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Mapping Disciplinary Relationships in Astrobiology: 2001 - 2012

By

Jason W. Cornell

Accepted in Partial Completion Of the Requirements for the Degree

Master of Science

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MASTER'S THESIS

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Jason W. Cornell

November 2014

Mapping Disciplinary Relationships in Astrobiology: 2001 - 2012

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

By Jason W. Cornell
November 2014

Abstract

Astrobiology is an emerging field that addresses three fundamental questions: 1) How does “life,” defined as a “self-sustaining chemical system capable of Darwinian evolution,” (Mullen, 2013, p.1) in the Universe begin and evolve? 2) Does life exist elsewhere in the Universe? & 3) What is the future of life on Earth? With such intriguing questions, all rooted in human concerns, success in answering these questions depends upon the integration of diverse scientific disciplines, including the social sciences as well as the humanities. In this thesis, I state that integration can only happen through interdisciplinary knowledge production, defined as the process of answering a question, solving a problem, or addressing a subject involving several unrelated academic disciplines in a way that forces them to cross subject boundaries in order to create new knowledge and theory (Klein & Newell, 1998). Thus, this thesis addresses the following question – What are the barriers to the social sciences and humanities having a clear presence in Astrobiology research? And what are future prospects for acceptability and funding for interdisciplinary research in Astrobiology, especially from the National Aeronautics and Space Administration (NASA), which is the largest source of funding for Astrobiology (NRC, 2008)?

In this thesis I review abstracts and categorize disciplinary identities

of research articles published in *Astrobiology*, the oldest journal dedicated solely to Astrobiology, from 2001 to 2012. I then create annual spatial maps of Astrobiology research articles using bibliometrics, which are methods used to quantitatively analyze and create maps of academic literature origins. Specifically, I determine 1) the number of disciplines involved in specific *Astrobiology* articles, as well as 2) the extent to which a research article cites diverse disciplines. From this information, maps showing the predominance of disciplines as well as the distribution of citations, known as *disciplinary diversity*, are created. By looking at the organization of research, questions are raised about how disciplinary structures came about and what relationships exist among research disciplines.

These questions are then analyzed through psychological and sociological ideas used to describe interdisciplinary research relationships. The results suggest that research shows little embeddedness (i.e. connection with) among multiple disciplines, likely due to entrenched *disciplinary culture* and *privileging*, in which researchers have a tendency to value and collaborate only with similar disciplines. This study concludes by offering a number of recommendations regarding promoting effective integration of the social science and humanities into Astrobiology.

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Introduction

Astrobiology, Interdisciplinary Research, and Society

Since its inception in 1958, the National Aeronautics and Space Administration (NASA) has accomplished previously inconceivable feats of scientific advancement from putting satellites in orbit to landing the first humans on the moon. By continually pushing current technological boundaries in space flight and cosmic data collection, NASA remains a leading force in scientific research. It does this primarily by stimulating interest in space exploration, science, and technology for the public. Although founded over 55 years ago, NASA initially, and repeatedly since then, advanced projects that require integrated teamwork of multiple disciplines. Perhaps more importantly, however, is how these groundbreaking projects, many including exploration of space, have inspired humanity to view Earth and the Universe in a new way with questions such as 1) How does “life,” defined as a “self-sustaining chemical system capable of Darwinian evolution,” (Mullen, 2013, p.1) in the Universe begin and evolve? 2) Does life exist elsewhere in the Universe? & 3) What is the future of life on Earth? All of these questions have increasing societal interest and answering them has become an objective at NASA.

Although NASA has been advancing multidisciplinary research since its inception, these new questions are more challenging and complicated than objectives outlined for previous missions at NASA that put satellites in orbit, as they are rooted in concerns directly related to the origin of life and future of humanity. And although the number of interdisciplinary research (IDR) projects¹ has increased across all scientific fields in the past 30 years (Fiore, 2008), some suggest that modern science has proved helpless in the face of complex problems – no matter how successful collaborative projects have appeared in the previous decades (Berkes, Colding, & Folke, 2003). Arguments have been made that these increasingly complex problems, which usually transcend traditional disciplinary boundaries, will require collaboration

Complexity is certainly a key issue addressed by interdisciplinary research projects. New theories about modes of IDR, especially that based in Psychology and Sociology have been increasingly reorganized as important (Gibbons et al., 1994; Sokolova, 2013). The primary measure of success in IDR is the ability to address complexity, and arrive at a new, holistic understanding of an investigated problem (Repko, 2012). Such

¹ IDR is defined as "a process of answering a question, solving a problem, or addressing an issue that is too broad or complex to be dealt with adequately by a single discipline or profession... [It] draws on disciplinary perspectives and integrates their insights through construction of a more comprehensive perspective" (Klein & Newell, 1998, p.3).

integration differs from a separate, individualistic disciplinary approach; instead, it addresses problems as a whole, rather than as a mere sum of its parts.

The creation of life on Earth is an example of an interdisciplinary topic – specifically the different perspectives and views on the origins of life. The different perceptions of how life began cannot be understood without first understanding the various disciplinary perspectives on life. In particular, disciplines offer understanding on the differing perceptions and histories. To approach researching the creation or evolution of life, a well-rounded position would take into account variety of perspectives from Biology, Theology, Psychology, Sociology, and maybe even Political Science. From these disciplines, an understanding of whether life (Biology) has evolved, the reasoning behind positions or beliefs (Theology) of various groups, the implications (Sociology) of particular views about life, and the utility of current laws and their social effects (Political Science) could be useful in answering the previously raised questions.

Approximately 16 years ago, NASA made a decision to restructure its funding operations to allow more collaboration among researchers in an effort to answer these questions by formalizing its study under “Astrobiology.” Recognizing the complexity and magnitude of this new field, NASA sought to promote combining the disciplinary knowledge of university researchers, academics, and industrialists under one integrated

research effort known as the NASA Astrobiology Institute (NAI). It is headed and funded by NASA, providing support for collaborative research projects related to Astrobiology, and allowing access to data that normally would not be available outside NASA.

At about the same time as the forming of the NAI, Universities including University of Arizona, University of Washington, and Penn State University began offering certificates of completion and dual-PhD degrees in Astrobiology. As such, Astrobiology became a solid research focus for a variety of disciplines including the Geosciences, Physics, Engineering, and Biology. To house this new research and knowledge produced by these efforts, academic journals such as *Astrobiology* were formed. Captured in these articles is the disciplinary thought of researchers in the form of focused knowledge production, which subsequently defines the boundaries of Astrobiology as a field. By analyzing these articles, the representation of individual disciplinary contributions can be determined.

As will be shown in this thesis, the journal *Astrobiology* published 768 research articles between 2001 and 2012, 98% of which were interdisciplinary according to counts of the number of different disciplinary journals cited. Yet less than 3% of the research articles had citations from or were co-authored by scholars in the Humanities or Social Sciences. Further, almost all research was co-authored by researchers in similar disciplines.

The fact that Astrobiology covers topics addressing complex social, cultural, and ethical questions should make interdisciplinary research a foundation of Astrobiology studies. Interdisciplinary research is a necessary tool for studying complex problems. One of the objectives of this thesis is to explore the trends of knowledge production and determine if Astrobiology is based in single disciplinary studies, or rather moving towards interdisciplinary research.

But to truly understand the nature of IDR, I propose we look at it from another viewpoint, specifically a spatial one. With the intent to understand how research is situated in Astrobiology, a field some claim contains over 110 disciplines (Aydinoglu, Suomela, & Malone, 2014), spatial representation of the interactions between Astrobiology disciplines is necessary to obtain an understanding about trends in research. Specifically, such spatial interactions or mapping could assist in understanding relationships and diversity among these disciplines by deconstructing their cognitive base (Van Raan, 2000; Bordons, Morillo, & Gomez, 2004; Porter *et al.*, 2006 and 2007). In this thesis I map two things – The disciplinary origins of articles appearing in *Astrobiology* between 2001 and 2012 as well as the disciplinary citations produced in these articles.

The maps will help identify, to a certain extent, the degree to which disciplines have become integrated. I also will explore the potential cause of these relationships. To accomplish this, literature describing the

psychological and social barriers of interdisciplinary research will be examined. Further, I consider external influences on knowledge production, especially that of the NASA Astrobiology Institute. My intent is to identify disciplines and the relationships associated with IDR and to help foster a more interdisciplinary Astrobiology, one that includes the Social Sciences and Humanities in its research.

This thesis is organized into six chapters. The first chapter is an introduction. Chapter 2 covers the process of knowledge production, defines disciplinary, multidisciplinary, and interdisciplinary research, and covers theories used to describe integrated, interdisciplinary work. Chapter 3 presents the history, development, and current state of Astrobiology. Chapter 4 presents and discusses the methods used to map the disciplinary origin as well as citations to other disciplines and relationships in *Astrobiology* articles published from 2001 to 2012. Analysis of these maps is discussed in Chapter Five. Chapter 6 concludes with recommendations for IDR research within Astrobiology as well as further research that I would like to conduct.

Knowledge Production and Interdisciplinary Research

The advancement of IDR in the 1960s was connected with seeing a need for major changes at United States universities including attempts at adoption of a holistic worldview in problem solving, and the call for academia to serve actual societal needs (Klein, 1990; Repko, 2012). This academic change followed shortly after the passing of many significant laws directing appropriate agencies to explore social and economic effects of certain government actions. These laws included the Civil Rights Act (1957), Interstate Highway Act (1956), Food, Drug & Cosmetic Act (1956), and the National Aeronautics and Space Act (1958). Latané (1981) has argued that such academic change following in the wake of passage of these Acts is not coincidental. Government agencies including NASA may be viewed as leaders in IDR, and even perhaps bearing the responsibility of how it developed.

There may, in fact, be a correlation between passage of federal laws and the heightened awareness of societal needs at universities. Yet the production of knowledge is still the domain of individual disciplines. In this section knowledge production is covered from its most basic meaning to more complex knowledge production methods. Then, an explanation about the differences in disciplinary, multidisciplinary, and interdisciplinary research is put forth. Finally, psychological and sociological research

ideas of IDR are covered.

What is Research?

Research in its simplest form is exactly what the French root *recerchier* and its derivative *recherché* are defined as – to go about searching and seeking (Research, n.d.). For most people, research is about seeking information, whether to better understand a health care plan or decide what political candidate would best represent their personal interests. In either case, someone is searching for information to increase his or her knowledge on a subject. Martyn Shuttleworth (2008) gives the oft-cited and broad definition as “any gathering of data, information and facts for the advancement of knowledge” (para. 1). He states that reading a factual book or even surfing the Internet (if information is gained) is a type of research.

Other definitions exist, however, that eschew the mere gathering of data, collecting of observations, recording of experiences, developing of plans, and discussion among stakeholders to solve real-world problems as research. For example, while these may be valuable activities, Winder states knowledge creation first becomes research when the data and information we have gathered are systematized, analyzed, and fed back into academic communities (2003). This is, in fact, what distinguishes scientific knowledge from non-scientific knowledge (Audi 2003).

From my personal worldview, research is a unique or creative form of work that follows a system or protocol in order to produce new information – both in and outside academia. For my purposes, information is a new product conveyed or presented to others. The purpose of the work is to develop an informed opinion. This is achieved when information on what others have written on the subject has been acquired and shared. Information by definition needs to be shared to become research. In contrast, work that produces “information” not shared with others is beneficial only to the researcher, and could be considered part of his or her skill acquisition.

In contrast to my working definition, research is usually understood as a process to produce new knowledge to deepen our understanding of a specific phenomenon. This could include work of direct relevance to the needs of commerce, industry, and the public. Research pushes forward the boundaries of knowledge within a particular discipline and challenges existing subject boundaries (RAE 2001).

No matter which definition is followed, the hourglass image or model seems reasonable to assume for how research is conducted. The hourglass model begins with a huge breadth for research, begins narrowing by focusing on the pertinent information (like the neck of the hourglass), as defined by the methods, and then expands in the form of discussion and results. The typical steps followed in conducting classical

research are:

- Identifying the research problem
- Reviewing literature to collect as much existing information on the problem as possible
- Clarifying or defining the purpose of research
- Determining specific research questions
- Choosing a conceptual framework or hypotheses
- Choosing a methodology for data collection
- Collecting data
- Analyzing and interpreting the data
- Reporting and evaluating research
- Communicating the research findings and recommendations. (Trochim, 2006)

All of these steps are critical and should not be compromised in any manner. While one may conduct research individually, it is not a solitary activity. Research is built on the knowledge that others have acquired and shared and also provides direction for the next researcher. Research is an ongoing, collaborative process and should not be compromised by deviating from the proper steps.

What is Knowledge Production?

According to the Oxford English Dictionary, knowledge is “facts,

information, and skills acquired by a person through experience or education; the theoretical or practical understanding of a subject” (Knowledge, n.d., para.1). In practice, however, there are many possible variations of this definition. For example, “[knowledge is] the ideas or understanding which an entity possesses that are used to take effective action to achieve the entity's goals.... and is specific to the entity which created it” (Denning, 2000, p. 6). Denning further stipulates that understanding of knowledge requires a firm grasp of its implicit relationship with information.

Distinguishing among information, data, and knowledge can be problematic. Drucker (1993) states that “knowledge is like the sound of the tree that falls in the forest when no one is there: it doesn't exist unless people interact with it” (p. 16). More specifically, knowledge is information that changes something or somebody – either by becoming grounds for actions, or by equipping an individual or institution to be capable of different or more effective action (Igonor, 2002). Fleming contextualizes the relationship of knowledge and information using degrees of context and understanding below:

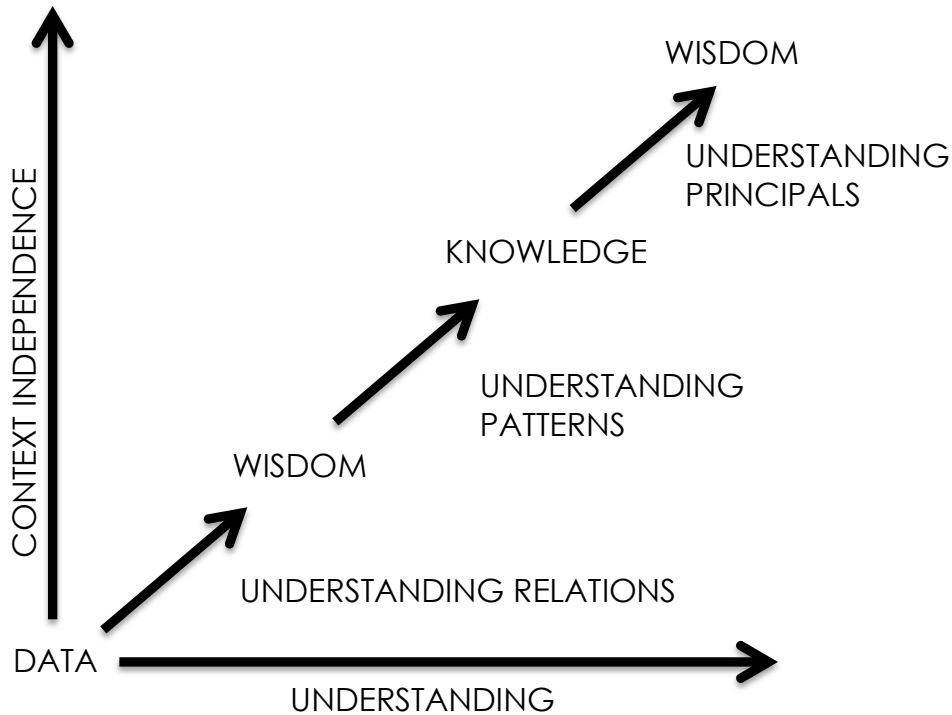


Figure 1 - Flowchart of Knowledge Production.
(Adapted From Fleming 1996)

Fleming concludes that information relates to description, definition, or perspective – who, what, where, and when. Knowledge, however, requires strategy, practice, method, or approach – how. And wisdom embodies insight, moral dimensions, or archetype – why.

In the academic sense, new knowledge is generated through research. Gibbons et. al. classified and distinguished modes of knowledge production in their book *The New Production of Knowledge* (1994). Specifically, they distinguished between what they call “Mode 1” and “Mode 2” knowledge production as well as the five primary categories

that comprise them. Mode 1 is the more traditional mode of knowledge production – discipline-based, linked to cognitive processes, and characteristic of university-style research, often referred to as pure knowledge. Mode 2 is characterized as applied knowledge production, linked to contextualized applications, transdisciplinary² in nature, meant for problem solving, and characteristic of networked research (Choung, 2014). Below in Table 1 is Hessels and Lente's (2008) comparison of these research types.

	Mode 1 ("pure knowledge")	Mode 2 ("applied knowledge")
Problem solving	Academic context	Context of application
Knowledge base	Disciplinary	Transdisciplinary
Extent of organization	Homogeneity	Heterogeneity
Process of knowledge production	Autonomy	Social accountability
Quality of knowledge	Traditional / Peer review	Novel quality control

Table 1 – Mode 1 vs. Mode 2 Knowledge Production. (Adapted from Choung 2014)

² Transdisciplinary is nearly identical in meaning to interdisciplinary, but involves non-academic participants.

Problem Solving – Mode 1 problems are set and solved in a context governed by the interests of a specific community such as a research discipline. Mode 2 knowledge production takes place in a context of application which involves a much broader range of perspectives.

Knowledge Base – Knowledge is formal and defined according to the procedures of academic disciplines in Mode 1. In Mode 2, however, knowledge is problem-oriented. Specifically, multiple disciplines are used to solve problems by drawing on their respective disciplinary knowledge and applying it simultaneously. New knowledge is that which is not easily reducible to any one academic discipline.

Organization – In Mode 1, disciplinary knowledge is usually developed at universities and other institutions of higher education. These institutions are considered isolated in relation to real-world problems. In Mode 2, problem-solving teams produce knowledge with members from various institutions: firms, government institutions, research universities, and laboratories.

Process of Knowledge Production – In Mode 1, the reference points for disciplinary knowledge are academic peers and others in the discipline itself. In contrast, Mode 2 knowledge production addresses many problems of great social importance or commercial value.

Quality of Knowledge – Mode 1 employs the traditional peer review process associated with academic journals for quality control. While peer

review exists in Mode 2, it also includes a wider, more temporary and heterogeneous set of practitioners, collaborating on a problem defined in a specific and localized context.

A significant point of emphasis in this review is that both forms of knowledge production can co-exist, and will continue to coexist. They are neither mutually exclusive nor completely independent of one another. In reality, their co-existence depends as much on the response of institutions that are currently supporting Mode 1 as on the social diffusion and application of Mode 2 (Choung, 2014).

What is the Nature of Academic Journals?

Science is rooted in the production of knowledge, which is a shared experience based on a common understanding of some aspect of the physical or social world. For that reason, conventions of science must be followed in order to maintain the validity and reliability of scientific knowledge (Committee, 1995). Subsequently, if these conventions are ignored, the quality of science can suffer.

Refereed publishing by means of academic journals is one of those conventions and allegedly began in 1665 when Henry Oldenburg created the world's first scientific journal *Philosophical Transactions* for the newly founded Royal Society of London. The purpose of his journal was to solve a number of problems faced by early scientists publishing randomly, but

foremost was the desire to establish precedence of findings. Frankly, early authors wanted to be publicly acknowledged and their claim to knowledge secured before sharing their results with colleagues (House, 2014).

One of the traditions *Philosophical Transactions* also created was registering the name of the authors, as well as the date manuscripts were received by Oldenburg. This information, as well as the manuscript's contents, were recorded and published in each issue. Clearly, this would secure their claim and allow them to share their results without fear of intellectual theft. Not all works were published in their entirety since the Council of the Royal Society, before approval of publication, reviewed all of them. Apparently, this is the first recorded instance of peer review. Further, collecting and consolidating the issues created as a repository of scientific knowledge. Surprisingly, the four tenets of *Philosophical Transactions* – registration, dissemination, peer review, and archival record – were so profound that most journals still follow them today.

Academic journals are more than just a conglomeration of these tenets, however; for they perform a unique role in scholarship. They contain articles that serve as on-the-record, validated public statements of the claims made by its authors (House, 2014). They use peer review to protect scientific integrity and promote the sharing of research with other colleagues. They can help authors discover problems and help strengthen

the credibility of their research. The necessity of having quality control measures for published work, thus, is important to the scientific community, and without such measures, the quality of published work would not be what it is today.

What are Disciplines?

When searching literature for the definition of a discipline, one theme becomes abundantly clear – there is little consensus in academia on the term. Historically, the Oxford English Dictionary suggested the origin of discipline refers to the student: "Etymologically, discipline, as pertaining to the disciple or scholar, is antithetical to doctrine, the property of the doctor or teacher; hence, in the history of the words, doctrine is more concerned with abstract theory, and discipline with practice or exercise" (Discipline, n.d., para. 1).

