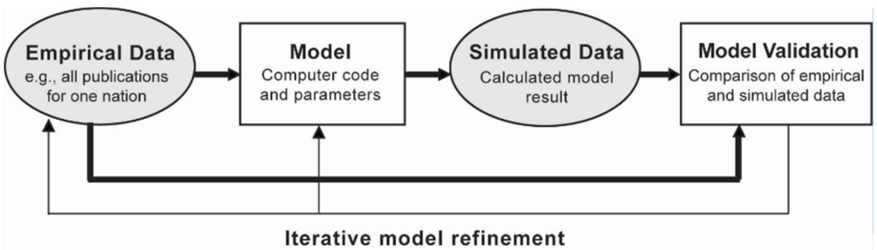
An introduction to modeling science: Basic model types, key definitions, and a general framework for the comparison of process models

Katy Börner, Kevin W. Boyack, Staša Milojević, Steven Morris. (2011) In *Scharnhorst, Andrea, Börner, van den Besselaar (Eds) Models of Science Dynamics. Springer Verlag.*

Modeling Process

1. Formulation of a scientific hypothesis about the identification of a specific structure or dynamics. Often, this hypothesis is based on analysis of patterns found in empirical data.
2. Algorithm design and implementation using either tools (e.g., NetLogo, RePast) or custom codes that attempt to mathematically describe the structure or dynamics of interest.
3. Simulated data are calculated by running the algorithm and validated by comparison with empirical data.
4. Resulting insights frequently inspire new scientific hypotheses, and the model is iteratively refined or new models are developed.



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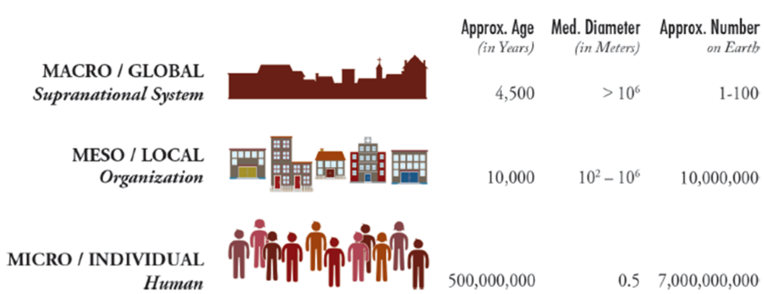
Sample Model #1

PNAS Co-Evolving Author-Paper Networks (MESO)



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Modeling the Co-Evolving Author-Paper Networks

Börner, Katy, Maru, Jeegar & Goldstone, Robert. (2004). The Simultaneous Evolution of Author and Paper Networks. PNAS. Vol. 101(Suppl. 1), 5266-5273.

The TARL Model (Topics, Aging, and Recursive Linking) incorporates
- A partitioning of authors and papers into topics,
- Aging, i.e., a bias for authors to cite recent papers, and
- A tendency for authors to cite papers cited by papers that they have read resulting in a rich get richer effect.

The model attempts to capture the roles of authors and papers in the production, storage, and dissemination of knowledge.

Model Assumptions
- Co-author and paper-citation networks co-evolve.
- Authors come and go.
- Papers are forever.
- Only authors that are 'alive' are able to co-author.
- All existing (but no future) papers can be cited.
- Information diffusion occurs directly via co-authorships and indirectly via the consumption of other authors' papers.

- Preferential attachment is modeled as an *emergent property* of the elementary, local networking activity of authors reading and citing papers, but also the references listed in papers.

