AN AMBIENT SEMANTIC INTELLIGENCE MODEL FOR SCIENTIFIC RESEARCH

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ABSTRACT

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Scientific curiosity is the key motivation behind most of the scientific and philosophical achievements of human kind. It is defined in our theory as an intrinsically motivated desire to make sense of potentially everything that are proper subjects of science and philosophy. Paradoxically, the concept of scientific curiosity itself is one of the least studied subjects in the history of science and philosophy. In an age of 'attention economy' where the biggest problem is not the unavailability of information but its overabundance, the need for effective information-filtering systems becomes more conspicuous. Therefore, studying the design of information systems that effectively adapt to human curiosity is a highly significant area of research. Our study first constructs a theory of scientific curiosity which provides a grounding for an effective computational model that aims at augmenting scientific curiosity and aiding scientific research. The theory initially delineates the concept of 'scientific curiosity' and constructs a unified framework within which various insights and data coming form a variety of research areas come together in a concise and coherent way. The basic forces that influence the direction of human curiosity among alternative items of information, i.e. content-bearing resources, are described as the cognitive dynamics of scientific curiosity. Those dynamics, which are rooted in human personality, are (1) expansion dynamics, (2) completion dynamics, (3) explication dynamics, (4) perfection dynamics and (5) interest dynamics. The influences coming from each dynamics interact in analogy to a vector space and such interactions determine the final motion of human curiosity. Those motions are formulated as patterns of selections made by scientific curiosity in the face of time constraint and the identified patterns are used for analyzing the curiosity traits of individuals. Human curiosity interacts strongly with the technological environment in line with the idea of extended cognition. With the image of a scientific researcher embedded into a library, the study clarifies the coupling of and interaction between human curiosity and the available external resources. This perspective allows for a smooth transition from a unified theory of curiosity to the question of what types of technology designs can best augment scientific curiosity and aid scientific research. After this step the available technologies are analyzed and the concept of ambient semantic intelligence for scientific research is introduced. Ambient systems are highly adaptive, personalized and context-aware systems, whereas semantic intelligence has the capabilities of representing ontology-based meaning-systems effectively, enabling semantic interoperability and filling semantic gaps via reasoners. Ambient semantic intelligence combines those features and enables systems that process ontology-based semantic information and adapt to human curiosity traits, which in turn augments human curiosity and aids scientific research in a unique way. The thesis includes a toy model that implements such a design and discusses its problems as well as significance for the future of Cognitive Science.

Keywords: Curiosity, universal curiosity, scientific curiosity, ambient semantic intelligence, cognitive dynamics of scientific curiosity, scientific collaboration

ÖZ

BİLİMSEL ARAŞTIRMA İÇİN ÇEVRELEYEN ANLAMSAL ZEKA MODELİ

Subaşı, Ahmet
Doktora, Bilişsel Bilim Bölümü
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Bilimsel merak insanoğlunun bilimsel ve felsefi başarılarının büyük kısmının ardında yatan kilit bir güdülenmedir. Kuramımız içerisinde bilim ve felsefenin olağan konularına dair potansiyel olarak herşeyi içkin bir güdülenme ile anlamlandırma arzusu şeklinde tanımlanmıştır. Bir tezat olarak, bilimsel merak kavramının kendisi bilim ve felsefe tarihi içerisinde en az çalışılmış alanlardan birisidir. 'Dikkat ekonomisi' çağında en büyük sorun bilginin yeterince elverişli olmaması değil çok bol olmasıdır ve bundan ötürü etkili bilgi-filtreleme sistemlerine olan ihtiyaç daha da göze çarpar hale gelmiştir. Bu nedenle, insan merakına etkili biçimde uyum sağlayan bilgi sistemlerinin tasarımı üzerine çalışma yapmak oldukça önemli bir araştırma alanı haline gelmektedir. Bizim çalışmamız öncelikle bilimsel merakı artıracak ve bilimsel araştırmaya destek olacak berimsel bir model için gerekli zemini sağlayacak bir bilimsel merak kuramı inşa etmektedir. Kuram öncelikle bilimsel merak kavramının sınırlarını belirlemekte ve farklı araştırma alanlarından gelen içgörüleri ve verileri birleşik bir çerçeve içerisinde özlü ve bağdaşık olarak bir araya getirmektedir. İnsan merakının farklı bilgi parçaları, diğer bir değişle içerik taşıyan kaynaklar, arasındaki yönünü belirleyen temel güçler bilimsel merakın bilişsel dinamikleri olarak betimlenmiştir. Kökleri insan kişiliğinde olan bu dinamikler (1) genişleme dinamiği, (2) tamamlama dinamiği, (3) açımlama dinamiği, (4) mükemmelleştirme dinamiği ve (5) ilgi dinamiğidir. Herbir dinamikten gelen etkiler vektör uzayı örneksemesine uygun olarak etkileşmekte ve insan merakının nihai hareketini belirlemektedir. Bu hareketler bilimsel merakın zaman kısıtı karşısında seçim yapma örüntüleri olarak formüle edilmekte ve tanımlanan örüntüler bireylerin merak davranış çizgilerini analiz etmek için kullanılmaktadır. İnsan merakı teknolojik çevresiyle ortamında biliş fikrine uygun olarak güçlü biçimde etkileşmektedir. Çalışma, kütüphanenin içine yerleşik bilimsel araştırmacı imgesini kullanarak, insan merakı ve elverişli dışsal kaynaklar arasındaki eşleşmeyi ve etkileşimi netleştirmektedir. Bu türden bir perspektif merakın birleşik kuramından ne tür bir teknoloji tasarımının bilimsel merakı artıracağı ve bilimsel araştırmayı destekleyeceği sorusuna yumuşak bir geçiş sağlamaktadır. Bu adımdan sonra mevcut teknolojiler analiz edilmekte ve bilimsel araştırma için çevreleyen anlamsal zeka kavramı tanıtılmaktadır. Çevreleyen sistemler yüksek düzeyde uyum sağlayıcı, kişiselleşmiş ve bağlamın farkında sistemlerdir. Anlamsal zeka ise ontoloji tabanlı anlam sistemlerini etkili biçimde temsil edebilir, anlamsal karşılıklı işlerliği mümkün kılar ve anlamsal boşlukları akıl yürütücülerle doldurabilir. Çevreleyen anlamsal zeka bu özellikleri bir araya getirir ve ontoloji tabanlı anlamsal bilgiyi işleyebilen ve insan merak davranış çizgilerine uyum sağlayabilen sistemleri mümkün kılar ki bu da sonuç olarak insan merakını artırır ve bilimsel merakı benzersiz biçimde destekler. Bu tez aynı zamanda bu türden bir tasarımı uygulayan bir oyuncak modeli de içermekte ve modelin hem sorunlarını hem de Bilişsel Bilim alanı için önemini tartışmaktadır.

Anahtar Kelimeler: Merak, evrensel merak, bilimsel merak, çevreleyen anlamsal zeka, bilimsel merakın bilişsel dinamikleri, bilimsel işbirliği

To My Beloved One

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASC	Ambient Semantic Computing
BIDC	Broad Interest Domain Community
BN	Bayesian Network
CAVE	Computer Assisted Virtual Environment
CFL	Curiosity Formula List
IJSC	International Journal of Semantic Computing
IAU	International Association of Universities
NLP	Natural Language Processing
PPP	Popularity, prestige, popular score
SR	Scientific Researcher
WWW	World Wide Web
W3C	World Wide Web Consortium

CHAPTER 1

1. INTRODUCTION

Aristotle begins his Metaphysics with the famous statement: "All men by nature desire to know" (Aristotle, 1987). Although the desire to know is a basic condition of all intellectual achievements marked by humankind, ironically, the phenomenon of 'curiosity' itself has rarely been an object of philosophical inquiry throughout the intellectual history. Ilhan Inan, being one of the few philosophers who has systematically studied the subject of curiosity and written a book about it points out this issue in the beginning of his work:

> For more than two millennia, philosophers have been engaged in discussions concerning the notion of knowledge. Much has been said on issues such as what knowledge is, how it is possible, what kinds of knowledge there are, and a host of related issues. Various theories of knowledge have emerged that attempt to answer these questions, and the debate is still as alive as when it first started. One good reason for this is that knowledge is important for us. Some believe that knowledge of certain things has intrinsic value, but even ones who think otherwise still think the study of knowledge is of upmost importance for philosophy. Epistemology has significantly flourished after the twentieth century, leading to more detailed and rigorous discussions concerning certain epistemic notions that relate to knowledge. There is now an abundant literature especially on justification, belief, and truth, the three parts of knowledge in its so-called classical analysis. A lot has been said about the notion of inquiry as it is considered to be a fundamental driving force in our quest for knowledge. But oddly enough epistemologists have paid little attention to the more basic motivation that has led us to start inquiring into the unknown. That is curiosity (Inan, 2012).

In the field of psychology there has been a heightened interest starting from the second half of the 20th century. Berlyne is one of the leading contributors to curiosity studies and he makes a similar remark in his seminal work *A Theory of Human Curiosity:*

> Few phenomena has been the subject of more protracted discussion than human knowledge. Yet this discussion has usually paid little attention to the motivation underlying the quest for knowledge […] (Berlyne D. E., A Theory of Human Curiosity, 1954).

Although this lack of interest has been conspicuous, the potential of what can be collected today into a multidisciplinary archive of curiosity literature cannot be underestimated. Both philosophical and psychological literature provide a rich set of theoretical insights and a reasonable foundation for future research. Yet, this potential seems not to be fully realized by some of the relevant academic disciplines such as Cognitive Science. To present why Cognitive Science is critical for the future of curiosity research, it is relevant to mention the recent developments in technology and how it has affected our lives.

Digital Revolution and Information Age have fundamentally changed the way we make research. None of the students of 2015 can think of writing an academic article without leveraging the internet, digital libraries and search engines. Increasingly more digital resources are becoming available for researchers worldwide and the tools for accessing the digital information are becoming more and more sophisticated. Yet, there still seems to be a huge gap between the theoretical insights of accumulated curiosity literature and the technological advancements. Indeed, there is even no significant sign of awareness regarding the possible synergy between them. Cognitive Science is at an advantaged position in bridging this gap and creating a new and exciting field of research for two reasons: (1) Cognitive Science can use its methodological tools and multidisciplinary approach for constructing a unified model of curiosity by gathering insights from Philosophy, Psychology and Artificial Intelligence and (2) it is only Cognitive Science that can communicate those insights with cognitive modeling approach of artificial intelligence in order to come up with an actual computational design. The aim of the present study is to make such a proposal.

1.1. PROBLEM STATEMENT

The basic research questions are as follows:

1) How can the theoretical insights of various disciplines on the subject of curiosity be integrated into a comprehensive and unified cognitive theory of curiosity?
2) How can this unified theory be utilized for an engineering model?
3) What are the strengths and weaknesses of such a model?
4) What is the future of such a field of research?

1.2. SIGNIFICANCE OF THE STUDY

Curiosity is an intrinsic motivation to know. Scientific curiosity is an intrinsic motivation to know the proper subjects of science and philosophy as opposed to, for example, being curious about a person's privacy. As a uniquely human motivation, scientific curiosity has become the driving force behind all scientific achievements of human kind from the discovery of writing to Curiosity's mission to Mars. Any such achievement is a product of the diligent researcher spending relentless time and effort for research. In an age of Digital Revolution, any study that has the promise of improving the way human cognition and the computer system interacts during research process would have an obvious value.

A quick glance into big data related articles on the internet would give an idea about the incredible pace of digital revolution. According to Harvard Business Review "As of 2012, about 2.5 exabytes of data are created each day, and that number is doubling every 40 months or so. More data cross the internet every second than were stored in the entire internet just 20 years ago" (McAfee & Brynjolfsson, 2012). It is not only the volume of data that is astounding. The transition of World Wide Web from a simple document publishing medium into an interactive platform with path-breaking social media functionalities and its march towards Semantic Web are also indicative of the future direction of technology. A major problem coming out of the majestic increase in data volumes and the increasing sophistication of web technology is about how to organize and access the available data optimally. The advancements in search engines, the proliferation of social media for various verticals and increasing number of comprehensive digital repositories are some of the solutions that have received wide acceptance among the digital community. The academic community and researchers of all types are a subset of the beneficiaries of these technologies. It is almost impossible to think of a researcher writing an article without leveraging Google, checking some articles from EBSCOhost online research databases and using Twitter for messaging with colleagues for collaboration. Although the benefits of the current technologies are undisputable, there stills seems to be a long way to go for an ideal coupling between man and machine for an optimal research process. One of the reasons that leads to such a verdict is the observation that there is no literature studying comprehensively the research process with such an end. As the research process is highly influenced by human curiosity and its dynamics, curiosity studies would be an integral part of such an endeavor. As stated in the beginning, curiosity studies have never been a systematic subject of engineers related to the field and we have so far no viable model that can be utilized for such a design. AI studies and especially knowledge representation have gone a long way since its inception and there are many successful solutions in the market such as medical diagnosis systems and virtual assistants. Expert systems effectively support decision making processes and widely used in many realms. Nonetheless, all these instruments and many more have not concentrated its powers around the problem of scientific research.

Having made this observation, it is worth mentioning the significance of 'research' and specifically 'scientific research' itself. Without a doubt, human species owes all of its greatest achievements to its quest for knowledge. Without our unique relationship with knowledge we could have been no better than any of the non-human species. In the modern age we have the obsession for optimizing all of our production systems for the utmost yield and scientific research has been the dynamo for advancing the science of efficiency. Interestingly, we are still wasting a lot of good time, energy and resources for repetitive and redundant tasks during our scientific research processes. When the number of graduate students and academicians in the world is concerned, the cash equivalent of this waste is easy to imagine. We are extremely connected via internet, but every hour and day a lot of students all around the world are writing their thesis about their same supposedly 'original' ideas, they are wasting a lot of time finding out the most significant contributions to their research area to begin their studies with, they are realizing that their 'original idea' has already been articulated by some other academician, whose article they received too late and they are totally unaware of this colleague in the other end of the world who is actually writing a 100% complementary article to what they are on to. This is only a simple and partial list of inefficiencies that we are going through. Even finding a solution that effectively addresses these problems would be a valuable contribution. However, what can be achieved is much more than that. We can design collaboration systems that complement our opinions, give us an optimized and complete reading list right at the beginning of our research, connect us with related researchers and their work, and automatically process the available information for deriving more information for our use like an academic expert system. Moreover, such a system can also generate a curiosity behavior model of the user and personalize the outputs according to that model.

The overall vision that targets all those benefits and more are named Ambient Semantic Intelligence Model for Scientific Research. It will be built upon the theoretical insights of curiosity literature as well as the modern technological tools such as ontology engineering, rule engines, NLP and social media.

1.3. ORGANIZATION OF THE DISSERTATION

There are five chapters in the dissertation. The first one is the introduction. The basic research problems and the significance of the research are mentioned in this chapter.

The second chapter is reserved for literature review. With subsections for philosophy, psychology, extended cognition theory, technologies for research and collaborative learning, the theoretical context of the model to be offered will be given together with the relevant concepts and discussions that will be referred to during its scaffolding.

The third chapter will be devoted to the construction of the unified cognitive theory of curiosity and its extended version. Before switching to the next chapter, the theory will be linked to an overview of the Ambient Semantic Intelligence Model for a smooth transition.

The fourth chapter will discuss the building blocks of the Ambient Semantic Intelligence Model and will gather the components into a whole using the tools and methods introduced in the same chapter. There will also be a depiction of the overall proof-of-concept system design.

In the final chapter the significance and basic problems of the model will be discussed and ideas for the future of the research will be mentioned followed by some final remarks in the conclusions section.

CHAPTER 2

2. LITERATURE REVIEW

This chapter will start with an overview of the contributions of philosophy and psychology to the field of curiosity research. Extended mind theory, which is the third section of the chapter, is relevant as a theory that establishes a connection between cognition and technologies that can be conceptualized as extensions of it. Finally, there will be a survey of the current technologies that facilitate and aid research process as well as the field of collaborative learning, which leverages those technologies.