Other definitions are "when groups of scholars share a cluster of interests, methods of study, and norms of communication, they participate in a discipline" (PORT, 2013, para. 1) and "disciplines are defined in part and recognized by the academic journals in which research is published as well as the institutions and academic departments to which faculty belong" (Finkelstein, 1983, p. 100). Both definitions suggest a similar organization of disciplines in the form of a tree structure, with branches of science at the top, which are then broken

down into sub disciplines. For example, common branches of science are:

- Natural Sciences
- Mathematics
- Social Sciences
- Humanities (including Linguistics and the Arts)
- Professional and Applied Sciences

Structured below, or as part of these branches are disciplines, such as Geology and Earth Sciences falling under the Natural Sciences or Psychology and Anthropology belonging to Social Sciences.

There doesn't exist a formal criterion for the status of an academic discipline. Thus, the classification scheme should be considered fluid. Disciplines vary between well-established ones that exist in almost all universities and have well-defined rosters of journals and conferences and obscure ones supported by only a few universities and publications. A major discipline usually has several sub disciplines or branches, and the distinguishing lines between these are often both arbitrary and ambiguous (Abbott, 2001).

Nonetheless, “discipline” has clearly become a term for the organization of learning and the systematic production of new knowledge (Krishnan, 2009). Disciplines are identified with subjects taught at universities, but there is more to disciplines than performing a “supervisory” role regarding subjects taught in an academic setting.

Krishnan provides a list of criteria to indicate whether a subject is indeed a distinct discipline (2009):

- 1) disciplines have a particular object of research, but may be shared with another discipline;
- 2) disciplines have a body of accumulated specialist knowledge referring to their object of research, which is specific to them and not generally shared with another discipline;
- 3) disciplines have theories and concepts that can organize the accumulated specialist knowledge effectively;
- 4) disciplines use specific terminologies or a specific technical language adjusted to their research object;
- 5) disciplines have developed specific research methods according to their specific research requirements; and, perhaps most crucially
- 6) disciplines must have some institutional manifestation in the form of subjects taught at universities or colleges, respective academic departments, and professional associations connected to it. (p. 9)

From these criteria it becomes clear that narrowness of focus is fundamental to the concept of academic disciplines. A discipline is then by proxy, the practice of focus. Repko provides a recent and more refined definition compiled from certain criteria (2012):

Academic disciplines are scholarly communities that specify which phenomena to study, advance certain central concepts and

organizing theories, embrace certain methods of investigation, provide forums for sharing research and insights, and offer career paths for scholars.... Each discipline has its own defining elements, phenomena, assumptions, epistemology, concepts, theories, and methods that distinguish it from other disciplines. (p. 4)

In contrast, Petts et al. (2008) suggest that “disciplines are constructs borne out of historical processes involving both objects and methods of study” and further states “disciplines produce criteria of scientific practice, shape careers, and are deeply structured” (p. 596). Buanes and Jentoft (2009) emphasize the importance of disciplines in identity formation: “Disciplines provide members with access to a knowledge base, but also with a personal and professional identity embedded in an epistemic community” (p. 449).

Further, a discipline defines boundaries – determining what is to be considered, and what is not. The process of defining and focusing upon what is to be studied is the process of specialization. And “it’s this observable process of specialization that allows the tracking and change of disciplines over time through academic journals and published research” (Dirks, 1996, para. 12). I propose that the development of a discipline begins with the specialized research of scholars who focus on a new piece of knowledge. A community of researchers then forms around this knowledge, and then defines a method of research for exploring it.

Development of the community depends upon support from universities, academic departments, or institutions to keep the discipline from disappearing into obscurity. Also, the knowledge needs to be reproduced and passed on “from one generation to the next by means of specific educational preparation” (Apostel, 1979, p. iv), referred to as institutionalism.

Understanding the organization of science in disciplines is somehow taken for granted as a part of knowledge production. The formation of new disciplines, however, comes with institutional conditions (Woodward, 1991). For example, when the genesis of a new discipline that crosses traditional boundaries takes place, the worldviews and disciplinary culture of the discipline with the strongest presence has a tendency to become the point of integration. Thus, the theories and methods of the minor disciplines conform to the strongest (Gibbons et al., 1996). When this effect is combined with institutional policy, which normally represents the strongest individual discipline, choosing the individual members with least resistance to change is the easiest path. As such, a club mentality, or good ol' boy structure can take hold.

Disciplinarity, Multidisciplinarity, and Interdisciplinarity

This section will provide definitions and discussion the concepts of disciplinarity, multidisciplinarity, and interdisciplinarity. Since the concept

of interdisciplinarity is complex, exists in many forms and with many interpretations, first understanding disciplinaryity may help clarify interdisciplinary characteristics.

A discipline represents a group of researchers working on a specific set of research questions, using the same set of methods, and working towards a similar goal – and thus, disciplinaryity is the act of that research. Disciplinary studies embody the “normal problem solving” that takes place within the bounds of a single, recognized academic discipline within a “paradigm” (Kuhn, 1962). An example of disciplinary research is a geologist trying to locate rocks on Earth that are similar to those on Mars. After the Mars rovers provided data about rock types and mineral abundances on the planetary surface, similar environments on Earth could then be identified and studied as analog environments. The purpose was to understand geological processes on Mars using the research practices and knowledge of Geology, but then relate such study back to phenomenon on earth.

Multidisciplinarity is a project that involves several different academic disciplines researching one theme or problem but with multiple disciplinary goals. Knowledge is exchanged among participants from their respective disciplines, but they do not aim to cross subject boundaries to create new knowledge and theory. The research process occurs in

parallel with the purpose of comparing results, but without integrating disciplinary knowledge.

Borda et al.'s (2001) research titled *Pyrite-Induced Hydrogen Peroxide Formation as a Driving Force in the Evolution of Photosynthetic Organisms on an Early Earth* exemplifies multidisciplinary research. The common theme of the project was to investigate how biomarkers of organisms that required oxygen to live could be found in 3 billion-year old rocks, a time prior to significant oxygen levels on Earth. Geologists had found biomarkers while dating the rocks that were inconsistent with similar aged formations. Biologists shared their disciplinary knowledge of photosynthesis to insist oxygen would need to be available for the discovered biomarkers to be present, and said the rock must be much younger than expected.

Geochemists – geologists specializing in Earth chemistry – then provided a plausible scenario. In the absence of high levels of oxygen, pyrite is stable and reacts with water to create hydrogen peroxide. This reaction creates free oxygen, thus providing the mechanism for early photosynthesis to develop. In this example, all of these separate disciplines worked towards one theme, sharing their disciplinary knowledge, and loosely collaborating while advancing their discipline by cataloguing the rock record (Geology) and increasing their understanding of photosynthesis and early life (Biology).

Klein & Newell (1998) define interdisciplinarity as:

a process of answering a question, solving a problem, or addressing a subject that is too broad or complex to be dealt with adequately by a single discipline or profession... [It] draws on disciplinary perspectives and integrates [their] insights through construction of a more comprehensive perspective. (p. 393)

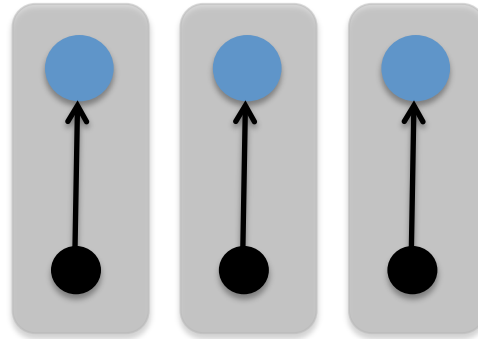
The National Academies report (Committee, 2005) on facilitating interdisciplinarity research focuses more on the process than the product by stating

interdisciplinary research is a mode of research by teams or Individuals that integrates 1) perspectives/concepts/theories and/or 2) tools/techniques and/or 3) information/data from two or more bodies of specialized knowledge or research practice. (p. 26)

From these definitions a more applied version is created for this thesis. Specifically, interdisciplinary projects involve several unrelated academic disciplines in a way that forces them to cross subject boundaries in order to create new knowledge and theory. The purpose is to solve a common research question. Unrelated means that the disciplines have contrasting research paradigms, such as qualitative and quantitative or between analytical and interpretative approaches to research. An example would be a project that brings together researchers from both the Humanities and the Natural Sciences. This is illustrated on the next page in Figure 2.

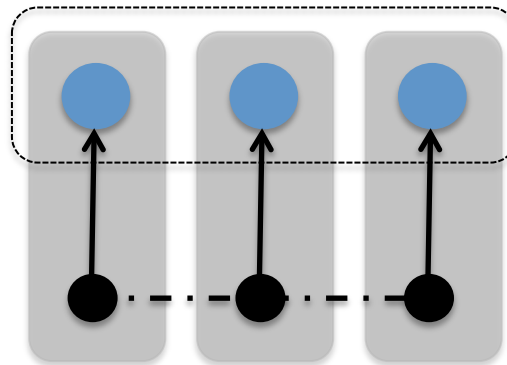
Disciplinary

- Within one academic discipline
- Disciplinary goal
- No cooperation with other disciplines
- Development of new disciplinary knowledge



Multidisciplinary

- Multiple disciplines
- Multiple disciplinary goals under one theme
- Loose cooperation with other disciplines for exchange of knowledge
- Disciplinary theory development



Interdisciplinary

- Crosses scientific and academic boundaries
- Common goal setting
- Integration of disciplines
- Development of integrated knowledge and theory

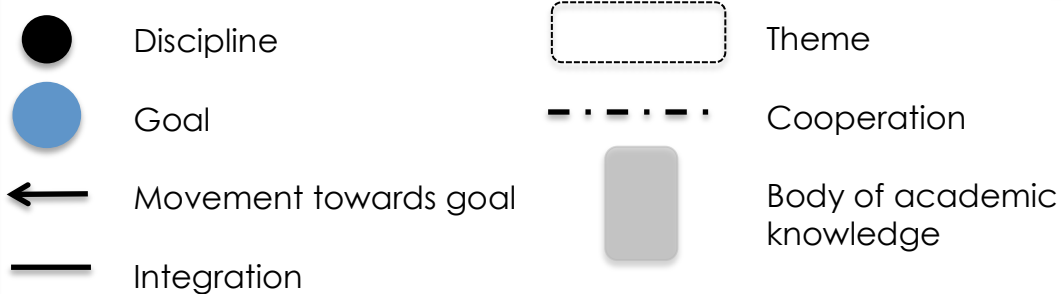
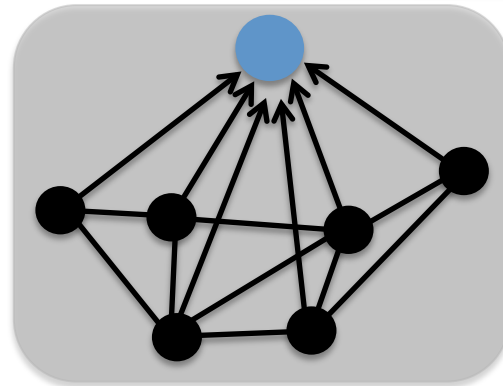


Figure 2 – Disciplinarity, Multidisciplinarity & Interdisciplinarity.
(Adapted from Tress, Tress, & Fry 2006)

Theoretical Foundations of Interdisciplinary Research

Perhaps the main feature of interdisciplinarity is its dual nature as a cognitive and a social process (Sokolova 2013). Lave (1991) suggests that cognition is socially shared, while others stress that social and cognitive processes that occur during group interaction are tightly interwoven (O'Donnell et al., 1997). However, for analytical purposes these theories are divided into two; those derived from both Sociological and Psychological ideas (Sokolova, 2013).

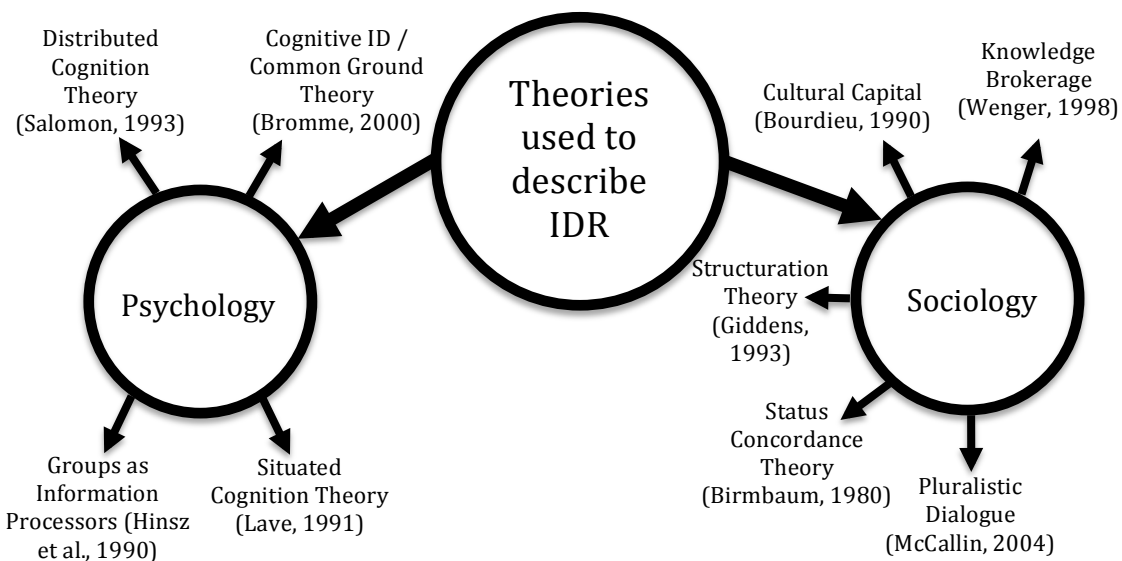


Figure 3 – Theories commonly used to describe and characterize Interdisciplinary Research. (Adapted from Sokolova 2013.)

Theories from Psychology

Bromme (2000) explores IDR through cognitive psychology, looking at the cognitive processes of a group, as well as at the individual traits of researchers crucial to the success of interdisciplinary research. He builds a theory of cognitive interdisciplinarity upon the theory of common ground developed by Clark (1996), which describes the processes of establishing a basis for comprehension. Common ground primarily deals with language as an instrument of communication. Bromme writes about language difficulties that researchers from different academic backgrounds encounter, and the necessity of establishing a common language.

Situated cognition theories (Lave, 1991) view teams as communities regulated by norms and language, functioning within cultural contexts (Lave, 1991). Negotiation, which begins at the inception of disciplines coming together, is essential to align the various languages. A secondary effect of negotiation, however, is that some disciplines might acquire higher status than others, which can become problematic for integrating disciplinary knowledge.

Similarly, the theory viewing groups as information processors applies the understanding of individual cognitive processes to a group (Hinsz, Tindale, & Vollrath, 1997). This theory explores how individual

knowledge is shared and modified within a group, and which information is transferred. During interactions among individuals a working memory is activated, representing the ideas that individuals have at that. If such ideas are shared, they become part of a collective working knowledge. Similar to situated cognition theory, disciplinary status might affect the process of sharing information, silencing certain types of knowledge, or moving aside to more dominant forms.

Distributed cognition theory extends information processing theory by drawing more specific parallels between the elements of individual and group information processing, such as long-term and working memory (Salomon, 1993). Long-term memory of a group is conceived as the information distributed among its individuals, some of which is shared by the group, whereas some remains private (Sokolova, 2013). The theory describes the development of the group in time, in which its knowledge and skills change as a result of continuous interactions of its members, and the exchange becomes more organized (Salomon, 1993).

In summary, the reviewed theories from cognitive psychology highlight: the importance of common language; the importance of negotiation; the influence of status in the creation of new knowledge; and the emergent properties of knowledge that is created by overcoming the limitations of single investigator driven research.

Theories from Sociology

The common theme in sociological theories is that scientific disciplines are a reflection of the social system of knowledge production in general. In particular, Lingard et al. (2007) acknowledges three sociological theories in their analysis of IDR: knowledge brokerage (Wenger, 1998); cultural capital (Bourdieu, 1990); and structuration theory (Giddens, 1993). According to Sokolova (2013):

The three theories allow the authors to show how they act as knowledge brokers, crossing boundaries between disciplines and aligning their diverse languages, creating a common unified knowledge; analyze the way in which they negotiate on the basis of diverse value systems, as well as the amount of cultural and symbolic capital possessed by each individual as a result of belonging to a particular discipline, and [to demonstrate] the way in which they agree on the meaning and value of their work; finally, reflect on the structure and agency of IDR: how the underlying structures influence the process and are in turn recreated or transformed by the group processes. (p. 12)

The authors emphasize that it is important to negotiate “identity” in an interdisciplinary team, and that writing is complicated by the political decisions based on the current academic value structure. For example,

the second name to appear in order on a publication is valued higher than the third or fifth.

The theory of pluralistic dialoguing suggests that the researchers on an interdisciplinary team engage in constant discussions, communications, and debates (McCallin, 2004). For this method to succeed, however, team members must challenge their own ways of thinking, often a product of disciplinary culture, and be open to new scientific perspectives. Pluralism implies that they are ready to embrace such perspectives in order to develop an understanding of the problem at hand (Sokolova 2013). As seen with many of the theories in psychology, the issue of power and positioning among the disciplinary cultures is brought up.

Birnbbaum and Gillespie (1980) provide a study of interdisciplinary collaboration on the basis of status concordance theory, according to which there exists a hierarchy of status among researchers according to their professional level in academia, their role in the project, and the perceived prestige of their discipline. This is usually more prevalent during the early stages of research and diminished as time progresses because the “whole” work product then outweighs the initial perceptions of status. Thus, a barrier is presented before research ever begins and must be overcome prior to collaboration. Strang (2010), for example, noted the

difficulties encountered when integrating the social and natural sciences:

Equality is rarely achieved. Research collaborations are also social, economic, and political relationships to which people bring very unequal levels of social, economic, and political capital. ... In addition to these delicate issues of relative wealth and status, each disciplinary area has a distinct culture and identity composed of its ways of thinking, its theory and methods and its particular languages. Collaborative research needs to be organized so that people can be confident that their disciplinary identities will not be denigrated, appropriated, or consumed by assimilations. (p. 6)

Similarly, Rosenfield and Kessel (2008) also identify status barriers as a factor constraining collaborative research. They stated that Sociology researchers often found themselves ignored by other scientists, or their contributions to a project being regarded as inferior. Finally, Petts et al. (2008) pointed out how some disciplines may be given more attention and privilege than others. For example, projects often focus on the scientific aspects of a problem, while social and cultural factors are ignored.

Campbell (2005) supports the view of the importance of power relationships in an interdisciplinary research group, and states social scientists are sometimes invited to a project as an afterthought, or to fulfill funding criteria. This dynamic leaves social scientists in a powerless

situation and contributions are not integrated with the primary research problem. Others suggest the power issue stems from the nature of disciplines themselves, and ultimately shape the culture of disciplines through enforcement of social and institutional conditions (Murphy, 2011).

In summary, the theories from sociology highlight; knowledge brokerage across disciplines in creating a common knowledge; distribution of cultural capital; negotiation of identity; disciplinary thinking; as well as status, power, and culture as important components of interdisciplinary research.

Conclusions

The most important aspect from this section is that IDR plays a fundamental role in collaborative science endeavors. Interdisciplinary research is rooted in disciplines and relies on the integration of various insights. Disciplines should be viewed as communities, and their epistemic foundations define them based on both their diversity and specialization. Although traditional single-investigator driven (disciplinary) approaches are ideal for many scientific endeavors, coordinated teams of investigators with diverse skills and knowledge may be helpful for studying complex social problems with multiple causes, as with Astrobiology (National, 2008).

What is Astrobiology

History and the Changing Definition of Astrobiology

The first record of the term Astrobiology³, at least as it is used today, was recorded on 26 March 1995 when a NASA manager presented a research plan titled “Life in the Universe” to the chief scientist and administrators at NASA (Dick, 2006; Strick, 2004). In the presentation, a case was made that barriers between the separate research disciplines at the NASA Ames Research Center should be removed, allowing unhindered collaboration in the production of cutting edge science. While many changes resulted from the meeting, one is of particular note – the chief administrator for space sciences, Wes Huntress, said he preferred the term “Astrobiology” over “Life in the Universe” (Dick & Strick, 2004). This statement was the first step in Astrobiology becoming a recognized field of science.

The first official definition of Astrobiology appeared in the 1996 *NASA Strategic Plan* as

the Study of the living Universe. This field provides a scientific foundation for a multidisciplinary study of (1) the origin and

³ The term “Astrobiology” has only begun to appear with any substantive frequency in the past 20 years, but science conducted in the field has been recorded to at least the 19th century (Billings, 2012). See (Billings, 2012) and (Dick & Strick, 2004) for a detailed account of the development of Astrobiology and related research efforts prior to the formation of the NASA Astrobiology Institute (NAI).

distribution of life in the Universe, (2) an understanding of the role of gravity in living systems, and (3) the study of the Earth's atmosphere and ecosystems.

The plan also said that the Ames Research Center “has been assigned the lead role for Astrobiology within the agency” (p. 2).

But the definition was not solid. In September 1996, during a three-day workshop comprised primarily of NASA scientists, but also including academics and industry contractors, the definition was elaborated upon. This group decided that Astrobiology could best address the three aforementioned research questions by focusing research on the origins of life, interactions between Earth and its biosphere, sustaining life in space, and the human exploration of Mars. Over the next two years, budget cuts were made at NASA, but the public's interest in Astrobiology was growing (Dick & Sticker, 2006). To mitigate the costs while keeping the Astrobiology initiative moving forward, NASA partnered with academic institutions to continue research projects.