Modeling the Co-Evolving Author-Paper Networks

Börner, Katy, Maru, Jeegar & Goldstone, Robert. (2004). The Simultaneous Evolution of Author and Paper Networks. PNAS. Vol. 101(Suppl. 1), 5266-5273.

```
// Initialization
generate #_papers  papers and assign a random topic to each paper;
generate #_authors  authors and assign a random topic to each author;
randomly assign #_co-authors+1 authors to papers of the same topic;
// Simulation
for each year  do {
    add #_new_authors new authors, deactivate authors older than #_author_age;
    for each topic do {
        randomly partition set of authors into author_groups of size #_co-authors+1;
        for each author_group do {
            for each new_paper to be produced, do {
                generate new_paper;
                randomly select #_read_ papers  from existing papers;
                get all references of read_ papers  up to #_reference_path_length;
                for each new_paper_reference do {
                    select a time_slice  from (start year to curr_year-1) with probability given in aging_function;
                    randomly select a paper published or cited in this time_slice; as a new_paper_reference;
                    add the new_paper_reference to new_paper;
                }
            }
        }
    }
    add all new papers to the set of existing papers;
    add new links to author and paper information;
}
```

```
----------------------------------------
Model Parameters (0=without, 1=with)
----------------------------------------
0/1  Topics
0/1  Co-Authors
0/1  Consider References
0    Aging Function
----------------------------------------
Model Initialization Values
----------------------------------------
2  # Years
5  # Authors in Start Year
5  # Papers in Start Year
2  # Papers Consumed (Referenced) per Paper
1  # Papers Produced per Author each Year
5  # Topics
1  # Co-Author(s) per Author
1   # Levels References are Considered
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    for each topic do {
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        for each author_group do {
            for each new_paper to be produced, do {
                generate new_paper;