2.1 CURIOSITY IN PHILOSOPHY

As mentioned in the beginning of the first chapter, there has not been much attention given to the problem of curiosity throughout the history of philosophy. The problems around knowledge such as what knowledge is and how we can attain it seem to have shadowed the concerns about why we desire to know in the beginning. When Aristotle emphasizes that all human beings by nature desire to know, this seems to be the statement of a fact about human beings taken for granted rather than being a problem to be elaborated upon. The feeling that drives our quest for knowledge is called 'thauma' by the ancient philosophers, which is more accurately translated as 'wonder'. Some preferred to use words 'curiosity' or 'inquisitiveness' with definitions that are more or less similar: 'appetite of curiosity', 'appetite for knowledge' and 'love of truth'. The history of philosophy gives us sporadic mentions about the concepts of 'wonder, curiosity and inquisitiveness' in a similar fashion. They are not attempts to philosophize about the concepts but are mostly some introductory statements made about issues that are more popular subjects of philosophy.

In spite of this, there has been some recurring themes around the concept(s). One of those themes is whether curiosity (or wonder based upon the context) is a virtue or a vice. Although, unsurprisingly, it has been frequently seen as a virtue that is the driving force behind our love for truth and philosophy, in some contexts it is pejoratively called as 'the lust of the eye', where it is perceived as some unnecessary inquisitiveness that distracts our attention from more important things such as the knowledge of God as in the case of St. Augustine. Although St. Augustine himself was a very curious personality, his interpretation of the concept of 'curiosity' was biased toward things which we do not tend to associate with scientific curiosity such as gossiping and voyeurism. Yet, knowledge about nature was also part of the things that Augustine saw as a risk against things that he attributes a higher value to. Therefore, philosophical and metaphysical convictions have had an influence on how 'desire to know' has been subjected to moral evaluations and how it was subcategorized into good and bad versions. Hume, similarly, had this distinction between good and bad versions of curiosity, where the former was associated with love of knowledge and the latter was associated with the inquisition of other people's privacy.

Hobbes is one of the first modern philosophers to give an unconditional praise for curiosity without an expression of similar worries and he also gives an explicit definition for it (Inan, 2012):

> Desire, to know why, and how, CURIOSITY; such as is in no living creature but Man; so that Man is distinguished, not only by his Reason; but also by this singular Passion from other Animals; in whom the appetite of food, and other pleasures of Sense, by prædominance, take away the care of knowing causes; which is a Lust of the mind, that by a perseverance of delight in the continuall and indefatigable generation of Knowledge, exceedeth the short vehemence of and carnall Pleasure (Hobbes, 1994).

The second theme around curiosity has been about the conditions of its occurrence. Descartes, for example, argued that wonder and astonishment (which he called ‘passions of the soul’) are instigated by novel and surprising pieces of information based on whether this information is ‘suitable to us or not’ quite similar to what Berlyne discussed in the 20th century (Descartes, 1989). Heidegger’s approach differs from this widely held idea about the conditions of curiosity and he makes a distinction between wonder and astonishment/admiration/amazement in which the object of wonder becomes not something unusual but on contrast what is the usual becomes unusual when it becomes the object of wonder (Heidegger, 1994).

Another important theme, which is indirectly but quite usefully related to the subject of this dissertation, is the question of what makes curiosity possible. Though this philosophical question does not seem relevant to any engineering model as such, some of the recent answers articulated around the topic provides a good theoretical grounding for a model in which Natural Language Processing becomes a critical component. Ilhan Inan’s discussions in his seminal book “The Philosophy of Curiosity” will be the basic reference point for elaborating on this connection:

> As I shall argue in detail later, a comprehensive account of how we have developed the aptitude for being curious requires us to engage in a discussion on how curiosity relates to the use of language. In particular the linguistic act of reference to the unknown is what I take to be a requirement for being curious. This is true at least for the kind of curiosity that we enjoy that finds its expression in language in the form of a question. It was only in the latter part of the twentieth century that philosophers finally concentrated on what a question is, how it relates to its possible answers, and related issues (Inan, 2012).

In order to do justice to the emphasis on the reference to the unknown, it is useful to give some thought to Plato’s famous Meno’s Paradox, which Inan thinks to be indirectly related to the question of how curiosity is at all possible and became a departure point of (Plato, 1978) his concept: ‘inostensible reference’. Here is the related passage from Plato’s Meno, where the problem of inquiry is formulated:

> Meno: And how will you inquire, Socrates, into something when you don’t know at all what it is? Which of the things that you don’t know will you propose as the object of your inquiry? Or even if you really stumble upon it, how will you ever know that this is the thing which you didn’t know? (Plato, 1978, 80d5–8)
> Socrates: I know, Meno, what you mean; but just see what an eristic argument you are introducing—that it is impossible for someone to inquire into what he knows or does not know; he wouldn’t inquire into what he knows, since he already knows it and there is no need for such a person to inquire; nor into what he doesn’t know, because he doesn’t know what he is going to inquire into (Plato, 1978, 80e2–6).

Although the argument seems to be trivial at first glance, the question is quite valid: how do we seek what we do not know? If we already know something, there is no need to inquire; if we do not know what we are inquiring into, how is it possible that we seek it? Similarly, if we desire to know something, it would mean that we have an idea about what we are seeking to possess, which is paradoxically not the case. Thus, the logical conclusion is that inquiring into something unknown is impossible.

Inan argues against some of the answers articulated by Plato and his scholars such as ‘Recollection Theory’ and ‘The Partial Knowledge Theory’. The Recollection Theory says that our immortal and omniscient souls already knew everything but we have forgotten them, so what really is happening is that we are recollecting them rather than learning from scratch. For this argument, Inan objects with the question that how we can know whether what we have recollected is actually the thing that we were looking for. The idea in the partial knowledge argument is that we must have some true beliefs about an object to be able to inquire into it. Inan challenges this idea with the argument that we cannot know whether our beliefs are true when our beliefs do not amount to knowledge. His example is a situation where someone falsely believes that a student took his book from his desk and he develops a curiosity about which student could do this, although the truth is that a house-keeper took the book. This rather subtle epistemological argument plausibly eliminates this theory as a satisfying solution.

Inan’s own solution to this problem focuses on our linguistic capacity to refer to the unknown. He gives Kripke’s example about the discovery of Neptune. When the scientist Leverrier started inquiring into “the planet perturbing the orbit of Uranus” he did not have any perception of the planet Neptune, which was the actual referent of his definite description. Inan extends this idea into a conceptual distinction between ostensible and inostensible terms, where the former signifies referencing objects that are immediately available to our senses and the latter refers to the linguistic act of referring to the unknown. He also adds that whether there is actually a planet that perturbs the orbit of Uranus or not is not relevant to the possibility of curiosity; the existence of such a concept is enough. What happens if this planet is discovered or not discovered is that the inostensible term turns into an ostensible one. This capability is also key to our ability to ask questions. When we ask who took my book away, we are referring to something unknown. This is the very essence of a question**.** The linguistic and logical mechanisms for formulating the unknown, which enables the curiosity motive to go will be under further scrutiny in the next chapters of the dissertation.

Another work that needs to be mentioned belongs to Schmitt and Lahroodi (2008). In their article *The Epistemic Value of Curiosity*, they raise a couple of interesting points about curiosity. Firstly they argue for an appetitive account of curiosity which takes it to be a motivationally original desire to know that draws our attention to an object and sustains it. More interestingly than this widely discussed topic, they argue for three properties of curiosity which are ‘tenacity’, bias towards epistemic interests and ‘independence from interests’. Tenacity refers to the idea that curiosity leads to curiosity about related issues; bias towards epistemic interests is about the obvious observation that we are more curious about things that are of interest to us; and independence from interests refers to the observation that curiosity does also fix our attention on objects in which we have no prior interest in (Schmitt & Lahroodi, 2008). The last two ideas might seem to be contrasting, but we must have all experienced moments in our lives where we find ourselves immersed into a subject completely out of our list of interests. This does not preclude the fact that we are mostly biased toward being curious about objects of our interest. Thus, interest is a factor of curiosity but not the sole determinant of it. This point will also be elaborated in the following chapters.

2.2. CURIOSITY IN PSYCHOLOGY

There has been relatively more interest in curiosity in the field of psychology especially starting from the second half of the 20^{th} century. However, like most of the topics in psychology William James has set the early foundations work on curiosity at the end of 19^{th} century. In the *Principles of Psychology* James distinguished between excitation by mere novelty in the environment and a second category referred to as 'scientific curiosity' the object of which is specific items of information. The efforts to categorize and delimit curiosity has continued and Daniel Berlyne, who is among the prominent figures having a systematic contribution to the field, made a four-fold categorization, which similarly distinguished between perceptual and epistemic types (Berlyne D. E., A theory of human curiosity, 1954). In this categorization, perceptual curiosity is about exploratory activities of animals typically described as novelty seeking behavior, whereas epistemic curiosity refers to the uniquely human type of exploration mediated by language. The exploration of symbolically representable contents using the capacity of language has in some other contexts been radically separated from general sensation seeking, but despite being under the same category of 'curiosity' within Berlyne's schema, he also emphasized the difference strongly. There is a further subcategorization of epistemic curiosity into specific and diversive curiosity. In Loewenstein's words (1994):

> In the four-way categorization produced by these two dimensions, specific perceptual curiosity is exemplified by a monkey's efforts to solve a puzzle, diversive perceptual curiosity is exemplified by a rat's exploration of a maze (in both cases with no contingent rewards or punishments), specific epistemic curiosity is exemplified by scientist's search for the solution to a problem, and diversive epistemic curiosity is exemplified by a bored teenager's flipping among television channels (p.77).

Both James' 'scientific curiosity' definition and Berlyne's 'specific epistemic curiosity' definition include being directed toward specific items of information. Although not explicitly stated in James' definition, both include a symbolic component. Also both are related to scientific activity. Although there is no reason why specific epistemic curiosity would not be directed toward, for instance, someone else's private life, in the following chapters of this dissertation 'scientific curiosity' will be delimited as specific epistemic curiosity directed toward regular objects of philosophical and scientific inquiry.

Another pervasive topic in the psychology literature has been the motivational nature of curiosity. If curiosity is a motivation, what type of a motivation is it? Is it intrinsic or extrinsic? How does it differentiate between human beings and animals? Is it primary or secondary (derivative of other basic drives? Is it triggered by internal states or external stimuli or both?

By definition, a motivation is intrinsic if it leads an organism to act for the sake of itself rather than for some extrinsic reason. Both in philosophy and psychology, curiosity is predominantly taken to be an intrinsic motivation although it is acknowledged that people can desire to know things for extrinsic purposes as well. This perspective also gets support from animal studies in which exploration behavior is intrinsically triggered when faced with novel stimulus:

> Collectively, the early studies on exploration achieved two ends: first, through the variety of measures and test procedures that they employed, the general and initially vague term exploration was given specific reference to such behaviors as orienting or locomoting toward, investigating, sniffing, and manipulating particular objects or patterns; secondly, the findings of these studies demonstrated that an animal would explore a stimulus object or pattern to the extent that it was novel, unfamiliar, complex, or provided a change in the animal's present or recent pattern of stimulation (Fowler, 1965, p.68).

Although there seems to be a wide consensus about this intrinsic quality, there has been much controversy on the underlying cause of curiosity among scholars. Is curiosity a homeostatic drive like hunger, which intensifies in the case of sensory deprivation or is it a drive like fear which is triggered when faced with an environmental stimulus? Although "it is generally acknowledged that that no drive fits squarely into either of these categories" and "all drives are influenced by both external stimuli and internal states" (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994), the discussions around the issue has been pervasive. The differences in perspective also influenced the focus on different aspects of the problem. Berlyne, having adopted the belief that curiosity is invoked by external stimuli, focused more on situational determinants of curiosity. The idea is that curiosity is triggered by "collative variables", "incongruity" or "stimulus conflict". This perspective is generically called "incongruity theory".

> In the 1950s, a rather different account of curiosity was developed independently by Hebb, Piaget, and Hunt, who each reached the same conclusion from very different starting points. This account can be summarized by three basic propositions. First, curiosity reflects a natural human tendency to try to make sense of the world. Second, this need is not constant but is evoked by violated expectations. Thirds, there is an inverted U-shaped relationship between evoked curiosity and the extremity of such expectation violations. Like Berlyne, therefore, these theorists saw curiosity as evoked by incongruity. However, their focus was on only one of the categories of incongruities mentioned by Berlyne: violations of expectations. Also, most incongruity theories dropped Berlyne's assumption that curiosity is a drive (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994).

Although not totally uniform, the common emphases of incongruity theories have been more or less the same. What is variously called as incongruity, cognitive dissonance, incompatibility between ideas, collative variables, stimulus conflict describes a type of tension between our current cognitive state and incoming external information. Consistently, incongruity theories has been referring to 'making sense' conspicuously. Kagan, as the proponent of a version of incongruity theories, proposes 'the need to make sense' as the underlying cause of curiosity (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994). Although the underlying cause of curiosity seems to be an elusive concept, the incongruity theorists seem to be presupposing what Kagan proposed as a causal explanation. Also the U-shaped relationship between evoked curiosity and the level of the violation of expectations is an important conclusion of the empirical studies that will be referred to later in this dissertation.

One important thing to note is that among all incongruity theorists, it was Berlyne who made the most extensive empirical studies to test the arousal potential of what he called collative variables (complexity, novelty and surprise). His complicated empirical settings yielded conclusions that supported his predictions as to the link between conflict and curiosity (Berlyne D. E., A Theory of Human Curiosity, 1954).

Loewenstein is another key figure in the psychology literature on curiosity. After giving a comprehensive review of curiosity theories in his seminal work *The Psychology of Curiosity,* he proposes what he calls "information-gap" perspective as an integrative interpretation of curiosity. He mentions that his ideas are borrowed from "Gestalt psychology, social psychology, and behavioral decision theory" and he also endorses Kagan's idea that the underlying cause of curiosity is the need for making sense (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994). Before getting further into Loewenstein's perspective, it will be relevant to revisit Berlyne's path-breaking work, *A Theory of Human Curiosity,* where he gives a list of schools of psychology that address the issue of the factors underlying the selectivity of epistemic curiosity. His formulation as 'selectivity property of epistemic curiosity' is very accurate and informative. The question is fairly simple: Why do we seek or learn one piece of information rather than another? (Berlyne D. E., A theory of human curiosity, 1954) When we are hungry, we direct toward food and when we are thirsty we direct towards water. What determines what we are directing toward when we are 'thirsty for knowledge'? This question will also inspire our notion of 'cognitive dynamics of scientific curiosity' later to be proposed. Going back to what Berlyne has to say about the schools of thought, he starts with a description of the Psychoanalysis school and secondly mentions the Gestalt school, which is also a reference point for Loewenstein's proposal:

> (2) Gestalt psychology. Although the Gestalt psychologists have not produced a systematic account of curiosity, it is not difficult to guess how such an account would go. They explain much of behavior by the 'principle of closure', the tendency to act in such a way as to close a 'gap', whether in a perceived figure or in some other aspect of the 'behavioural world' (Koffka, 1935; Wertheimer, 1945). It is evident that curiosity consists precisely of a drive to fill in such gaps in the subject's experienced representations. But again, we have no definition precise enough to tell us infallibly what will constitute a 'gap', nor which gaps will have precedence over others (Berlyne D. E., A theory of human curiosity, 1954).

After finally mentioning reinforcement theory, Berlyne begins developing his own incongruity based accounts and he makes a relevant critique of a possible Gestalt account by asking what the principle for selecting one gap over another would be in such an account. This point is worth noting before getting into Loewenstein's information-gap theory.

The information-gap theory endorsed by Loewenstein has similarities to what is described by Berlyne in the above passage. A similar perspective was also articulated by James such that 'scientific curiosity' arises from "an inconsistency or gap in … knowledge, just as the musical brain responds to a discord in what it hears" (James, 1950, quoted in Loewenstein). Interestingly, James seems to have given a very light summary of both information-gap and incongruity approaches. However, Loewenstein gives more emphasis on the former and holds that "the information-gap theory views curiosity as arising when attention becomes focused on a gap in one's knowledge. Such information gaps produce the feeling of deprivation labeled curiosity. The curious individual is motivated to obtain the missing information to reduce or eliminate the feeling of deprivation" (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994). He also utilizes some aspects of Decision Theory and incorporates the idea of 'curiosity as a reference-point phenomenon' into his framework.