These collaborations were so successful that in May 1998, NASA announced the formation of the NASA Astrobiology Institute (NAI) and designated it as "launching a major component of NASA's Origins Program," whose purpose was to determine if other Earth-like planets exist and if life had taken hold on nearby planets. Their intent was to create an innovative way to develop the field of Astrobiology and provide a

scientific, astrobiological framework for understanding flight missions. Since that time, NASA Headquarters, i.e. management, has provided the institutional home and determined the organizational structure for Astrobiology. While discussed later, the most significant aspect of NAI is that it organizes and describes a set of research goals for Astrobiology every 5-6 years through a published document called the “NASA Astrobiology Roadmap.”

In 1998, the NAI described Astrobiology in their Roadmap and publically as

the study of life in the Universe. It provides a biological perspective to many areas of NASA research, linking such endeavors as the search for habitable planets, exploration missions to Mars and Europa, efforts to understand the origin of life, and planning for the future of life beyond Earth. (NASA, The Astrobiology Roadmap 1998, para. 1)

Later in 2003, the definition was refined and expanded:

Astrobiology is the study of the origins, evolution, distribution, and future of life in the Universe. It requires fundamental concepts of life and habitable environments that will help us to recognize biospheres that might be quite different from our own. Astrobiology embraces the search for potentially inhabited planets beyond our Solar System, the exploration of Mars and the outer planets,

laboratory and field investigations of the origins and early evolution of life, and studies of the potential of life to adapt to future challenges, both on Earth and in space. Interdisciplinary research is needed that combines molecular biology, ecology, planetary science, astronomy, information science, space exploration technologies, and related disciplines. The broad interdisciplinary character of astrobiology compels us to strive for the most comprehensive and inclusive understanding of biological, planetary and cosmic phenomena. (NASA, The Astrobiology Roadmap 2003, para. 1)

This definition remained intact, although the goals of the NAI were changed slightly, until 2012.

In 2012, NASA was using the following description on their Astrobiology webpage, which was written by Dr. Linda Billings many years earlier for NASA (personal communication):

Astrobiology [as] the study of the origin, evolution, distribution, and future of life in the Universe. This multidisciplinary field encompasses the search for habitable environments in our Solar System and habitable planets outside our Solar System, the search for evidence of prebiotic chemistry and life on Mars and other bodies in our Solar System, laboratory and field research into the origins and early evolution of life on Earth, and studies of the potential for life to

adapt to challenges on Earth and in space.

(<http://science.nasa.gov/planetary-science/astrobiology/>, para. 1)

As of October 2014, the working definition according to NASA's website is that

Astrobiology is the study of the origins, evolution, distribution, and future of life in the Universe. This interdisciplinary field requires a comprehensive, integrated understanding of biological, geological, planetary, and cosmic phenomena. Astrobiology encompasses the search for habitable environments in our Solar System and on planets around other stars; the search for evidence of prebiotic chemistry or life on Solar System bodies such as Mars, Jupiter's moon Europa, and Saturn's moon Titan; and research into the origin, early evolution, and diversity of life on Earth. Astrobiologists address three fundamental questions: How does life begin and evolve? Is there life elsewhere in the Universe? What is the future of life on Earth and beyond? (<http://astrobiology.nasa.gov/nai/about/>, para.1)

Of particular importance is that no other definition of Astrobiology exists in Western academic literature. Some European scholars prefer the term Bioastronomy; which is defined similarly to NASA's Astrobiology definition, so the difference is only semantic. And while Astrobiology programs exist at universities and other institutions, I have found no better alternative definitions to those provided by the National Aeronautics and Space

Administration.

Astrobiology in Practice: Involvement in NASA Space Missions

Robotic space missions are part of NASA's work, and the development of these missions helps to shape research projects at the agency. The NAI is directly involved in NASA missions by participating in the selection of mission targets, supporting the development of science instruments and mission architecture, and performing the analysis of data received by the equipment. Mission parameters at NASA are shaped in part by research supported by the Astrobiology program and in turn, the results from NASA's missions serve to guide the future of astrobiology research.

Below is a timeline and summary of missions that includes specific participation by astrobiologists and supported by elements of the Astrobiology program. There are currently 12 active missions, summarized in **Table 2 – NASA Space Missions**, below:

Mission	Years Active	Relevance to Astrobiology
Hubbel	1990 - Present	Identify habitable worlds, planet formation, and age of the universe.
Cassini/Titan	1997 - Present	Study life potential and possible habitation of other planets and moons.
Mars Odyssey	2001 - Present	Provide maps and chemical elements on Mars. Also communication beacon for MERS.
MERS	2003 - Present	Search for and characterize rocks for evidence of water activity and life possibility on Mars.
Spitzer	2003 - Present	Telescope for looking at distant galaxies,

		searching for life and organic molecules on habitable planets.
SOFIA	2007 - Present	Study formation of new solar systems, identify complex molecules in space, observe planets.
Dawn	2007 - Present	Study remnants of early solar system to determine if water could have been delivered to Earth from them.
Kepler	2009 - Present	Identify potential habitable planets and identify signs of life elsewhere in Universe.
O/OREOS	2010 - 2011	Determine microbe viability/survivability in Space.
Space Lab	2011 - Present	Mars habitability, climate, and Geology.
LADEE	2013 - Present	Collect data on Lunar atmosphere.

Table 2 – NASA Space Missions and their Astrobiology components.

An example of Astrobiology research being produced from a NASA space mission comes from the completed Phoenix Mars polar-lander mission, which launched in August 2007 and went silent in November 2008. The lander was designed to conduct in-situ sampling and analysis of Martian surface and subsurface soil and ice. Science objectives were to study the history of water on Mars, search for evidence of habitable zones that could support life, and assess the potential for life in the ice-soil boundary of the Martian arctic region.

Actual data and observations made from the lander came from the test equipment on board that included multiple cameras, robotic arms, thermal and evolved gas analyzer, multiple microscopes, a wet chemistry lab, a thermal and electrical conductivity probe for measuring

soil conditions and atmospheric conditions, and a meteorological station. While not a complete list, some of the significant results from the mission included discovering ice below the surface, recording snow falling from cirrus clouds, observing weather, and determining soil and rock chemistry.

In the context of Astrobiology, the most obvious and reported information was the discovery of ice and snow, which confirmed water on the planet. Since water is one of the requirements for every living organism discovered on Earth so far, it increased the possibility of life on Mars. It also means water is available on the planet and could possibly be used if habitated in the future. Another aspect of Astrobiology is determining the future of life in the universe. Soil chemistry revealed a large amount of perchlorates, a principal ingredient in rocket fuel, which could provide a source of energy if colonized. There was significantly more data produced in a brief time from this short mission and the possible uses for this data are nearly limitless given the objectives of Astrobiology.

At the same time that Astrobiology plays a key role in many solar system exploration missions, astrobiologists also make extensive use of data produced by other space science projects to conduct research in areas such as prebiotic chemistry in interstellar space, the formation of habitable planets, and extraterrestrial environments where prebiotic chemistry or life may have occurred. The University of Washington's Astrobiology (UWAB) program, for example, studies life and evolution on

earth. Researchers from Paleontology and Geochemistry use stable-isotopes from ancient sedimentary rocks to determine when the main forms of microbial metabolism arose and whether this caused environmental change in the atmosphere and oceans. Researchers also use organic geochemistry to study molecular fossils such as hydrocarbons and kerogen in ancient rocks to discover hydrocarbon biomarkers that constrain the evolution of microbial ecosystems. Other UWAB researchers explore the role viruses play in microbial evolution in hydrothermal vent communities.

Arizona State University's Astrobiology program designs, builds, and tests equipment that supports investigations focusing on exploring Earth's extreme environments, such as camera lenses capable of withstanding harsh environments. This equipment is then used to search for life in extreme environments on Earth, such as Antarctica or deep-sea vents, in the search to understand the extent of life on this planet. Modifications can be made and adapted for use on a probe landing in a freezing ocean on one of Saturn's moons or placed on a Mars rover. Development, field-testing, and implementation of these instruments fall under Astrobiology as well.

NASA Astrobiology Institute

As mentioned earlier, NASA formally established the NASA

Astrobiology Institute (NAI) in 1998, a virtual, distributed organization of research teams lead by NASA that integrates astrobiology research and training programs with the national and international science communities.⁴ Direction for NAI is derived from NASA's Headquarters' Management, which is communicated to the greater Astrobiology community via the Roadmap.⁵ The Roadmap is prepared in consultation with the scientific community and outlines multiple pathways for research and indicates how they might be prioritized and coordinated. The NAI also solicits advice from the Space Studies Board of the National Resource Council. As of 2014, NAI's mission is to:

carry out, support and catalyze collaborative, interdisciplinary research; train the next generation of astrobiology researchers; provide scientific and technical leadership on astrobiology investigations for current and future space missions; explore new approaches using modern information technology to conduct interdisciplinary and collaborative research among widely-distributed investigators and, support learners of all ages by

⁴ As defined by NAI's website at <http://astrobiology.nasa.gov/nai/about>

⁵ The NASA Astrobiology Roadmap provides guidance for research and technology development across NASA and will be discussed in detail later in the section.

implementing formal, informal, and higher education programming and public outreach. (<http://astrobiology.nasa.gov/nai/about/>)

NAI's teams⁶ of researchers are supported through cooperative agreements between NASA and each team's respective institution; these agreements involve substantial contributions from both NASA and the teams themselves. Currently, the NAI has 15 teams comprised of over 840 researchers distributed across 180 institutions. There are also 13 international partner organizations. The Director and a small staff at "NAI Central," located at NASA Ames Research Center in Mountain View, California, administer the Institute. Each team's Principal Investigator, together with the NAI Director and Deputy Director, comprise the Executive Council. Its role is to consider matters of Institute-wide research, space mission activities, technological development, and external partnerships.

Roadmaps and the Change in Astrobiology

The NASA Astrobiology Roadmap is provided by NASA Headquarters management as a public document outlining Astrobiology. Input for the Roadmap is solicited from a group of government scientists

⁶ Teams are selected through a competitive bid process approximately every 5 years. Occasionally, NASA solicits applications for a new team inside of the 5-year cycle. (<http://astrobiology.nasa.gov/nai/teams/>)

and technologists, universities, and private institutions. The Roadmap is formulated in terms of science goals that outline key domains of investigation. For each of these goals, NASA develops science objectives that outline more specific high priority efforts for the next three to five years. These objectives are then integrated into NASA strategic planning and includes example Investigations, which offer cases of specific research tasks that are both important and timely. It is important to emphasize that these investigations are intended principally to be illustrative of relevant tasks, and that additional equally important investigations can be envisioned.

There have been three Roadmaps produced since the NAI's formation, each providing changes to the definition, principles, and goals of NAI focused research. Of particular note is the evolution of being “multidisciplinary” (1998) to “multidisciplinary in content and interdisciplinary in implementation” (2003 & 2008) and finally becoming an “interdisciplinary field” (2014). These Roadmaps are summarized below in Table 3.

Roadmap Definitions		
1998	2003	2008
Astrobiology is the study of life in the Universe. It provides a biological perspective to many areas of NASA research, linking such endeavors as the search for habitable	Astrobiology is the study of the origins, evolution, distribution, and future of life in the Universe. It requires fundamental concepts of life and habitable environments that will help us to	Astrobiology addresses three questions that have been asked in various ways for generations: how does life begin and evolve, does life exist elsewhere in the Universe, and what is the future of life on Earth and

<p>planets, exploration missions to Mars and Europa, efforts to understand the origin of life, and planning for the future of life beyond Earth.</p>	<p>recognize biospheres that might be quite different from our own. Astrobiology embraces the search for potentially inhabited planets beyond our Solar System, the exploration of Mars and the outer planets, laboratory and field investigations of the origins and early evolution of life, and studies of the potential of life to adapt to future challenges, both on Earth and in space. Interdisciplinary research is needed that combines molecular biology, ecology, planetary science, astronomy, information science, space exploration technologies, and related disciplines. The broad interdisciplinary character of astrobiology compels us to strive for the most comprehensive and inclusive understanding of biological, planetary and cosmic phenomena.</p>	<p>beyond? Accordingly, the discipline of astrobiology embraces the search for potentially inhabited planets beyond our Solar System, the exploration of Mars and the outer planets, laboratory and field investigations of the origins and early evolution of life, and studies of the potential of life to adapt to future challenges, both on Earth and in space. Interdisciplinary research is required that combines molecular biology, ecology, planetary science, astronomy, information science, space exploration technologies, and related disciplines. The broad interdisciplinary character of astrobiology compels us to strive to achieve the most comprehensive and inclusive understanding of biological, planetary, and cosmic phenomena.</p>
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Roadmap Principles		
1998	2003	2008
<p>Astrobiology is multidisciplinary, and achieving our goals will require the cooperation of different scientific disciplines and programs.</p>	<p>Astrobiology is multidisciplinary in its content and interdisciplinary in its execution. Its success depends critically upon the close coordination of diverse scientific disciplines and programs, including space missions.</p>	<p>Astrobiology is multidisciplinary in its content and interdisciplinary in its execution. Its success depends critically upon the close coordination of diverse scientific disciplines and programs, including space missions.</p>

Astrobiology encourages planetary stewardship, through an emphasis on protection against biological contamination and recognition of the ethical issues surrounding the export of terrestrial life beyond Earth.	Astrobiology encourages planetary stewardship through an emphasis on protection against forward and back biological contamination and recognition of ethical issues associated with exploration.	Astrobiology encourages planetary stewardship through an emphasis on protection against forward and back biological contamination and recognition of ethical issues associated with exploration.
Astrobiology recognizes a broad societal interest in our subject, especially in areas such as the search for extraterrestrial life and the potential to engineer new life forms adapted to live on other worlds.	Astrobiology recognizes a broad societal interest in its endeavors, especially in areas such as achieving a deeper understanding of life, searching for extraterrestrial biospheres, assessing the societal implications of discovering other examples of life, and envisioning the future of life on Earth and in space.	Same as 2003.
In view of the intrinsic excitement and wide public interest in our subject, Astrobiology includes a strong element of education and public outreach.	The intrinsic public interest in astrobiology offers a crucial opportunity to educate and inspire the next generation of scientists, technologists and informed citizens; thus a strong emphasis upon education and public outreach is essential.	Same as 2003.

Roadmap Goals		
1998	2003	2008
Understand how life arose on the Earth.	Understand the nature and distribution of habitable environments in the Universe.	Understand the nature and distribution of habitable environments in the Universe. Determine the potential for habitable planets beyond the Solar System, and characterize those that are observable.
Determine the general principles governing the organization of matter into living systems.	Explore for past or present habitable environments, prebiotic chemistry and signs of life elsewhere in our	Determine any past or present habitable environments, prebiotic chemistry, and signs of life

	Solar System.	elsewhere in our Solar System. Determine the history of any environments having liquid water, chemical ingredients, and energy sources that might have sustained living systems. Explore crustal materials and planetary atmospheres for any evidence of past and/or present life.
Explore how life evolves on the molecular, organism, and ecosystem levels.	Understand how life originates from cosmic and planetary precursors.	Understand how life emerges from cosmic and planetary precursors. Perform observational, experimental, and theoretical investigations to understand the general physical and chemical principles underlying the origins of life.
Determine how the terrestrial biosphere has co-evolved with the Earth.	Understand how past life on Earth interacted with its changing planetary and Solar System environment.	Understand how life on Earth and its planetary environment have co-evolved through geological time. Investigate the evolving relationships between Earth and its biota by integrating evidence from the geosciences and biosciences that shows how life evolved, responded to environmental change, and modified environmental conditions on a planetary scale.
Establish limits for life in environments that provide analogues for conditions on other worlds.	Understand the evolutionary mechanisms and environmental limits of life.	Understand the evolutionary mechanisms and environmental limits of life. Determine the molecular, genetic, and biochemical mechanisms that control and limit evolution, metabolic

		diversity, and acclimatization of life.
Determine what makes a planet habitable and how common these worlds are in the Universe.	Understand the principles that will shape the future of life, both on Earth and beyond.	Understand the principles that will shape the future of life, both on Earth and beyond. Elucidate the drivers and effects of microbial ecosystem change as a basis for forecasting future changes on time scales ranging from decades to millions of years, and explore the potential for microbial life to survive and evolve in environments beyond Earth, especially regarding aspects relevant to US Space Policy.
Determine how to recognize the signature of life on other worlds.	Determine how to recognize signatures of life on other worlds and on early Earth.	Determine how to recognize signatures of life on other worlds and on early Earth. Identify biosignatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured in situ or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify biosignatures of distant technologies.
Determine whether there is (or once was) life elsewhere in our solar system, particularly on Mars and Europa.		
Determine how ecosystems respond to environmental change on time-scales relevant to human life on Earth.		

Understand the response of terrestrial life to conditions in space or on other planets.		
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Table 3 – Summary of NAI Roadmaps. The text in each block comes directly from the 1998, 2003 & 2008 NASA Astrobiology Roadmaps.

Social Sciences and Humanities in Astrobiology

Some argue there has been progress in three of the four Roadmap principles above, “while systematic attention to societal issues arguably has lagged since some interesting early efforts “(Race et al., 2012 referencing Connell et al., 2000, p. 958). Recognizing this deficiency, scholars from the Social Sciences and Humanities gathered in 2009 to create a “Roadmap of Astrobiology Societal Issues” (Race et al., 2012). The conference ultimately identified five areas of research focused on human-centric issues such as how Astrobiology relates to the meaning of life and exploring human relationships with other worlds and types of life. A product from this conference is that in 2011, an experimental interdisciplinary Focus Group on Astrobiology and Society was established under the NASA Astrobiology Institute (NAI). The main tasks of the Focus Group were to

- Refine the draft Astrobiology Roadmap of Societal Issues through community input and discussions;
- Disseminate the information to both the astrobiology community and external researchers, and

- Provide an ongoing forum where researchers in the astrobiology community and those in relevant humanities and social science areas will be able to learn, interact, and possibly collaborate on research questions of interest.

(p. 963)

The focus of the group is addressing “issues likely to arise if and when extraterrestrial life is discovered – and to consider what foundational or other information will be useful in preparing to respond to public questions” (Race et al., 2012, p. 959). To accomplish the tasks above, tentative plans to 1) develop a dedicated website under the auspices of the NAI, 2) compile an online database of cross-disciplinary literature and resources for both astrobiology scientists and external experts in humanities and social science research; and 3) coordinate online and virtual communications in order to identify and include diverse scholars and prioritize key crossover research areas related to Astrobiology’s societal implications were developed (Race et al., 2012). While research in Social Sciences and Humanities existed in the context of Astrobiology prior to this conference, this was the first time that NASA was specifically involved in guiding and prioritizing research in these disciplines.

Examples of research conducted prior to this conference includes Rummel et al's Ethical Considerations for Planetary Protection in Space

Exploration: A Workshop, which examines the ethical practices that should frame research activities as humanity explores outer space (2012).

Similarly, Dick's Critical Issues in the History, Philosophy, and Sociology of Astrobiology makes a case for "what the history, philosophy, and sociology of astrobiology can mean as an intellectual field of study" (2012, p. 906). While both papers address issues related to Astrobiology, neither are integrated into research projects that are being conducted under the objectives of Astrobiology. As such, these endeavors appear to contribute disciplinary knowledge into the larger field of Astrobiology.

Spatial Representation of Astrobiology Knowledge Production

Background and Purpose

Apparent from the NAI's Roadmaps, the idea of Astrobiology as an interdisciplinary collaboration and mode of knowledge production is strong. Since direction is not given on how to successfully perform interdisciplinary projects; it could be assumed that some form of natural collaboration would present itself among disciplines. The following analysis suggests changes among collaborative disciplines over time and helps to determine how well research has become integrated. To investigate this, the content of *Astrobiology* will be analyzed from 2001 to 2012, in terms of articles citations to other disciplines.

Astrobiology journals

There are currently two professional journals that publish research in Astrobiology – *Astrobiology*⁷ and *The International Journal of Astrobiology*.⁸ *Astrobiology* was formed in 2001 and was the first journal to focus its content solely on Astrobiology research. *The International Journal of Astrobiology* followed shortly after, with the first issue being published in 2002. *Astrobiology* has a slightly higher total number of research articles

⁷ *Astrobiology* – <http://www.liebertpub.com/overview/astrobiology/99/>

⁸ *The International Journal of Astrobiology* – <http://journals.cambridge.org/action/displayJournal?jid=IJA>

published annually, averaging 64 compared to 42. Other than the publishing house, no other significant differences exist between the two journals.

Impact factor is a measure of the frequency with which the average article in a journal has been cited in a particular year or period. More specifically, the annual impact factor is a ratio between citations and the recent citable items published. Thus, the impact factor of a journal is calculated by dividing the number of current year citations to the source items published in that journal during the previous two years. I chose Thomas Reuter's impact factor as the deciding metric for this thesis.