                randomly select #_read_ papers from existing papers;
                get all references of read_ papers up to #_reference_path_length;
                for each new_paper_reference do {
                    select a time_slice from (start year to curr_year-1) with probability given in aging_function;
                    randomly select a paper published or cited in this time_slice, as a new_paper_reference;
                    add the new_paper_reference to new_paper;
                }
            }
        }
    }
    add all new papers to the set of existing papers;
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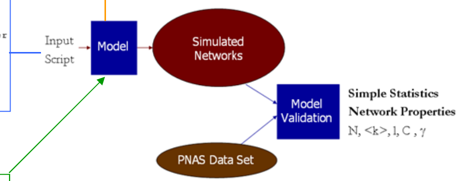


Aging function

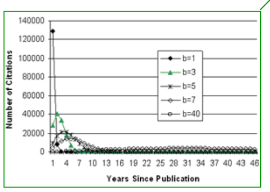


Table 3 Statistics for SIM data

Year	#p	#a	#r	#c	a#ca
1981	1624	3953	0	756	8.21
1982	1040	5200	31200	112161	4
1983	1118	5590	33540	21397	4
1984	1197	5985	35910	10224	4
1985	1275	6375	38250	6184	4
1986	1353	6765	40590	4687	4
1987	1432	7160	42960	3573	4
1988	1510	7550	45300	2816	4
1989	1589	7945	47670	2219	4
1990	1667	8335	50010	1853	4
1991	1745	8725	52350	1634	4
1992	1824	9120	54720	1431	4
1993	1902	9510	57060	1167	4
1994	1981	9905	59430	1040	4
1995	2059	10295	61770	767	4
1996	2137	10685	64110	632	4
1997	2216	11080	66480	522	4
1998	2294	11470	68820	400	4
1999	2373	11865	71190	265	4
2000	2451	12255	73530	125	4
2001	2529	12645	75870	0	4
Total	**37316**		**1070760**	**173853**	

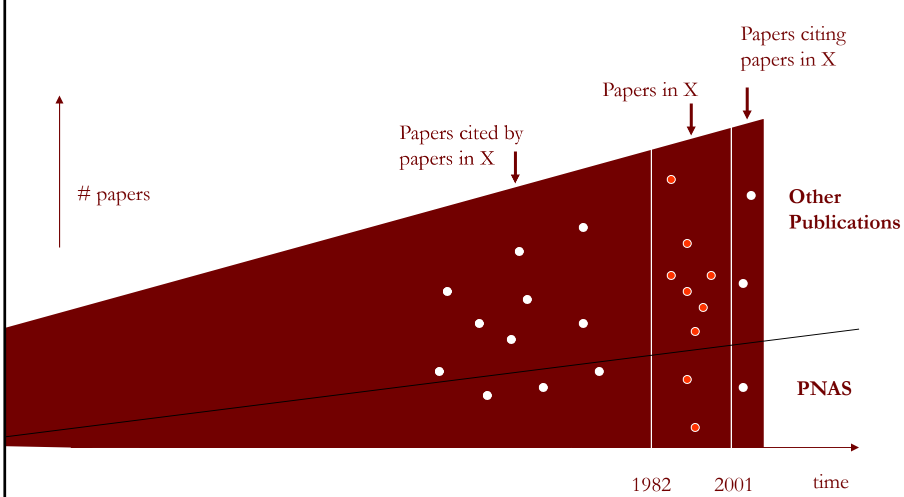
Table 2. PNAS Statistics

Year	#p	#a	#r	#c	a#ca
1982	1669	5201	46665	156690	3.92
1983	1611	5142	46685	161437	3.98
1984	1695	5583	49834	174161	4.22
1985	1846	6325	55662	191750	4.38
1986	2042	7209	64379	218229	4.76
1987	1924	7061	59110	207729	4.88
1988	2035	7471	63116	215227	4.8
1989	2088	7959	65883	215437	5.01
1990	2066	8031	66019	207138	5.15
1991	2382	9559	77740	223102	5.25
1992	2500	9812	80949	211238	5.29
1993	2413	9770	79848	193867	5.55
1994	2600	10656	86176	187353	5.56
1995	2476	10429	82021	151249	5.66
1996	2765	11803	99061	148622	5.96
1997	2618	11255	96788	122908	6.12
1998	2711	12328	100973	107764	6.48
1999	2603	12182	97018	76080	6.69
2000	2501	12201	94181	44131	7.6
2001	2575	13038	97450	16357	8.4
Total	**45120**		**1509558**	**3230469**	

Model Validation