> In decision theoretic terms, what one wants to know can be thought of as one's informational "reference point." The most developed application of the reference-point concept is in decision making under uncertainty. New reference-point theories of decision making under uncertainty, most prominently Kahneman and Tversky's (1979) prospect theory, underscore the subjective nature of attainments; the same absolute level can be viewed positively or negatively depending on the decision maker's reference point (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994).

According to this approach, curiosity arises when one's informational reference point for a specific domain is higher than the level of his current knowledge. We feel deprived when we compare ourselves with others and similarly we become aware of our ignorance when we see others who are more knowledgeable than us. Therefore, curiosity depends on a contrast between one's objective state and a subjective reference point. Based on this perspective intensity of curiosity raises when directed to items that resolve uncertainty (which close the information gap) and similarly if, as in the case of insight problems, a piece of information (the insight) throws light to the overall problem and therefore fills a more significant information gap (as opposed to information that is unlikely to yield the same effect), curiosity toward that information must be higher. There is also empirical evidence that supports his conclusions (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994). Loewenstein also proposes that curiosity should be positively related to one's knowledge in a particular domain, since he assumes that focus on missing information would be higher in a familiar domain. Although this proposition is supported by empirical evidence by the studies of Berlyne and others, there are also cases where a negative relationship can be seen. Loewenstein explains those cases with the decrease in the objective value of the specific item of information such as the case when we solve a jigsaw puzzle of an unknown picture and at a particular moment we start guessing the final picture and the rest of the pieces lose their significance. In a way this can be conceptualized as reaching a subjective satisfaction or saturation point effecting the inner dynamics regarding the reference point. In addition to these powerful insights coming from information gap perspective, Loewenstein brings interesting social and psychological dimensions to the understanding of curiosity. People tend to lose curiosity when they are overconfident about their knowledge. Appreciation of ignorance has a direct influence on our desire to know. As a very important point for our model to be developed, "one way for people to gain an accurate perception of what they do not know is to have them make guesses and receive accuracy feedback" (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994).

Child studies is another field of research that provides important insights about curiosity. Children are known for their restless questions. We tend to associate adults asking too many questions with a childish spirit. Moreover, children ask questions about simply everything, since, if we take some of Loewenstein's ideas, their information level is not mature enough to lead them to focus on any domain. Similar to the importance Inan gives to the ability to formulate questions with regards to our ability to be curious, Berlyne and many others have also given importance to questioning although their focuses differed. As formulated by Berlyne and Frommer, "questioning is a form of epistemic behavior, that is, behavior directed toward, and reinforced by, acquisition of knowledge [and] it is motivated primarily by epistemic curiosity, conceived as a condition of high drive or arousal induced by conceptual conflict" (Berlyne & Frommer, 1966). Berlyne and Frommer (1966) also discovered indications that increasing age raises the sensitivity for information gaps and questions that resolve uncertainty.

Chouinard is one of the researchers that has made insightful studies about child questioning. Her study specifically focuses on factual versus explanatory questions asked by children and how their frequencies change over time. Before introducing her empirical work, she also offers a theoretical framework about children's cognitive engagement:

> The child is engaged with something, and brings an existing conceptual structure to the situation. […] a conceptual structure is defined as some area of knowledge, such as a concept, category or domain, that consists of both particular facts (pieces of information, possibly learned in isolation, possibly even by rote memorization), and explanatory/predictive core principles that unite those facts and make predictions about them and the concept/category/domain in question. The child encounters some problem (i.e., incomplete knowledge, or a gap in knowledge; some contradiction in expectation or knowledge already in place; ambiguous information or circumstances), and this leads to a state of disequilibrium. This state motivates the child to ask a question to get information that can resolve the problem at hand. The response that the child receives gives information about which direction the knowledge state should now be pointed toward; the answer itself shows the child how to revise/reorganize the structure, or which new knowledge structure should be used as a replacement. This information is applied to the current knowledge structure, which is revised in light of new information, whether that revision is just to add information that was missing (enrichment, sometimes referred to as the simple accumulation of facts/knowledge) or to reconceptualize the knowledge state in some way (conceptual reorganization, which involves a new organization of the conceptual structure, primarily through its explanatory core principles). The child then proceeds with the new knowledge structure, and sees how this works out (Chouinard, 2007).

Chouinard's emphasis on cognitive structures and conceptual reorganization is motivated by the same theoretical convictions as incongruity theorists in that they all focus their ideas to the interplay between the current cognitive state of the individual and her external environment. This perspective is also consistent with Kagan's idea that 'the need to make sense' is the underlying cause of curiosity, therefore of our questioning behavior. Leaving aside this theoretical detail, some of the significant findings of Chouinard's empirical studies on children's question asking behavior are that (1) the majority of the questions asked by children (from years 1 to 5) is about acquiring information, (2) most of the questions are factual, yet as the children get older there is a significant shift from factual information to explanatory principles and (3) children ask more information about biological phenomena when engaged with animals as opposed to other settings (Chouinard, 2007). It is possible to draw more general conclusions about human curiosity such as the idea that collecting a critical level of factual/perceptual data triggers the desire to 'make sense' of the data by exploring to underlying principles that organize and give a foundation to that multitude. Such argumentations will be done further in the following chapters in an effort to give a unified perspective to the various findings of both philosophy and psychology literatures.

Finally, it is worth giving some thoughts on the literature on interests. One of the renowned authors on the subject of interest is Paul J. Silvia. He argues that no research has demonstrated the concepts of interest and curiosity to differ (Silvia, 2006). Therefore, he uses the concepts interchangeably as motivations that lead people to engage with certain activities, objects or ideas for their own sake. However, this approach removes the boundaries between symbolic and non-symbolic types of curiosity or as in Berlyne's four-fold categorization between perceptual and epistemic types. Engagement alone should not be sufficient condition for curiosity, or at least for what has consistently been delimited as ‘scientific curiosity’ or ‘specific epistemic curiosity’ in the literature. Prelinguistic human babies can engage with a ball of wool out of some intrinsic interest much a like a cat can do. And it would not be unacceptable in common parlance to call this engagement as curiosity, but this would obviously not refer to a type of curiosity with epistemic quality. Therefore, Silvia’s approach seems to rule out some quite useful theoretical distinctions, which are critical to many threads of fruitful philosophical and scientific research as well as our model. Interest is obviously one of the basic factors that determine what we are curious about. However, this fact does not change the validity of the question of why we select specific pieces of information within our interest domains over others that are also within the same interest domains. Most of the ideas reviewed in this study are still applicable in a similar fashion. We would be more inclined to direct toward an information item within our interest domain if it has more objective value and resolves an uncertainty as opposed to some other item that lacks these qualities. Moreover plausible ideas such as ‘independence from interest’ (Schmitt & Lahroodi, 2008) become totally irrelevant with such a stance. Thus, rather than behaving interest and curiosity per se indifferently, it is more fruitful to make some theoretically justified distinctions among them and treat interest from a wider perspective of personality psychology . This issue will be further elaborated in the coming chapters.

2.3. EXTENDED COGNITION THEORY

Extended cognition theory basically holds the view that cognitive processes extend beyond the boundaries of the body and interact with the environment they are embedded into. It is not the environment that does the ‘knowing’ obviously, but ‘knowing’ cannot be isolated from the environment as well. This shift of perspective from the traditional understanding of cognition with a closed processing center to an emphasis on structural coupling between cognition, body and environment has become a pervasive topic in cognitive sciences for the last decades. Influenced also by the embodied approach to robotics, this perspective opened up the possibilities for new ways to approach how various aspects of our cognition couples with and dependent upon its environment. The significance of this theory for the purposes of this dissertation is that it sheds light on how human cognition couples with technology or how we think through technology as an integral part of our environment and body. In an interesting passage that David Chalmers wrote in his foreword to Andy Clark’s *Supersizing the Mind* (2008), he says:

> A month ago, I bought an iPhone. The iPhone has already taken over some of the central functions of my brain. It has replaced part of my memory, storing phone numbers and addresses that I once would have taxed my brain with. It harbors my desires: I call up a memo with the names of my favorite dishes when I need to order at a local restaurant. I use it to calculate, when I need to figure out bills and tips. It is a tremendous resource in an argument, with Google ever present to help settle disputes. I make plans with it, using its calendar to help determine what I can and can’t do in the coming months. I even daydream on the iPhone, idly calling up words and images when my concentration slips.
> Friends joke that I should get the iPhone implanted into my brain. But if Andy Clark is right, all this would do is speed up the processing and free up my hands. The iPhone is part of my mind already (Clark, 2008).

This rather odd idea of iPhone becoming part of our minds becomes more plausible when we start thinking about our own lives. As a researcher, for example, can we imagine thinking without our laptop and Google? Can we really draw thick borders between recollecting an idea from our long-term memory and recollecting an idea from academic database through typing a couple of keywords into the search engine? Even if there might be many philosophical objections to this idea, the very practical reality of the increasing 'interaction' of our minds with technology is undisputable. In *Cognition in the Wild* Hutchins (1995) gives a very vivid picture of distributed cognitive processes in a navy ship. These ideas about extended cognition will inspire our ideas about extended curiosity and how curiosity and technology coupling can be enhanced with our proposed model.

2.4. TECHNOLOGIES FOR RESEARCH

In the previous section, we have given a brief summary of the extended cognition theory which has the potential to brigde the gap between what we know about curiosity and how human-computer interaction can be relevant to what we know about it. In this section, a list of current technologies used during research will be given to evaluate the level of interaction/coupling we are currently having with the available technology. The technologies listed in this section will provide benchmarks and inspiration for the model to be proposed in the following chapters. Their weaknesses against what we are to propose will be elaborated on later in the dissertation.

2.4.1. WORLD WIDE WEB

World wide web is the single most important technology that revolutionized the way we are publishing and accessing information. All of the technologies listed below depend their existence to www. Therefore, any fundamental change in www technology is directly related to the future potential of solutions to be developed. Just as the transition from Web 1.0 to Web 2.0 marked the proliferation of social media and interactive applications of all sorts, the transition from Web 2.0 to Web 3.0, also called Semantic Web, has the potential to revolutionize how we organize information and process it.

The basic idea behind Semantic Web is an abstract model for knowledge representation that decouples data from applications in a way that both can evolve independently. This standardized model that provides machine readability enables any application to consume the data resources using that model. This great capability also makes possible machine processing in which incredible amounts of published information are not only sensible to human beings but also to machines. Our model will also make use of the elements of Semantic Web technology and there will be a discussion about how the advances in Semantic Web technology and usage may influence the future of our research.

2.4.2. SEARCH ENGINES

Search engines offer a practical solution to our need to access relevant content. Without them www would be too small for us no matter how much information it includes, since what is inaccessible would also be invisible to us. What search engines basically do are crawling the web accross the links, indexing all the content, ranking the query results based on specific algorithms such as the famous page-rank algorithm and displaying them in a forms that simplify for the user to choose among alternative query results. Modern search engines are increasingly incorporating conceptual networks for relating conceptually linked strings and semantic metadata as well as some other semantic web components. Besides general seach engines that index all web, there are also vertical search engines focusing on particular domains like medical search engines, academic search engines and blog search engines. Researchers of all types extensively use search engines for tasks from checking wikipedia for getting some initial information about a new concept to visiting philosophy dictionaries such as Stanford Philosophy, from surfing on the web for exploring the main the contributors of a subject matter to searching for specific articles, from finding people that work on the same subject to skimming through their CVs and from searching digital libraries to searching within e-books.

Despite all of those useful functions and the undisputable centrality of search engines to the success and usability of www, they have particular limitations. First of those limitations stems from the fact that Web 1.0 and Web 2.0 are designed for the display of content rather than semantically organizing it. What it there to be indexed is simply dummy strings with some sporadic metadata. There is no actual semantics and a logical structure that allows for inference or machine processing. Contrast the assistance taken from a librarian to using keywords where the search engine cannot differentiate between the literal meaning of the keyword and the semantic context of that search item. Semantic Web has the promise to fill three gaps: (1) through the utilization of sophisticated ontologies systems can actually 'understand' the semantics behind search items, (2) more efficient multimedia search engines can be designed that leverage that 'understanding' and (3) the ability to make queries in natural language and description logics can offer more natural user interfaces (Linckels & Meinel, 2011). In addition to those, Semantic Web enables inferencing and automated reasoning that enhances search experience. Most of the search engines in the market, general or vertical, do not leverage most of these new possibilities. Moreover, the degree of personalization of the current search engines are quite limited and user-behavior models they are based on, if they have one at all, are also quite superficial.

2.4.3. DIGITAL REPOSITORIES

The collection of written resources in repositories has been an activity as old as human civilization. We have gone a long way from inscripting onto rocks and clay tablets to digital repositories. With the increasing trend of digitalization of the resources, the availability of information is becoming incredibly high. On the other hand, digital repositories are becoming increasingly smarter with stronger search engines and better user interfaces and the variety of resources are increasing with the availability of multimedia content. Bibliographic databases such as Scopus provides tens of thousands of abstracts and academic journal articles in various topics with search engines and other useful features such as citation analytics (which are also acccessible via APIs for developer communities).

2.4.4. SOCIAL MEDIA

Social media has become one of the centerpiece of modern living as well as the life of researchers. Enriched and fast electronic communication possibilities enable the research community to communicate effectively for all types of information exchange. Besides Facebook, Twitter, blogs, online forums, chat rooms and Google Groups, which are some of the standard channels for peer communication, possibilities such as social cataloging and bookmarking enables researchers and academicians to access each others' read-lists, contacts and bookmarks. Analytics tools such as social network analysis, on the other hand, provide a lot of good insights about how academic community is connected.

2.4.5. REFERENCE MANAGEMENT APPLICATIONS

Another technology that is extensively used by researchers is reference management applications. Applications such as Mendeley helps researchers to organize and display their resources in a practical way, make use of the metadata in formats such as PDF and manage their references. Tools like Mendeley also offer online collaboration features.

2.4.6. RECOMMENDER SYSTEMS

Recommender systems use tools and techniques such as machine learning, information retrieval and data mining to guide users to items of person-specific interest among a large space of possible selections. Recommenders systems can be used in e-commerce sites to recommend the products that are of interest to users as well as scientific digital repositories where books and articles of interest are presented to the users. In content-based recommendation systems the attributes of the historically selected content-bearing resources of the users are analyzed and used for personalized offering of new interest items. In collaborative recommendation the system identifies users that have similar interests to the target user and their analyzed interest characteristics are used for new recommendations.

2.4.7. ONLINE COLLABORATION SYSTEMS

Collective generation of a document or media file by a group of people distributed over a network is becoming an increasingly popular activity in academics as well as in businesses. With cloud tools such as Google Docs, documents can be edited real-time and supported by additional features such as keeping track of the editions. One thing to note about current state of the collaboration systems that they are not providing any sophisticated functions such as computer aided reasoning support or inferencing over the contributions of each researcher. Quite similar to the differentiation between Web 2.0 and Web 3.0, current collaboration systems simply offer a platform for entering and displaying information, but there is no intelligence incorporated into it. In the widest sense, the model to be offered in this dissertation can be called an intelligent online collaboration system.

2.5. COLLABORATIVE LEARNING

Collaborative learning occurs when a group of people learns or decides to learn something together utilizing one another’s resources, ideas and skills. The participants of collaborative learning are also accountable to each other for the success of the task. With the advance of social media and collaboration tools, the methodologies and environments of collaborative learning has marked significant advances. The power of collaborative learning and community assisted research is undisputable and its promise for the future of humanity is remarkable. Any effort for more efficient and effective collaboration would also contribute to the benefits that humanity is to get from collaborative learning.

CHAPTER 3

3. COGNITIVE DYNAMICS THEORY OF SCIENTIFIC CURIOSITY

As mentioned in the introduction and literature review, there are a lot of good theoretical insights about what 'scientific curiosity' is about and there are a lot of exciting technologies that aid our research processes. However, we also mentioned that there is still a line of research which can fill a huge gap almost invisible to the academic and engineering community. The aim of this chapter will be constructing a unified theory of scientific curiosity, which will provide a theoretical foundation to the ambient semantic intelligence model to be proposed in the next chapter.