According to Thomas Reuter's impact factor webpage:⁹

The impact factor is useful in clarifying the significance of absolute (or total) citation frequencies. It eliminates some of the bias of such counts which favor large journals over small ones, or frequently issued journals over less frequently issued ones, and of older journals over newer ones.

(<http://ipscience.thomsonreuters.com/citationimpactcenter/>)

This statement indicates that the difference in total articles published becomes a non-factor when determining significance of research based on the total number of citations created. Since part of this thesis is to

⁹ <http://wokinfo.com/essays/impact-factor/>

determine disciplinary diversity, a greater number of citations would be preferable and subsequently, the journal with a higher impact factor is more appropriate for analysis.

With both journals being indexed by Thomas Reuters, the impact scores were readily available from the Web of Science,¹⁰ and summarized below:

	<i>Astrobiology</i>	<i>International Journal of Astrobiology</i>
Year	Impact Factor	Impact Factor
2013/2014	2.512	0.826
2012	2.803	1.452
2011	2.15	1.723
2010	2.362	1.097
2009	3.257	-
2008	2.989	-

Table 4 – Astrobiology Journal Impact Factors

Although Thomas Reuter's did not index *The International Journal of Astrobiology* until 2010, the four years available for comparison clearly show *Astrobiology* as having a consistently higher impact factor. Given the significant difference between impact factors, which is partially based on the number of citations produced, *Astrobiology* was chosen as the reference journal for this thesis. A timeframe of 2001 to 2012 was chosen to

¹⁰ <http://wokinfo.com>

accurately represent as many articles as possible – inception of the journal in 2001 and a cutoff of 2012, allowing two full years of citations to be accumulated. Using data from 2013 or 2014 could skew the projections since there has not been enough time for other researchers to cite research published then.

Astrobiology declares itself

the leading peer-reviewed international journal for astronomers, biologists, chemists, geologists, microbiologists, paleontologists, and planetary scientists designed to advance our understanding of life's origin, evolution, and distribution in the Universe.

This authoritative journal disseminates the most current findings and discoveries coming out of recent interplanetary exploration and laboratory - and field-based research programs.

(<http://www.liebertpub.com/overview/astrobiology/99/>)

The Editor-in-Chief is Sherry L. Cady, PhD and Chief Scientific Officer at the Pacific Northwest National Laboratory. The editorial board includes over 50 individuals from government agencies such as NASA as well as the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in Japan, universities throughout the world, and institutions including the Search for Extraterrestrial Intelligence Institute (SETI) in California.

With regards to the coverage provided by *Astrobiology*, the submission guidelines state:

Astrobiology brings together research scientists from around the world to test hypotheses and methodologies, and advance theories with regard to the origins of life, the search for life, our understanding of the distribution and evolution of life, and the ways in which life interacts with its environment. Topics included in this multidisciplinary science are discussed in articles by Morrison (2001) in *Astrobiology* Volume 1, Issue 1, Des Marais et al. (2003) in *Astrobiology* Volume 3, Issue 2, and Des Marais et al. (2008) in *Astrobiology* Volume 8, Issue 4. *Astrobiology* also welcomes research articles in fundamental space biology, that is, articles that discuss the responses of terrestrial life when exposed to conditions (such as microgravity and enhanced radiation) that would apply beyond Earth. Such research is basic to understanding the ability of Earth life to move beyond its planet of origin.

(<http://www.liebertpub.com/forauthors/astrobiology/99/>)

The three articles from 2001, 2003, and 2008 referencing which topics are covered in *Astrobiology* are based on the NASA Astrobiology Roadmap Goals of 1998, 2003, and 2008, respectively. The discrepancy in years for the first article is based on the establishment of the journal in 2001, three years after the first roadmap. As such, *Astrobiology* should be representative of the research and objectives set forth in the Roadmaps, which is seemingly accepted by academia.

How to Measure Researcher Interdisciplinarity

Porter, Cohen, Roessner, & Perreault have built a framework for gauging how interdisciplinary a body of research is through two metrics of measurement (2007). Both draw upon the Web of Knowledge (WoK) Subject Categories (SCs) as key units of analysis. Specifically, *integration* measures the extent to which a research article cites diverse Subject Categories. *Specialization* considers the spread of SCs in which the body of research is published. All of the methods and formulae in this section are from the aforementioned Porter, Cohen, Roessner, & Perreault publication (2007), unless otherwise noted.

The Web of Knowledge is an academic indexing service for over 12,000 publications spanning the past 90 years and is provided by Thomas Reuters. Coverage includes the Natural Sciences, Social Sciences, and Humanities. The total number of research articles and conference proceedings exceeds 8.2 million records. While tools to access, analyze, and manage research information are provided by the WoK, only the access and citation service are used for this thesis.

Subject Categories are variables defined by Thomas Reuters Web of Science to classify articles, but are generally synonymous with research disciplines. For example, an article about the formation of rocks would be indexed under the Geology Subject Category. If the article were about

the effects of bacteria (Biology) on formation of rocks, it would be classified under the Geology, Multidisciplinary subject category.

To build their measures they used the definition from the National Academies Report (2005):

Interdisciplinary research is a mode of research by teams or individuals that integrates 1) perspectives/concepts/theories and/or 2) tools/techniques and/or 3) information/data from two or more bodies of specialized knowledge or research practice. (p. 5)

Examples of specialized knowledge or research practice are further defined as "low temperature physics, molecular biology, developmental psychology, toxicology, operations research, and fluid mechanics" (p. 119). This distinction is important as it separates multidisciplinary from interdisciplinarity in their framework. The former occurs during situations where elements from different disciplines are present, while the latter constitutes a more integrated relationship between disciplines. For example, a paper citing multiple disciplines in specialized areas such as astrophysics, quantum mechanics, and thermodynamics would be considered multidisciplinary, but not interdisciplinary in nature.

Integration is the key factor to measuring interdisciplinarity, as it provides the basis for distinguishing between fully integrated research projects generating a new knowledge from piecemeal multidisciplinary research rooted in their own disciplinary knowledge. The general strategy

for measuring interdisciplinarity for this thesis is based on the following premise:

- Integration of knowledge not routinely found within a research field equates to greater interdisciplinarity.
- Examination of the spread of a paper's references, i.e. the number of citations referring to the original paper.
- Measurements relating papers' cited articles to their corresponding Subject Categories.

The calculations for these metrics are based on the WoK, which includes the Science Citation Index, Social Science Citation Index, and the Arts and Humanities Citation Index. The general method for searching the WoK includes a general search that retrieves summary information on papers, or a citation search that retrieves summary information on each paper that cites the papers searched for.

They further 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?
- Citations spread across SCs for the entire set of papers.

- Citations to the papers spread across Subject Categories.

Calculation Matrix

To measure how closely SCs relate to each requires generating a representative sample of scientific publishing. A measure for correlating the papers is determined using the Klavans and Boyack cosine formula (2008) adjusted for expected value based on frequencies. This Subject Category cosine matrix provides the values used in all further calculations and is calculated from observations (counts) x, y as:

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

An example of this calculation related to Subject Categories is shown in the example below:

Records	Subject Categories	Multidisciplinary Sciences	Geology	Physics
6523	Multidisciplinary Sciences	1	.695	.187
5086	Geology	.695	1	.141
4117	Physics	.187	.141	1
3922	Biology	.641	.827	.131

Table 5 – Subject Category Calculations

This cosine matrix then provides a variable for calculating the Integration (I), which is being used as an indicator of how much distinct research knowledge is being cited across multiple Subject Categories. Integration is calculated by the formula and shown in Table 6.

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

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

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

Explanation of the Integration Formula:

- Weight cells by normalizing the frequency of citations. For instance, the Biology × Geology cell weight = $(5 \times 3)/100 = 0.15$.
- The diagonal cells as well as the cells below the diagonal are

included. Cells above are not included to avoid double-weighting interactions.

- Multiply the cell weight by the respective cosine value (Table 6 – Integration Matrix).
- Sum up the cells included, divide by the sum of the included cell weights to obtain the Disciplinary score.
- Subtract this Disciplinary score from 1 to get the Integration score, “I.”

# of citations	Subject Categories	Multidisciplinary Sciences	Geology	Physics	Biology
1	Multidisciplinary Sciences	.01			
5	Geology	.05	.25		
1	Physics	.01	.05	.01	
3	Biology	.03	.15	.03	.09
10	Sum	.10	.45	.04	.09

Table 6 – Integration Matrix

Specialization (S) is calculated using the information on the SCs in which a researcher's publications appear. Note that S does not use cited SC information at all, making it independent of I. To calculate specialization, the formula and procedures below were used:

$$S = \frac{\sum [(\# \text{ of papers in } SC1)^2 + \dots (\# \text{ of papers in } SCn)^2]}{\sum [(\# \text{ of papers in } SC1) + \dots (\# \text{ of papers in } SCn)]^2}$$

- For the set of journal articles, count the number of publications in each of the Subject Categories.
- Square the count for each Subject Category; then sum these.
- Divide that sum by the square of the sum of all the counts.

For example, suppose there are 5 publications in SC1; 3 in SC2; 1 in SC3; and 1 in SC4. The numerator would be $25+9+1+1=36$. The denominator would be $(5+3+1+1)^2 = 100$. So, $S = 0.36$.

These calculations can then be used to create a graph of integration and specialization with quadrant boundaries drawn at the mean values, respectively. While this chart is not specifically replicated in this thesis, it's valuable for understanding the correlation between specialization and integration. Specifically, researchers whose work integrates more diverse research knowledge (high Integration) tend to be less specialized, publishing in a wider span of Subject Categories (low Specialization). This is shown in Figure 4 below.

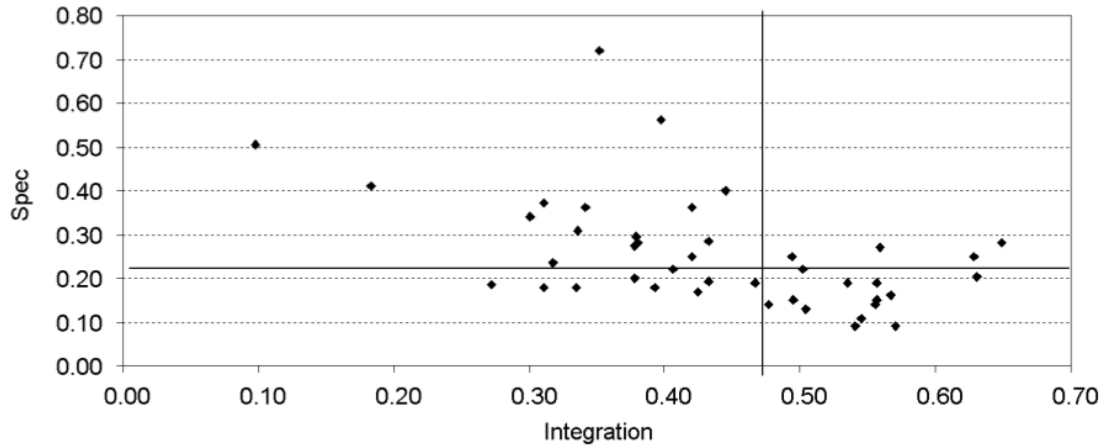


Figure 4 – Integration vs. Specialization Correlation

From this matrix, which relies on the Indicators of interdisciplinarity (Integration & Specialization), Rafols & Meyer created a tool that identifies the Subject Categories of the articles in which the original data are referenced, performed a factor analysis identifying identical Subject Categories, and calculated the strength of the relationship based on total number of identical citations (2009). This calculation is called the diversity, and represents the number, balance, and degree of difference between disciplines. Thus, diversity of the Subject Categories in the references is the reverse of specialization, which represents the Subject Categories of the journals in which the papers are published. According to Rafols and Meyer (2009)

the distinction between diversity in referencing and publishing is insightful and useful to differentiate between multidisciplinary and

interdisciplinary research. However, since both integration and specialization are based on Subject Categories in the calculation matrix, they are correlated and useful for recognizing trends in the projection. (p. 7)

With these variables, a map can be generated in which three aspects of disciplinary diversity can be inferred:

- the variety of disciplines (i.e., discrete research areas, the SCs, shown by the number of nodes in the map)
- the balance, or distribution, of disciplines (relative size of nodes)
- the diversity, or degree of difference, between the disciplines (distance between the nodes)

An example of this projection is shown in Figure 5 below.

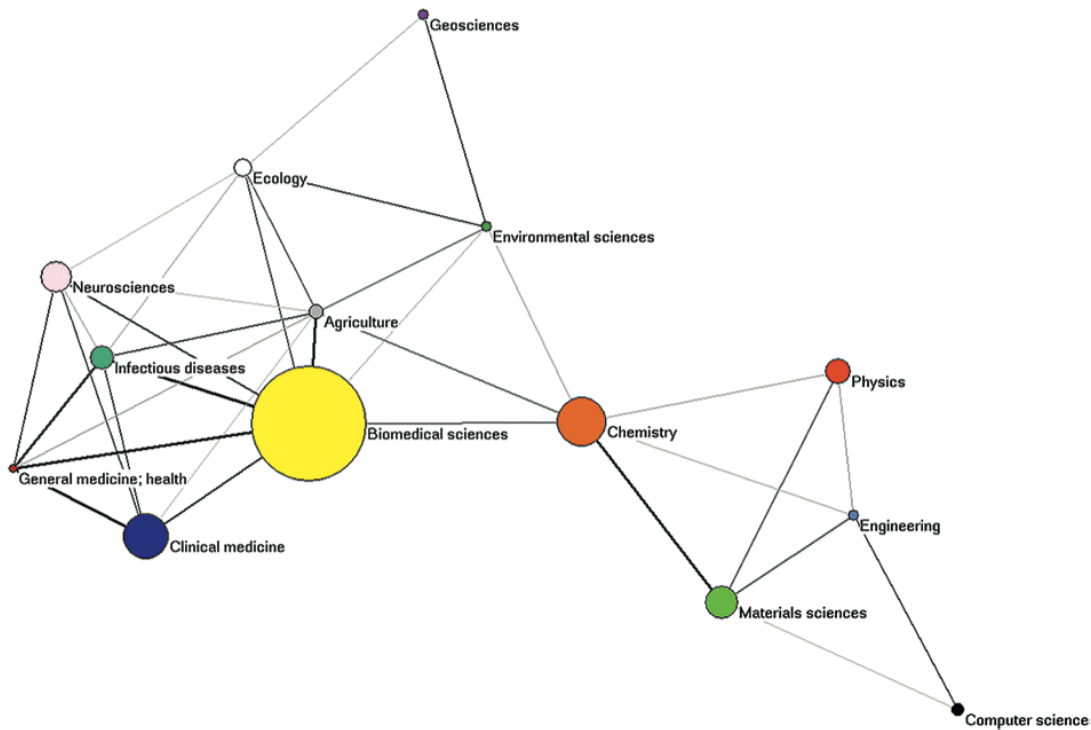


Figure 5 – Disciplinary Relationships. Example map of 14 disciplines showing the relationship between specialization, integration, and disciplinary diversity. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to the cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines. Figure from Rafols & Meyer 2009.

Methodology and Results

Two maps will be generated per year for analysis – The first to show number of articles per discipline published and the second to show the extent of integration, which can help to determine the interdisciplinarity among the disciplines used in both generating the articles and those citing them. The first map uses an overlay tool hosted by Georgia Tech

University's IDR website¹¹ called the map of science to explore the range of disciplines covered by research articles¹² published in *Astrobiology* from 2001 through 2012. The overlay technique visualizes the spread of publications over the global map of science,¹³ a spatial structure of the relationship of all science categories through the analysis of Subject Categories¹⁴ and common citations among disciplines. The intent of this map is to provide the context of:

1. Number of major disciplines published in *Astrobiology*, as represented by Subject Categories.
2. Balance of disciplines, whether publications are evenly distributed across disciplines or some disciplines are more predominant.

The Subject Category nodes displayed on this map are based on the ratio of total articles published per discipline. For example, in a year with 100 total research articles, 50% of which are Geology, will have the same size node as a year with 50 total articles, of which 50% are Geology.

¹¹ <http://idr.gatech.edu/index.php>

¹² Only research articles were used for this analysis. Abstracts, letters, conference proceedings and summaries were not included.

¹³ <http://idr.gatech.edu/concept.php#sthash.kbu6AE0e.dpuf>

¹⁴ Subject Categories are variables defined by Thomas Reuters Web of Science to classify articles, but are generally synonymous with research disciplines, e.g. Chemistry.

For the second map, the program Pajek,¹⁵ an open source large network analysis tool, is used to create a spatial projection using the mathematical matrix described in the section above. The three primary elements of analysis generated from the matrix and represented by the projection are; 1) Integration, the extent to which a research article cites diverse Subject Categories 2) Specialization, which considers the spread of Subject Categories in which the body of research is published and 3) Diversity, defined as the differentiation between short-range interdisciplinarity (Chemistry & Planetary Systems) and long-range interdisciplinarity (Social Science & Geology) disciplines (Porter et al., 2007; Rafols & Meyer, 2010).

Step by Step Procedures

The first step was to download the metadata for all of the articles published in *Astrobiology* from 2001 through 2012¹⁶. Each issue's metadata were downloaded separately, then combined by year using EndNote¹⁷ citation software. Since all articles, including conference abstracts, book reviews, and other non-research related writings are included in the

¹⁵ <http://pajek.imfm.si/doku.php?id=download#pajek>

¹⁶ Metadata includes the article title, authors, and issue information, saved in the .RIS format. Data retrieved from Mary Ann Liebert, Inc's website at <http://online.liebertpub.com/loi/AST>.

¹⁷ EndNote is citation software produced by Thomas Reuters, available at <http://endnote.com>.

metadata; I had to manually remove them from the reference list. The total number of articles compiled for each year is summarized in the top section of Table 7. A complete bibliography for each year's articles is available in Appendices A-L.

Year	Total Articles	Used Articles
2001	42	30
2002	56	32
2003	76	70
2004	35	30
2005	59	46
2006	61	53
2007	69	66
2008	108	67
2009	93	89
2010	84	82
2011	92	90
2012	114	113

Subject Categories

	Geo	Chem	Bio	Eng	Soc Sci	Phys	Planet Sys	Comp Sci & Tech
2001	26	26	28	12	1	8	16	6
2002	30	30	22	16	0	7	14	10
2003	56	56	50	21	0	12	23	18
2004	25	25	25	8	0	9	14	4
2005	44	44	44	11	1	15	20	5
2006	47	47	47	14	0	8	29	10
2007	60	60	58	8	1	8	32	2
2008	62	62	60	17	0	14	26	17
2009	77	77	70	31	1	16	44	18
2010	71	71	68	25	0	22	61	16
2011	80	80	77	36	6	26	59	18
2012	96	96	96	48	12	38	66	44

Table 7 – Top - Total *Astrobiology* articles and number of research articles used per year. **Bottom** – Number of Subject Categories assigned to discipline per year.

Each year's data were then uploaded to Thomson Reuters Web of Science¹⁸ separately. Since *Astrobiology* is a Thomas Reuters catalogued publication, there were no articles unavailable in the Web of Science database. The analysis tool was then selected for and a text file produced containing the number of Subject Categories associated with the annual list. After downloading this file for 2001, it was then uploaded to the Georgia Tech IDR overlay tool webpage,¹⁹ with the output shown in Figure 6, which was not expected, and provided no useful information.

Examining the data in the Web of Science text file revealed that all of the articles had been assigned to the "GEOSCIENCE MULTIDISCIPLINARY," "BIOLOGY," and "ASTRONOMY ASTROPHYSICS" Subject Categories at a 100% rate, meaning all of the articles contained subject matter appropriate to all three disciplines. No other Subject Categories were present in the text file. All 12 years of articles were uploaded and all of the respective text files contained exactly the same three designations, indicating Thomas Reuter's has not performed an in-depth examination of each article's content, resulting in their designations not being useful for this thesis.

