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Measuring researcher interdisciplinarity

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We offer two metrics that together help gauge how interdisciplinary a body of research is. Both draw upon Web of Knowledge Subject Categories (SCs) as key units of analysis. We have assembled two substantial Web of Knowledge samples from which to determine how closely individual SCs relate to each other. "Integration" measures the extent to which a research article cites diverse SCs. "Specialization" considers the spread of SCs in which the body of research (e.g., the work of a given author in a specified time period) is published. Pilot results for a sample of researchers show a surprising degree of interdisciplinarity.

Background

Research spirals inward; science cascades outward. This dual image supports a vital realization – scientific advance requires knowledge transfer among researchers who may focus tightly on extremely circumscribed research issues. The typical research

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investigation burrows into detail, cumulating information, probing for nuances. Once completed, the challenge shifts abruptly to communicating the research findings. Research knowledge needs to be suitably conveyed to others working on the same immediate problem – and to a wider circle of colleagues working on related problems – and beyond, to those who may gain usable knowledge for different applications from the findings.

Go back for a second to the time one of us (Porter) was working on his dissertation in Psychology (1970–1972). Most scientists (using the term inclusively to cover social scientists, engineers, and other researchers) published in the same half-dozen or so journals that they regularly read. Publication processes might take a couple of years. The limited quantity of information that one could digest prompted keeping close track of developments only in one's immediate research area. One didn't keep up with the Psychology literature; one followed developments in the study of memory, favoring particular organisms as subjects, for certain memory forms, affected by particular stimuli & conditions, etc. The notion of a "research trail," narrowly tracked, made sense. At its best, this efficiently directed researcher efforts to resolving the problem at hand. At its worst, this led to inbred patterns of research leading to no lasting value.[1]

The inherently opposing tendencies – focus vs. outreach – now play out in a richer context than in earlier scientific eras. Wider and faster information access is the pivotal change force. Electronic databases, the internet, and networked computers, accessed daily by essentially every scientist in the world, provide dynamic research knowledge resources. Yet, scientific norms suited to earlier eras linger. The scientific disciplines that arose in the 19th and 20th centuries still dominate academic life (somewhat less so for researchers in government or industry). One's professional identity, institutional home (department), and external peer group (professional societies) are discipline-centered. However, even in the early 1970's, the Psychology Department at UCLA did not reflect a unified field. Rather, it was home for, among others, clinical psychologists and neuroscientists who did not share the same paradigm, subject matter, or research methods.

The discrepancies between disciplinary roots and research realities loom large. In the 1970's and 1980's interest in interdisciplinary research processes picked up momentum. The notion was to identify and overcome barriers to more effective research knowledge transfer across domains. Good insights into issues, influences, and mechanisms emerged.[2] For whatever reasons (especially decline of research funding), the study of interdisciplinary research processes waned just as funding of major interdisciplinary units expanded (e.g., U.S. National Science Foundation Engineering Research Centers and Science & Technology Research Centers programs).

Moving to the present, we find explosive growth in emerging research arenas, including genetics & biotechnology, information science & technology, and advanced materials and nanotechnology. Obviously these research frontiers pay little heed to 19th century disciplinary boundaries. How can we expedite progress in research and development? Various parties at interest see the lowering of disciplinary barriers as vital. This has triggered renewed interest in promoting interdisciplinary research and its counterpart, interdisciplinary teaching. In particular, our own efforts derive from the National Academies Keck *Futures Initiative* (NAKFI) – a $40 million, 15-year program to boost interdisciplinary research in the U.S. [www.keckfutures.org].

NAKFI evaluators have dual interests in measuring interdisciplinarity. At the macro scale, we seek to estimate and track the extent of interdisciplinary research ("IDR") in the U.S. At the micro scale, we want to evaluate whether NAKFI conferences and seed grant programs increase the interdisciplinarity of participants' research (and teaching). But as Morillo et al. note, "we do not have appropriate indicators to measure interdisciplinarity."[3] This paper presents our approach to measuring how interdisciplinary a particular body of research is – whether that of one researcher, a group of researchers, or a research domain.

Premises in measuring interdisciplinarity

What is interdisciplinarity? Terminology varies and definitions abound. We apply the following definition, based on a National Academies report:[4]

Interdisciplinary research (IDR) is 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.

As Morillo et al. state:[3] "we consider 'multidisciplinarity' as a basic situation in which elements from different disciplines are present, whilst 'interdisciplinarity' is a more advanced stage of the relationship between disciplines in which integration between them is attained." *Integration* is the key concept here – distinguishing the "seamless cloth" of IDR, from the "patchwork quilt" of multidisciplinary research, and the more restricted focus of disciplinary research. We don't emphasize the creation of new "interdisciplines" per se – i.e., transdisciplinary research. Elsewhere we review earlier findings on IDR, explore these distinctions, and consider the variety of related causes and effects.[2,5]

We focus first on the body of research of a given researcher. Specifically, we want to compare the outputs of Researcher A for a time period (e.g., 3 years) just before participating in a NAKFI program to that of his/her work in a corresponding time period after. That said, the main exemplars of that body of research will usually be scientific papers. In most research arenas, journal articles and/or conference papers are important. In others, patents are the exemplary outputs. And in some arenas, various other forms reflect the essential outputs of research activity: reports (sometimes confidential, sometimes in "gray literatures"), software, and process improvements (perhaps kept as trade secrets).

We acknowledge that research is not solely measured by its outputs. Interdisciplinarity can also be gauged in terms of: *proposals* (e.g., topical emphases, collaboration) or *projects* (e.g., teaming arrangements, mixed funding sources). In addition, assessment may focus on other interdisciplinary professional facets*: teaching* (e.g., cross-departmental, co-teaching) or *affiliation* (e.g., joint appointments in multiple departments, participation in organized research units). But for now, our attention is directed to research outputs in the form of sets of papers. We will draw heavily on citations (referencing) among papers; this can be considered a form of research *outcomes.*

Our strategy to measure interdisciplinarity (elaborated in succeeding sections) is based on the following premises:

- Integration of knowledge not routinely found within a research field equates to greater interdisciplinarity.
- Such integration can be measured by examining the spread of a paper's references.
- We devise measures by relating papers' cited journals to their corresponding Subject Categories (research fields, as assigned by Thomson Institute for Scientific Information – ISI – accessible through their Web of Knowledge – WoK – site).
- The interdisciplinarity metrics take into account the inter-relatedness of Subject Categories.
- Additional measures can be derived from the degree to which cited Subject Categories relate to that of the journal of the paper, and from the spread of publications across Subject Categories.

Empirical aspects in measuring interdisciplinarity

Many information resources are interesting candidates in gauging interdisciplinarity. We briefly note a few. Our focus on researchers leads us to begin with their CVs. Recent studies of science highlight the wealth of information to which CVs provide entrée.[6] On a pilot group of researchers from two research universities, we explored whether some aspects, including *educational background* (e.g., whether cross-disciplinary or not) and *position*, correlated with interdisciplinary publication. For example, educational background from B.S. to Doctorate to current position for 6 of the 17 researchers was cleanly disciplinary (e.g., all degrees and affiliation in the same field). For the other 11, it was more diverse (e.g., degrees in Chemistry and Physics, current affiliation in Computer Science/Math department). Surprisingly, papers by those with relatively pure disciplinary backgrounds seemed at least as interdisciplinary. In addition, departmental affiliation aligns with the top ISI publication Subject Categories for only about 10 of 17. So, for now, we set aside these "influence factors" as interesting in their own right, but not a strong indicator (or predictor) of IDR research output.

Let's turn to research papers. These are probably the most accessible, most clear-cut entities on which to gauge interdisciplinarity of the underlying research. Papers can be treated at various degrees of detail, including:

- Bare essentials – #, co-authoring, where published (journal)
- Key text – add information from titles, abstracts, keywords
- Full text – add information from the entire paper

We set aside co-authoring for now. Those who key on collaboration as the essence of IDR would likely avail themselves of co-authoring information as the primary measure. We key on integration, and note that this can be accomplished by a single author as well as by a team; so, given our conceptualization of IDR, co-authoring becomes secondary.