In the first section, the concept of 'scientific curiosity' will be delimited with references to the discussions mentioned in the literature review chapter. In the second section, the concept of sense-making will be elaborated. In the third section, a cognitive theory of scientific curiosity will be offered gathering and reinterpreting all the useful insights coming from the relevant disciplines contributing to the field of curiosity studies. The next section will incorporate the idea of extended cognition into the cognitive theory to be offered. Finally, all the components of the theory will be wrapped up in the fifth section into what will be called Cognitive Dynamics Theory of Scientific Curiosity.

3.1. DELIMITING SCIENTIFIC CURIOSITY

Both Berlyne and James delimit a type of curiosity that is directed toward specific items of information. James call it scientific curiosity and Berlyne calls it specific epistemic curiosity. Although James uses the term 'scientific' his definition does not rule out the possibility that such a curiosity may be directed toward other people's private lives or some very isolated detail of our daily lives. In the context of this dissertation, 'scientific curiosity' or 'specific epistemic curiosity' will be further delimited as 'an intrinsic motivation to make sense of the proper subjects of science and philosophy in a systematic way'. This definition does not rule out the questions such as 'the meaning of life' or 'the dynamics of social interactions' per se, but these questions must be handled in a disciplined way and carry a systematic component to it. 'Disciplined way' loosely refers to a paradigmatically accepted scientific methodology or an intellectual activity that respects the standards of valid reasoning depending on the context. The word 'systematic' is also used loosely, but it simply presupposes a holistic relationship between the established meaning system of the individual and the newly incoming item of information. Yet, again how can we clarify what type of an informational process is systematic rather than being non-systematic as conceptualized in the context of our theory? In order to clarify the concept, we need to revisit the ideas borrowed from the Gestalt psychology and Kagan's proposal that 'making sense' is the underlying cause of the desire to know. Thus, a relevant question to ask would be what makes it different to make sense or understand from simply receiving an information.

3.2. SENSE-MAKING

The act of 'sense-making' presupposes a preestablished system of meaning structured by 'ontologies'. When we make sense of a new item of information, we are not simply registering it to our long term memory in an isolated way. In our brains, everything is related to everything else. We may receive relatively isolated information which does not fit into any of our mental schemas, however this is never a desirable or even a healthy situation. This is a result of the basic mechanisms of the human intelligence. In a study of human intelligence Spelke (2003) states that "natural languages provide humans with a unique system for combining flexibly the representations that they share with other animals. The resulting combinations are unique to humans and account for unique aspects of human intelligence." The uniqueness of those representations stems from the ability of human intelligence to transcend the limits of fixed core representations of nonhuman animals and it is this ability that enables "representations to be combined across any conceptual domains that humans can represent and to be used for any tasks that we can understand and undertake" (Spelke, 2003). These combinatorial representations are not disorganized stacks of information but they are self-organizing and dynamic cognitive systems. The structure of those cognitive systems can be represented as a network with a core and periphery and multiple cores and peripheries within each core in a way similar to the cosmological systems. The dynamic and self-organizing property of cognitive systems are described neatly by Friedman in reference to Quine's model of knowledge:

> Our system of knowledge, in Quine's well-known figure, should be viewed as a vast web of interconnected beliefs on which experience or sensory input impinges only along the periphery. When faced with a 'recalcitrant experience' standing in conflict with our system of beliefs we then have a choice of where to make revisions. These can be made relatively close to the periphery of the system (in which case we make a change in the relatively low-level part of natural science), but they can also – when the conflict is particularly acute and persistent, for example –affect the most abstract and general parts of science, including even the truths of logic and mathematics, lying at the centre of our system of beliefs. To be sure, such high-level beliefs at the centre of our system are relatively entrenched, in that we are relatively reluctant to revise them or give them up (as we once were in the case of Euclidean geometry, for example). Nevertheless, and this is the crucial point, absolutely none of our beliefs is forever 'immune to revision' in light of experience (Friedman, 2002).

Friedman's depiction is particularly important in that it gives a vivid picture of how our cognitive system dynamically reacts to new data in relation with the state of its own structure. A similar construal of the cognitive system is also pervasive in psychology. Especially incongruity theorists influenced by the Gestalt school emphasize the tendency to construct systematic meaning wholes a lot. Loewenstein (1994) stresses this point in his work:

> […] the incongruity theorists' notion that there is a natural human need for sense making has received broad support from diverse areas of research, although little of it was cited by incongruity theorists. As Gilovich (1991, p.9) wrote, "We are predisposed to see order, pattern, and meaning in the world, and we find randomness, chaos, and meaninglessness unsatisfying. Human nature abhors a lack of predictability and the absence of meaning" (p.83).

Much like Friedman, as a philosopher, depicted how the cognitive system reacts to new information in a dynamic way Gestalt psychologists also attempted to depict this dynamic property of human cognition. According to Gestalt theory there is a fundamental human tendency to make sense of information by organizing it into coherent “wholes.” More importantly these theorists also argued that what they call Gestalt creation also has motivational force (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994). At this point, Piaget’s concepts of assimilation and accommodation deserve particular attention.

> According to Kakar (1976, p.192), curiosity for Piaget “plays a part in the search for coherence and organization. It is a motive force in the need to order reality.” Second, Piaget viewed curiosity as the product of cognitive disequilibrium evoked by the child’s attempt to assimilate new information into existing cognitive structures. Such a need would naturally arise when reality diverged from expectations, pointing to the inadequacy of existing cognitive structures” (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994).

Children’s attempts to assimilate new information into their existing mental schema or accomodating to it reflect the same cognitive dynamics. All these evidence point to a dynamic and systematic sense-making process run by the cognitive machinery of humanscompl. Going back to our original question of delimiting scientific curiosity, our intrinsic motivation to make sense of the proper subjects of science and philosophy in a systematic and disciplined way is nothing but the adult expression of the workings of this cognitive machinery.

3.3. COGNITIVE DYNAMICS OF SCIENTIFIC CURIOSITY

Human curiosity operates through an interaction between the cognitive machinery and its environment. A comprehensive cognitive account of human curiosity has to say something as to the nature of this cognitive machinery and its information processing method as well as the nature of its interaction with the ‘external’. If the focus is scientific curiosity, as it is here, there must be a clear delimitation of the concept as well. Finally for an account to be truly comprehensive, it has to unify the insights about the situational determinants and selectivity dynamics of curiosity coming from various resources into one coherent framework as well as giving a description of how these dynamics interact. Up until this point, we have been preparing the background for the construction of such a theory. To start doing that we will initially list the basic points about ‘cognitive machinery’, ‘curiosity dynamics’ and ‘scientific curiosity’:

Cognitive Machinery:

1. Human cognitive system is a self-organizing and dynamic informational network with a core and periphery and multiple cores and peripheries within each core.
2. The nature of human information processing is bound by its systematic property such that any incoming item of information is processed as an input into the preexisting system of meanings and in interaction with it.
3. This process is less technically called sense making and sense making has motivational force.

Curiosity Dynamics:

1. Human beings have an intrinsic motivation to make sense.
2. Human curiosity is a cognitive force to make sense, which directs human attention to particular items of information to be processed.
3. Human curiosity is bound to the systematic sense-making dynamics of cognitive machinery.

4. Human epistemic curiosity is selectively biased toward certain items of information.
5. The types of information that become objects of selective bias, according to studies, are:
    a. Novel information
    b. Perceived information gaps
    c. Core insights or principles
    d. Incongruity with the current state of the individual's meaning system
    e. Areas of interest
    f. Things that are related to areas of interest
6. The curiosity can also demonstrate independence from interests.

Scientific Curiosity:

1. Scientific curiosity is delimited as an intrinsic motivation to make sense of the proper subjects of science and philosophy in a systematic and disciplined way.
2. Systematic in this definition refers to constructing structured meaning systems about the proper subjects of science and philosophy.
3. Disciplined in this definition refers to a paradigmatically accepted scientific methodolog or an intellectual activity that respects the standards of valid reasoning depending on the context.

To further formulate the points above, we will make the following assumptions:

1. Scientific curiosity is an intrinsic motivation to make sense of potentially everything that are the proper subjects of science and philosophy (universal curiosity assumption).
2. Due to time constraints, universal curiosity selects specific items of information that maximize the expected satisfaction (optimization assumption).
3. These selections display certain directional patterns. Cognitive dynamics refers to the forces responsible for such patterns.
4. These cognitive selections can be best described on the basis of on a relevant model of cognitive machinery depicting its structure and processes.
5. The structure of cognitive machinery is a dynamic system of meanings with cores and peripheries.
6. The dynamic processing of human cognitive machinery can be described by the capacities of language and logic.
7. The forces (cognitive dynamics with magnitude and direction) of curiosity that determine cognitive selections are rooted in human personality (personality driven cognitive dynamics assumption).
8. There might be external dynamics that determine cognitive selections as well (instrumental desire to know).
9. All those forces interact before they determine the final selection.
10. If we collect enough information about the curiosity patterns of the individual on the basis of a reliable model, we can reach conclusions about his personal curiosity traits.

There are certain basic concepts and assumptions in the points above. The first assumption is the 'universal curiosity' assumption. This assumption also provides a grounding for the optimization assumption. Without bounds of time, an insatiable force as (scientific) curiosity does not stop until it makes sense of everything that are proper subjects of science and philosophy. Given the time boundedness of human curiosity, personality driven cognitive dynamics are at work to maximize the satisfaction by determining cognitive selections toward the highest valued items of information within a given time period.

Universal curiosity assumption can be challenged in a couple of ways. First of all, it is obviously not the case that all human beings feel the craving for knowing everything but not doing so because they do not have enough time. Yet, it is plausible to counter this challenge with the argument that universal curiosity assumption is not an assumption about human beings per se but about curiosity as an abstract force. Curiosity motivation itself is insatiable although some other emotions might override insatiable curiosity or suppress it in different ways. If unbridled by fear, daily concerns, discouraging learning experiences and so on, a curious being as humans would be infinitely curious about everything, which would instigate the desire to make sense of everything. Our life spans, however, are unfortunately limited. Therefore, curiosity as an abstract force has to act within such constraints. Another theoretical insight that supports this view is Schmitt & Lahroodi's concept of 'independence from interests'. Although we are predominantly biased toward directing our attention to items of information that fall under our interest domains, we occasionally find ourselves immersed into 'things' that we have no prior interest into. This might be an occasion where one of our curious friends starts telling about another strange subject during the dinner or one of our engineer relatives starts explaining a very marginal issue about his interest topics in a very enthusiastic way and we strangely find ourselves taken by their enthusiasm. Sometimes we even ask more of the story and try to get to the details although this could be our first and last relationship with that story. Another case that partially supports this view is polymaths of all times. People who are born with an unending thirst for knowledge. They have no interest domains, because they are simply interested in everything under the sky or even above it. They have dozens of books about each and every subject and they make us feel that these poor people died before they could complete the rest of one million books that were waiting to be written by them. Finally, we see a similar unbridled curiosity in kids. Kids simply ask questions about everything. No question coming from our children surprises us. We never expect them to ask questions from a specific domain. This might lead us to think that children's minds are tabula rasa and that is why they need to fill it with some knowledge from every domain for practical purposes. Although this account is plausible to a certain extent, it does not fully explain cases where 'every domain' contains philosophical and metaphysical issues, which have no practical value for a regular kid. An alternative way to explain the dispersed nature of children's questions would be that their 'universal curiosity' (potential curiosity about everything) has not yet been constrained by personal and social forces and they enjoy their purely natural intrinsic motivations.

As now we have the theoretical ground for the universal curiosity assumption, we can begin talking about the optimization assumption. The standard optimization problem is about maximizing a utility function subject to a budget constraint. In the case of curiosity time constraint replaces budget constraint. Loewenstein has pioneered the work on curiosity where the problem is formulated in terms of decision theory and utility maximization (Loewenstein, Exotic Preferences: Behavioral Economics and Human Motivation, 2007). He also contributed a lot to the idea of formalizing these forces for a mathematical model of maximum expected utility:

> Here we formalize the concepts of importance, salience, and surprise, all of which, we assume, contribute to attention weight. The importance γ_i of a question Q_i reflects the degree to which one's utility depends on the answer. Thus, for example, for an egocentric, but insecure, individual, the question, "Do other people like me?" is likely to be of great importance because the answer matters to the individual. Salience, distinctly, reflects the degree to which a particular context highlights the question. If, for example, an individual hears that another person was talking about her (with no further details), the question of whether the comments were favorable or not will become highly salient. We denote the salience of question Q_i as $\sigma_i \in \mathbb{R}_+$. Finally, surprise is a factor that reflects the dependence of attention on the dynamics of information revelation, and specifically on the degree to which receiving new information changes one's beliefs (Golman & Loewenstein, 2015).

We will follow a similar path and argue that selectivity property of curiosity can be formulated as a function with the objective of maximizing expected satisfaction (utility). In order to reach conclusions about how to measure satisfaction for any informational selection, we first need to analyze the patterns of cognitive selections that a person displays within a given time period and understand which cognitive dynamics are at work. As cognitive dynamics are driven by personality, any measured pattern can be treated as reliable information about person's relatively stable curiosity traits. Finally we can use those findings about curiosity traits for defining the value of each item of information within the expected utility function for future predictions. In this chapter we will to analyze what type of cognitive selection patterns human mind exhibits and what type of cognitive dynamics are at work based on the literature discussed in the second chapter. Before doing that we will make a definition of the concept of 'resource' which will be referenced in the following sections.

3.3.1 COGNITIVE RESOURCES

A resource is any supply or source from which benefit is obtained. It is related to the concept of utility in economics, which refers to the satisfaction experienced by the customer from a good. In line with Loewenstein's arguments, we assume that information does not have utility due to its instrumental value for decision making that raise utility, but due to the intrinsic motivational quality of curiosity, it is a utility in itself. Based on these, we shall refer to any content-bearing unit such as an author, a book, a chapter in a book, a paragraph, a piece of writing, a sentence, a statement or even a concept as a cognitive resource with its subjective utility. These resources are the reference points for curiosity. They can be selected as external resources such as books in a library shelf or a group of scholars in a university or they can be internal resources referenced by the tools of language and logic. In this framework, any unknown entity referenced by what Inan calls 'inostensible reference' is also a resource. Curiosity is about the selection of resources due to the intrinsic satisfaction derived from them.

For example, a person may have an interest topic and he may love reading books about it. There may be ten available books on a shelf and the person selects three of them to read because their names are related to his interest topics. These books are resources for this person. There may be twenty professors at a faculty and a student wants to be closer to one of them since what he knows is quite desirable to acquire for this student. These professors are resources for this person. There may be five blog posts about different subjects and a person selects one topic among them. These blog posts are resources for this person. These are external selections. Internally, there might be a lot of different ideas floating around in a physics student's mind, but she might want to know about 'the nature of dark matter' more than any other subject in physics. The nature of dark matter is unknown to her just like the knowledge in the professor's head is unknown to the other student. They all use their reasoning capacity before deciding which resources to direct toward. In the first case, the student knows that 'everything has a nature' and 'dark matter is something', therefore he knows that there is some resource referred to as 'the nature of the dark matter.' This resource is what he selects as an object of his curiosity. Similarly, a student knows that one has to know a lot to be a professor, this person is a professor about the subject that she is interested in, and therefore that professor must be knowing a lot of things about her interest topic. That professor is her resource. Recognizing resources that are unknown becomes possible through human reasoning capacity and the selection occurs as a result of the interplay between cognitive dynamics of curiosity, which will be elaborated in the following sections.

3.3.2. EXPANSION DYNAMICS

Expansion dynamics refers to the forces behind novelty seeking behavior. Novelty is one of the factors that instigate curiosity as grounded by many studies including that of Berlyne's. Within our own framework, novelty-seeking will be described as expansion dynamics in that novelty allows us to add up to what we already have rather than repeating it. It is an exploratory pattern of behavior, where what is unfamiliar is more attractive than what is familiar, since it is only what is unfamiliar to us that can expand the limits of our current meaning system. In the macro level expansion dynamics is an expression of universal curiosity. Some working assumptions regarding the expansion dynamics can be formulated as follows:

> <u>Expansion Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A varies from what one already knows more than B, A is preferred over B.
>
> <u>Expansion Dynamics Formula-2:</u> All the rest being the same about resources A, B and C, if one has no prior information related to A, B and C and if one has to pick two of them due to time constraint, if A and B is close to each other in terms of content and C has the highest variation, A and C is preferred to A and B and B and C is preferred to B and A.