¹⁸ <http://www.isiknowledge.com>

¹⁹ <http://www.idr.gatech.edu/upload.php>

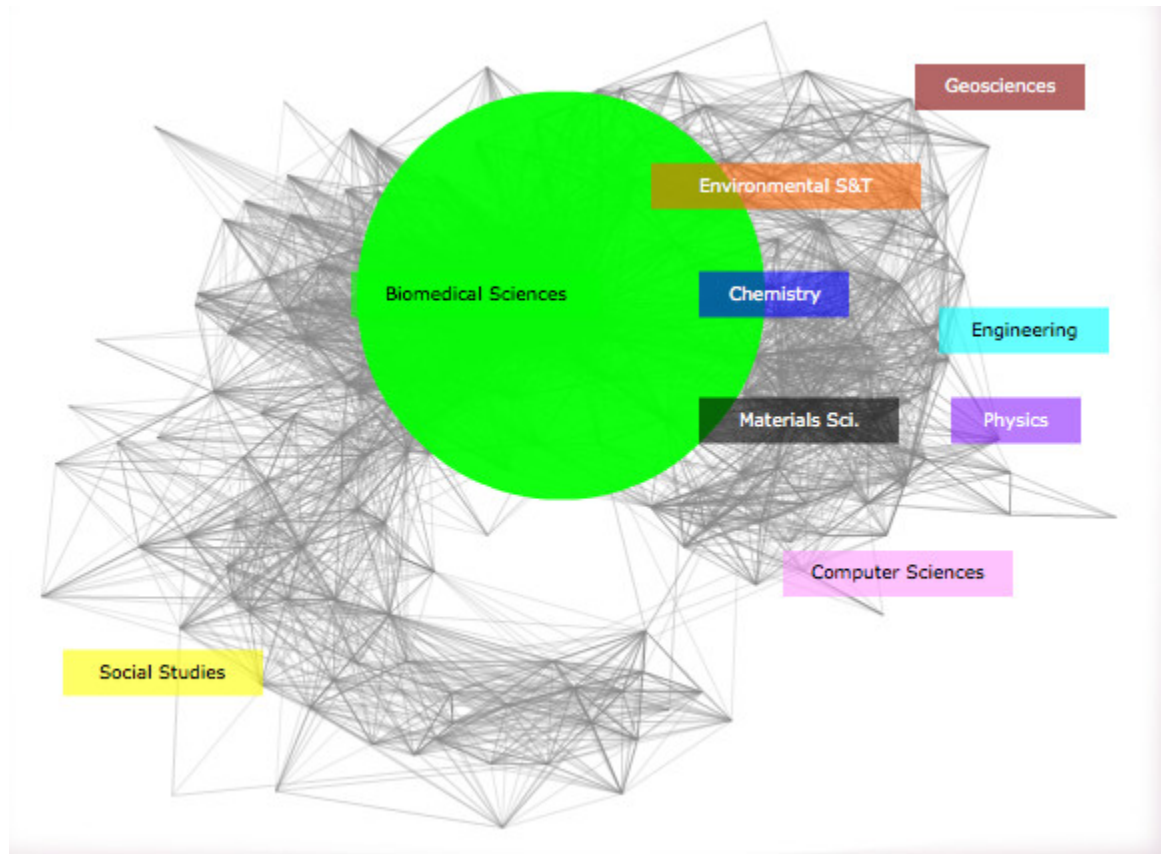


Figure 6 – Original output for 2001 *Astrobiology* articles. The assigned Subject Categories were meaningless and could not be used. Manual classification of all 768 research articles was required.

To overcome this barrier, I performed a manual examination of the abstracts for all 768 articles to identify key words and themes in order to create appropriate Subject Categories. In total, there were 35 disciplines that I reduced to the following eight macro-disciplines including Biology, Chemistry, Computer Science & Technology, Engineering, Geosciences, Physics, Planetary Systems, and Social Sciences. This categorization process is based on description of the Subject Categories (synonymous with discipline) used by the Web of Knowledge. Using the master list of all 160 categories, the identified keywords were associated with each of the appropriate Subject Categories. For example, if the keywords such as “galaxy” and “constellation” were identified, they would be associated with the Astronomy & Astrophysics Subject Category.

Astronomy & Astrophysics

Category Description:

Astronomy & Astrophysics covers resources that focus on the science of the celestial bodies and their magnitudes, motions, and constitution. Topics include the properties of celestial bodies such as luminosity, size, mass, density, temperature, and chemical composition, as well as their origin and evolution. This category includes some resources on planetary science that focus on astrophysical aspects of planets. General resources on planetary science are placed in the GEOCHEMISTRY & GEOPHYSICS category. (http://ip-science.thomsonreuters.com/mjl/scope/scope_sci/)

Or if the abstract contained keywords such as rover, space lander, or words associated with analytical equipment such as “wet chemistry lab,” they were associated with robotics.

Robotics

Category Description:

Robotics includes resources that cover the branch of engineering devoted to the design, training, and application of robots, mechanical devices capable of performing a variety of manipulation and locomotion tasks. Resources in this category draw from the fields of mechanical and electrical engineering, cybernetics, bionics, and artificial intelligence.

(http://ip-science.thomsonreuters.com/mjl/scope/scope_sci/)

These categories, which totaled 35 after reviewing all of the abstracts, were then grouped into eight larger macro-disciplines based on their location on the web of science, as shown in Table 8.

Geology

Biogeochemistry
Geochemistry
Geology, Physical
Geophysics
Mineralogy

Physics

Astronomy
Astrophysics
Particle Physics
Physics, Atomic
Physics, Multidisciplinary
Physics, Particle
Mathematics

Planetary Systems

Ecology
Environmental Science
Plant Science

Biology

Biophysics
Biochemistry
Cellular Biology
Microbiology

Chemistry

Inorganic
Organic
Applied
Physical

Computer Science & Technology

Remote Sensing
Telecommunications
Spectroscopy

Engineering

Materials Science
Robotics
Thermodynamics

Social Sciences

History
Psychology
Philosophy
Religion
Sociology

Table 8 – Macro-disciplines and sub-disciplines in Astrobiology

An example of the categorization method is shown using the abstract from Trainer et al.'s 2004 article Haze Aerosols in the Atmosphere of Early Earth: Manna from Heaven. Key terms used for classification are underlined:

An organic haze layer in the upper atmosphere of Titan plays a crucial role in the atmospheric composition and climate of that moon. Such a haze layer may also have existed on the early Earth, providing an ultraviolet shield for greenhouse gases needed to warm the planet enough for life to arise and evolve. Despite the implications of such a haze layer, little is known about the organic material produced under early Earth conditions when both CO₂ and CH₄ may have been abundant in the atmosphere. For the first time, we experimentally demonstrate that organic haze can be generated in different CH₄/CO₂ ratios. Here, we show that haze aerosols are able to form at CH₄ mixing ratios of 1,000 ppmv, a level likely to be present on early Earth. In addition, we find that organic hazes will form at C/O ratios as low as 0.6, which is lower than the predicted value of unity. We also show that as the C/O ratio decreases, the organic particles produced are more oxidized and contain biologically labile compounds. After life arose, the haze may thus have provided food for biota.

This article contains keywords associated with the discipline environmental sciences including “atmospheric composition and climate,” “greenhouse gases,” “haze aerosols,” and “Earth,” which are categorized into the larger macro discipline of planetary systems. Keywords associated with Chemistry are “CO₂ and CH₄” as well as “experimentally demonstrate.” Geosciences was also chosen based on the “Earth” and “moon” keywords.

This categorization required slightly more work, however, as the abstract does not use terms unique to Earth or Geosciences. To make this determination, I deemed the “early Earth” statement as synonymous with an analog environment, and subsequently related to the Geosciences. Finally, The terms “biologically labile compounds,” “life arose,” and “biota” are categorized into the biological sciences. For classification purposes, this article received tallies for Geosciences, Planetary Systems, Chemistry, and Biology.

A tally was created for each discipline contained in every article, with the summary for each year available in the bottom section of Table 7. The percentage of each discipline was then calculated by dividing by the total number of articles for the year, and the data manually entered into the appropriate text files. An example of the text file used for the 2001 Subject Category projection:

```

**Analyze.txt
//Subject Categories for Astrobiology 2001
Web of Science Categories records % of 30
GEOSCIENCES MULTIDISCIPLINARY 26 86.667
BIOLOGY 26 93.333
PHYSICS 28 26.667
SOCIAL SCIENCES 12 3.333
ENGINEERING 01 40.000
CHEMISTRY 08 86.667
COMPUTER SCIENCE 16 20.000
ENVIRONMENTAL SCIENCE 06 53.333
(0 Web of Science Categories {0} {1} value(s) outside display options.)
(0(0.000%){0} records{1} do not contain data in the field being analyzed.)

```

The text files were then uploaded to the Georgia Tech University's IDR website individually, with the outputs catalogued by year at the end of this chapter. For reference, the output for all articles catalogued by Thomas Reuters in 2007 is shown in Figure 7.

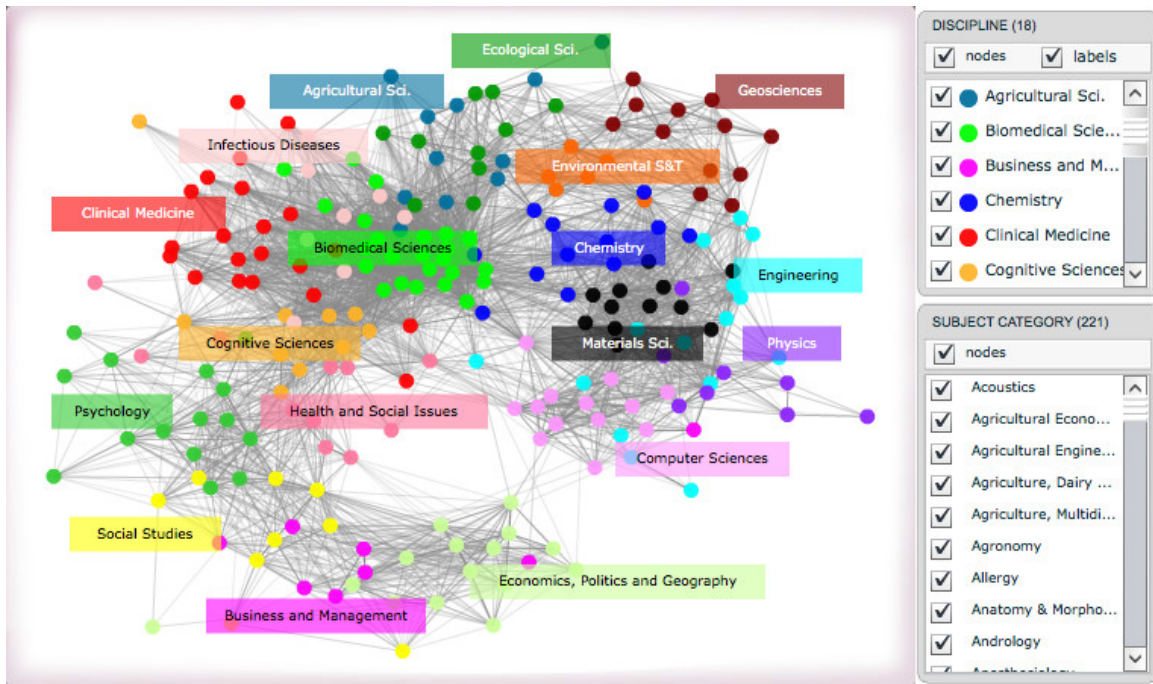


Figure 7 – The Map of Science for all articles catalogued by Thomas Reuter's in 2007. Figure from Rafols, Porter, & Leydesdorf at <http://idr.gatech.edu/detail.php?tab=1&id=1>

The second projection, which projects the total number of citations created by the article as well as the number of cross references among those disciplines, followed the same premise but used slightly different software. To retrieve a complete set of references, the articles in Appendices A-L were uploaded to the Web of Science and the option to

select all articles using these citations was chosen. Similar text files to those above were downloaded for these new datasets. Since each text file contained between 1,677 (2001) and 38,456 (2010) records, no manual Subject Category allocation was performed.

Given the significantly higher amount of data in these projections, the program Pajek was used for analysis because it provides more display options and control over the map presentation. The first step was to transform the Web of Science text file using the SC2007.exe program in the toolkit available from the Georgia Tech IDR webpage. The resulting .vec file was then imported into Pajek and converted to another .txt file for use with the program ISE.exe, also available as part of the overlay toolkit. The ISE.exe program runs the mathematical matrix, outputs another .vec that can be used in Pajek as explained above. After importing the new .vec file into Pajek, a new map of science exploring discipline diversity was created.

The outputs of these maps were difficult to read because they had thousands of points and lines in a small area, so I modified them to allow greater clarity and easier interpretation of the spatial relationships. Of most importance is that small points, indicating various sub-disciplines, were grouped into larger node to appear similar to the first projection. Second, the map of science has a different orientation, which may be confusing, so it was removed completely from the background. The results

for both projections are shown below in Figures 8 – 31. Each page represents a year, with the Subject Category projection on top and the discipline diversity on the bottom.

2001

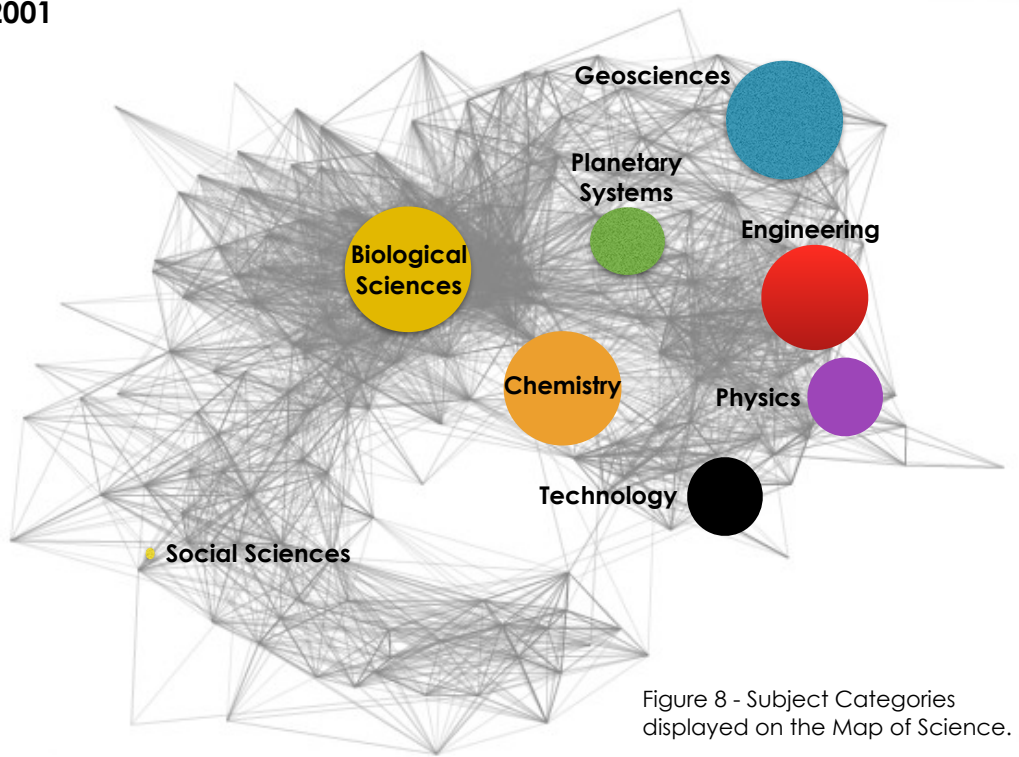


Figure 8 - Subject Categories displayed on the Map of Science.

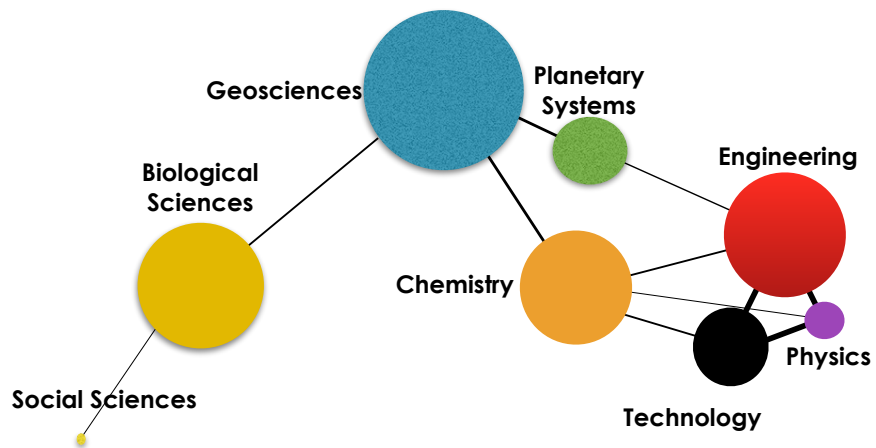


Figure 9 - Core structure of Astrobiology 2001. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

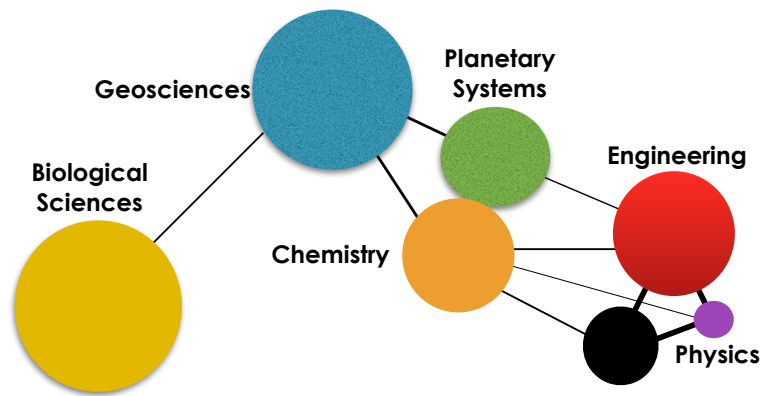
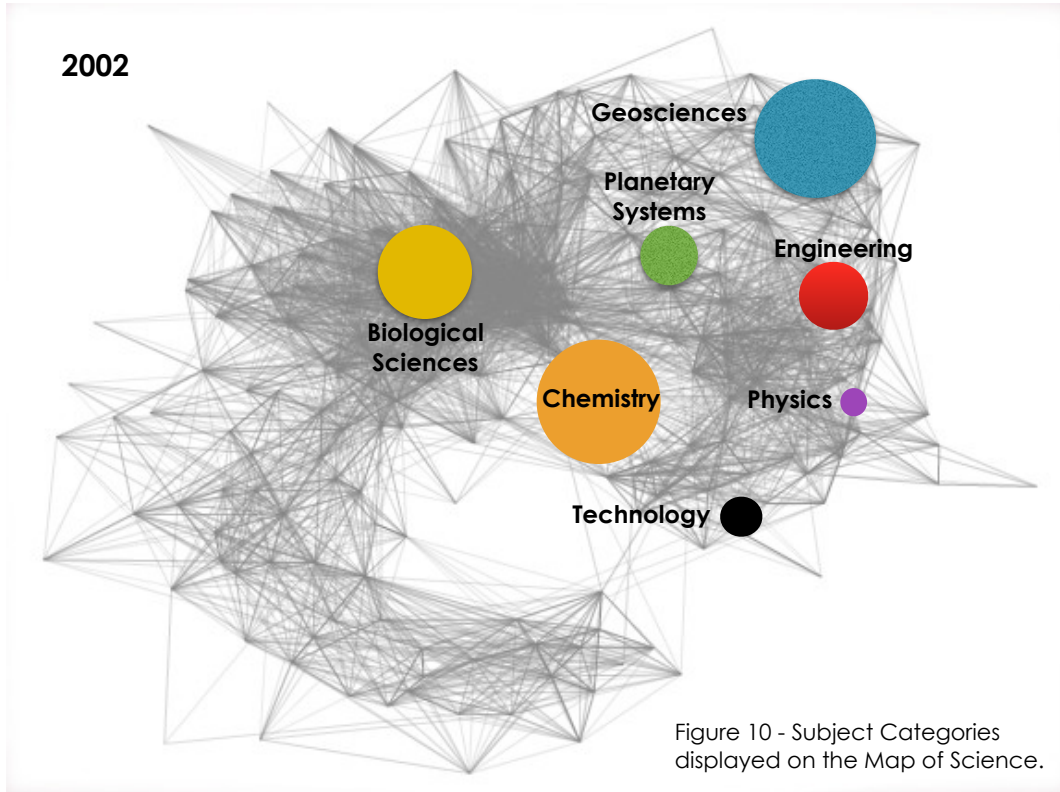


Figure 11 - Core structure of *Astrobiology* 2002. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2003

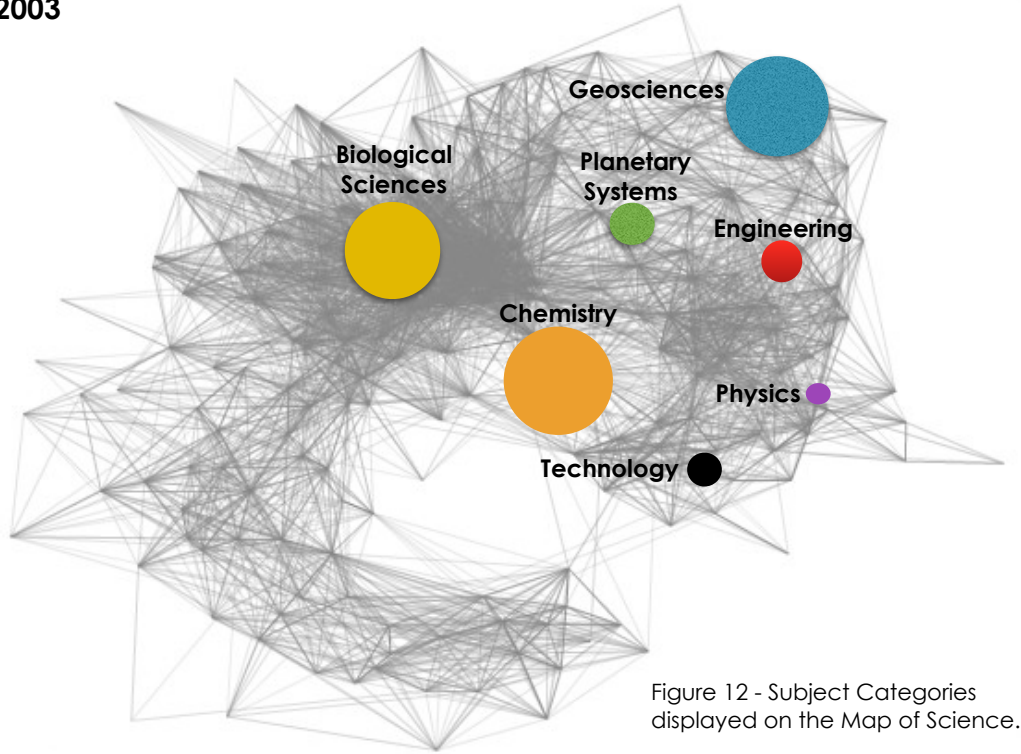


Figure 12 - Subject Categories displayed on the Map of Science.