The properties of the networks generated by this model are validated against a 20-year data set (1982-2001) of documents of type article published in the Proceedings of the National Academy of Science (PNAS) – about 106,000 unique authors, 472,000 co-author links, 45,120 papers cited within the set, and 114,000 citation references within the set.

20-Year PNAS Dataset (1982-2001)

Coverage in terms of time span, total number of papers, and complete author's work



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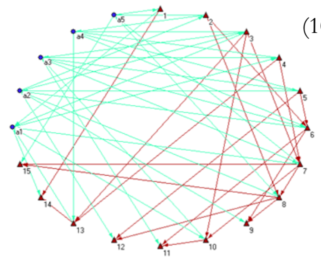
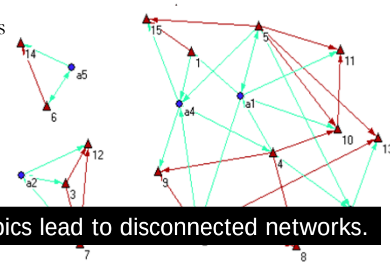
The TARL Model: The Effect of Parameters

(0000)

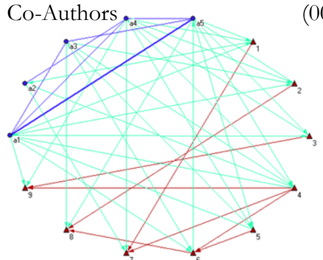


(1000) Topics

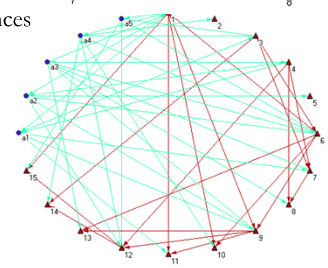


Topics lead to disconnected networks.

(0100) Co-Authors



(0010) References



Co-authoring leads to fewer papers.

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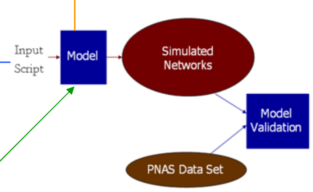
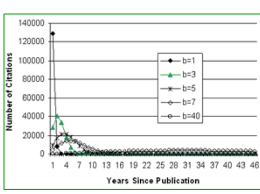
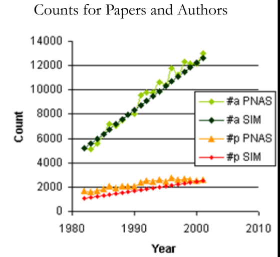


Simple Statistics
Network Properties
N, <k>, l, C, γ

Aging function



Counts for Papers and Authors



Counts for Citations

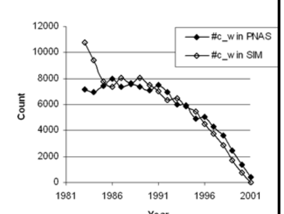


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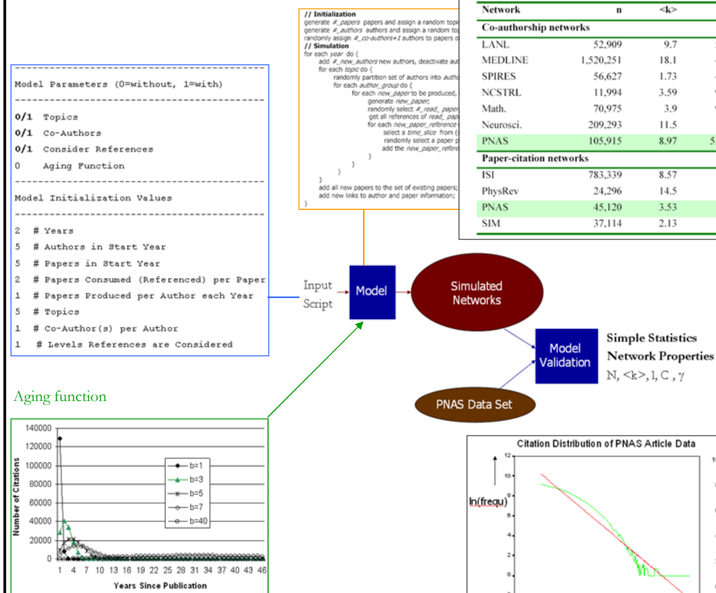
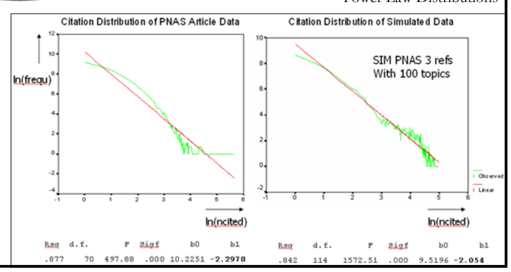
Table 2. Properties of co-author & paper citation networks comprising number of nodes n, average node degree <k> path length l, cluster coefficient C, and power law exponent γ. Source references are given in the left column.

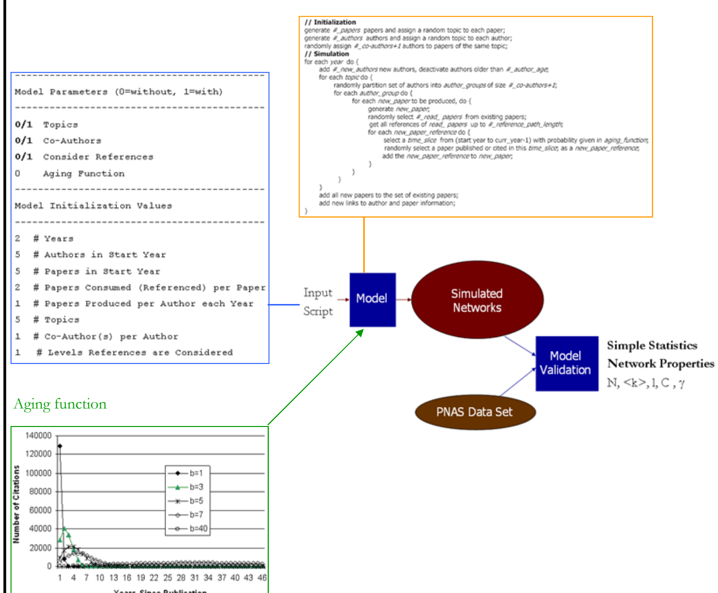
Network	n	<k>	l	C	γ	Reference
Co-authorship networks						
LANL	52,909	9.7	5.9	0.43	--	Newman, (2001a; 2001b; 2001c)
MEDLINE	1,520,251	18.1	4.6	0.066	--	
SPIRES	56,627	1.73	4.0	0.726	1.2	
NCSTRL	11,994	3.59	9.7	0.496	--	
Math.	70,975	3.9	9.5	0.59	2.5	Barabasi et al., (2002)
Neurosci.	209,293	11.5	6	0.76	2.1	
PNAS	105,915	8.97	5.89	0.399	2.54	
Paper-citation networks						
ISI	783,339	8.57	--	--	3	Redner, (1998)
PhysRev	24,296	14.5	--	--	3	
PNAS	45,120	3.53	--	0.081	2.29	
SIM	37,114	2.13	--	0.074	2.05	



Co-Author and Paper-Citation Network Properties

Power Law Distributions