3.3.3. COMPLETION DYNAMICS

Completion dynamics describes the forces that instigates curiosity about the things that complete our knowledge about a certain domain. The concept of completion directly refers to the insights coming from the Gestalt accounts of curiosity as well as Loewenstein's arguments about the positive relationship between one's knowledge of the domain and curiosity:

> There are two reasons for anticipating such a relationship. First, as one gains information about a particular topic, there is an ever-increasing likelihood that one will focus on what one does not know rather than on what one knows. According to the information-gap perspective, such a focus on missing information is a necessary condition for curiosity. To illustrate, consider an individual who knows the capitals of only 3 of the 50 states. Such a person is likely to frame her or his knowledge as such (i.e., that she or he knows 3 state capitals). However, a person who knows the capitals of 47 states is more likely to frame her or his situation as one of not knowing 3 state capitals. Thus, as information about a topic increases, one's attention is more likely to be attracted to the gap in one's knowledge (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994).

To differentiate between expansion dynamics and completion dynamics, expansion is not bound to meaning-subsystems that triggers the tendency to complete. In a sense it is more generic. Completion is about the meaning-wholes that exist in our total existing meaning-system. For example, a psychology student would have scattered information about many different subjects of psychology. If completion dynamics is at work for any of those subjects, she would prefer to get one piece of information that will complete her picture for this subsystem rather than any other piece of information that expands her meaning system without such an effect. Interestingly the feeling of completeness has a subjective nature. This interesting point is well expressed by Loewenstein:

> Although a positive relationship between curiosity and knowledge is a central prediction of the information-gap perspective, in practice, the relationship between information and curiosity may not be so simple because new information can change the perceived size of the information se, causing the reference point to shift. New information provides an ever-changing idea of what there is to be known. For example, when one sets out to learn a new language, the relevant information set may initially seem small, and curiosity should be commensurately strong. But as one begins to learn the language and becomes aware of its complexities, the perceived information set –what there is to know- is likely to increase. Thus, curiosity may well decline early on rather than increase, even as one gains proficiency in the language.
>
> There is a second reason why curiosity may not increase with knowledge. Sometimes, as one gains information, the objective value of a particular item of information declines, even though it remains unknown. For example, when one is completing a jigsaw puzzle of an unknown picture, there may be a particular moment at which one guesses with confidence the content of the picture (e.g., the Mona Lisa). At this point, one's curiosity to see a particular piece of the puzzle completed is likely to decline because one can infer its content with some accuracy (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994).

We find the explanations given above quite important since they provide a vivid picture of the psychological aspect of completion dynamics. Although completion dynamics has the force to move cognition toward certain items of information as opposed to others, one's perception of the completeness of a meaning-subsystem (such as the picture of Mona Lisa) can work as a positive force where some unrelated item of information might be more attractive to the mind than what completes the meaning-subsystem further. Based on those insights some working assumptions regarding the completion dynamics can be formulated as follows:

> <u>Completion Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem, while B does not, A is preferred over B, provided that completeness perception is not already satisfied.
>
> <u>Completion Dynamics Formula-2:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem with greater effect than B, A is preferred over B, provided that completeness perception is not already satisfied.

3.3.4. EXPLICATION DYNAMICS

Referring back to completion dynamics, we can imagine different ways of completing a picture. Based on our cognitive model depicted as a meaning system with cores and peripheries, if any item of information completes a meaning-subsystem at the core, then it is expected to have a higher effect on completion dynamics than that of a peripheral information. For example, a student might start collecting a lot of facts about a certain subject and if she has the chance to learn some fundamental principle which explains all the facts, she would prefer to know it as opposed to just another fact. As have been seen in the findings about children's questions, children tend to ask more questions about explanatory principles as opposed to factual ones as they get older. Similarly, the accrual of factual information increases the need to reach out to information that keep all factual information together as core organizing principles. Similar to the pace of children's behavior during their development, human adults can be argued to display a similar transition of curiosity from factual to explanatory information. One has to have some idea about the motion of planets before being curious about the laws that define its motions. Even Kepler had to rely on many observations before having the desire to uncover the underlying principles of planetary motion. Therefore, explication dynamics has a direction from factual information to explanatory principles. Scientific laws, scientific hypotheses, explanatory principles, core definitions, rules and formulations are among those core information. Explication dynamics describes the force that influences selectivity toward core information as opposed to peripheral information. Some working assumptions regarding the explication dynamics can be formulated as follows:

> <u>Explication Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem at the core, while B does it at the periphery, A is preferred over B, unless there is a specific reason to collect peripheral information or the meaning-subsystem is in an initial (child-like) stage.
>
> <u>Explication Dynamics Formula-2:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem at the core with greater effect than B, A is preferred over B, unless there is a specific reason to collect peripheral information or the meaning-subsystem is in an initial (child-like) stage.

3.3.5. PERFECTION DYNAMICS

Having a meaning-system is not the same thing as having a coherent meaning system. Also no matter how coherent our meaning systems are there is always the possibility that some recalcitrant information comes and shatters all that we think we know. This is why the dynamic property of the meaning systems must be emphasized. It is not only by the addition of new information that our meaning systems become dynamics, they constantly change structure and connectivity based on the type of the information. This aspect has been emphasized a lot by the incongruity theorists. Human cognition seems to be favoring information that is incongruous, surprising, conflicting, incompatible and challenging. The stimulating aspect of cognitive dissonance has been supported by many studies mentioned earlier in this dissertation. However, there is also an inverted U-shaped relationship between curiosity and the level of violated expectations (Loewenstein, The Psychology of Curiosity: A Review and Reinterpretation, 1994). Referring back to Quine's model, a recalcitrant information standing in conflict with our system of beliefs might evoke curiosity, but if we are at the brink of a personality crisis where all that we have believed in is going to be shattered with a piece of information, we might want to avoid it as well. Leaving aside these exceptional cases, human curiosity seems to be inclined toward what is required for the perfection of one's meaning-systems. Incongruous information is an input to either test the pre-established coherence or an opportunity for fixing the current imperfections. Based on these views, some working assumptions regarding the perfection dynamics can be formulated as follows:

Perfection Dynamics Formula-1: All the rest being the same about resources A and B, if A is incongruous to a meaning-system, while B is not, A is preferred over B, unless there is a specific reason to avoid this.
Perfection Dynamics Formula-2: All the rest being the same about resources A and B, if A is incongruous to a meaning-system with greater effect than B, A is preferred over B, unless there is a specific reason to avoid this.

3.3.6. INTEREST DYNAMICS

Interests are deeply rooted in our personality that is shaped by to our genetic structure, culture, development and social environment. Although we have discussed that they are not the sole determinants and are even occasionally overridden by universal curiosity, interests are one of the most powerful dynamics that influence cognitive selectivity. Some people are passionate about flowers so they want to know everything about them. Some people are passionate about starts and even the most interesting information about flowers does not excite them as much as a new information about stars. If a person is truly interested in sports cars, they sometimes memorize each and every detail about all major sports car models. Interest dynamics is such that it expands one's interest toward related subjects. Tenacity property of curiosity discussed by Schmitt & Lahroodi corresponds to this property. We are also interested (in diminishing degrees) in things related to our objects of interest. For example, if one is interested in trees, it is more likely that he is interested in the forest ecosystem more than the sports cars (unless it is another interest of his).

Another important point about interest dynamics is its relationship with social dynamics. As mentioned above interest dynamic is deeply rooted in our personality that is also shaped by sociocultural environment. We are more interested in things that are receiving more attention by other people (popularity), that are produced or respected by noteworthy people (prestige) and that are highly-valued by people (evaluation). A person might be interested in sports cars but certain sports cars are highly popular and prestigious. It is more likely that such a person is more powerfully interested in those sports cars as opposed to less popular ones. Based on these views, some working assumptions regarding the perfection dynamics can be formulated as follows:

Interest Dynamics Formula-1: All the rest being the same about resources A and B, if A is under the interest domain of one, while B is not, A is preferred over B, unless universal curiosity overrides interest dynamics.
Interest Dynamics Formula-2: All the rest being the same about resources A and B, if A is a greater interest for one compared to B, A is preferred over B, unless universal curiosity overrides interest dynamics.
Interest Dynamics Formula-3: All the rest being the same about resources A and B, if A is related to one's interest domain while B is unrelated, A is preferred over B, unless universal curiosity overrides interest dynamics.
Interest Dynamics Formula-4: All the rest being the same about resources A and B under one's interest domain, if A has a higher total weighted average score of prestige, popularity and participant evaluation than B, A is preferred over B, unless there is an exclusive reason determined by the person.

3.3.7. INTERPLAY BETWEEN COGNITIVE DYNAMICS OF CURIOSITY

Cognitive dynamics of curiosity such as expansion dynamics, completion dynamics, explication dynamics, perfection dynamics and interest dynamics are all cognitive forces that interactively determine cognitive motions, i.e. cognitive selectivity. None of these forces are isolated, but they work in interaction. There are also external (instrumental) dynamics that join this interaction. The best way to visualize these forces are through physical vectors. Each vector has a magnitude and direction just as each cognitive dynamics has a motivational magnitude and direction. The interplay between different vectors define the final movement of the object and the higher the magnitude of a vector the higher influence it has.

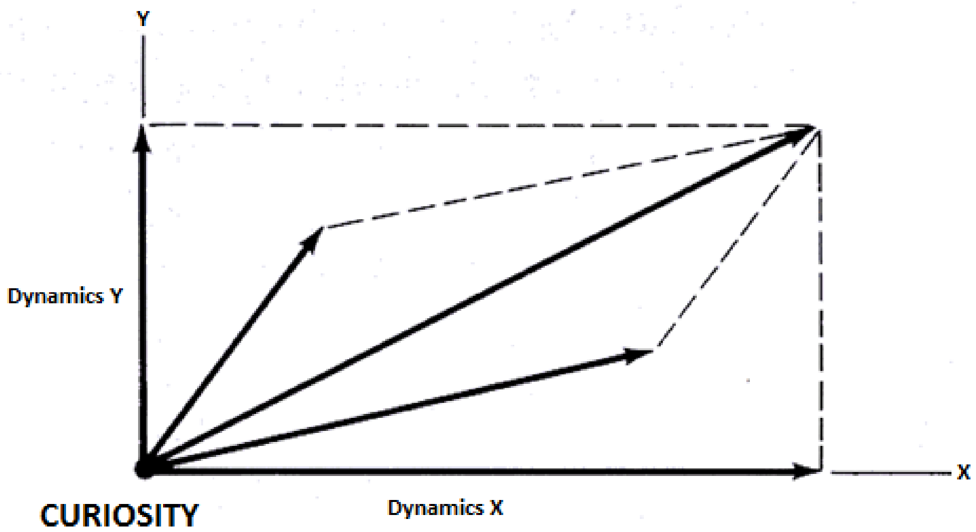

Figure 1. The vector space as an analogy to the interplay between cognitive dynamics

To further substantiate the idea that cognitive dynamics interactively define cognitive motions, we will formulate some hypothetical scenarios that bring together interacting forces.

<u>Scenario A:</u>

Person P is absolutely equally interested in topics A and B. He has a limited time for surfing on the internet and wants to read something in the Wikipedia. He heard that that there is some information X about A that is incongruous with what he knows and there is some other information Y that is missing in his picture of B. If the perfection value of X and completion value of Y is absolutely equal, person P has no incentive for preferring A over B and vice versa. In such a case the selection will be based on chance factors.

Scenario B:

Person P is interested in subject A. She has access to different items of information about the subject and related subjects. Information X is a peripheral item of information about A that does not cause any significant change in the core understanding of the subject, whereas there is a central item of information Y about Subject B, which is closely related to subject A and it is throwing light to some of the key observed phenomena about B. In such a case interest dynamics and completion dynamics are in conflict. P would prefer a core item of information related to A to a core item of information related to B. However, in this case, although X is about the domain that A is more interested in, A may prefer Y since it powerfully completes some subject (meaning-subsystem) B closely related to A.

Scenario C:

Person P is highly interested in subject A. He makes a lot of informative conversations about his interest subject in a social occasion. After a certain amount of time, he hears a friend talking enthusiastically about a strange subject. He decides to leave the ongoing conversation about his interest subject to join the conversation about the strange subject.

Scenario D:

Person P is interested in subject A. One of her friends brings her two books. Book A contains ideas that challenge her ideas about the subject and book B has a lot of new information which does not seem to conflict any of her current ideas. If P's perception of her current level of knowledge is too low, she might choose to fill up her mind with the information contained in B before confronting with any challenge and expansion dynamics are at work. If P's perception about her current level of knowledge is high, she is more likely to select A and try to meet the challenge.

Scenario E:

Person P is a scientist. He spent all his life to the subject of dark matter. He has written a large book for his theories about the nature of the dark matter. One day he is informed that there is one new experiment which yielded conclusions which have the potential to shatter all of his core assumptions. He might avoid reading this book or he might be highly willing to read it in the first occasion in order to meet the challenge, modify his ideas or understand the truth about his interest subject.

Scenario F:

Person P is a cognitive science student. He is interested in philosophy and psychology equally. He has time for reading ten books. He starts reading one philosophy book about epistemology as one of his interest topics (interest dynamics). He picks the second book again from the field of epistemology because he does not feel that he has a clear picture of epistemological issues yet (completion dynamics over expansion dynamics). He picks the third book again from epistemology because although now he has a satisfying level of general information about epistemology, he finds the subject of 'coherence theory of truth' interesting and wants to learn more about it (interest dynamics and completion dynamics). He reads a book about it and starts to have a better idea. He asks his friends what to read next. One of his friends has read many books for the same subject and he offers two books. One has a different perspective on the subject and the other one challenges the widespread ideas in the field. He wants to see the different perspective and picks the first one (completion dynamics and expansion dynamics). This book relates coherence theory of truth with Gestalt psychology as an attempt to explain the human tendency to form coherent belief systems. This book instigates a curiosity about the underlying cause of why people seek coherence (explication dynamics and completion dynamics). He reads the last four books from the field of Gestalt psychology (completion dynamics).

Scenario G (introspection):

I am interested in the subject of curiosity. I have read all of the popular articles about the topic (interest dynamics). I have not stuck to one discipline but tried to read from as many as possible (expansion dynamics). I was particularly curious about the underlying cause of curiosity (explication dynamics). Meno's Paradox was also interesting in that I felt that I can offer a solution for this problem (perfection dynamics). I read a couple of articles from decision making theory because they were necessary for understanding Loewenstein's ideas (completion dynamics). I would like to read more books on personality theory to understand how it is shaped (completion dynamics). If I would have to choose between two books one of which challenges incongruity theory and one of which talks about a new situational determinant of curiosity, I would choose the second one (completion dynamics), since I feel I have enough grounding for the former. As I feel that I have a complete picture of the curiosity, I am more interested in reading an article on user behavior modeling relevant to my curiosity model than another book on curiosity (expansion dynamics) unless it is something really challenging, surprising (perfection dynamics) or novel (completion dynamics). If someone told me that some author unknown to me is quite famous for his contributions to the field of curiosity studies, I would be utterly interested in her work (interest dynamics).

3.3.8. PERSONALITY DRIVEN COGNITIVE DYNAMICS OF SCIENTIFIC CURIOSITY

As can be seen in the scenarios above the relative strength of each dynamics depends on our personality formation. Some people are specialists and some are generalists. A generalist would opt for expansion, while a specialist would opt for completion. Some people are perfectionists and obsessive, which leads them to collect everything regarding a domain while making sure that everything is well-organized. They might want to fill the puzzle until the very last piece although they already see the final picture. Some people suffice with average amount of information with an average coherence. They want to explore new landscapes and establish seemingly distant connections. Some people have powerful interest topics and they do not want to learn anything else. Some people are like ancient polymaths and they want to expand their bird's eye view to as many subjects as possible. Some people do not care about the popularity of a resource but care a lot about its prestige and value. Some are only interested in things that are popular. Some people always want to go deeper into the heart of the topic, while some prefer to stay on the surface. What makes us those decisions are deeply rooted in our personality. That is why we propose the concept of 'personality driven cognitive dynamics of scientific curiosity.' Now that we have some clear formulations about the selective expressions of cognitive dynamics of scientific curiosity, we can keep track of the selective patterns of any individual to draw conclusions about the personal curiosity traits. If we have information about those traits, we can predict the future behavior of that individual or we can aid his curiosity behavior by presenting him what maximizes his expected satisfaction using this information. Technology design for aiding and augmenting human curiosity will be handled in the next sections. Before coming to that subject, we will introduce the concept of extended curiosity, which is a description of how human curiosity interacts and couples with its environment at the current stage of technology.