We considered trying to categorize papers based on their keywords or classification codes (e.g., as assigned by database indexers to identify what the paper addresses), as others have done to good effect.[7] In other applications, we have used such information to cluster papers, identify research themes inductively, define research domains, and track R&D advances.[8,9] We also have the capability to enrich available keyword sets by extracting noun phrases from titles and abstracts – an approach Kostoff and colleagues have used to locate papers.[10] We could also use keyword sets (ontologies) imported from outside sources.[11] Such approaches would offer advantages in assessment of papers and patents wherever they appear or are indexed. That said, we presently back off from these approaches because of their complexity and cost. Much work would be needed to devise a viable methodology to gauge the interdisciplinarity of sets of papers reflecting diverse research areas. In contrast, the approach we pursue is restricted to content indexed by one key information resource – ISI's WoK.

Our approach relies on the WoK, which includes the Science Citation Index, Social Science Citation Index, and the Arts and Humanities Citation Index. For a given researcher, one can search WoK in two ways:

- general search – retrieves summary information on papers by that researcher, including co-authors, co-author affiliations, journal, subject category, year, and references (first author, year, journal, volume, first page)

- citation search – retrieves summary information on each paper that CITES papers authored or co-authored by our researcher, including authors, title, journal, subject category, year, keywords, and cited references

Key limitations in using WoK include:

- it does not generally include conference papers and does not include patents at all [there is a separate ISI database containing conference papers]
- coverage varies considerably among research areas
- keywords are not well controlled

Our pilot assessment concluded that coverage was quite good, but not uniform across a wide range of science, engineering, and bio-medical domains. We compared publications between CVs and search results in WoK. This is not as exact as it might seem as CV inclusion is not always complete and variations in citation leave some ambiguity. We deemed coverage to be excellent or very good for 12 of 17 researchers in our pilot sample. We consider coverage "good" for 4 others (WoK containing from 65-85% of their CV's journal papers). We assessed coverage as "bad" for 1 Sports Medicine specialist. Medical research was quite well-covered (2 judged "excellent" and 1 "good"). Engineering is not covered as extensively by WoK, but it is acceptable – 3 judged "very good" (Chemical Engineering, Biomedical Engineering, Industrial Engineering) and 2 "good" (Electrical and Mechanical Engineering). These pilot results caution against cross-field comparisons without explicit checking of WoK coverage.

We recognize that interdisciplinarity is not a unitary construct with a clear, single indicator. At one extreme, one can conceive of researchers who always publish in the same research field. Even among such scientists, we would like to differentiate those who integrate source materials from multiple fields from those who draw on a narrower range of sources. At the other extreme, imagine researchers who publish each of their papers in a different field. Again, we might deem some of them as more interdisciplinary than others.

For instance, one of the 17 pilot researchers who kindly provided CV information to us publishes in several research fields (Table 1 shows the Subject Categories represented). Perusal of these fields suggests strong common threads of this polymer chemistry work among materials science, chemistry, physics, and more or less related fields. Those other fields include: crystallography, which could reasonably reflect techniques being applied; biomedical engineering, which could be an application domain; education, which could dovetail with teaching of the principles being researched. Such empirical findings suggest the desirability of a metric to get at how closely the research fields represented are associated.

Table 1 also includes information on the Subject Categories ("SCs") cited (referenced) by this researcher's 116 papers (published from 1988–2004) and the 876 articles citing these papers (as of Jan. 14, 2006). Note the Sums. The Sum of SCs of the papers equals 122% of the number of papers; that is because many journals are associated with more than one SC. The 116 papers reference 2172 items – not all of which are journal articles covered by Web of Knowledge. However, the total number of cited SCs is a bit larger (2250) because some journals are associated with multiple SCs.

Table 1. Distribution of one researcher's 116 papers across research fields

Subject Category (SC)	# of papers published in journals associated with this SC	# of cites BY these papers to papers in journals associated with this SC	# of cites TO these papers by papers in journals associated with this SC
CHEMISTRY, MULTIDISCIPLINARY	56	369	138
POLYMER SCIENCE	26	451	127
CHEMISTRY, PHYSICAL	14	226	268
MATERIALS SCIENCE, MULTIDISCIPLINARY	13	193	117
PHYSICS, CONDENSED MATTER	6	123	45
CHEMISTRY, ORGANIC	5	142	70
EDUCATION, SCIENTIFIC DISCIPLINES	4	27	3
CHEMISTRY, MEDICINAL	3	26	11
CRYSTALLOGRAPHY	3	38	40
CELL BIOLOGY	2	44	3
ENGINEERING, BIOMEDICAL	2	59	27
MATERIALS SCIENCE, BIOMATERIALS	2	58	27
CHEMISTRY, ANALYTICAL	1	62	61
CHEMISTRY, APPLIED	1	4	8
ELECTROCHEMISTRY	1	75	53
ENGINEERING, CHEMICAL	1	30	10
MATERIALS SCIENCE, TEXTILES	1	0	3
PHYSICS, ATOMIC, MOLECULAR & CHEMICAL	1	26	6
MULTIDISCIPLINARY SCIENCES	0	57	7
MATERIALS SCIENCE, COATINGS & FILMS	0	33	5
PHARMACOLOGY & PHARMACY	0	32	7
BIOCHEMISTRY & MOLECULAR BIOLOGY	0	29	15
PHYSICS, APPLIED	0	24	27
CHEMISTRY, INORGANIC & NUCLEAR	0	18	15
PHYSICS, MULTIDISCIPLINARY	0	12	1
MEDICINE, RESEARCH & EXPERIMENTAL	0	11	0
NEUROSCIENCES	0	10	4
BIOTECHNOLOGY & APPLIED MICROBIOLOGY	0	9	6
BIOPHYSICS	0	2	14
PSYCHIATRY	0	3	6
Sum (All occurrences for the 116 papers)	142	2250	1124

Notes to table: These do include self-citations (by authors or co-authors to their own work).

The last column shows the SCs associated with journals that cite the 116 papers. Again, one citing journal could be associated with more than one Subject Category (hence the tally of citing SCs – 1124 – exceeds the 876 citing articles). Table 1 shows all the Subject Categories in which he publishes and all of the SCs that he cites more than 5 times, or that cite his work more than 5 times.

Table 1 indicates that our researcher draws on research intelligence from much the same fields in which he publishes – note that the four dominant SCs are the same, although the order changes (he mostly references Polymer Science but publishes mostly in Multidisciplinary Chemistry). His work, in turn, mainly is used by these same fields; again the same four SCs dominate the "cites to," but the order shifts again, with Physical Chemistry the main user of his findings. Note some of the differences too. Other Subject Categories also show up with quite different emphases. He substantially references work in Organic Chemistry and Condensed Matter Physics in which he rarely publishes, but these same SCs also heavily cite his work. He draws upon Cell Biology and Multidisciplinary Sciences, but these rarely cite his work. [Multidisciplinary Sciences is a quite special SC as it includes the leading cross-disciplinary outlets of *Science, Nature,* and *Proceedings of the National Academy of Sciences (PNAS)*.] Biophysics is an SC that cites his research in which he has not published and rarely cites.

We explored classifying specific Subject Categories into broader areas (e.g., Engineering, Life Sciences). There are many different area classifications. In this pilot work, we tried 13 broad research areas. Of those, this researcher published in 7 (Chemistry & Materials Science; Physics; Education; Medical, Health & Veterinary Sciences; Technology; Life, Bio & Agricultural Sciences; Engineering & Energy). This gives us pause – does one coherent research stream that touches into 7 broad research areas reflect more or less interdisciplinarity than another which reflects dissociated interests? The pilot findings suggest that it would be preferable to develop similarity measures among the Subject Categories rather than try to categorize SCs into broader areas.

Based on our assessment of various approaches to measure interdisciplinarity, and these pilot results, we determined to pursue use of the ISI Subject Categories as basic units of analysis. The SCs are used by ISI to classify journals. The process entails a combination of

1. empirical information on journal-to-journal citation patterns, with
2. editorial judgment as to journal coverage.