Topics: The number of topics is linearly correlated with the clustering coefficient of the resulting network: C= 0.000073 * #topics. Increasing the number of topics increases the power law exponent as authors are now restricted to cite papers in their own topics area.

Aging: With increasing b, and hence increasing the number of older papers cited as references, the clustering coefficient decreases. Papers are not only clustered by topic, but also in time, and as a community becomes increasingly nearsighted in terms of their citation practices, the degree of temporal clustering increases.

References/Recursive Linking: The length of the chain of paper citation links that is followed to select references for a new paper also influences the clustering coefficient. Temporal clustering is ameliorated by the practice of citing (and hopefully reading!) the papers that were the earlier inspirations for read papers.

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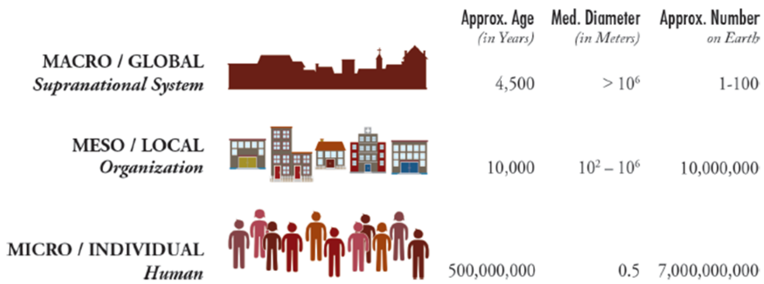
Sample Model #2

U.S. Funding Distribution (MESO)



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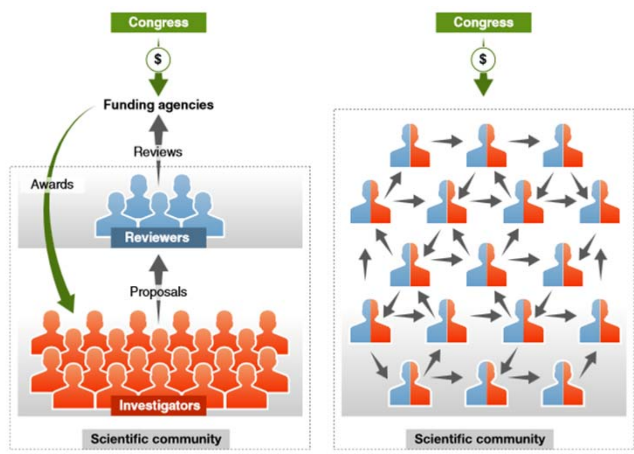
From funding agencies to scientific agency: Collective allocation of science funding as an alternative to peer review

Bollen, Johan, David Crandall, Damion Junk, Ying Ding, and Katy Börner. 2014. EMBO Reports 15 (1): 1-121.



Existing (left) and proposed (right) funding systems. Reviewers in blue; investigators in red.

In the proposed system, all scientists are both investigators and reviewers: every scientist receives a fixed amount of funding from the government and discretionary distributions from other scientists, but each is required in turn to redistribute some fraction of the total they received to other investigators.

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Bollen, Johan, David Crandall, Damion Junk, Ying Ding, and Katy Börner. 2014. EMBO Reports 15 (1): 1-121.

Assume

Total funding budget in year y is t_y

Number of qualified scientists is *n*

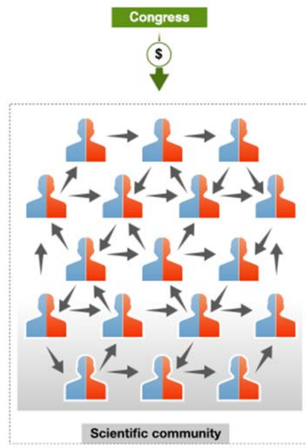
Each year,

the funding agency deposits a fixed amount into each account, equal to the total funding budget divided by the total number of scientists: t_y/n.