3.4. EXTENDED CURIOSITY

The idea of embedded cognition construes the technological environment as part of our minds. Mind, body and environment are parts of the cognitive process without a clear-cut distinction. Even a piece of paper is a technological tool that is part of our environment. We use writing as a way of thinking. We think on paper. Good academicians write a lot and writing on a piece of paper helps them organize their thoughts. Andy Clark talks about a famous conversation between the physicist Richard Feynman and historian Charles Weiner to in his *Supersizing the Mind*:

> Consider this famous exchange between the Nobel Prize–winning physicist Richard Feynman and the historian Charles Weiner.[1] Weiner, encountering with a historian's glee a batch of Feynman's original notes and sketches, remarked that the materials represented "a record of [Feynman's] day-to-day work." But instead of simply acknowledging this historic value, Feynman reacted with unexpected sharpness:
>
> "I actually did the work on the paper," he said.
>
> "Well," Weiner said, "the work was done in your head, but the record of it is still here."
>
> "No, it's not a *record*, not really. It's *working*. You have to work on paper and this is the paper. Okay?" (from Gleick 1993, 409, as cited in Clark, 2008)
>
> Feynman's suggestion is, at the very least, that the loop into the external medium was integral to his intellectual activity (the "working") itself (Clark, 2008, p. xxv).

If we adapt this perspective to our theory of curiosity, we can easily say that loop into the external medium is integral to the dynamics of curiosity. When we desire to know some 'resource' as defined in our theoretical framework, it is not that we only select the internal content of our minds. Human mind displays very dynamic motions toward resources, which may be a transition from a statement to another by the mechanisms of logic or a transition from an external resource to another one. To make this depiction more vivid, we will focus on 'the curious person in the library' as an epitome to extended curiosity and analyze what is actually going on with the curiosity of this person.

3.4.1. THE CURIOUS SCIENTIST EMBEDDED INTO THE LIBRARY

We have a curious scientist called Albert. Albert has an unbridled scientific curiosity about all aspects of life since his childhood, but he is mostly interested in stars. So he chose to study cosmology in his graduate degree. He has nothing to do all Saturday and he want to read some interesting stuff until dinner before he goes out with his friends. He lives in the campus and library is 5 minutes away. He goes to the library, visits the section full of cosmology books, grabs a book about dark matter and starts reading it.

Albert is reading and thinking at the same time. A lot of ideas rush into his mind while reading. He comes to a very interesting page which discusses the nature of dark matter. He finds a reference to a name, who is introduced by the author as a significant scientist that has a very interesting contribution to the field. Albert's curiosity directs his mind toward this name. The goes to the bibliography and finds the book written by this person. He searches the library database, finds the book and starts reading it. He is totally immersed by the book. He knows that dark matter amounts to 80% of the universe and its nature is one of the greatest mysteries in physics. And he feels that he is having a better grasp of the issue. He suddenly sees that the author of the book is trying to meet the challenge of a counter-argument by one of his opponents. Albert quickly goes to the internet and starts surfing on the net for finding some information about this opponent. He reads his ideas and main objections and sees that the discussion revolves around the hypothetical elementary particle axion. He moves his attention to axion and searches some of the newer articles about axion to see whether there is anything new that he does not already know. He knew things about axion but in the framework of this new discussion, axion starts to have a new status for him and that is why it is important to reach out to the latest resources about the issue. He suddenly finds an article which does not seem to be a physics article, but he is taken by its content while skimming the articles relevant to his current interest. This article is about history of physics and it tell things about aether. He suddenly has this strange idea that axion could be treated as aether in a couple of decades and these discussion might become void. While thinking this he keeps on reading about the history of physics and he finds some very interesting information about the history of medicine. He suddenly feels that reading about such historical issues is quite enjoyable and he wants to have a bit from each of those interesting things. He starts making a Wikipedia search and he jumps from one hyperlink to another. After some roaming, he feels that he should continue with the history of physics to have a general picture of its flow from ancient to modern time. He keeps on reading until he has a fair amount of information about the subject and he starts telling some of the interesting information to his friends during the dinner. He does it so enthusiastically that one of his friends, who has nothing to do with sciences or history, becomes very interested in the topic and he makes some internet search about similar things the next day.

If we analyze the story on the basis of curiosity and its motions, we can realize some quite distinguishable patterns. One thing is that there has been a seamless flow between internal and external resources, mental constructs and Wikipedia, rushing of new ideas and picking another physical book from the library and surfing on the net for finding the newest articles after that. To repeat this description in slow motion: The initial resource was the concept of “the nature of dark matter.” This resource had an intrinsic utility for Albert due to interest dynamics. The resource also had availability in that there has been books and articles around the topic. This interest drifted Albert’s attention from certain books to others by the help of citations and bibliography, which made other sources available for him. When he wanted to expand his information about the subject of axion, the surfed the internet to find the most differentiating article. He went to library databases and also to Wikipedia for some initial information. Then after some time of engagement with the interest topic being influenced by the forces of perfection dynamics and completion dynamics, he found himself immersed into a topic he had no visible prior interest. As ‘universal curiosity’ is generalist in character he first made an exploration on the field of history of science driven by expansion dynamics. This expansion is quickened and multiplied by the hyperlink based structure of Wikipedia, which mimics the conceptual organization of human mind. The quick roaming from one link to another gave him a level of satisfaction as a generalist and at a certain level of information, he became inclined to completing some of the subtopics with some further information. There might be some external dynamics at force at this stage such as finding a coherent story to tell his friends in the evening. After this experience, the enthusiasm of Albert attracts the curiosity of his friend during the dinner and he becomes his point of reference.

This story gives a good depiction of how our curiosity couples with external medium. In a library with a countless number of books and multimedia resources instantly accessible to cognition, human curiosity moves freely from one resource to another without differentiating between the internal and the external. Even reading a conventional hardcover book with sentences, pages, references, citations and the bibliography which connects the book with the resources in the rest of the library is an example of an incredible degree of extendedness. When we think about the digital technologies that are available today this degree becomes even higher. Previously unimaginable amount of data is accessible to our cognitive consumption. Library of Alexandria can now be carried in a USB in our pockets. We have the whole World Wide Web, various e-libraries, Turnitin, Citesteerx, EBSCOHOST, academic collections, Google Scholar, countless number of digital papers, articles, dissertations, news and what not. This is incredible and we are so much used to it that we take it for granted. In the next section we are going to wrap up all the insights in this chapter including that of extended curiosity into a unified theory called Cognitive Dynamics Theory of Scientific Curiosity.

3.5. COGNITIVE DYNAMICS THEORY OF SCIENTIFIC CURIOSITY

When discussing different approaches to artificial intelligence, Russell and Norvig describes cognitive modeling approach as such:

> If we are going to say that a given program thinks like a human, we must have some way of determining how humans think. We need to get *inside* the actual workings of human minds. There are three ways to do this: through introspection—trying to catch our own thoughts as they go by; through psychological experiments—observing a person in action; and through brain imaging—observing the brain in action. Once we have a sufficiently precise theory of the mind, it becomes possible to express the theory as a computer program (Russell & Norvig, 2010).

Cognitive Dynamics Theory aims to bridge a long gap between philosophy and psychology on the one side and artificial intelligence on the other side. As mentioned by the authors we have tried to get inside the actual workings of human curiosity by reference to empirical studies as well as rigorous philosophical arguments. Like all of the motivations, curiosity motivation also has a directionality. In an abstract sense, curiosity makes our minds move just like the cat would move to the food when hungry. However, it is utterly difficult to describe what type of a movement curiosity causes and what type of a medium this movement occurs. When we say words like ‘children move from facts to core principles’, we are actually describing a very elusive process. This movement obviously happens in our minds, but it is not easy to depict the origin and the destination. What we tried to manage in our theory construction phases has been to cover all those gaps for a truly comprehensive theory. By discussing sense-making and the meaning-systems we have visualized a structure with cores and peripheries within which the cognitive movements can be described. We also delimited the concept of scientific curiosity so that we can be more specific about our reference. Another aspect of the theory is that it brings together all the theoretical insights of different disciplines and schools of thought into one coherent framework. In this framework, even seemingly contradictory ideas about ‘interest’ and ‘independence from interests’ finds a coherent place through a description of universal curiosity and its time constraint. We could also manage to give clear formulations for each cognitive dynamics in the form of selective patterns and give a clear picture of how they interact within this framework. Finally, the idea of extended curiosity bridged the gap between cognition and technology, which brought us to a unified theory ready to be utilized for a computational model. Below we summarize the basic concepts and assumptions of the Cognitive Dynamics Theory of Scientific Curiosity before we move on to the next chapter:

1. Human cognitive machinery is a dynamic system of meanings with cores and peripheries.
2. Humans have an intrinsic motivation to make sense of potentially everything that are proper subjects of science and philosophy. This motivation is called 'universal scientific curiosity.'
3. The capacities of human cognition such as language and logic define the way this dynamic system of meaning operates and transforms such as forming references to the unknown.
4. Human cognition is seamlessly coupled with its environment including the technological tools, therefore human curiosity also extends seamlessly to whatever extension is pro
5. There are cognitive forces that interactively determine the cognitive motions toward content-bearing resources. They optimally influence cognitive universal scientific curiosity to make cognitive selections on the basis of maximum expected satisfaction under time constraint.
6. These forces are called cognitive dynamics of scientific curiosity.
7. In order to model these forces comprehensively, a theory needs to rely on a model of the structure of cognitive machinery, which, in Cognitive Dynamics Theory, is the dynamic system of meanings with cores and peripheries.
8. The list of cognitive dynamics is:
    a. Expansion Dynamics
    b. Completion Dynamics
    c. Explication Dynamics
    d. Perfection Dynamics
    e. Interest Dynamics
9. Cognitive dynamics determine the final cognitive motion in interaction in analogy to a vector space.
10. Cognitive dynamics are rooted in human personality.
11. A person's resource selection patterns on the basis of the cognitive dynamics model can be used to reach conclusions about the person's curiosity traits.
12. A good characterization of a person's curiosity traits can be used for predicting the future motions of curiosity. Such a predictive power can be utilized for an optimized coupling between scientific curiosity and technology, which will be called 'augmented curiosity'.

In the next chapter, we will propose an ambient semantic intelligence model that has the promise to aid and augment scientific research processes. There will also be a toy model as proof of concept. The aim of the next chapter is also to demonstrate that the basic assumptions of Cognitive Dynamics Theory provides a strong grounding for a working computational model, which, in turn, provides a platform to test and enhance the Cognitive Dynamics Theory.

CHAPTER 4

4. AMBIENT SEMANTIC INTELLIGENCE MODEL FOR SCIENTIFIC RESEARCH

There are two possible ways that philosophical and psychological work on human curiosity can interact with computer engineering. One of them is through the field of artificial curiosity. For the last two decades there has been some interesting work done by Jürgen Schmidhuber and many others on artificial curiosity focusing on the design of curious agents. The field extends reinforcement learning theory with formalized theories of intrinsic motivations such as interestingness.

> Even in absence of external reward, babies and scientists and others explore their world. Using some sort of adaptive predictive world model, they improve their ability to answer questions such as: what happens if I do this or that? They lose interest in both the predictable things and those predicted to remain unpredictable despite some effort. We can design curious robots that do the same (Schmidhuber, 2006).

The quest for developing curious robots is an exciting one. Formal theory of intrinsic motivations is based upon maximizing intrinsic reward for creation or discovery of novel and surprising patterns that enable improved prediction.

> Deciding where to explore next is a ubiquitous challenge in reinforcement learning and optimization. Inspired by the human drive to discover "interesting" parts of the world, one formal interpretation of *artificial curiosity* [1], [2], [3] defines momentary *interestingness* as the first derivative of the quality of an adaptive world model, where quality is measured in terms of how much the current model is able to compress the data observed so far. Something is interesting if it contains new, yet learnable regularities that can be used to *better* predict or compress the data, taking into account the limitations of the model's learning algorithm (Schaul, Sun, Wierstra, Gomez, & Schmidhuber, 2011).

Although inspiration comes from the human curiosity as stated above, there are some obvious simplifications and reductions implicated by the formal interpretation mentioned above. Although such type of a simplification might be a practical necessity, it is always possible to enrich such models by taking human mind as a benchmark for future improvement in the field of artificial intelligence as envisaged by the cognitive modeling approach.

Cognitive Dynamics Theory proposed in this thesis potentially provides a good deal of insights for the design of better curious agents and enhanced formalizations. The current formal interpretation of interestedness focuses strongly on the information that potentially increase predictability. In our framework, predictability is related to explication dynamics. The knowledge of core principles regarding a domain (such as the principles of planetary motion) brings about higher predictability (about observable facts about planetary motion). However, there are many other dynamics waiting to be addressed by current artificial curiosity literature. Whether those dynamics are relevant to the field or whether they can be formalized usefully are issues to be elaborated on.

A second possible way of interaction between curiosity theory and computer engineering is through developing systems that aid and augment human curiosity. As mentioned earlier, we already have many quite useful technologies that are heavily utilized to satisfy our curiosity. Some of the technologies listed earlier are World Wide Web, search engines, digital repositories, reference management applications and online collaboration systems. We have already described how these technologies interact and couple with scientific curiosity through examples such as curious scientist Albert. However, we are still far away from an ideal coupling between scientific curiosity and available technology potential. The easiest way to understand this gap is thinking about our own scientific research experiences.

Let us suppose that a person wants to write a book about curiosity. The first thing that this person would probably do is to sit in front of his computer and make some searches in an attempt to understand the most significant resources about the subject. If he writes ‘curiosity’ on the Google he will get many query results unrelated to what he is seeking such as the NASA mission to Mars. He might change the search query to ‘curiosity studies’ and this time more relevant things start coming. Loewenstein’s famous article is the first query result. Yet, again, other than this article most of the other query results are still irrelevant. There are some web sites talking about how curiosity enhances our living and how it is related to success, which is not interesting for a scientific study. Now he goes to Wikipedia to try the same words. Wikipedia gives a very neat summary of the concept of curiosity and a good deal of references including Berlyne, Loewenstein and some other less known author, whose small article includes some more useful references. These resources can be used to reach out to many others through their citations section. He also visits Citeseerx and in the first twenty query results are not very satisfying in that they do not include many articles directly related to curiosity studies and they do not include any of the important contributors referred to in the previous searches. However, when the search continues if the person finds one of the names that he is familiar to from his previous searches he can continue hyperlinking over the citations until he has a good network of significant resources. Finally, he sends messages from all social media channels to the students and scholars around him to ask for their opinion about the matter.

Now let us ask this question to ourselves: there are more than a billion internet users in the world and there are many people who has done some sort of research on the same subject. We have all required technology for describing information resources in a portable and interoperable format such as Semantic Web formats and we have all connectivity that we need, why do we not have a collaboration platform which can gather and process information in the form of a giant global graph such that we have a comprehensive list of personalized resources that aids and augments our scientific curiosities? To substantiate the motivation behind proposing an ambient semantic intelligence model for scientific research, we will start with introducing some key concepts.

4.1. SEMANTIC INTELLIGENCE

The W3C definition of the Semantic Web is “a common framework that allows data to be shared and reused across application, enterprise, and community boundaries” (World Wide Web Consortium (W3C), 2015). This definition is close to the definition of semantics: “Semantics is the study of meaning communicated through language” (Saeed, 2003). Human language provides a common framework for people to communicate meanings similar to the common framework W3C is offering as the Semantic Web standards. In the case of the latter, however, the sole purpose is not communicating meaning among people but among machines as well. Tim Berners-Lee describes the Semantic Web as “a web of data that can be processed by machines” (Berners-Lee, Hendler, & Lassila, 2008). Another critical feature of the Semantic Web is it decouples application layer from data layer and enables data portability.