ISI's WoK website, under *Journal Citation Reports*, provides descriptions of each SC, for instance:

Cell Biology Category Description:

Cell Biology includes resources on all aspects of the structure and function of eukaryotic cells. The principle characteristic of resources in this category is an emphasis on the integration at the cellular level of biochemical, molecular, genetic, physiological, and pathological information. This category considers material on specific tissues, differentiated as well as embryonic.

This SC contains 155 journals as of November, 2005; however the cumulative thesaurus we are using (from ISI) contains 189 journals that have been included in Cell Biology (e.g., journal names change).

The SCs depict an ever-evolving set of research fields. These slowly change over time to reflect current research practices. ISI kindly provided us a thesaurus of 244 current and recent SCs, as of early 2005. This thesaurus associates the journals included in WoK to particular SCs. The journal set also changes over time. Each journal is associated with between 1 and 6 SCs, distributed as follows for the 10,550 journals in this electronic thesaurus:

- 6 SCs – 1 journal is associated with this many SCs
- 5 SCs – 25 journals
- 4 SCs – 198 journals
- 3 SCs – 877 journals
- 2 SCs – 3032 journals
- 1 SC – 6417 journals

So, some 39% of journals included in WoK are associated with >1 SC.

Those studying scientific process have often used SCs to classify scientific activity. Cunningham profiled British science using ISI information.[12] His analyses warn that coverage of various research areas by SCs is not uniform (see also Table 2).

Table 2. Subject category file characteristics

WoK VP Files	India	US	US
Temporal coverage	2004 publication year	March 30, 2005, publication week	March 30, May 14, & June 11, 2005, publication weeks fused
Publications	20,558	8,484	23,381
SCs (for those publications)	194	203	239
Cited References	410,669	155,798	596,194
Cited Journals (distinct sources, not all are journals per se)	63,336	33,291	95,526
SCs cited (of 244 total SCs)	235	236	244
SCs cited in >=300 records	94	34	122
SCs cited in >=100 records	142	92	181
SCs cited in >=30 records	179	174	220
SCs cited in >=10 records	199	215	232

SC coverage favors research domains with well-established journal sets, especially in the physical and mathematical sciences. He notes that other categorizations (namely that of SPRU, the Science Policy Research Unit at the University of Sussex, where he was doing this research) also cover fields unevenly. For our purposes, the SCs offer the best accessible coverage of which we are aware. Morillo and colleagues have mapped links among SCs based on shared journal assignments[3] and recently studied the relative interdisciplinarity of newly emerged versus older SCs.[13] New SCs had a greater percentage of journals assigned to multiple SCs, higher percentage of links outside their Broad Area (they used 9 broad areas), stronger links, and more diverse links. Moya et al. used co-citation of SCs as the basis to map their interrelationships.[14] Boyack et al. work with journal inter-associations, using SC categorization as a validity check, in mapping science.[15]

SCs hold appeal in their relative coherence. As illustrated by "Psychology," disciplines are not unitary. The granularity of the SCs is highly consistent with our definition of IDR with its illustrative "bodies of specialized knowledge or research practice." Of the 244 SCs with which we are dealing, 9 include the term, "multidisciplinary" and 3 include "interdisciplinary." Most of these, like "Chemistry, Multidisciplinary," seem to behave much like the other SCs. One special SC is "Multidisciplinary Sciences." Its 69 journals include *Proceedings of the National Academy of Sciences, USA; Science;* and *Nature.* These broad-scope journals include papers from multiple fields, but this does not imply that any given paper is inherently multi- or interdisciplinary.[5] In its interrelationships with other SCs, Multidisciplinary Sciences acts much like other high frequency biomedical SCs (e.g., Biochemistry). Here are ISI descriptions of two such multidisciplinary or interdisciplinary SCs:

Mathematics, Interdisciplinary Applications

[# of journals in JCR, as of Nov., 2005 = 52] *Category Description:*

Mathematics, Interdisciplinary Applications includes resources concerned with mathematical methods whose primary focus is on a specific non-mathematics discipline such as biology, psychology, history, economics, etc. Resources that focus on specific mathematical topics such as differential equations, numerical analysis, nonlinearity, etc., are covered in the

Multidisciplinary Sciences

[# of journals in JCR, as of Nov., 2005 = 45] *Category Description:* Multidisciplinary Sciences includes resources of a very broad or general character in the sciences. It covers the spectrum of major scientific disciplines such as Physics, Chemistry, Mathematics, Biology, etc. *Nature* and *Science* are the preeminent resources in this category and serve as typical examples. The Web site of the National Science Foundation is a good example of a web resource included in this category. Some specialized resources that have a wide range of applications in the sciences also may fall under this category. The journal *Fractals–Complex Geometry Patterns and Scaling in Nature and Society* would be an example of such a resource.

We distinguish three different ways to consider Subject Category distribution pertinent to measuring interdisciplinarity:

- *Publication* spread across SCs – How many different SCs are represented by the set of papers in question? What is the frequency distribution across these SCs?
- *References* ("citations by") spread across SCs – Either examined per paper or for the entire set of papers
- *Citations* to the paper(s) spread across SCs – Either examined per paper or for the entire set of papers

Reverting to our integrative definition for IDR, the distribution of references holds primacy. Diversity in publication certainly reflects diversification, but it may or may not indicate integration of intellectual content. *Diversity of references cited by a paper logically seems the best gauge of intellectual integration.* That is, for each given paper, examine the SCs that it references. Papers that cite more discrete SCs pertaining to some unspecified mix of substantive topics, methods, and/or concepts are presumed to be more interdisciplinary. We acknowledge that a wide spread of cited references does not unequivocally demonstrate intellectual integration. Eto notes that disciplinary scientists could collaborate, each bringing in purely disciplinary contributions. The sum of these, reflected in the spread of cited SCs could appear quite diverse, yet the collaborators may not have truly integrated this knowledge.[16] Nonetheless, we find "Integration" as reflected in diversity of cited SCs to be a compelling IDR metric. A counterbalancing perspective, to which we do not ascribe, is that IDR *requires* collaboration. On the other hand, we believe that much IDR does reflect cross-disciplinary collaboration.

Generating a "Science Matrix"

Our strategy to determine how closely SCs relate to each other is first to generate a large, representative sample of scientific publishing. We then ascertain the extent of *co-citation* of particular SCs [as did Moya et al].[15] We have compiled three one-week samples of papers (by searching the "most recent week" on WoK, as of March 30, May 14, and June 11, 2005, for papers with at least one U.S. author affiliation). We have compared results with a one-year sample of WoK papers with an author affiliation from India. For these samples we examine SCs cited within each given paper. We then calculate measures of association for the SCs across the respective sets of papers. We have explored Pearson correlation, but favor the closely related cosine measure. In text analyses, cosine generally fares slightly better than correlation.[17] Klavans and Boyack, working with co-citation measures (for mapping of science generally), favor cosine adjusted for expected value based on frequencies.[18] Our resulting SCxSC cosine matrix provides the values we use in all further analyses. The cosine can be calculated from observations (counts) *x, y* as:

$$\frac{\sum_i (x_i y_i)}{\sqrt{\sum_i x_i^2 \sum_i y_i^2}}$$

We believe these values of SC-SC interrelationship are reasonably robust. Table 2 shows selected U.S. and India sample characteristics. The rationale is that these are reasonably representative, large science samples. Indeed, since we are basing SC-SC relationship upon co-citation of Subject Categories within papers, the fact that the total sample is not perfectly representative should not pose major problems. We do need to think about attendant issues – e.g., the one-week samples could have clumps – special issues or uneven indexing (e.g., handling multiple issues of certain sources as they come available to WoK). WoK does not generally cover conference proceedings, but we note some such materials. We also expect SC-SC associations to evolve, so any resulting "science map" would shift over time, requiring periodic updating. Some SCs are heavily represented, while others are very lightly or not covered. Of the 244 SCs, 50% are cited 300 or more times, and 90% are cited at least 30 times, in the 3-week USA sample, upon which we base our calculations.