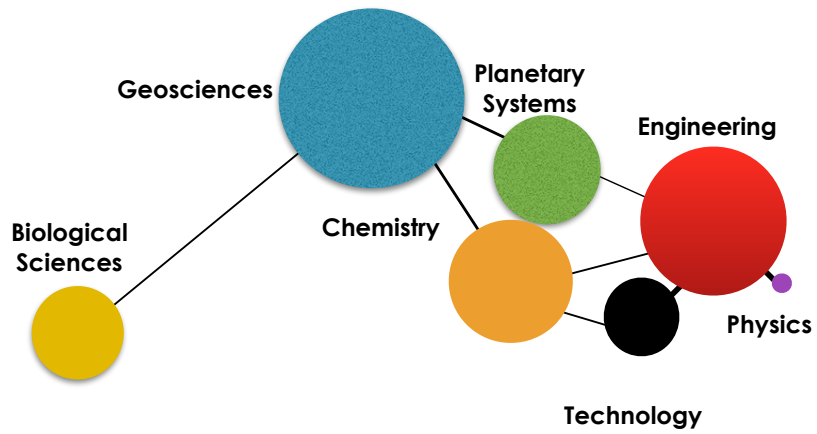


Figure 13 - Core structure of *Astrobiology* 2003. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2004

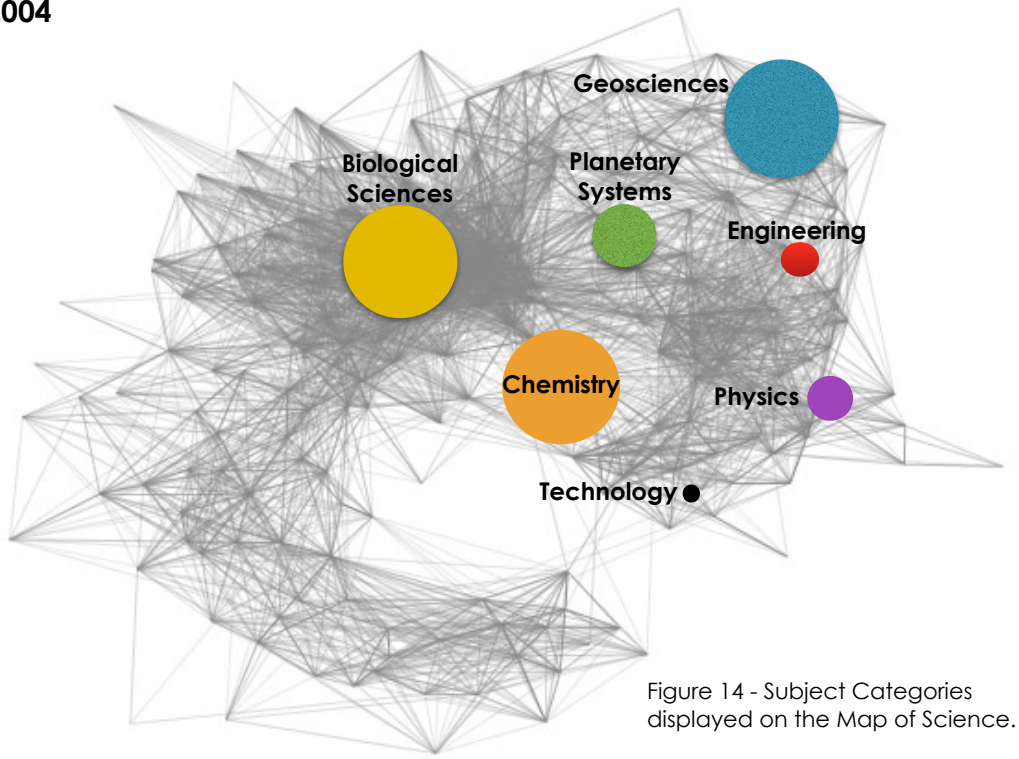


Figure 14 - Subject Categories displayed on the Map of Science.

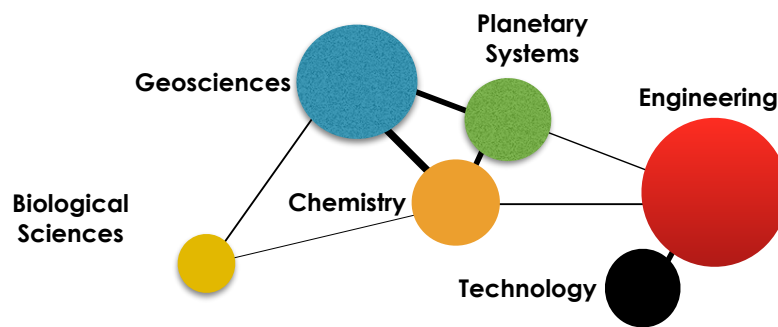


Figure 15 - Core structure of *Astrobiology* 2004. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2005

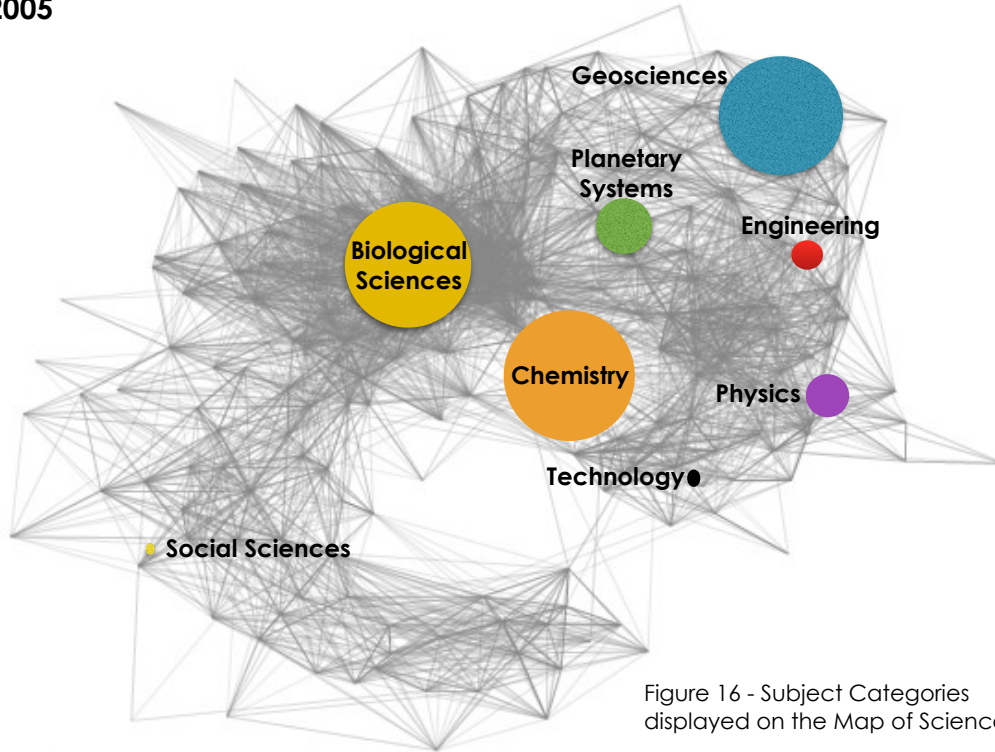


Figure 16 - Subject Categories displayed on the Map of Science.

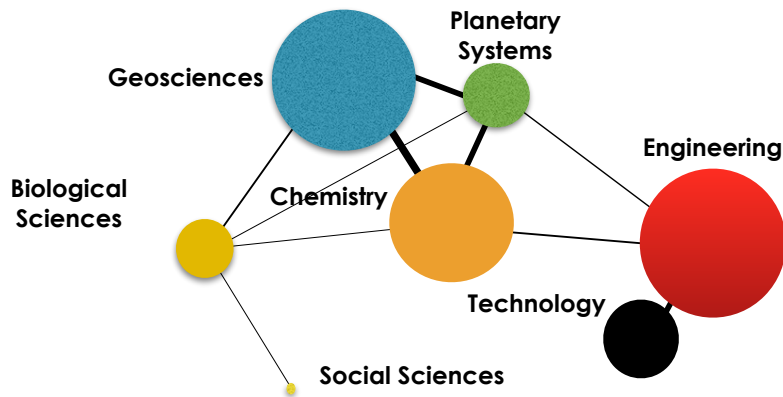


Figure 17 - Core structure of *Astrobiology* 2005. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2006

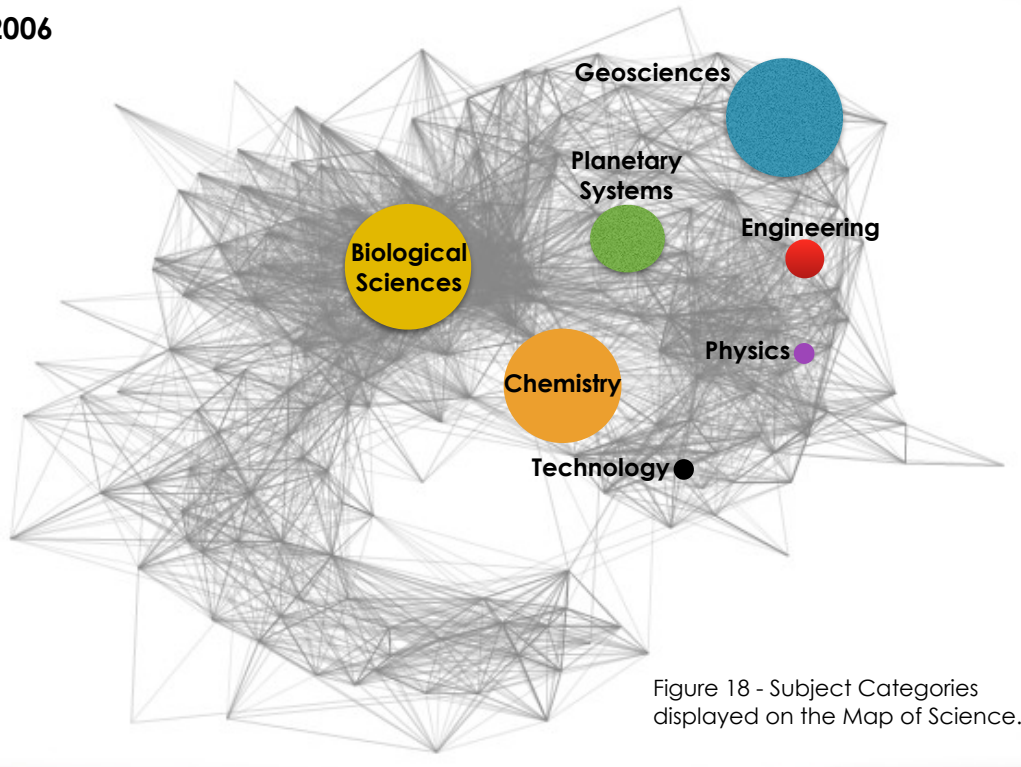


Figure 18 - Subject Categories displayed on the Map of Science.

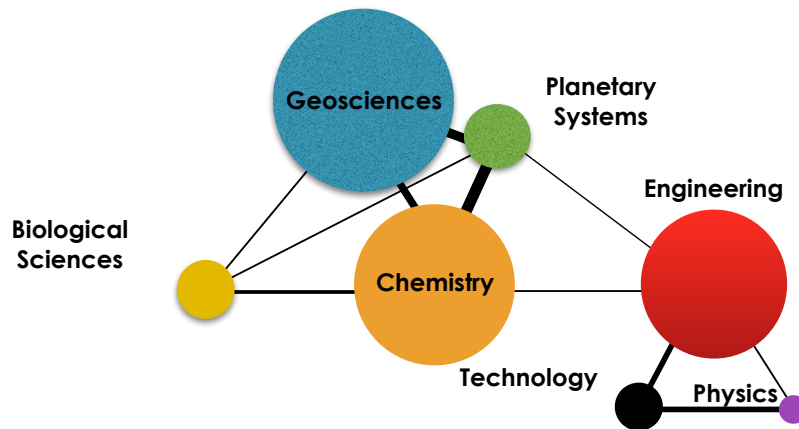


Figure 19 - Core structure of *Astrobiology* 2006. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2007

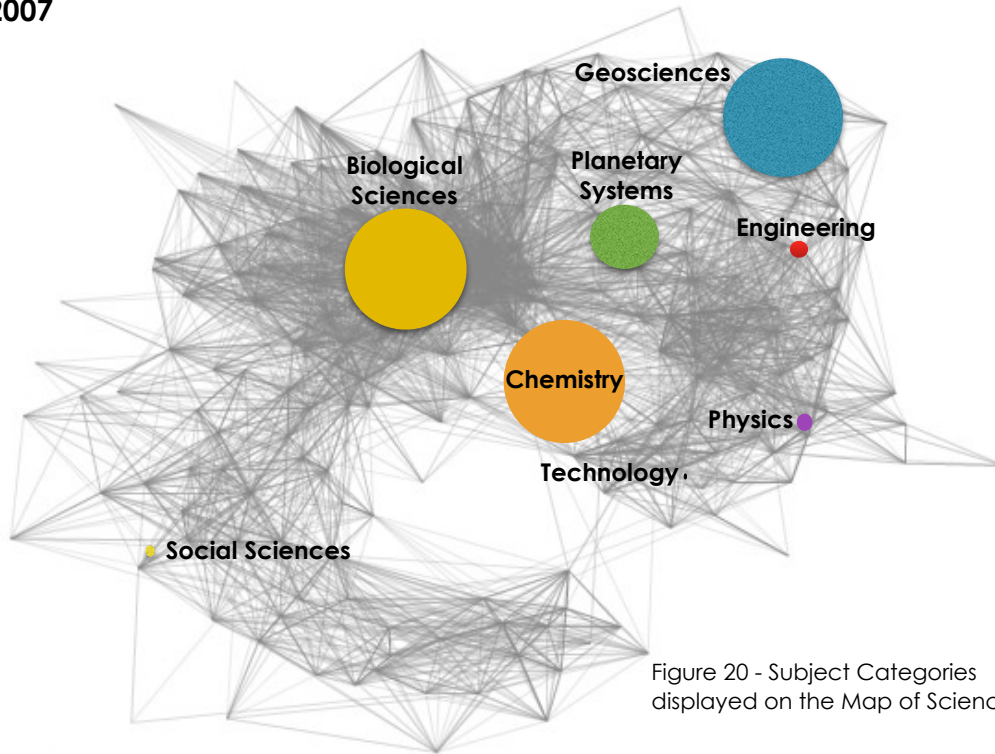


Figure 20 - Subject Categories displayed on the Map of Science.

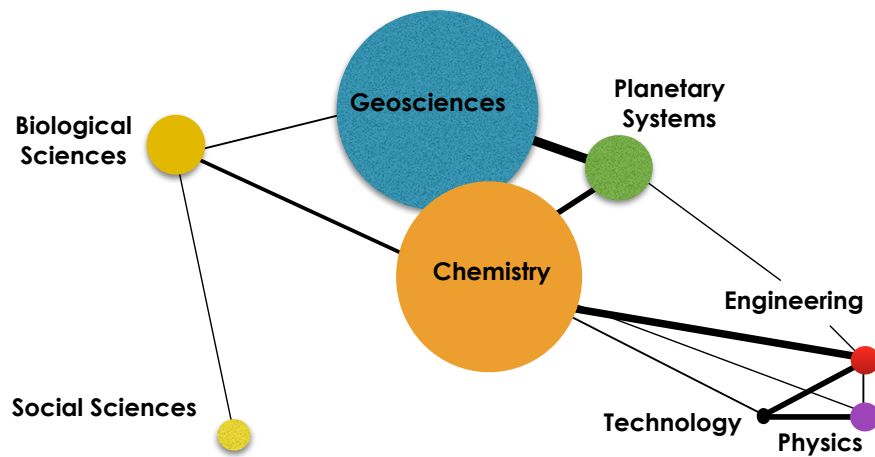
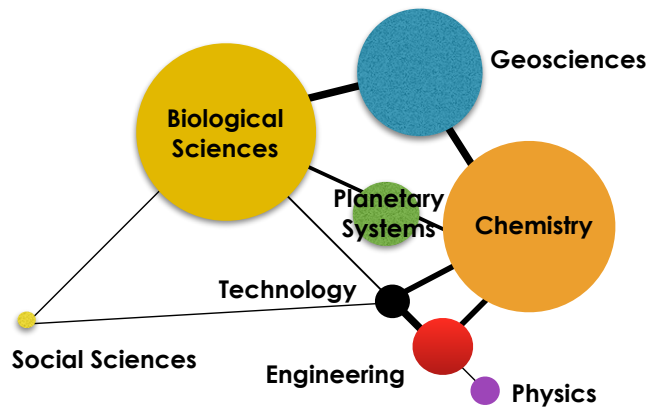
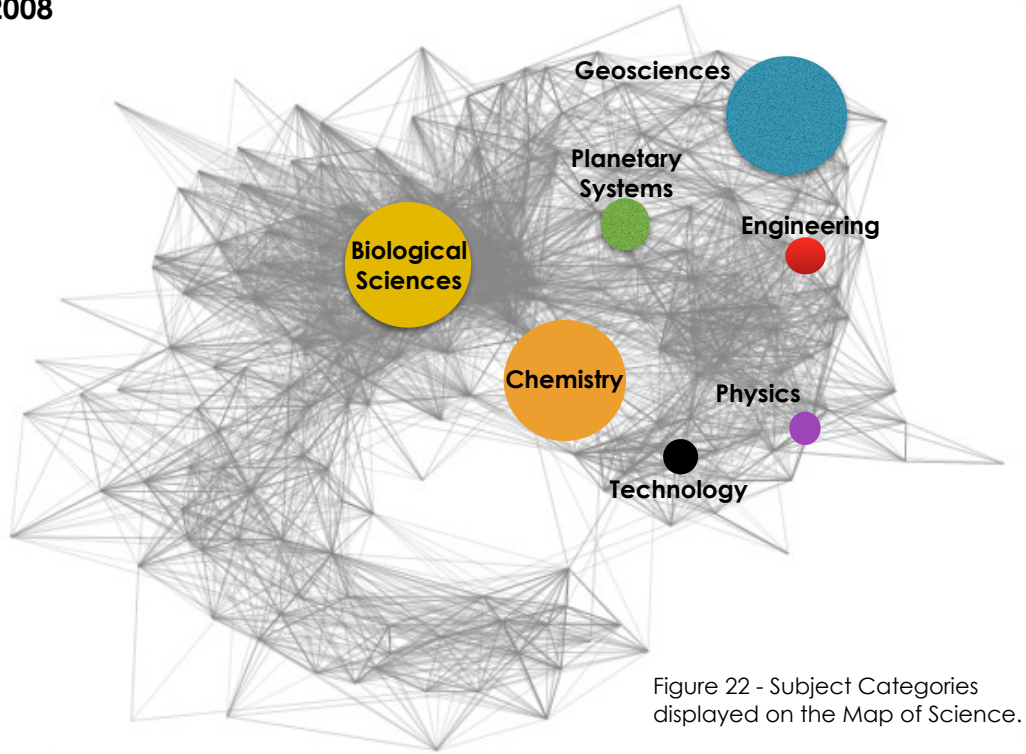


Figure 21 - Core structure of *Astrobiology* 2007. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2008



2009

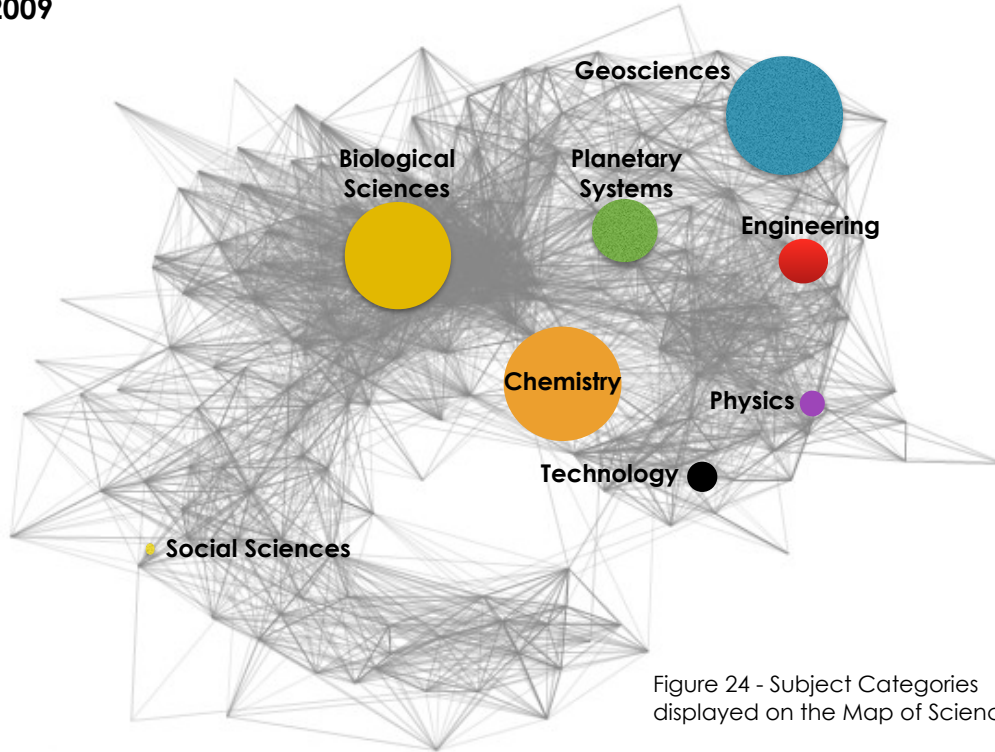


Figure 24 - Subject Categories displayed on the Map of Science.