Each scientist must distribute a fixed fraction of received funding to other scientists (no self-funding, COIs respected).

Result

Scientists collectively assess each others' merit based on different criteria; they "fund-rank" scientists; highly ranked scientists have to distribute more money.



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From funding agencies to scientific agency: Collective allocation of science funding as an alternative to peer review

Bollen, Johan, David Crandall, Damion Junk, Ying Ding, and Katy Börner. 2014. EMBO Reports 15 (1): 1-121.

Example:

Total funding budget in year is 2012 NSF budget

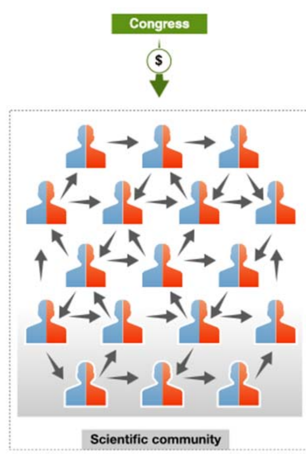
Given the number of NSF funded scientists, each receives a $100,000 basic grant.

Fraction is set to 50%

In 2013, scientist *S* receives a basic grant of $100,000 plus $200,000 from her peers, i.e., a total of $300,000.

In 2013, *S* can spend 50% of that total sum, $150,000, on her own research program, but must donate 50% to other scientists for their 2014 budget.

Rather than submitting and reviewing project proposals, *S* donates directly to other scientists by logging into a centralized website and entering the names of the scientists to donate to and how much each should receive.



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Model Run and Validation:

Model is presented in http://arxiv.org/abs/1304.1067

It uses **citations as a proxy** for how each scientist might distribute funds in the proposed system.

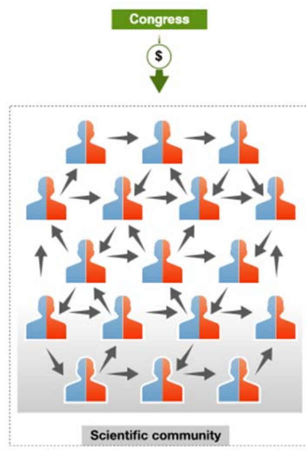
Using 37M articles from TR 1992 to 2010 Web of Science (WoS) database, we extracted **770M citations**. From the same WoS data, we also determined 4,195,734 unique author names and we took the **867,872 names** who had authored at least one paper per year in any five years of the period 2000–2010.

For each pair of authors we determined the number of times one had cited the other in each year of our citation data (1992–2010).

NIH and NSF funding records from IU's Scholarly Database provided 347,364 grant amounts for 109,919 unique scientists for that time period.