Our interests reside mainly with research in the sciences, medicine, and engineering, with less interest presently in the social sciences and little in the humanities. Coverage in the India and U.S. datasets mirrors these emphases well (i.e., it is thinnest in the arts and humanities). For instance, in matching the USA and India results, we checked for SCs included in one but not the other. Present for India, but not the U.S.-March 30, were: Architecture, Folklore, and American Literature. Present for the U.S.-March 30, but not for India, were: Criminology, Industrial Relations, Medieval & Renaissance Studies, and Religion. The combination of U.S. for three weeks cited all the SCs.

Our immediate focus is to assess the interdisciplinarity of U.S. authors, so we use the U.S. SCxSC cosine matrix for the three sample weeks combined. We compared a range of SC intercorrelations among the US and India samples, and these generally corresponded very well. We examined correlations and cosine values. Table 3 shows cosine values for 4 high frequency SCs to give a sense of how these range for U.S. and India samples.

We selected 26 SCs representing a range of research areas. We aligned the SCxSC cosine matrices, calculated using for India and for the combined 2-week (Mar. 30 and May 14) U.S. samples. The correlations of these cosine values correspond well (averaging 0.96). For instance, the "Biochemical research methods" correlation of 0.98 is based on comparing the pairs of cosine values, U.S. and India, for this SC with each of the other 243 SCs.

Effectiveness in associating journals with SCs depends on the development of our thesaurus. The initial thesaurus was provided by ISI in early 2005. Its accuracy will drift over time as ISI changes its assignments of journals to Subject Categories and their set of SCs itself evolves. Our thesaurus can continue to improve as we discover additional journal-SC matches. There are over 16,000 journal entries (the thesaurus includes journals as they evolve over time) and the format of cited journal names differs somewhat from those in the thesaurus. Currently, we have worked it to the point of diminishing returns on the three U.S. week-long searches and the India 2004 search.

Table 3. Illustrative cosine values [based on extent of papers co-citing SCs]
Table 3A. US (combined 3 weeks)

# Records	Selected Subject Categories	Multidisciplinary Sciences	Biochemistry & Molecular Biology	Medicine, General & Internal
6523	Multidisciplinary Sciences	1	0.695	0.187
5086	Biochemistry & Molecular Biology	0.695	1	0.141
4117	Medicine, General & Internal	0.187	0.141	1
3922	Cell Biology	0.641	0.827	0.131

Table 3B. India 2004

# Records	Selected Subject Categories	Multidisciplinary Sciences	Biochemistry & Molecular Biology	Medicine, General & Internal
5293	Multidisciplinary Sciences	1	0.579	0.179
4345	Biochemistry & Molecular Biology	0.579	1	0.163
2061	Medicine, General & Internal	0.179	0.163	1
1969	Cell Biology	0.496	0.732	0.139

We have worked through multiple iterations:

- Apply our current best "Find-Replace" (F-R) thesaurus in *VantagePoint* to the cited journals from a WoK search; apply the F-R thesaurus also to the Journal-Subject Category (J-SC) thesaurus. The objective is to match journal nomenclature (that is not consistent to begin).
- Apply the J-SC thesaurus to the WoK search results (journals).
- Review the journals not assigned to an SC; use this information to enhance the F-R and J-SC thesauri.

For the combined file of 23,381 U.S. WoK publications for three weeks in 2005 (March 30, May 17, and June 11), we have 95,526 "cited journal" names (after cleaning). These include huge numbers of citations to articles in certain journals (e.g., *PNAS, Nature, Science*) on down through single papers citing some 72,000 sources. It is a highly skewed distribution! Most of the singly cited sources are not even journals. For instance, some singly cited items:

- 000104 AIAA (conference paper)
- 0092 USGS (presumably a government report)
- 145 U Suss I Dev Stu (possibly a thesis)
- Acta Crystallogr A 6 (a variant on a recognized journal title)
- in press Infancy (not yet published)
- Indian J Fisheries (journal not included in WoK)

In general, unless there is a clear match between the "cited journal" name and a journal in our J-SC thesaurus, we leave it out.

For NAKFI purposes, we have settled on use of the U.S. SCxSC interrelationships (cosine matrix) as we are focusing on U.S.-authored research publications. As noted above, the U.S. SCs correspond highly with those for India. We don't think that American research is very different from research authored by others. The three weeks provide a sizeable sample to assure reasonable robustness. Table 2 gives some summary distribution characteristics for the 3-week US sample (23,381 papers). For the Cited Journal SCs, all 12 with fewer than 10 occurrences fall in the Arts and Humanities. These do not pose serious concerns for NAKFI assessments. Publication SCs coverage is based on a smaller sample by a factor of 25 (i.e., the average U.S. journal paper cites 25 references). Nonetheless, the coverage is solid – 239 of 244 possible SCs are present. Of those, 222 appear in at least 10 records; 191 in at least 30 records.

Others map science in various ways, for various purposes. For instance, Klavans and Boyack are interested in an overarching map per se, to show how various fields piece together.[15] We seek to measure the degree of association among SCs, so have generated a particular form of "science map" – actually a 244 x 244 matrix of cosine values for the Subject Categories based on co-citation of SCs within papers (Table 3a illustrates a small portion). The next section incorporates this SC similarity matrix in assessing interdisciplinarity.[*]

Methods: Assessing the interdisciplinarity of sets of papers

Setting out the steps in the calculations clarifies what is going on:

1. The WoK abstract record for a given paper (by one of the researchers under scrutiny) lists each of its cited references. Most references are to journal articles and those are the only ones we are analyzing.

[*] The matrix is available as a *VantagePoint* file for analyses.

2. For the paper itself, and for each of the paper's references, we identify the journal in which it appeared.
3. We then apply the dual thesauri introduced previously [first, "Find and Replace" to match journal name abbreviation variations; second, "Journal–SC," to associate journals to SCs].
4. We use the combined U.S. SCxSC cosine matrix to gauge the degree of association among the resulting sets of SCs.
5. We compute measures of interdisciplinarity based on a researcher's set of papers. For each paper we compute interdisciplinarity measure(s) based on the distribution of SCs. We derive measures based on both the spread of SCs referenced, and on the SC (or SCs) for the journal in which the paper was published. We use the general U.S. SCxSC cosine values to measure the relatedness of the resulting SC sets.
6. We compute measures for a given researcher based on the set of papers examined.

The steps yield a set of SC instances for a given paper. Some references will generate no SCs, either because there is no journal (e.g., reference is to a thesis, report, or patent), the journal is not indexed by WoK, or the Journal-SC thesaurus has failed to capture a link that actually exists on WoK. We have extensively examined results on the U.S. and India samples to capture as many journals as feasible. Most of the remaining misses are attributable to journal name variants. We take a conservative approach, not assigning a journal to an SC unless we are quite sure that WoK does so.

Note that this assignment of a reference is based on its journal. Alternative measures, in principle, could include examining its terms (in its title, keywords, and/or abstract) to assign its research field. This is not practical in that WoK does not provide any of that information for the "cited references." Note also that these data combine SC counts arising two ways: 1) one journal may be associated with multiple SCs, or 2) different SCs arise from different references. After considerable reflection, we elect not to distinguish these. Our rationale is that both mechanisms suggest inclusion of elements of the knowledge resident in that SC in the parent paper that is referencing them.

Scaling issues arise. The average paper references on the order of 20 sources. Suppose one paper cites only 5, while another cites 100. Should we tally absolute SC instances or proportions? A related issue concerns the form of the distributions observed. As with most bibliometrics, distributions tend to be highly skewed (Table 1 is typical). One often sees very few high frequency entities and many low frequency ones. This can make categorization of "all" instances extremely costly. Our pilot findings suggest using proportions and not worrying about classifying all low frequency instances.

Experimental samples

To try out these new metrics, we generated 3 separate researcher samples – A, B, and C:

A. *Pilot Sample:* We sampled faculty from one research university seeking to span the Physical Sciences, Biomedical Sciences, Engineering, Computer Science & Math. We obtained CV's from 14 volunteers; then searched Web of Knowledge (WoK) for their career publications. To include some Medical researchers, we added 3 faculty from a medical school, for a total of 17.
B. *Applicants:* Researchers who applied to attend interdisciplinary NAKFI conferences on signaling, nanoscience, or genomics – a total of 20.
C. *AAU:* To counterpoint possible institution-specific biases of A and the interdisciplinary inclinations and topical foci of B, we added another broad sample selected from the Association of American Universities. We again sought to span the Physical Sciences, Biomedical Sciences, Engineering, Computer Science & Math. We identified candidates deliberately ranging from Assistant to full Professor. We selected 2 faculty from Brandeis; 3 each from Brown, Caltech, Carnegie Mellon, and Columbia; and 1 from Cornell to give us 15. Each is from a different department, and we favored people with less-common names to facilitate WoK searching, for those with at least 5 papers since 2001.