> At their core, semantic technologies decouple applications from data through the use of a simple, abstract model for knowledge representation. This model releases the mutual constraints on applications and data, allowing both to evolve independently. And by design, this degree of application-data independence promotes data portability. Any application that understands the model can consume any data source using the model. It is this level of data portability that underlies the notion of a machine-readable semantic web (Segaran, Evans, & Taylor, 2009, p. xiii).

Another critical feature of the Semantic Web is that it enables data modeling in the form of ontologies. With the use of ontologies, items of information or ‘resources’ as used in the Semantic Web terminology are given a structure with the resource description frameworks such as RDF and N3, which, in turn, provides the semantic quality to the otherwise unrelated stack of data. In a sense, with ontologies and a common framework for communicating those ontologies, software systems begin to make sense of data:

> To the degree that semantic software systems need a model of the world from which to make sense of the knowledge that they operate on, we as system designers are also ontologists. But while the philosophers are trying to sort out the order of the universe, we need only concern ourselves with creating order and describing relationships of things important to our applications (Segaran, Evans, & Taylor, 2009, p. 128).

The reader would realize the commonality between the cognitive model we have offered for our Cognitive Dynamics Theory and the description about sense-making software systems above. Ontologies makes possible structured systems of meaning, which in turn makes possible sense-making. Every new resource is incorporated into the preexisting ontology and gains its meaning in relation to it. Moreover, ontology-based semantics also makes inference possible:

> Ontologies allow us to express the formal rules for inference. When software reads our ontology, it should have all the information necessary to draw the same conclusions from our data that we did. When the actions of software are consistent with the rules expressed in the ontology, we say that the software has made an *ontological commitment* (Segaran, Evans, & Taylor, 2009, p. 129).

The power of semantic intelligence is that it provides the capacity to fill the semantic gap between human cognition and the operational data. The popularity of the standard framework also boosts the possibilities of ‘sense-making’ human-to-human and human-to-machine collaboration. Therefore, semantic intelligence has to be a key component of any computational design aiming to aid and augment human curiosity.

4.2. AMBIENT INTELLIGENCE

Semantic intelligence is a key and necessary condition of a good computational design for augmented curiosity, but it is not sufficient. For an ideal coupling between curiosity and technology, the systems must be personalized in that they should be tailored to the cognitive dynamics of a person's curiosity and be able to adapt dynamically to the changes in behavior. The system must be context aware and react relevantly to the person's situational context. And finally, the researcher should be well embedded into the system such that his natural interactions with his environment should feed data into the system and generate relevant transformations or outputs. These are qualities that make up 'ambient intelligence.'

A vivid example to ambient intelligence is Computer Assisted Virtual Environment (CAVE) in which a human being is located in a cube shaped room with projectors directed to all walls. The person in the cube wears a 3D glass and is embedded into the virtual environment. The sensors attached to the glasses convey the motion of the person to the computer and the projectors adjust to retain the person's perspective. In very simple words, the system understands the direction or intention of the user and adapts to his situation dynamically. Embeddedness and adaptability are two qualities that make such an experience immersive.

Figure 2. A person embedded in the Computer Assisted Virtual Environment (Wikipedia, 2015)

If the person turns right all the projectors change their perspective accordingly. If the person wants to move again the projectors adjust to his needs. If we used the same concept with human curiosity, an ambient intelligence system must be able to adjust to the cognitive motions (curiosity traits) of the person dynamically during the search and research processes. The system must also be able to collect and interpret all the inputs coming from the user in order to enhance adaptability and interaction.

4.3. AMBIENT SEMANTIC INTELLIGENCE

Ambient semantic intelligence brings together the features of semantic intelligence and ambient intelligence. The concept is new and there might be nuances in its usage. However, despite the discussions around the concept has a long way to go, it already reflects one of the most important trends in the technology, which is what we call 'better coupling' between cognition and the environment.

In the IJSC Special Issue on Ambient Semantic Computing (ASC), Mühlhäuser and Gurevych makes a neat introduction to the concept:

> ASC is an emerging research area that is concerned with novel methods, algorithms, and concepts which fruitfully combine what we call *Ambient Intelligence* and *semantic technologies*. By Ambient Intelligence, we refer to approaches that emphasize the dawning era of networked 'anytime anywhere' computers, worn by users and encountered in everyday life – without being perceived as computers. Ubiquitous Computing and Pervasive Computing can be considered to be synonymous to Ambient Intelligence despite the fact that different authors have provided slightly different definitions (e.g., emphasizing either the use of AI methods or the importance of HCI in Ambient Intelligence). Context-aware computing, multimodal and tangible interaction, and smart environments are examples for more focussed research fields comprised in Ambient Intelligence research.
>
> By semantic technologies, we refer to Natural Language Processing (NLP), ontology related research, and computer perception approaches (vision, video analysis, situation detection, handwriting and speech recognition, etc.) that target human understanding of the media 'perceived' by computers. We are convinced that the vision of Ambient Intelligence, i.e. a world of omnipresent 'hidden' computers that truly aid human beings – and neither hinder nor annoy nor frighten nor threaten – can only be achieved if these machines can deal with concepts that reflect human understanding and common sense. Therefore, the 'smartness' of ambient intelligence must be combined with the 'naturalism' of semantic technologies. In a nutshell, Ambient Semantic Computing aims at a world where humans interact naturally with the smart world around them. The hardware basis for this surrounding smart world are cooperating (embedded and wearable) computers. While this definition sounds much like the unrealistic promises of the early AI, the approach is indeed different since the understanding of a user's situation and goals (or needs, respectively) is based on the novel and fast-paced fields of research mentioned above (Mühlhäuser & Gurevych, 2008).

With today's internet technologies, the tremendous level of connectivity is well suited for developing ambient systems. With the advent of Ubiquitous Computing we are networked 'anytime anywhere'. Human computer interactions are becoming more context-aware and natural. Also, with the advances in semantic technologies, human understanding can be better addressed by the systems as discussed in the previous sections. Therefore, the concept of ambient semantic intelligence is the right match for any system that is based on a functional model of human curiosity; operates in an embedded, personalized, adaptable and highly-connected design; and aims at augmented curiosity and aided research.

4.4. WHY DO WE NEED AMBIENT SEMANTIC INTELLIGENCE FOR SCIENTIFIC RESEARCH?

When the level of technology available today is concerned, there seems to be a huge gap between what can be achieved in terms of augmented curiosity and aided research and what we currently have. However, in order to realize this gap, we first need to have a grasp of the concept of curiosity. As has been mentioned by almost all the contributors from all disciplines, the concept of 'curiosity' has been given minor attention. It is even a significant theoretical achievement to be able to communicate a concept such as 'augmented curiosity' and it is even a more significant one to have a theory of scientific curiosity which can provide the grounding for a functional model for ambient semantic intelligence. However, we still need to give a description of how our lives will be better if we have a successfully working system built on the basis of ambient semantic intelligence model in order to justify the effort to be given to such a research area.

There are 18.000 higher education institutions in the world (International Association of Universities (IAU), 2006). Estimated number of graduate students worldwide is 10,8 million; estimated number of faculty members is 6,16 million and estimated size of science and engineering workforce is 51,6 million (Price, 2011). According to Noorden (2014) Global scientific output doubles every nine years.

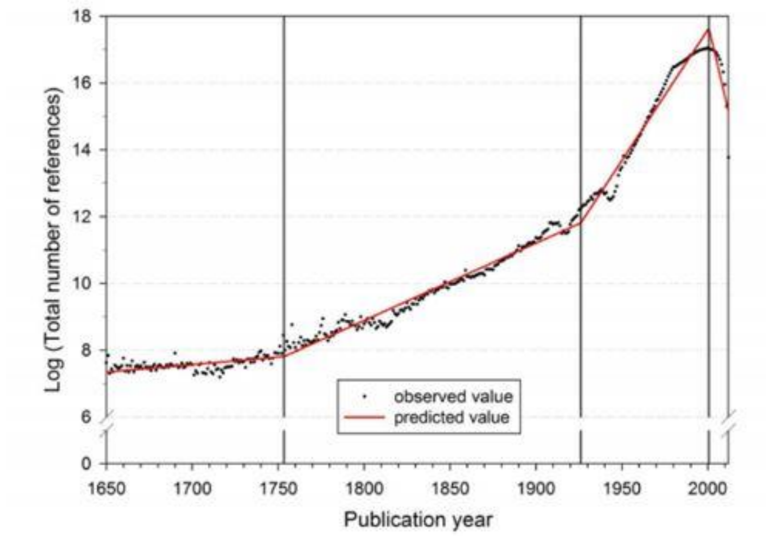

Figure 3. Segmented growth of the annual number of cited references from 1650 to 2012 (citing publications from 1980 to 2012) (Noorden, 2014)

The volume of academic publications and its rate of change is incredible. Tens of millions of academicians, researchers and students are contributing to this picture everyday spending tremendous amount of time and energy. Counting all of those contributors of science, whenever there is a new research they all go through similar processes. They all leverage 'technologies' from the hardcopy books to digital libraries; from pen and paper to word processors and they all go through similar processes such as making an initial survey on the internet, visiting the books at hand, visiting the library including the digital resources, making a reading list, reading the selected resources, taking notes, writing a draft, asking for review, making revisions and finalizing the article. Now let us assume that we have some kind of a system which can give us a comprehensive and personalized read-list as soon as we type in our research topic. Based on the estimated figures above, if this read-list would save 1 hour per researcher per year, the total annual savings of the global research community would be more than 5000 years. This figure alone shows how important it is to focus some energy to this field. What can be achieved by an ambient semantic intelligence model for scientific research, however, is obviously much more than offering read-lists. Although the purpose of this dissertation is not to offer the 'Google' of any such model, even the toy model we are to propose would have the following value propositions:

1) A collaborative platform in which scientific resources are communicated among the members such as:
    a. A list of the contributors to any interest domain.
    b. Research area of the contributors.

c. A list of the contributions of the contributors.
d. Source, type and subject of the contributions (resources).
e. Collative value of the resources (paradox, problem, dilemma, unsolved mystery)
f. Explicative value of the resources (core principle, solution, law)

2) A semantic model which makes ontology-driven inferences on the available inputs and automatically enriches the resources to be offered to the user.
3) A simple ambient feature which adapts to interest dynamics of the user and offers the resources that more likely to be selected by the person given time constraint.

There are obviously many other functions that such a system can include, but as our aim is to prove the concept of ambient intelligence model for scientific research, it provides a sufficient list of features for a toy model, which will be constructed in the next session.

4.5. TOY DESIGN FOR AMBIENT SEMANTIC INTELLIGENCE

To make the ideas discussed so far more concrete we will propose a toy design which will incrementally incorporate the core elements of ambient semantic intelligence model.

1) We construct an internet platform which enables researchers to enter their statements about the contributors to a specific research domain in the triple store format.
    a. They first select the domain
    b. They enter the triple stores
2) Researcher A from the field of psychology selects curiosity_studies as her domain and generates three triples about the contributors to the research domain:
    a. Loewenstein, contribute_to, curiosity_studies
    b. Berlyne, contribute_to, curiosity_studies
    c. James, contribute_to, curiosity_studies

The resulting directed graph is as follows:

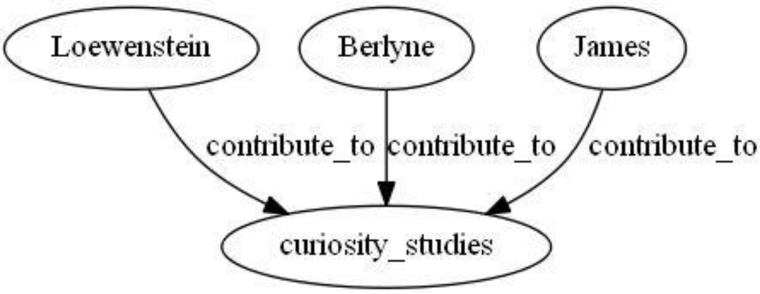

Figure 4. Simple directed graph of 3 statements about contributors to curiosity studies entered by a researcher of psychology

3) Researcher B from the field of philosophy selects curiosity_studies as his domain and generates three triples about the contributors to the research domain:
   a. Plato, contribute_to, curiosity_studies
   b. Inan, contribute_to, curiosity_studies
   c. Lahroodi, contribute_to, curiosity_studies

   The resulting directed graph is as follows:

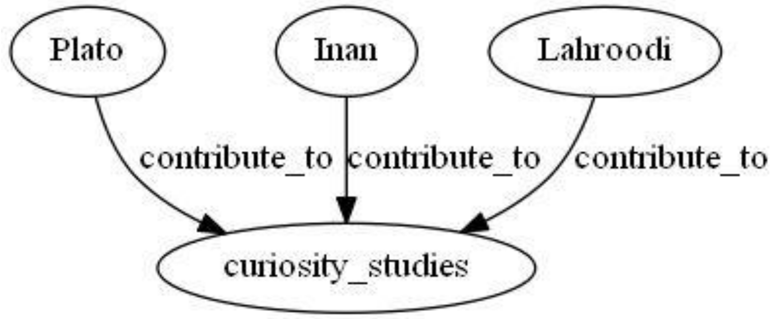

Figure 5. Simple directed graph of 3 statements about contributors to curiosity studies entered by a researcher of philosophy

4) Researcher C is a cognitive scientist and he has interdisciplinary interests. As he has computer science background, he starts with reading articles about artificial curiosity. As a member of the platform he generates three triples about the contributors to the research domain from this field:
   a. Schmidhuber, contribute_to, curiosity_studies
   b. Gomez, contribute_to, curiosity_studies
   c. Wierstra, contribute_to, curiosity_studies

   The resulting directed graph is as follows:

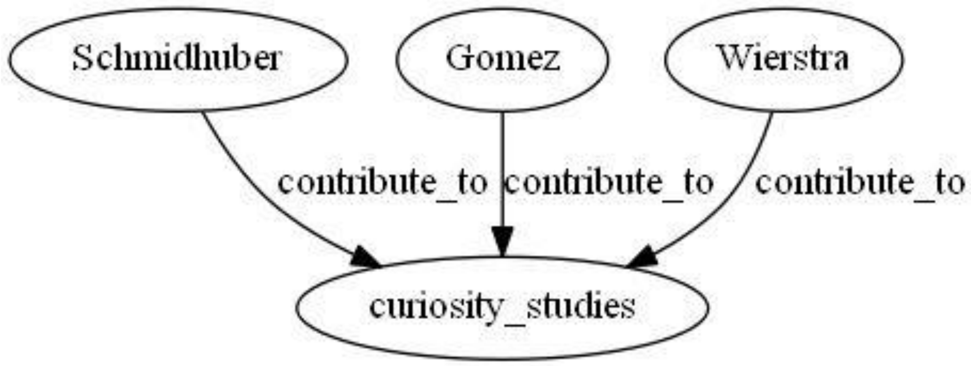

Figure 6. Simple directed graph of 3 statements about contributors to curiosity studies entered by a researcher of artificial intelligence

5) Researchers A, B and C do not know each other. Actually they are contributing to the platform from different corners of the world and they have no common social networking node to reach out to each other. All the statements in the platform are serialized in N3 format and available for SPARQL querying:

SELECT ?s WHERE { ?s ns1:contribute_to ns1:curiosity_studies.}

6) Researcher D joins to the platform and he wants to make research about the same subject. He wants to see a list of contributors to the field.