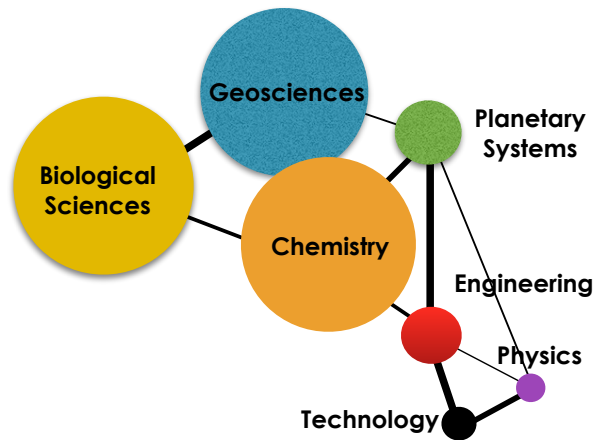


Figure 25 - Core structure of Astrobiology 2009. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2010

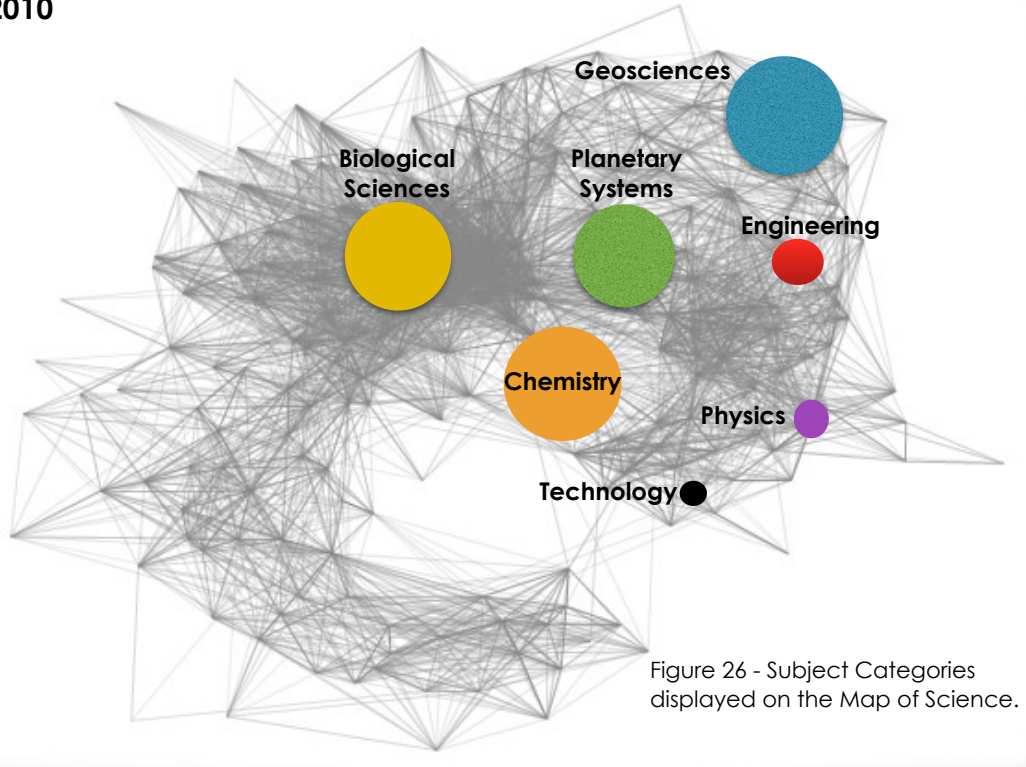


Figure 26 - Subject Categories displayed on the Map of Science.

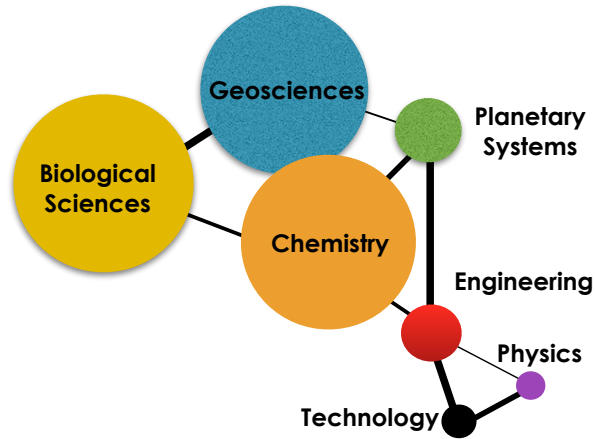


Figure 27 - Core structure of Astrobiology 2010. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2011

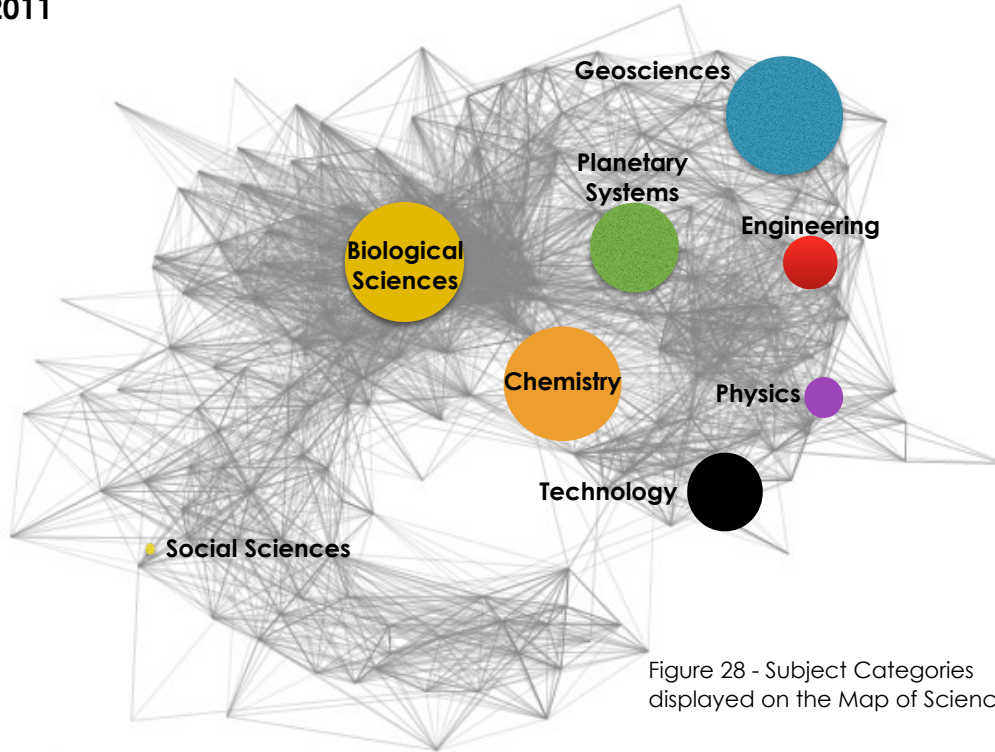


Figure 28 - Subject Categories displayed on the Map of Science.

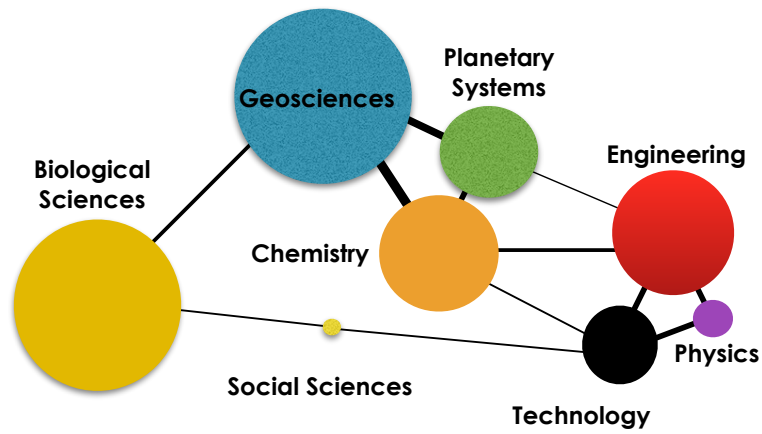


Figure 29 - Core structure of Astrobiology 2011. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

2012

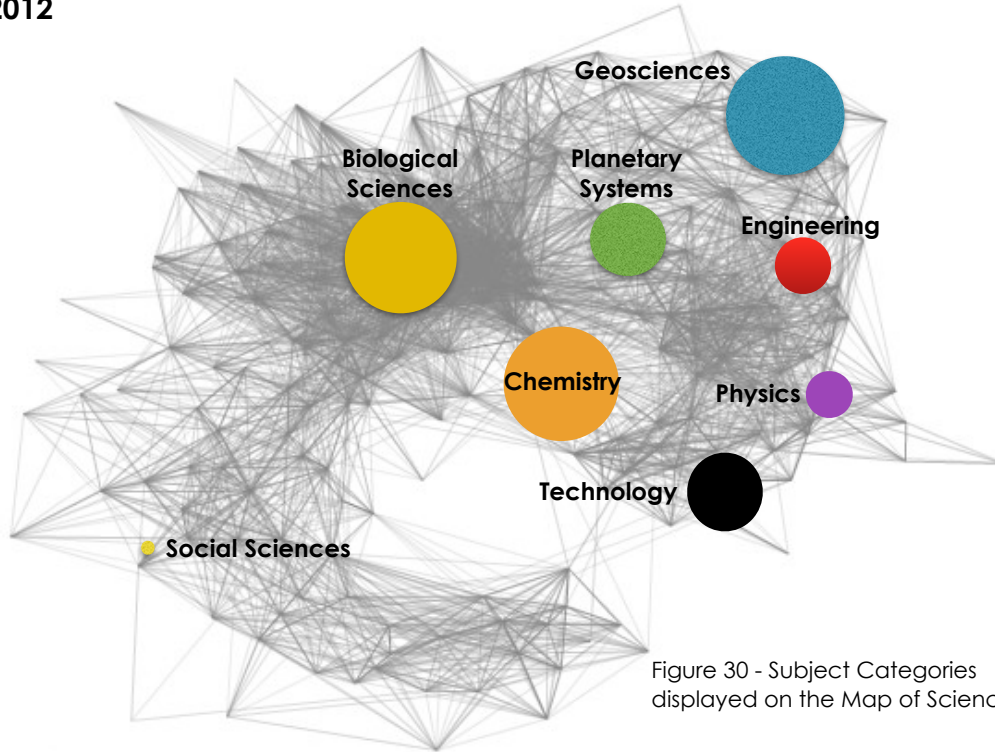


Figure 30 - Subject Categories displayed on the Map of Science.

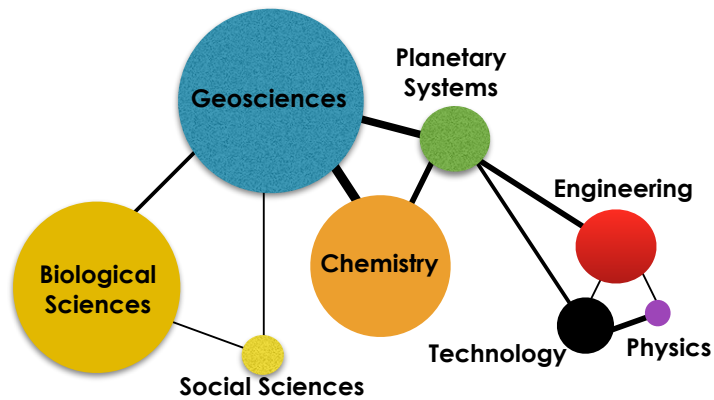


Figure 31 - Core structure of Astrobiology 2012. The size of the nodes is proportional to the number of citations produced. Distance between nodes corresponds to cognitive relationship. Line weight is relative to the number of articles identified as sharing common disciplines.

Analysis and Discussion of Results

After studying the spatial projections of how disciplinary affiliations in *Astrobiology* have organized into disciplinary clusters over the past 13 years, an examination of the general relationships was conducted. From this examination new questions about how the relationships came about, what processes create and sustain the particular patterns of distributions, and what possible relationships exist among research disciplines were revealed. Speculating on such relationships purely on disciplinary distribution is limiting without context, however, and thus the psychological and sociological issues surrounding interdisciplinary research might be germane. This section is broken down into the following three parts:

- General patterns of disciplinary relationships.
- Annual analysis of research articles – 2001 through 2012.
- Discussion of sociological and psychological research germane to IDR.

Patterns and Relationships of Disciplinary Distribution

The spatial patterns projected in Figures 8 – 31 can be summarized through the number of major disciplines identified, the total articles published from each of these disciplines, and the cognitive distance, or

number of citations between the distances, of the disciplines involved.

Specific notable observations include:

1. Eight major disciplines are identified as central nodes including Geosciences, Planetary Systems, Chemistry, Computer Science & Technology, Biological Sciences, and Social Sciences.
2. Geoscience and Chemistry are the largest hubs, representing both researcher affiliation and the most cross-referenced research.
3. Biology was a common research affiliation, but not significantly cross-referenced until 2008.
4. Social Science research is barely cross-referenced and was only part of a multi-nodal linkage in 2012, an abnormal year due to a special edition volume focused solely on Social Science and Humanities. (See Methodology Limitations)
5. Cognitive Distance – Biological Sciences and Social Sciences are disproportionately separated from the other disciplines.

Analysis of Spatial Projections by Year

While the general patterns related to Subject Categories are useful, further scrutiny under Porter et al.'s (2007) framework reveals relationships related to specialization and knowledge integration, which are represented by the weight of lines connecting the disciplines, the number of connecting disciplines, position to one another, and the organization of

disciplines. These factors can help determine the level the integration of research. The relationships are then examined using the disciplinary diversity guidelines outlined in the previous chapter to help determine whether disciplinarity, multidisciplinary, or interdisciplinarity is occurring. Over the twelve years of maps, three separate, yet chronological, groups with similar disciplinary relationships are apparent. These are discussed in the sections below.

Maps from 2001 – 2003:

From 2001 to 2003 only the Hubble telescope and Mars Odyssey missions were active at NASA. Cassini and Titan were still on their journey to Saturn, and subsequently there were no data from those missions. Since NASA had two projects that involved identifying planets, minerals, and geological features, it's not unexpected that the majority of publications were aligned with the Geosciences, Chemistry, the potential for life if the right conditions were found (Biology), and the equipment (Engineering & technology) used to detect these features (Figures 8, 10 & 12).

Other significant relationships are the multi-nodal linkages formed by Geosciences, Chemistry, and Planetary Systems as well as Engineering, Technology, and Physics (Figures 9, 11 & 13). The triangular pattern and proximity of nodes are indicative of high multidisciplinary within the groupings. Lack of a central node with multiple branches, however, is

consistent with low integration, meaning no significant interdisciplinarity has been achieved.

Maps from 2004 – 2007:

During this period the Mars Space Rovers (MERS) and the Spitzer telescope were added to NASA's active missions, bringing the total to four. Notable changes from the 2001 and 2002 years is the sharp reduction in Biology, Engineering, Technology, and Physics articles published (Figures 14, 16, 18 & 20). With the technology and equipment for these projects being established many years prior to launch, and geology data being returned from the Mars satellite and rovers, the disproportional ratios are not unexpected.

The diversity and integration projections (Figures 15, 17, 19 & 21) show the number of citations generated from the articles in Engineering significantly increased but were primarily linked with Chemistry and Geoscience. This connection was most likely caused from the surge of Mars Geology publications deriving their data from the equipment on board the Odyssey and the Rovers. While low in occurrence, there were enough citations of Social Science articles to create a node, but it only links through Biological Sciences, indicating a potential integration within those two disciplines only. Other significant relationships are the repeated multi-nodal linkages formed by Geosciences, Chemistry, and Planetary Systems as well as Engineering, Technology, and Physics. The triangular

pattern and proximity of nodes are indicative of high multidisciplinary within the groupings. The overall positioning and increased number of weak linkages across disciplines, however, indicate specialized disciplinary research — meaning all the references are from related disciplines.

Maps from 2008 – 2012:

In general, the ratio of publications per discipline remained the same from previous years (Figures 22, 24, 26, 28 & 30). The diversity and integration projections (Figures 23, 25, 27, 29 & 31) show the same multi-nodal linkage formed by Engineering, Technology, and Physics as well as Geosciences, Chemistry, and Planetary Systems grouping as seen in previous years. Slightly different is the proximity and addition of the Biological Sciences to the Geosciences, Chemistry, and Planetary Systems multi-nodal linkage, indicating a higher degree of integration.

The triangular pattern and proximity of nodes between the groups are indicative of high multidisciplinary within the triads, but not across the whole map. Also unique for this grouping and across the time period is the first substantial representation of a Social Sciences node in 2012. Given the position on the map as well as the number of unique integrations, the node has high diversity and low coherence, usually associated with potential interdisciplinary integration.

The closer positioning of disciplines and increased number of strong linkages across disciplines, however, indicates high diversity and low integration, meaning a potential instance of interdisciplinary knowledge integration exists. This research is the closest period of interdisciplinarity being reached, except for the complete lack of social science research.

Consistent patterns across all maps

In summary, despite 12 separate missions with varying premise as well as three changes in Astrobiology goals²⁰, the following patterns are dominant and consistent throughout the years:

1. Geosciences, Chemistry, and Planetary Systems form multi-nodal linkages, indicating multidisciplinary in themselves, but are not fully integrated with all disciplines.
2. Engineering, Technology, and Physics form multi-nodal linkages, indicating multidisciplinary in themselves, but are not fully integrated with all disciplines.
3. When published or cited, Social Sciences has high disciplinary diversity, but only potential integration through the Biological Sciences. This is due to the number of subjects covered within these disciplines, e.g. History and Philosophy of Exobiology, Telescope

²⁰ Astrobiology goals are covered on p. 45.

Programs, Evolutionary Biology, and Satellite Imagery, but only the Biological Sciences have significantly cross-referenced these disciplines in their research.

These results suggest Astrobiology is comprised of three separately integrated areas of research – Physical Sciences (Chemistry, Geoscience, Planetary Systems), Theoretical Sciences (Engineering, Physics, Technology), and the Biological Sciences. Although Chemistry could be interpreted as forming a central hub between the physical and theoretical sciences during some years, there is actually no significant integration between them. The appearance and positioning of Chemistry actually creates an illusion based on the two-dimensional projection and viewing angle. Further, an argument can be made that the Social Sciences are so under represented, the published articles can be discarded as outliers – they simply are not typical in *Astrobiology*.

Referring back to the definition for IDR in Chapter 2, there are three components to successful integration and production of new knowledge: 1) the necessity to solve complex problems using multiple disciplines 2) research is grounded in the original disciplinary insights 3) IDR combines insights into a new whole. Given the lack of social science and humanities components of published research, as well as the distinct multidisciplinary nodes of the physical and theoretical sciences, I contend *Astrobiology* fails to meet, at a minimum, component #3, and largely fails component

#1. As such, I turn to the foundations of IDR to help understand the organization of relationships observed.

Psychological and Sociological Theory Related to IDR

NASA practices a fairly laissez-faire style of research collaboration that allows researchers to fit their work into the science goals of the NAI Roadmap. This ultimately allows a natural order of science (Kuhn, 1962) to fall into place, which has been associated with disciplinary knowledge of prime importance. This is problematic for Astrobiology, which is meant to be “interdisciplinary in its implementation.”

Two theories of IDR address barriers of IDR integration in the context of normal science cycles – Pluralism (McCallin, 2004) and Status Concordance Theory (Birnbaum & Gillespie, 1980). Pluralistic dialogue states that for IDR to be successful, groups must challenge their own ways of thinking, which is often a product of disciplinary culture, and be open to new scientific perspectives. Often the energy required to collaborate is not present, which leads to the privileging of a single epistemological and disciplinary perspective. Ultimately, the researcher considers another discipline as simple or less complicated than his or her own, and does not feel collaboration is necessary to understand ones perspective.