Our main target in developing IDR indicators is to assess whether NAKFI experiences (special conferences, seed grants) alter the participating researchers' interdisciplinarity. We expect to focus on time periods of about 3 years pre- and post-. So, to determine whether the indicators are sensitive enough to pick up changes, we conducted these explorations on time-slices of the researchers' publications. Some analyses using all the indicated time periods include as large a sample as reasonable, but other results presented here focus on the more comparable 3-year periods:

A. *Pilot Sample*: Focus on 2002–2004; additional analyses use results for the same researchers for 1999–2001
B. *Applicants*: 3-year periods leading up to the NAKFI conference for which they applied: 5 Signaling Conference applicants (2001–2003); 4 Nano Conference applicants (2002–2004); 8 Genomics Conference applicants (2003–2005)
C. *AAU*: Focus on 2002–2004; additional analyses use results for the entire 2001–2005 period.

In additional calculations, for Sample A we also looked at papers published in the 1999–2001 period. This allowed us to see the extent of variation within individuals over successive 3-year periods. In our "max" calculations, we combined 1999–2004 for a

6-year span. For Sample B, we note that 2005 publications are somewhat shortchanged as the year was not complete. For Sample C, in our "max" version, we used their publications for 2001–2005 (with 2005 not complete). Our indicator assessments are not sensitive to these variations in time period.

We exclude individuals for whom we had fewer than 3 papers with at least 3 Cited SCs each. Our measures are inherently stochastic, so drawing conclusions on interdisciplinarity on tiny individual samples seemed inadvisable. For Sample A we required individuals to meet this test for both time periods; only 11 of 17 did so. For the 20 Sample B researchers, 17 met the criteria. And for Sample C, where we screened for those with at least 5 papers (2001–2005), only one failed the criteria for the 3-year period (2002–2004). We ran our analyses on each of the three sets separately, then combined. The results presented focus on the resulting composite set of 42 (11 + 17 + 14) researchers for the most comparable, 3-year time periods. In "max" sample calculations we show 43 researchers; this retains the one AAU person who has sufficient papers when we take the available 2001–2005 span. We apologize for this bit of complexity, but that one person turns out to be an outlier – the "Purist" profiled below. In studying our measures, sometimes we want to see the fullest range sensible; other times we want the most comparable time slicing.

Paper level metrics

Our primary target as an IDR indicator is Integration ("I"). To what extent does a paper indicate integration of distinct research knowledge in citing multiple Subject Categories? As with much of this exploratory development, we have tried many variations on this and additional measures. This section will also address Reach ("R"). The next section, which addresses measures at the Researcher level, introduces Specialization ("S"). We introduce the "I" measure with a simple computational illustration. The Appendix gives formulas and notes ongoing experimentation with those. Here we describe how we arrive at the metrics.

Suppose a paper cites 4 SCs to different degrees (Table 4). These are the same 4 SCs whose degree of association using the cosine measure appears in Table 3A. Our calculations follow the 6 steps listed under Methods. Recall that some journals are associated with more than one SC. So the results below could reflect 10 references, each to a journal linked to a sole SC. Or, they might reflect 1 reference to a journal that ISI classifies in all 4 SCs, plus an additional 2 references to a journal that is linked to both Biochemistry and to Cell Biology, plus 2 more references just to Biochemistry journals. Our rationale is to pick up discrete indications (references) to a given body of research knowledge (citing a given Subject Category), so we tally both forms together.

Table 4. Illustration: Cited Subject Categories for calculation of integration score

# of citations	Cited Subject Categories (SCs)	Multidisciplinary Sciences [# = 1]	Biochemistry & Molecular Biology [# = 5]	Medicine, General & Internal [# = 1]	Cell Biology [# = 3]
1	Multidisciplinary Sciences	0.01			
5	Biochemistry & Molecular Biology	0.05	0.25		
1	Medicine, General & Internal	0.01	0.05	0.01	
3	Cell Biology	0.03	0.15	0.03	0.09
10	Sum	0.10	0.45	0.04	0.09

We calculate Integration as follows:

1. Weight cells by normalizing the frequency of citations. For instance, the Cell Biology × Biochemistry cell weight = (5 × 3)/100 = 0.15.
2. We include the diagonal cells and the cells below the diagonal (we do not include cells above the diagonal, to avoid double-weighting interactions among distinct cells). We will later adjust the normalization to reflect just the included cells (sum = 0.68).
3. Multiply the cell weight by the respective cosine value (Table 3A). For instance, any diagonal cell's cosine value = 1 (with itself). The cosine value for "Cell Biology" × "Biochemisty" = 0.827 (based on the USA sample) – indicating that these two Subject Categories are closely associated. The cosine value for "Cell Biology" × "Medicine, General and Internal" = 0.131. [In general, cosine values among our 244 SCs tend to be considerably closer to 0 than to 1.]
4. Sum up the cells included (10 cells here); divide by the sum of the included cell weights (0.68) to get the Disciplinary score. [So if all the cited SCs were either one SC or had cosine values among themselves of 1, this would be a purely disciplinary paper.]
5. Subtract this Disciplinary score from 1 to get the Integration score, "I."

We explored using a threshold of requiring an SC to have more than a single citation, but decided it was preferable to include these as instances of knowledge being drawn in. Many papers in our sample had many single-citation SCs. Recognize that the use of the cosine measure weighting reflects our understanding that the disparity (cognitive distance) among SCs, not just the number of them, matters. We continue to experiment with formulations of Integration and Specialization (see Appendix).

We investigated an additional measure that we came to label "Reach." We considered combining this with Integration as a composite indicator, but decided to address it separately. We calculate Reach as follows:

1. Identify the Publication SC (assume this is singular, for the moment)
2. Identify all the Cited SCs, as above in calculating I.

3. For each Cited SC – multiply the number of times it appears by that SC's cosine value to the Publication SC
4. Sum those values for every Cited SC; divide by the total number of Cited SC occurrences.
5. Subtract this value from 1.

So, while "I" measures the extent of diversity among the Cited SCs, Reach ("R") measures the degree of distinction between those Cited SCs and the Publication SC. We call it Reach as it taps into the relatedness of the cited references to the research domain of the publication journal. Is the researcher bringing in knowledge from outside that domain?

Calculating R is tricky when the Publication journal is categorized in more than one SC. As an illustration, the journal, *Discrete Event Dynamic Systems—Theory and Applications*, is part of the core journal set of three SCs: Automation & Control Systems; Mathematics, Applied; and Operations Research & Management. So we have 3 Publication SCs to match against the Cited SCs. We generated credible arguments for using: the "Furthest" reach, the "Shortest" reach, and the Average. Results were not very sensitive to the choice.

More telling, the correlation between I and R within each of our 3 sample (maximum data) sets was 0.98, 0.89, and 0.52. The 0.52 correlation increases to 0.76 if 1 outlier is removed (the person with insufficient # of articles to be included in the 3-year comparisons). Figure 1 plots I vs. R for the 42 researchers (3-year time spans). The strong association between the two measures is apparent. For most purposes, this means one is largely redundant information. We prefer to focus on Integration (I) for its conceptual power – measuring the diversity of the referenced knowledge of a paper. We continue to explore R, particularly as a potential flag when it differs sharply from I (e.g., Researchers #18 and #20 in Figure 1). The notion of drawing on research knowledge from certain Subject Categories in articles reporting to other SCs is intriguing.

I (and R) are calculated at the Paper level. For each journal article covered by WoK that cites other journals covered by WoK, we can compute I (and R). Examining the sensitivity of I values, we have decided to exclude articles for which we compute fewer than 3 Cited SC instances. We found that our coverage of the SCs is imperfect. Over time it should improve as our J-SC thesaurus gets better and better by checking which journals are missed and correcting this as experience builds.