Simulation run begins in year 2000, in which every scientist was given a fixed budget of B = \$100k. In subsequent years, scientists distribute their funding in proportion to their citations over the prior 5 years.

The model yields funding patterns similar to existing NIH and NSF distributions.



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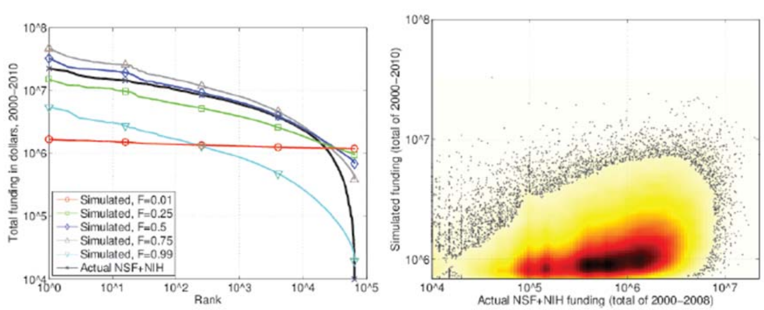

Fig. 2: Results of the distributed funding system simulation for 2000-2010. *(a):* The general shape of the funding distribution is similar to that of actual historical NSF and NIH funding distribution. The shape of the distribution can be controlled by adjusting F, the fraction of funds that scientists must give away each year. *(b):* On a per-scientist basis, simulated funding from our system (with F=0.5) is correlated with actual NSF and NIH funding (Pearson $R = 0.2683$ and Spearman $\rho = 0.2999$).

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Model Efficiency:

Using data from the Taulbee Survey of Salaries Computer Science (*http://cra.org/resources/taulbee*) and the National Science Foundation (NSF) the following calculation is illuminating:

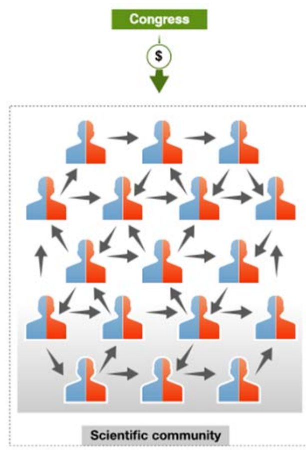
If four professors work four weeks full-time on a proposal submission, labor costs are about $30k. With typical funding rates below 20%, about five submission-review cycles might be needed resulting in a total expected labor cost of **$150k**.

The average NSF grant is **$128k** per year.

U.S. universities charge about 50% overhead (ca. $42k), leaving about **$86k**.

In other words, the four professors lose **$150k-$86k=$64k** of paid research time by obtaining a grant to perform the research.

That is, U.S. universities should forbid professors to apply for grants—if they can afford to forgo the indirect dollars.



To add: Time spent by researchers to review proposals. In 2012 alone, NSF convened more than 17,000 scientists to review 53,556 proposals.

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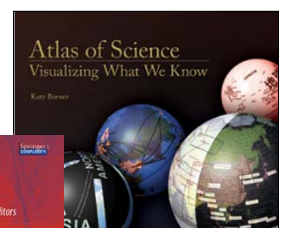

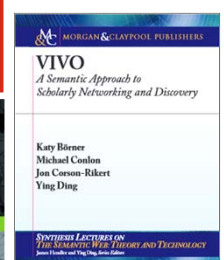

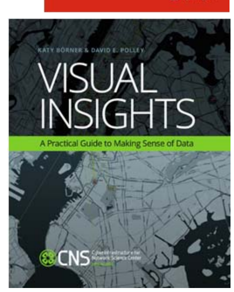

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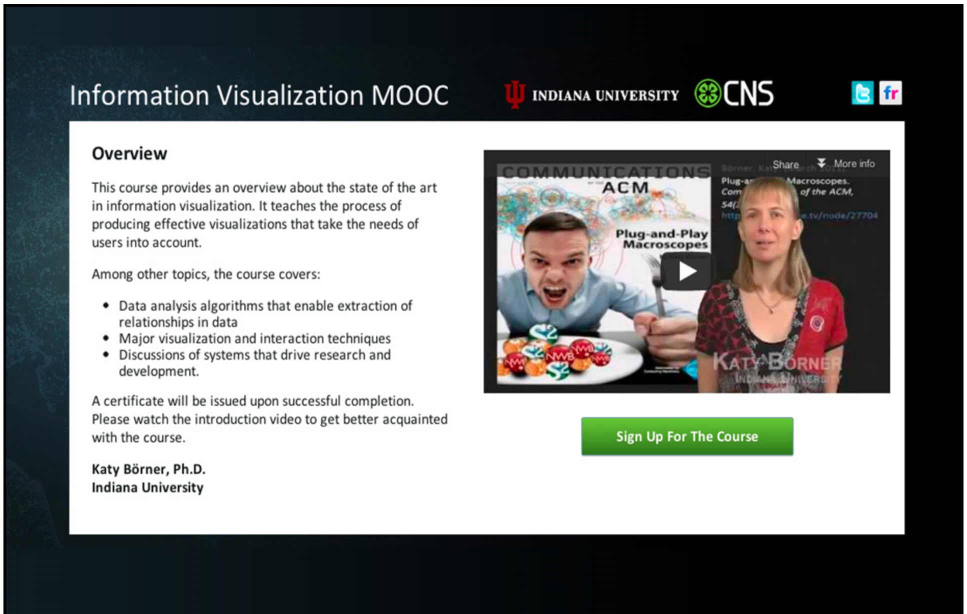

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