From my research, I suggest that both the lack of Social Science research and the cognitive distance of the Biological Sciences evidenced

in Figures 8 through 30 are tantamount to privileging. This is indicated by the distance being directly correlated with integration and the lack of multi-nodal linkages over time. The weak cross-referencing into the Biological Sciences, which are directly involved in the origins and evolution of life, suggests the knowledge produced in this field is constant and assumed to be complete by other disciplines. For example, a geologist may simplify evolution of cells and mineral requirements for life into an assumed model, and fit his or her research of mineral availability into it. No collaboration would then occur as he or she assigned an inherent value, in this case greater, to the biological model already.

Status Concordance Theory suggests that the success of a research project is strongly correlated to group dynamics and equal rank (Birnbaum & Gillespie, 1980). In particular, all disciplines must be viewed as equal when establishing a project. NASA's missions are contradictory to this thought as they exclude many disciplines and place emphasis on others. For example, according to NASA's website the MERS missions were important to Astrobiology so we could determine if "water existed on Mars, and whether it could have supported life in the past." This did not include the possibility of life originating on Mars, being present on Mars, or the implications to humanity if life is found on Mars. Instead, the value of the Geosciences and Biology is elevated based on the hope of finding certain minerals and water.

As apparent from the published research, there were also repeated triangular patterns and strong multi-nodal linkage of the Geosciences, Planetary Systems, and Chemistry as well as Physics, Engineering, and Technology, all disciplines nearly related to one another. I suggest this is a result of disciplinary culture, which describes the tendency of disciplines to work collaboratively with near disciplines, which share worldviews and similar theories of knowledge creation.

Methodology Limitations

I acknowledge there are shortcomings using the overlay tool including sample size and source bias. Further, since attribution of disciplines to Subject Categories within publications can be inconsistent, the overlay maps are only reliable with large numbers. Porter, Rafols, & Leydesdorff have estimated that at least 70 publications may be needed for a valid and reliable exploratory map, but recommend above 1,000 for accurate representations (2010). For this thesis, the mean number of articles for each year's Subject Category map was 70 articles, with 2001 through 2008 being below this figure, and 2009 through 2012 above. Thus, there certainly is room for a margin of error.

Another potential issue is that all of the articles are derived from one publication, leading to potential publication bias. Also, the social science and humanities nodes are present mostly due to the October 2012 issue of

Astrobiology, titled *SPECIAL COLLECTION: The History and Philosophy of Astrobiology*, which contributed 12 articles under the Social Science and Humanities Subject Categories to the matrix. A projection for 2012 was produced with the October issue omitted, and the results found to be nearly identical, with the exception of the absence of the Social Sciences node.

Although the projection provides a visual representation of IDR, namely the disciplinary diversity of publications, it only represents one perspective. Other aspects should be considered as well when assessing interdisciplinary research including *knowledge integration*, which specifically investigates whether the publication under study constitutes a directly interrelated body of research (Rafols & Meyer, 2010). Also, the maps remain a two-dimensional projection of a space, and therefore needs a large number of projections from different angles before a hypotheses can be formed on the basis of spatial relationships. Further, a mixed methodology survey targeted at astrobiology researchers could also be used to gauge disciplinary perceptions, which would strengthen the arguments of disciplinary culture and privileging affecting these patterns.

Review of Findings and Suggestions Moving Forward

The spatial projections of *Astrobiology* literature as well as the articles citing these articles indicate researchers in Astrobiology have tendencies to integrate with disciplines closely related to their own. Based on the description and premises of Astrobiology, I argue that the knowledge production fails to meet the definition of interdisciplinary research. A review of NASA's missions over the same time period and NAI's Roadmap show Social Science and Humanities research is not emphasized, and subsequently is not included in research teams. I suggest psychological and sociological themes are the basis for these correlations, making researchers significantly biased in their selection of research collaboration disciplines and partners. Specifically, this is likely due to entrenched *disciplinary culture* and *privileging*, which ultimately creates a system of multidisciplinary research collaborations, but does not foster creating new interdisciplinary knowledge.

Disciplinary culture

We often think of disciplines as distinct because their object of study differs. The psychologist looks at the workings of the mind while a geologist focuses on the workings of the earth and earth systems. As previously discussed, disciplines also differ in their methodologies, their cultural norms, and their ways of knowing. All of these factors can lead to

misunderstandings in interdisciplinary research. Thus, participants involved in IDR have to begin to think beyond traditional psychological explanations for behavior. Communication and collaboration is improved when participants understand that they are not only products of their upbringing and genetics, but of their disciplinary culture as well. For example, while physics may be given higher status than social sciences, it does not follow that the physicist will be the most competent in leading an interdisciplinary research project. Research groups that recognize and address such assumptions are more likely to successfully collaborate (Holthuis, 2012).

Privileging

Where there are differences in culture, there can also be over privileging occurring. In many groups, members may unknowingly assign status based on arbitrary physical characteristics such as race, height, or beauty. When group members also differ by discipline, participants have yet another characteristic in which to base their assumptions about one another and to privilege the knowledge of some over others. In western cultures, there is a fairly well defined hierarchy of disciplines from those considered to be the most difficult and immutable (physics and math) to those considered easier and more subjective (the social sciences and humanities). Thus, I argue, breaking down disciplinary barriers requires

respect, something that may take considerable patience and effort to achieve.

How to overcome these barriers

Communication is the core of effective interdisciplinary research collaborations. The conversations and connections that convey new insights require considerable effort, and must be supported by intentional efforts (Holthuis, 2012). As Spelt et al. (2009) notes, “Realizing desired learning outcomes demands consistent and well-designed learning environments within a coherent and learner-centered curriculum” (pg. 3). Given the complexity of working collaboratively outside of similar disciplinary cultures, researchers must fully understand and be able to address these challenges. Only then can they truly integrate the collective intelligence of the group.

A layer of complexity in communication is added when we work in interdisciplinary groups. Group participants differ in content knowledge, as well as in their language. This can lead to lack of understanding, or misunderstanding among group members. If unrecognized, the results can derail the collaboration completely. Thus, successful groups have someone who watches for moments when confusion or conflict is arising from linguistic differences, and has formal or informal authority to point out when language differences may be the source of confusion or tension.

In her research on interdisciplinary research projects, Rhoten (2003) has shown that the most successful groups have someone who plays what she calls the “bridge” role. The “bridge” acts as a hub of communication by linking disciplinary knowledge and connecting separate ideas among the researchers. This person reacts to situations or at particular moments in the project where it might be beneficial to focus on a particular approach and leads the group in that direction. Rhoten’s research findings show that what is key to group process is not whether or not an individual’s background is disciplinary or multidisciplinary, but that they have the ability to go between the two at the appropriate times (Holthius, 2012).

A major challenge in interdisciplinary research, then, is to broaden educational foundations so that the nature of the problem can be identified and the appropriate methods to address it can then be easily reached. Status concordance theory tells us that groups whose members can achieve such an understanding are more productive than groups that buy into a disciplinary hierarchy.

NASA’s Involvement Opportunity

Although several professional meetings have been convened in the past decade to discuss the implications of extraterrestrial intelligence, origins of life, and future of life in the Universe (Dick, 2010), only within the

past two years has a conference been held to address the broader implications of social sciences and humanities in the context of Astrobiology (Race et al., 2012). Interestingly, the National Aeronautics and Space Act of 1958 defines one of NASA's eight objectives as "the establishment of long- range studies of the potential benefits to be gained from, the opportunities for, and the problems involved in the utilization of aeronautical and space activities for peaceful and scientific purposes" (Sec 102a). Up until 2010, an average of one publication per ten years specifically addressed this part of the Space Act (Dick 2010), leaving the potential sociological benefits gained from NASA research largely unaddressed. Since NASA is the hub and focal point for directing Astrobiology research, the opportunity to direct or encourage this type of research should be underscored. Further, one of the premises of IDR defined in Chapter 2 is that the people or institutions that determine the rules are inseparable from the people who practice them, thus NASA may have ethical obligation to support and incorporate this research into its work plans.

In the realm of IDR, leadership has been highlighted as one of the most important factors related to group performance, including its cognitive functionality. Based on Rhoten's framework for the "bridge" role, I suggest NASA should take leadership by mandating certain criteria on appropriate projects to include the Social Sciences, Humanities, or other

appropriate discipline to study the effects on society. While this involvement may appear to go against the virtual framework of laissez-faire style cooperation currently practiced at NASA and laid out by the Roadmaps, it's been well established that change takes an authority figure to mandate it, just as in IDR itself. It should also be noted that, for example, the National Institute of Health requires at least between 3-5% of granted funds in both human genome and cancer projects to be dedicated to societal benefit studies of the projects, so the premise is not completely original. While this requirement may not result in new knowledge being created or have a major impact on the research results, it does recognize that breakthrough science could have profound impacts on how we live our lives if it takes on a broader scope.

This idea would not be without challenge of course. The task is ultimately forcing change of disciplinary culture. It would be intensive, requiring immense preparation and practice. The first step would be to identify what levels of research and projects require a bridge, and how to identify them. For example, the collaborative mission of sending the Mars Space Lab to the Red Planet would be considered significant and would warrant studying the effects on society if life or evidence of life was found. Using the rover XRD data to identify minerals present in the soil and the possibility of water being present at some point in history might not.

Secondly, providing some form of generalized training would be

beneficial to help the research teams recognize the disciplinary barriers that they may come across as well as barriers posed by their own prejudices. Finally, deciding whether the person acting as the “bridge” between disciplines would be NASA-appointed would be critical as well. The source and level of funding as well as the public interest could be variables in deciding NASA’s involvement as each variable comes with its inherent policy, influences, and potential bias.

As a final suggestion, I will adapt the framework explained by Borner et al. (2013), which differentiates between three levels (macro, meso, micro) of team science,²¹ as the basis for my suggestions to establish a bridge person into an IDR team. The actors, their role, and possible tools available to them would need to be considered. These factors have been combined into Figure 32 below.

This pyramidal structure does not imply that one category is more important than another, but rather that the potential to have an effect on society is greater at higher levels of the pyramid. Similarly, while the tools are not restricted to a particular level, I’ve tried to align within each respective category the tools that would be useful without completely

²¹ Macro-level focuses on general patterns, including statistical analysis of types and numbers of collaborations, and concerns organizational change. Meso level is interested in teams, their composition, group dynamics, interactions, and communication processes within them. Micro level is dedicated to individuals, their skills and competencies, and personal role in team communication and conflict resolution.

hindering the research process. After all, at some point work has to be accomplished.

Figure 32: Pyramid of Bridge Implementation into Astrobiology: Actors, Roles, and Tools

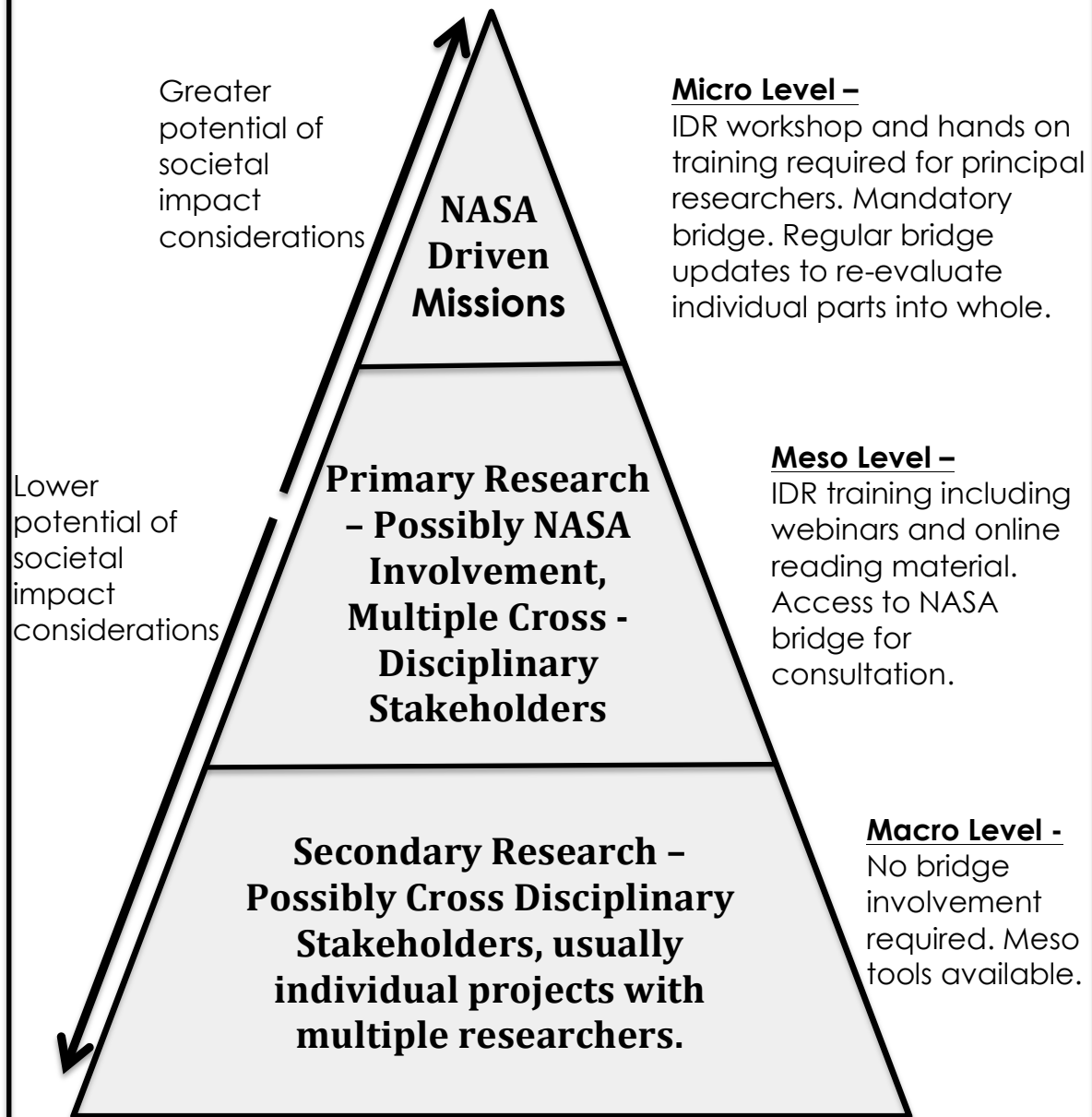


Figure adapted from Brown et al. (2014) and content inspired by Katz et al. (2011).

Limitations of this Thesis

Just as researchers engaged in IDR come together from various disciplines, I began this project with my own deeply held sociocultural perspectives. These perspectives are formed by my disciplinary backgrounds and with them comes preconceived mental models, cognitive maps, frameworks, and paradigms. In addition, as with any culture, the tools (spatial analysis), traditions (methods), and manner of communication during this project has been dictated by my disciplinary culture. During my time at University, both in undergraduate and graduate school as well as in my professional career, I've essentially been enculturated into the language, values, and traditions of many disciplines. I cannot say without bias that at some point I've become so entrenched in this culture that the lenses through which I've analyzed this problem cannot be critically examined. They certainly are the frame of reference through which I create meaning. Ultimately, my disciplinary culture is part of my research and holds bias as well.

Future Research

I would like to continue investigating the role of IDR in Astrobiology, especially at the government level, and help develop methods to increase collaboration opportunities for the next generation of researchers. To accomplish this, I imagine a complete institutional analysis

of NASA's Astrobiology Institute as necessary and essential to identify all the relationships and key players influencing Astrobiology research. Further, to successfully execute and change the culture and operation of institutions, its mode of decision-making must be fully understood. The nature of NAI should therefore be assessed, and a framework for institutional collaboration and joint decision-making should be established. Great care should be taken with the current institutional framework; as the same institutional structure imported into a new cultural context may still operate in much the same way as separate disciplines.

Epilogue

In this thesis, I examined the literature of Astrobiology with the intent to map the disciplinary relationships in this new and growing field. While forming the research question, I chose to investigate to what extent various disciplines have integrated under the umbrella of NASA's societal obligations to solve complex problems. I used significant literature on the theories of interdisciplinarity as well as on the knowledge production characteristics of interdisciplinary research projects as a guide. The relational maps produced in this thesis, however, show Astrobiology being comprised of three groups of similar disciplines working together in multidisciplinary efforts, with the Social Sciences and Humanities being practically non-existent. Ultimately, knowledge integration among the disciplines of Astrobiology does not appear to exist.

I then analyzed the disciplinary relationship maps based on theoretical foundations of IDR, and there was, in my opinion, indications of privileging in certain areas of study and disciplinary culture affecting how the disciplines collaborate or not. But, I also was curious as to why these entrenched disciplinary cultures existed in the first place, and how they could affect researchers working in Astrobiology. As such, I contacted three of the NAI affiliated Astrobiology programs at the University of Washington, University of Arizona, and Penn State University via their

general department email to ask if any researchers would be willing to discuss how research is conducted in their units. Two of the departments responded to my inquiry and I spoke with a post doctorate researcher at Penn State and a professor at the University of Arizona. The conversations were informal and structured by me explaining that I am a graduate student investigating the relationships between the branches of Astrobiology in the context of interdisciplinarity – and that I’m trying to understand how researchers perceive other disciplines. I thoroughly clarified that no part of the conversations would be used as “research,” in the sense that I was collecting publishable data, and that the discussions were simply providing me with background knowledge about Astrobiology researchers. Further, I stated that such information might appear in my thesis, but only as an afterthought.

When asked about experience or opinions working with researchers from disciplines different than their own, one said that the issue was “complex” and that working outside of one’s research group was “difficult.” Another expressed frustration in collaborative research and felt that someone had to be in charge for projects to work – and that person should be the one whose contribution is the closest to the research goal. I was provided with a humorous, yet serious question when one researcher responded by asking me if I had ever tried to teach calculus to a bunch of dance majors – because that’s what its like working with non-scientists.

This person further lamented that speaking with a physicist is like having a perpetually disappointed father who just feels bad that you don't understand what he is talking about.

These informal discussions help provide context for the more challenging aspects of IDR in the forms of barriers to collaborative research, but I also think they raise questions about the researchers themselves. For example, one of the comments made was that children who have a greater understanding of the world become physicists – a statement subjective in nature but also indicative of a deeply entrenched worldview likely reinforced by other physicists. This statement not only implies physicists are better at solving problems related to the “real” world, but implies a prejudice against other disciplines based on an arbitrary characteristic such as a particular educational degree.

Similarly, the comment made about Dance majors not understanding calculus implies that someone who specializes in non-science disciplines cannot easily understand Mathematics, which is being viewed as a more challenging, superior field. Further, it places emphasis on a largely qualitative discipline and discounts a whole group of people based on their epistemology – or simply put, how they know what they know. These include questions about what knowledge is and how it can be acquired, and even to a certain extent, which knowledge is pertinent to any given subject. The researchers I spoke with made comments that

implied that the learned knowledge of other disciplines is not viewed as pertinent to Astrobiology. More importantly, the way in which knowledge is attained – exclusively through positivistic science – is of primary importance.

Although I view the methodology and research of this thesis as sound, I believe the results from the thesis and conversations with researchers hint that further study of the researchers themselves is warranted. I speculate that researchers, together with their respective epistemologies, may play a role in the interdisciplinarity in Astrobiology. As I view it, there are two competing paradigms currently in Astrobiology – positivism and constructionism.

Positivism is where I speculate most researchers operate most of the time. They view the world and everything in it as real, and truthful. There is no question that the table is solid, and no doubt that research findings need to be statistically significant. Positivism is the testing of hypotheses and represents the usual world of science. Researchers strive to minimize bias and the research produced is considered valid and reliable. Usually positivistic research is quantitative in nature.

Constructivism, however, states that human beings construct their own social realities in relation to one another. Reality is viewed as subjective, and only through experience can knowledge be created.

One researcher's particular reality might be shared with other people, but

that same reality could also be constructed in quite different ways. Knowledge is not absolute. Rather, the researcher actively participates in constructing both methodology and results – no longer on the outside looking in.

So here is the dilemma – most disciplines are operating with a positivistic worldview. They are conducting statistically sensitive research, testing hypothesis, and viewing their work as real and substantive. But when applied to the complex problem solving required in Astrobiology, this faux infallibility can be exclusive and non productive.

This dominant attitude extends to NASA as well, which is influencing the development of Astrobiology through funding and providing data. NASA has the ability to dictate which knowledge is important and what science is prioritized. And by largely ignoring the Social Sciences and Humanities, it may be acknowledging that positivistic epistemology is to be privileged. This could be due to the academic background of the decision makers (managers) themselves.

Given these musings, I believe that for interdisciplinarity to manifest itself in Astrobiology, the first step will be to figure out how to convince researchers from different disciplines to talk to one another. They need to speak a common and meaningful language, or be comfortable with the language of researchers from different disciplines and epistemologies. But

even more important than figuring out how to talk to one another is finding a way to first listen.

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Appendix A - 2001 Astrobiology Articles

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Appendix K - 2011 Astrobiology Articles

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Appendix L - 2012 Astrobiology Articles

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