Were a given article to only reference a single journal (linked to a single SC), one time, we could argue that this should be scored as purely disciplinary. In fact, that article might well reference additional intellectual resources that we do not capture.

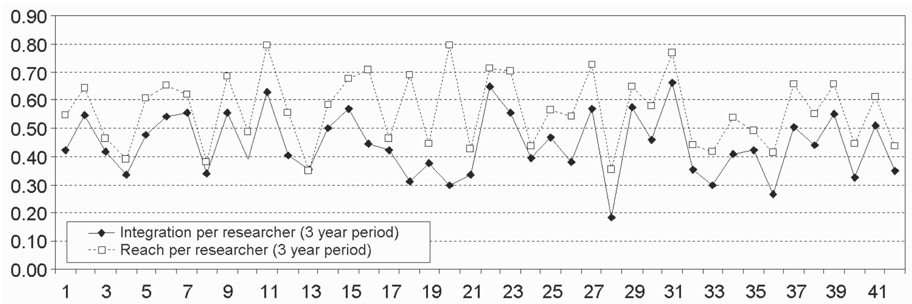

Figure 1. Integration vs. reach for 11 researchers

These could include cites of journals missed by our thesaurus, journals not covered by WoK, conference papers not covered by WoK, and miscellaneous other sources of knowledge (e.g., dissertations, reports, websites). We see far greater danger of erring by classifying articles based on 1 or 2 references than in excluding these. Note that we do include articles that cite only a single SC, so long as they do so at least 3 times. [Such an article would score I = 0.]

Researcher level metrics

Given that a researcher has authored (or co-authored) a particular set of papers, say in a given time period, how should we compute I for him or her? An obvious choice is to take the average of the I values for each included paper. And, indeed, that is what we have determined to do.

Before deciding, we did investigate distributional facets. We calculated the Standard Deviation for I for each of our researchers – reflecting the variance in Integration among the papers included. This tended to be relatively consistent across researchers. We also investigated the alternative of focusing on the 50% highest I values for the researcher. The rationale was that a researcher might well author both disciplinary and interdisciplinary papers. Even as NAKFI seeks to encourage IDR, it does not oppose disciplinary research. So, we might ignore the more disciplinary half of one's work and assess how far the research extends into interdisciplinarity in the other half of that body of work. We calculated this for Sample A; it correlated 0.95 with I. This high association, together with conceptual complexity, caused us to drop this alternative. So, one's I value is the average of one's papers' I values. We had the opportunity to show two of our pilot sample of researchers their profiling, and they found it reasonable, noting an expectation of differences by discipline.

Figure 2 provides another perspective on what Integration entails. Plots of the percentage of authored papers that cite each SC are shown for three researchers as indicative case illustrations. The steepest drop-off is for our second least integrative of the 42 researchers (I = 0.18) – 94% of his papers cite something from Statistics & Probability. His 15 papers cite 17 different SCs, but the proportion drops steeply – e.g., the second – fourth most cited SCs appear in only 44% of his papers; beyond the sixth most cited SC, the rest are referenced in only 1 of his 15 papers. In contrast, one of our most integrative (I = 0.57) researchers shows the most gentle slope. His 26 papers cite 51 SCs; 96% cite Biochemistry & Molecular Biology; 93% cite Cell Biology; 93%, Respiratory System; etc. His 23rd most cited Subject Category appears in 7 of his 26 papers. He draws on a width swath of research knowledge! Our middle slope is a researcher whose 57 papers cite 68 SCs in total; 100% cite something from Oncology, dropping to 74% for the second most cited SC (Medicine, General & Internal). As another benchmark, his 16th most cited SC appears in 25% of his papers. His I = 0.40 is slightly below average for our 42 researchers (see Results just ahead). As this illustrates, the extent of cross-fertilization of research knowledge among Subject Categories is quite remarkable. This far exceeded our expectations.

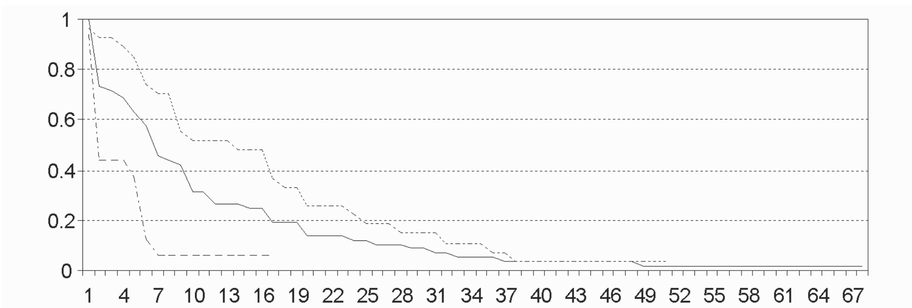

Figure 2. Relative citation frequency for 3 researchers

We also measure Specialization ("S"). We were attracted to this concept by Erin Leahey's work.[7] She considers Specialization as a researcher focusing tightly on one or a few subfields, rather than spanning many. She postulates that Specialization is a key characteristic affecting research productivity (considering that too much Specialization, as well as too little, may hamper publication).

As we thought about Specialization, we did not take it as the antithesis of Integration, but rather as a potentially orthogonal dimension. That is, one might integrate broad swaths of knowledge in writing to a relatively singular audience, or to multiple audiences. And, conversely, one might draw in research knowledge mainly from a single field, whether writing to one or multiple audiences.

We set out to measure Specialization using WoK Subject Category information. This differs from Leahey's data, but we adapt her formulation. We calculate S using the information on the SCs in which a researcher's publications appear. Note that S does not use Cited SC information at all; hence it is measured independently of I. Our formulation is:

1. For the set of journal articles, count the number of publications in each SC. [Again, we do not distinguish whether these derive from journals associated with single SCs vs. those associated with multiple SCs – although one might consider that as interesting data in its own right to get at IDR.]
2. Square the count for each SC; then sum these.
3. Divide that sum by the square of the sum of all the counts.

For example, suppose we have 5 publications in SC1; 3 in SC2; 1 in SC3; and 1 in SC4. The numerator is 25 + 9 + 1 + 1 = 36. The denominator is $(5 + 3 + 1 + 1)^2 = 100$. So, S = 0.36. If all 10 publications were just in SC1, then S = 1.0. If all 10 were each in a unique SC, then S = 0.1. Note that S only measures a set of papers, not individual papers. In our application, we take a researcher's body of work for a time period (e.g., 3 years) and use S to gauge the dispersion of those publications across ISI Subject Categories. [See the Appendix for further explorations in measuring Specialization.]

Results

The average levels of I and S are of interest. For the 43 researchers these are I = 0.43; S = 0.26. [If we eliminate the one researcher noted as an outlier, these shift by only 0.01.] The averages shown are based on researchers (i.e., we calculate each researcher's S and I score, and take the mean of those). Obviously, some researchers publish far more than others. We can also calculate overall averages weighted by how many papers each authored, yielding similar results: I = 0.42 and S = 0.24. The extent of Integration surprises us.

Another measurement concern is variability. Using the maximum data sampling, the range for I is 0.10 to 0.65 across the 43 researchers (the researcher whom we exclude in 3-year comparisons has the I = 0.10 score). The range for S is 0.09 to 0.72. The standard deviations are 0.12 for I and 0.13 for S. The Interquartile Range (the middle 50% of the values) helps get a sense of the distribution – IQR for I is 0.34 to 0.54; for S, it is 0.18 to 0.31.

We can also calculate standard deviations for each individual. For example, the Integration standard deviations range from 0.05 to 0.29. A high individual standard deviation suggests that one publishes both disciplinary and interdisciplinary (highly integrated) work. This might prove to be an informative measure in its own right.

An intriguing question is how do Integration and Specialization relate? As mentioned, we had hypothesized that they could well be orthogonal. We also thought in terms of a quad chart (Table 5). Figure 3 compiles the data from our three sets of researchers, using the maximum sampling, to give us 43 data points. We draw our quadrant boundaries at the mean values for S (0.26) and I (0.43).

Table 5. Relationship between Specialization and Integration

Specialization / Integration	Lo	Hi
Hi	Disciplinarian	Single interdiscipline specialist
Lo	Grazer	Renaissance integrator

As Figure 3 shows, I and S are not independent (orthogonal); there is a substantial negative correlation (-0.51). Researchers whose work integrates more diverse research knowledge (high I) tend to be less specialized, publishing in a wider span of Subject Categories (low S). The Upper Left Quadrant corresponds to a “Disciplinarian” – a researcher with a sharply focused agenda. The Lower Right seems to be the locus for the interdisciplinary researcher. Note that the Upper Right Quadrant (“Single Interdiscipline Specialist”) is essentially empty. The Lower Left (“Grazer”) is reasonably populated.

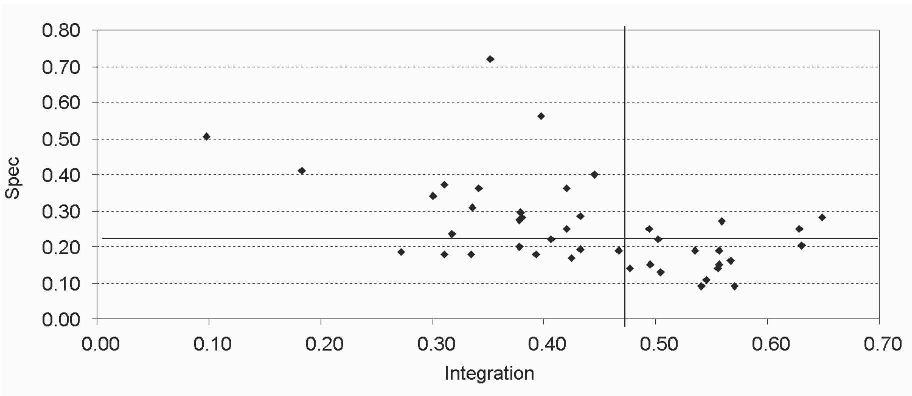

Figure 3. Specialization vs. Integration

A few individual examples give a sense of the interplay between Integration and Specialization. Here is a profile of one researcher with an I value right on the mean:

- The “Non-Specialized, Average Integrator” – S = 0.19; I = 0.43 – 8 papers, all involving Physics subfields. But these 8 papers cite a total of 18 SCs! Of those, 8 are Physics subfields; others include Multidisciplinary Sciences (7 of the 8 papers), Physical Chemistry (6 of the papers), Materials Science, Optics, Statistics & Probability, and Math.

A sampling of more extreme cases:

- 2 *Disciplinarians* (Upper Left Quad)
  - The "Specialist" – S = 0.72; I = 0.35 (the highest S score; note that I is not so low) – This reflects 7 papers, of which 6 are in Neurosciences; 1 in Physiology and 1 in Multidisciplinary Sciences. But note that his "discipline" – Neurosciences, is inherently quite interdisciplinary in nature.
  - The "Purist" – S = 0.51; I = 0.1; (Our lowest I score of anyone; one of the AAU researchers whose publication count for the narrower 3-year period falls below our minimum of 3, so is missing in the "N=42 researchers" analyses) – Based on 7 papers (for the 4.5 year period), all in Math (6) and/or Applied Math (2), with 1 also in the Statistics & Probability SC. These 7 papers cite 150 references that appear in 95 different sources (i.e., journals, with a few other forms, such as books). For those 95, we can associate journals (and, of course, not all are WoK journals) with only 3 different SCs: Mathematics (70), Mathematics, Applied (11), and Computer Science, Theory & Method (1). This is our exemplar in this sample of a disciplinary researcher!

Table 6. The renaissance integrator

#	Cited SC'3s / Papers	A	B	C	D	E	F	G	H	I
9	Spectroscopy	2	3	3	3	1	6	1	1	3
9	Physics, Particles & Fields	2	4	4	3	1	6	1	1	3
9	Instruments & Instrumentation	2	3	3	3	1	6	1	1	3
9	Nuclear Science & Technology	2	3	3	4	3	8	2	1	5
5	Engineering, Electrical & Electronic				1	2	2	1		2
3	Astronomy & Astrophysics		1			1		2		
2	Optics				1		3			
2	Physics, Atomic, Molecular & Chemical				1		3			
2	Physics, Multidisciplinary		1		1					
2	Physics, Condensed Matter					1	1			
2	Physics, Applied		1							1
1	Chemistry, Physical						1			
1	Thermodynamics		1							
1	Communication									1

- *Grazer* (Lower Left Quad) – S = 0.18; I = 0.27; This value is based on 34 papers, published in 9 SCs, citing 34 SCs. His I score is relatively low because his work concentrates heavily in Cell Biology; Biochemistry & Molecular Biology; and Multidisciplinary Sciences, which are heavily intercorrelated (Table 3A).

Table 7. The Integrator

#	Cited SC's / Paper	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
21	Microbiology	9	11	6	3	3	9	4	11	9	12	4	8	6	5	15	7	10	12	11	2	1
20	Biotechnology & Applied Microbiology	3	3	1	5	2	1	2	3	2	7	2	1	4	2	2	3	2	2	1		3
19	Multidisciplinary Sciences	2	1	4	1		4	1	1	3	1	2	3	1	1	7		1	5	2	1	2
17	Biochemistry & Molecular Biology	5	2		4	4		3	1	1	7	7	7	5	3	9	4	1	2	4		
16	Immunology	1	1		3	2		1	1	1	4	2	1	4	2		1	1	1	1		
15	Engineering, Environmental		2	2	1	2	2	15	4	2	1				1	2	1		1	3	1	
15	Environmental Sciences		6	6	1	2	4	22	5	2	1				1	2	3		2	5	1	
13	Chemistry, Analytical				2		1	1	1	3	1	1	3	2	1	6	1				1	
13	Limnology		1	11	3	1	3	1		1						1	2	1	1	1	3	
13	Oceanography			14	4	3	5			1			1		2	1	1	3	1	1	5	
11	Water Resources		2	1		1	1	6	3		1					1	1			1	1	
10	Geochemistry & Geophysics		16	12			6		7	5	1				7			1	3		7	
9	Geosciences, Multidisciplinary		3	7		2	5		2							1	1		2		5	
9	Geology			1		1	1		1					1	1	1	1		2			
9	Chemistry, Multidisciplinary		1	1			1	1	1		1				4	1					1	

- A *Renaissance Integrator* – S = 0.2; I = 0.63; reflecting 9 papers appearing in 6 different SCs (with 19 occurrences – i.e., each publication journal averages being in 2 SCs). The 9 papers combine for 88 references, consisting of 42 distinct sources (journals or such). Each paper cites at least 4 different SCs, and very evenly. Table 6 shows the number of occurrences of each Cited SC (row) in each paper (column).
- The leading *Integrator* – S = 0.28; I = 0.65; 21 papers (over a longer time period); note the richness of the research sources drawn upon – Table 7. This is a truncated listing showing only those Cited SC's appearing in 9 or more of the papers. Another 20 SCs are cited, but in fewer of his papers.

Our case illustration for the "Specialist" showed an I value of 0.35, near the 25^{th} percentile level. This researcher's 7 papers have 388 references to 73 distinct sources (journals, etc.), associated with 20 different SCs. The leading recipients of citation are Neurosciences (cited 250 times), Multidisciplinary Sciences (66 cites), Physiology (62), Opthamology (22), and Zoology (17) – all others receive 8 or fewer cites. So, this "low-Integration Specialist" really draws on quite distributed content. We also note that researchers with relatively few papers seem more apt to generate extreme I and S scores.

We investigated how scores varied by major disciplinary area. In categorizing our 43 researchers, 9 of them warranted inclusion in 2 major disciplinary categories. Table 8 counts those 9 in each of these (hence the #'s sum to 43 + 9). These are averaged over researchers (not weighted by papers). The Computer Science and Math categories showed similar values, for tiny samples, so were combined. They are the one major disciplinary group that seems notably different from the others in evidencing less Integration and more Specialization.

Table 8. Breakout by major discipline (for "Max" sample)

	#	Integr	Spec	Reach
Phys Sci	7	0.42	0.22	0.55
Life Sci	13	0.42	0.29	0.50
Med Sci	11	0.47	0.25	0.58
CS/Math	5	0.29	0.33	0.43
Engr	16	0.46	0.23	0.59

Discussion

We have derived three measures based on ISI Subject Category information for sets of research papers – Integration (I), Reach (R), and Specialization (S). While conceptually appealing, Reach correlated so highly with Integration that we do not see it as an independent descriptor. Integration and Specialization provide a rich, two-dimensional depiction of the nature of a body of research (i.e., one researcher's publications over a given time span).

The proposed metrics are a work in progress. We plan to continue to test them on varied and larger researcher samples. We also intend to continue comparing alternative formulations. We have examined additive models, but prefer the multiplicative (row by column frequency) approach presented here. We have tried exclusion of the diagonal (self-cite) cells, but found this conceptually unattractive. We will further compare a full matrix alternative on sets of researchers vs. our half-matrix (Table 5); we anticipate highly correlated results, but possibly more intuitive scaling. We also plan to explore alternative ways to treat the multidisciplinary SCs.

Perhaps the most remarkable finding of this exploration of new IDR metrics is the high level of interdisciplinarity indicated. Our expectations as to the degree of cross-SC citation and publication were greatly exceeded. These pilot results, for three distinct samples (43 researchers in total), show that researchers do extensively draw upon research knowledge from multiple domains.

Such levels of Integration are really notable. We illustrated several profiles of individual researchers. One of those, near the relatively low, 25th percentile of I scores (0.35) included 7 papers that drew upon (cited) research from 20 different ISI Subject Categories. Our leading Integrator (I = 0.65) had 9 papers that drew upon research from 31 SCs. The higher I score reflects more citation of more SCs (i.e., a gentler slope, as illustrated for three other researchers in Figure 2). The I score also incorporates use of the cosine measure to gauge how closely related such Subject Categories are, based on a good-sized national sample of articles.

We aspire to compile Integration and Specialization data for reasonable samples across disciplines. Will we see notable differences across major field (e.g., engineering, physical science), discipline (e.g., civil vs. electrical engineering), and/or SC? Having those data will benchmark research behavior. This is certainly necessary to assess "how interdisciplinary" Researcher A is. We hypothesize that different research norms, and coverage differences among SCs, will engender important differences, implying serious researcher by domain interaction effects. Also, compilation of research domain level data holds promise to track macro research behavior. Is a given research domain becoming more or less interdisciplinary over time? Is science in general becoming more interdisciplinary? (The NAKFI mission concerns this.)

It would be very interesting to develop "knowledge flow" models for research areas.[19] For instance, one could look at the collective work of attendees at a NAKFI conference to discern from which SCs they draw; where they publish; and which SCs use their results. Application of measures based on ISI Subject Category distribution has the potential to generate highly informative tracking of cross-disciplinary knowledge flows. The sequence is

- Patterns of cited SCs indicate incorporation of knowledge drawn from multiple sources
- Publication SC patterns reflect the research domains that the researchers are addressing
- Patterns of SCs of the journals in which articles cite those publications indicate distribution of the interdisciplinary research knowledge generated.

So, for a given paper, researcher, or body of research, we can profile from whence research knowledge is drawn, where the new knowledge is presented, and which research domains pick it up [to pursue this intriguing issue, see Boyack et al., Figure 5[15]]. Studies of such knowledge flows should speak to whether our conventional wisdom is well-founded. Are certain research domains foundational? For instance, can we demonstrate that Research "A" is drawn upon by (contributes to) Research "B" in another SC, which in turn is actively cited by Research "C" in other SCs? Does basic science contribute to technological development? Do certain research domains have higher cross-domain impact than others? If a research domain speaks just to itself, this could well be an indication of minimal benefit to science and society.[1]

Future extensions hold strong appeal. Kevin Boyack suggested exploring Integration's sensitivity to scale and examining I calculated across, as compared to within, a researcher's papers. Given the important, but ill-understood, role of *co-authoring* in IDR, it could be highly informative to examine this together with Integration and Specialization. Are co-authored works more likely to be highly IDR in terms of Integration? For papers covered by WoK we can obtain author organizational affiliations. Those give at least rough indications of discipline. Figuring out how to associate those disciplinary indicators with SCs presents a challenge. Short of that, we can compare the levels of Integration and Specialization of single-authored vs. co-authored papers by a given cadre of researchers. For instance, one of our researchers has many papers, but only one published in a journal in the Cell Biology SC. He is a co-author on that, so we wonder how much knowledge of cell biology he has internalized? One might separate papers on which our researcher is the first author (whether sole or not) to better understand his or her integrative stance. We considered just focusing on single-authored papers for certain analyses, but that sacrifices too much of the research data.

We nominate many issues that these new measures can help address. These include

- Do more interdisciplinary papers (higher I) have lower or higher impact (examine journal impact factors)?
- Do we see increased IDR just after receiving tenure? One might hypothesize that I increases, and S decreases, over research careers.
- As we differentiate more from less interdisciplinary researchers, one could then probe:

– Where do IDR researchers come from?
  [Informal, pilot-level characterization of the Pilot Sample backgrounds as relatively disciplinary (e.g., B.S. through PhD all in Chemistry) to quite multi-disciplinary did not correlate with how interdisciplinary their publications are.]
– Which research areas feature IDR? Why so?
  [Use of these measures to compare across research fields is somewhat precarious. All of the ISI Subject Categories are not equally fine-grained. SCs vary widely in how many journals they include and their coherence.[15] Citation norms differ greatly among fields as well. And a modest number of SCs constitute what Morillo and colleagues call "horizontal" disciplines.[3] We intend to explore these implications.]
– When we've identified highly IDR researchers, ask them what differentiates their work?
  [Tell them their papers are more IDR; explore with them their "secrets" in making this happen.]
– What institutional parameters nurture IDR?

We expressly invite comments and suggestions on how to improve and extend the measurement of research interdisciplinarity.

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Appendix: Formulas

Specialization (S):

$$S = \frac{\sum\left[(\#\ of\ \ papers\ \ published\ in\ SC_1)^2 + \ldots(\#\ of\ \ papers\ \ published\ in\ SC_n)^2\right]}{\sum\left[(\#\ of\ \ papers\ \ published\ in\ SC_1) + \ldots(\#\ of\ \ papers\ \ published\ in\ SC_n)\right]^2}$$

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

Integration (I):

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

where i=row, j=column, f= frequency

Where the Subject Categories (SCs) are those cited in a given paper. The summation is taken over the lower diagonal cells of this SC x SC matrix, inclusive of the diagonal. COS is the cosine measure of association between the two SCs, based on a national co-citation sample from Web of Science (as described in the text).

Reach (R):

$$R = 1 - \left[\sum\left(f_i \times COS\left(SC_i - SC_p\right)\right)\right]$$

Where f = frequency

Where SC_i is a given cited SC, and SC_p is a publication's SC. The summation is taken over each of the cited SCs for the given paper. COS is as above. Where a given publication is associated with multiple SCs, R is calculated for each. We explored using average R, smallest R, and largest R as the score for a given publication.

We continue to experiment with alternative interdisciplinarity metrics. This is a work in progress, with some current directions as follows:

- We have not actively pursued Reach due to its high correlation with Integration in these test samples.
- We have modified Specialization to incorporate the cosine values among the respective SCs. Its formulation thus comes to resemble the I calculation above, except that it is calculated for a body of research, not an individual paper; pertains to SCs instead of Cited SCs; and is not subtracted from 1.
- We are exploring calculating I for a body of research (set of papers). So, for instance, a researcher's I value would be calculated over the entire set of Cited SCs in those papers, rather than as the average of the I values for each individual paper.
- In calculating I, we are trying the full matrix, instead of the half-matrix form described here. [This is largely for conceptual simplicity; in our samples full-matrix I correlates extremely highly with half-matrix I (e.g., 0.99).]
- We are considering whether to treat the 'horizontal' SCs differently; that is the dozen SCs that include 'interdisciplinary' or 'multidisciplinary' in their name. At this time, we don't believe special treatment is warranted.