The resulting graph is:

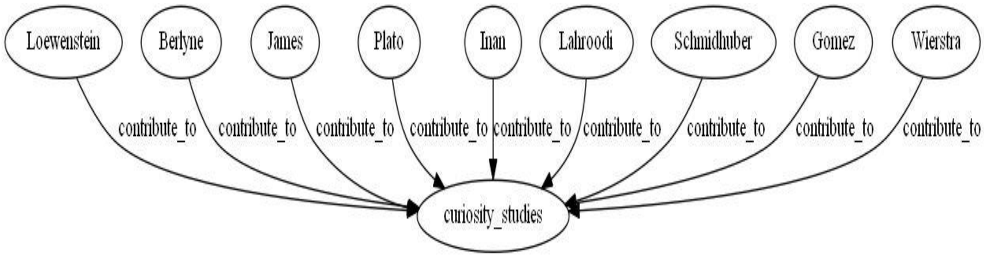

Figure 7. Simple directed graph of that unify statements about contributors to curiosity studies entered by all researchers

7) These resources start being part of Researcher D's embedded curiosity processes. Based on the weight of the dynamics at work, there might be many different requirements to augment the researcher's curiosity in many directions. At this stage the researcher is just enjoying the opportunity to have augmented 'reference points' for his curiosity, i.e. augmented resources.
8) Using reasoning capacity such as the ability to form inostensible references, the researcher begins to form these logical statements:
    a. I am curious about curiosity studies and I am intrinsically motivated to make sense of the field.
    b. I desire to know the contributors to the field to make a better sense of the subject.
    c. If contributor A has a significant contribution X (a concept, an idea, an article or a book) to curiosity, then I am curious about that, too.
    d. I desire to know contribution X, which is currently unknown to me.
9) For a better coupling with the curiosity processes of Researcher D, our system has to enhance itself to incorporate such inostensible references.
10) Researcher A, B and C further enter the significant contributions of their favored contributors in the same format using the predicate 'have_contribution':

    a. <u>Researcher A</u>
        - Loewenstein, have_contribution, The_Psychology_of_Curiosity
        - Berlyne, have_contribution, collative_variables_instigate_curiosity

- James, have_contribution, scientific_curiosity_arises_from_inconsistency_or_gap_in_knowledge

b. <u>Researcher B</u>
   - Plato, have_contribution, Menos_Paradox
   - Inan, have_contribution, The_Philosophy_of_Curiosity
   - Lahroodi, have_contribution, independence_from_interests

c. <u>Researcher C</u>
   - Schmidhuber, have_contribution, curious_robots
   - Gomez, have_contribution, formal_interpretation_of_interestingness_focus_on_information_that_increase_predictability
   - Wierstra, have_contribution, Curiosity_Driven_Optimization

The contributions described can be any resource such as books, articles, ideas, concepts or any other content-bearing unit.

11) Researcher D, again, makes a query about curiosity studies, but this time it is an augmented query as ‘I am curious about the contributors to the field as well as their contributions’.

The resulting graph is:

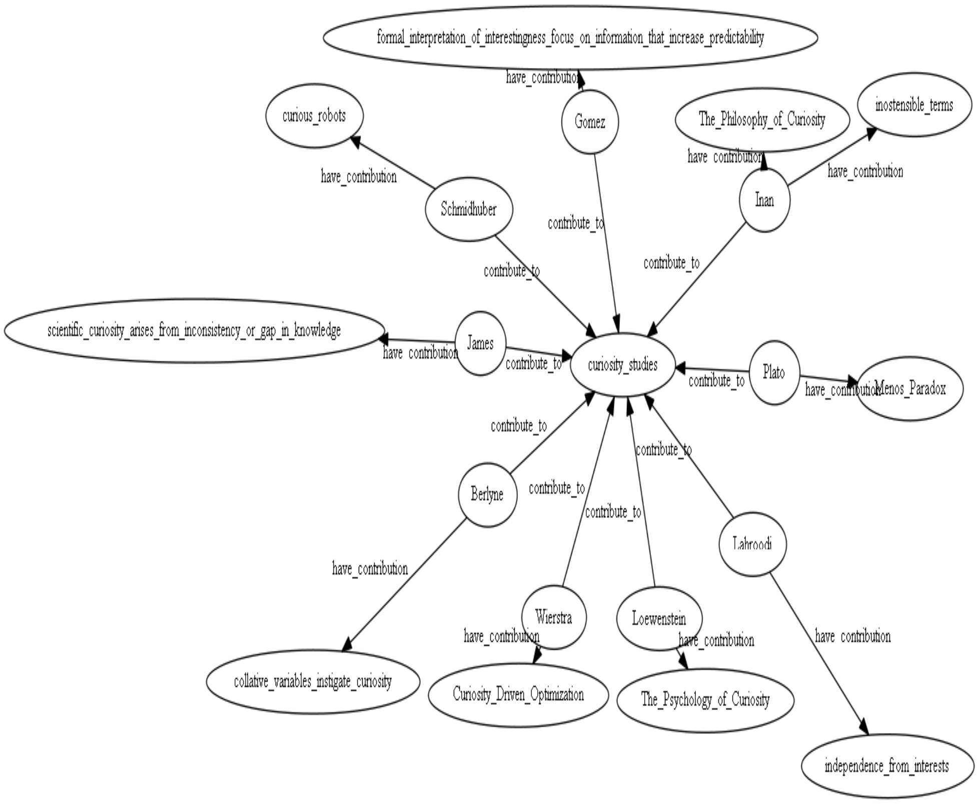

Figure 8. Simple directed graph that unify statements about contributors and their contributions to curiosity studies entered by all researchers

12) With the enhancement of contributor resource with contribution resource, the graph becomes richer and Researcher D has instant access to the immediate objects of his curiosity as depicted in the graph.
13) Researcher E also starts making research about the field. He has some previous information about the field and he heard that Inan is a significant contributor to the field. He informs the platform that he is exclusively interested in Inan. As of now the system has a simple 3-predicates ontology: interest domain, contributors and their contributions. This will be called 'curiosity ontology' in our framework. If a researcher is simply curious about the domain as in the case of Researcher D, then the platform displays all of the domain ontology network. If a researcher points to a specific node of the network, then the system does some reasoning. At this stage, some rules are introduced to the system for semantic reasoning. These rules are based on the observed patterns of curiosity as formulated in our Cognitive Dynamics Theory:

    <u>Interest Dynamics Rule-1</u>

    - If A is curious about Contributor A, then A is likely to be curious about the contributions of A.

    As soon as Researcher informs the system that he is curious about Inan, the system displays the following graph.

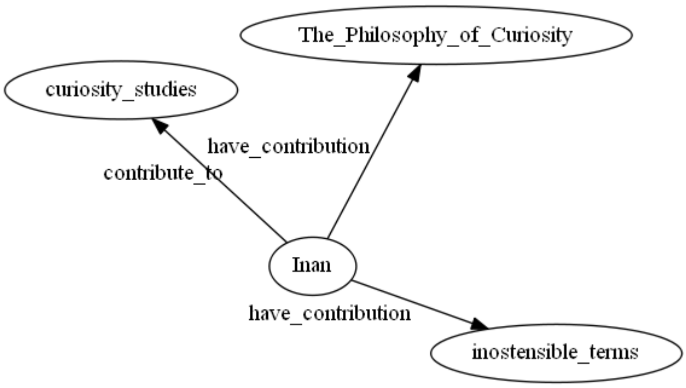

Figure 9. Simple directed graph of statements about contributions of Inan entered by all researchers

14) Researcher is happy to have access to some of the contributions of Inan to the field. However, there are significant limitations of this graph. Firstly, we do not know what type of a resource each contribution is. We improve our system with one more addition. Each entry of contribution will also indicate the type of the resource while making the entry such as:

    a. Inan, contribute_to, curiosity_studies
    b. Inan, have_contribution, The_Philosophy_of_Curiosity
    c. The_Philosophy_of_Curiosity, resource_type, book
    d. The_Philosophy_of_Curiosity, resource_subject, curiosity_studies

e. Inan, have_contribution, The_Philosophy_of_Curiosity
f. inostensible_terms, resource_type, concept
g. inostensible_terms, resource_subject, curiosity_studies

The resulting graph is:

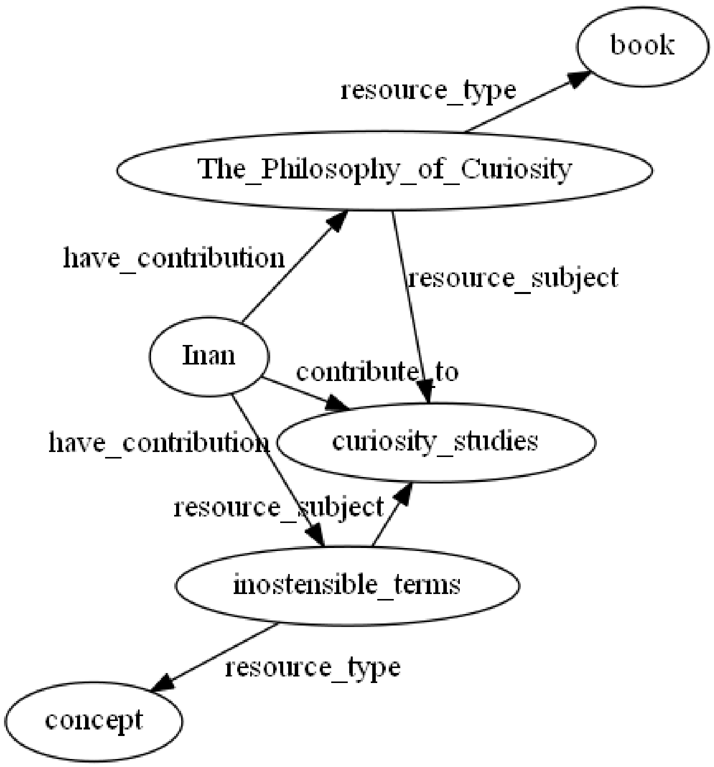

Figure 10. Simple directed graph of statements about contributions of Inan enriched by resource type and resource subject entered by all researchers

15) Now Researcher E knows clearly that Inan has two contributions one of which is a concept and one of which is a book. Yet, he still does not know where this concept is articulated. We do a further fine tuning with the statement:
    a. inostensible_terms, resource_source, The_Philosophy_of_Curiosity

Now the resulting graph becomes more informative:

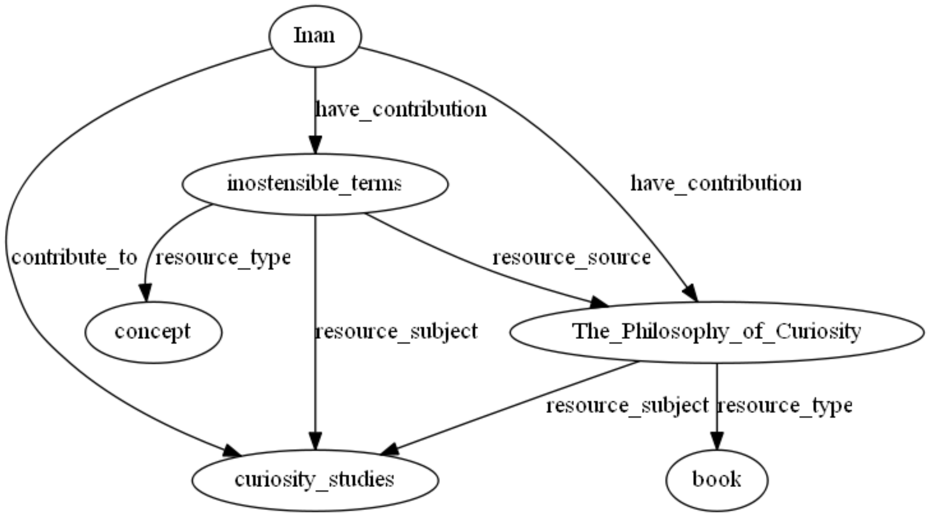

Figure 11. Simple directed graph of statements about contributions of Inan enriched by resource type, resource subject and resource source entered by all researchers

16) Researcher E now knows that there are two resources by Inan. Their subject is curiosity studies. One is a concept and one is a book. And more about the concept can be found in the book. What this picture lacks essentially is that it assumes that if someone is curious about Inan, he will only be interested in resources produced by him. We have demonstrated in our cognitive dynamics framework that human curiosity is also driven by the force of expansion dynamics. We are also curious about the things that are related to our object of curiosity.

Let us assume that being a passionate member of our platform, Researcher C (who has interdisciplinary interests) starts reading other resources and enters one more statement about Inan as well as an interesting theoretical link he has discovered between one of Loewenstein's ideas and Meno's Paradox:

a. Inan, curious_about, Menos_Paradox
b. Loewenstein, have_contribution, curiosity_as_a_reference_point_phenomenon
c. Menos_Paradox, related_to, curiosity_as_a_reference_point_phenomenon

We further enhance our ontology by inference rules formulated in line with expansion dynamics of scientific curiosity:

<u>Interest Dynamics Rule-2</u>

- If A is curious about any resource X, then A is likely to be curious about the other resources that X is curious about or related to X.

Researcher E (who is exclusively interested in Inan at this stage) is totally disconnected from Researcher C, who, as a dedicated member of the platform, keeps making new statements whenever he finds some interesting idea. Researcher E does not know the content of Inan's work, at the initial stage he does not have any idea about what he is curious about and what is the subject of one of his objects of curiosity (Meno's Paradox in this case).

Augmented by new inference rules the new ontology gives this graph for Researcher E at the first stage of his inquiry about Inan:

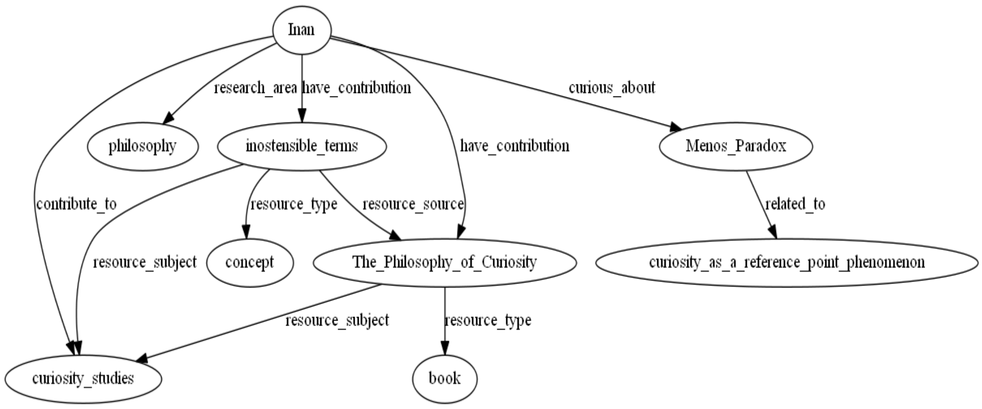

Figure 12. Simple directed graph of statements about contributions of Inan enriched by resource type, resource subject and resource source as well as resources that Inan is curious about or related based on the formulations informed by expansion dynamics

To describe from the beginning:

a. There are some independent statements being entered by people which may or may not be connected in any ways.
b. The descriptions about Inan is entered by Researcher B and Researcher C.
c. Researcher B entered descriptions about the contributors to curiosity studies from the field of philosophy as well as some of their contributions including that of Inan's. He has entered nothing related to what Inan is curious about regarding any subject matter.
d. Researcher C used the system to understand contributors and their contributions. The read some resources and he entered one statement about what Inan is curious about and one statement about the subject of his curiosity.
e. Researcher E uses the system and now he knows that Inan has two contributions, one being a book and one being a concept within that book; and that Inan is curious about something called Meno's Paradox which is related to something called 'curiosity as a reference point phenomenon'.

f. Being taken by expansion dynamics of scientific curiosity, Researcher E is now also curious about this mysterious connection between Inan, Meno's Paradox and 'curiosity as a reference point phenomenon'.
g. Our system, however, does not provide any information about who is the source of 'curiosity as a reference point phenomenon'.
h. This is inefficient because based on expansion dynamics, we have formulated that:
    - If A is curious about any resource X, then A is likely to be curious about the other resources that X is curious about or related to X.

   Therefore, if Researcher E is curious about 'curiosity as a reference point phenomenon', we would expect that he is also likely to be curious about who articulates that 'resource'.
i. The problem is that our system does not know that:

    - If Resource X has contribution Resource Y, X is also related to Y.

j. Therefore, we need to enhance our rule engine with a Curiosity Ontology Inference Rule-1 (such rules will be called 'Curiont Rules'):

   <u>Curiont Rule-1</u>

   - If X has contribution Y, then A is related to Y.

k. Now that we have this rule we will also start to have this statement (entered by Researcher C) in Researcher E's query space:

    - Loewenstein, have_contribution, curiosity_as_a_reference_point_phenomenon

After these revisions the graph that would be displayed to Researcher E is as such:

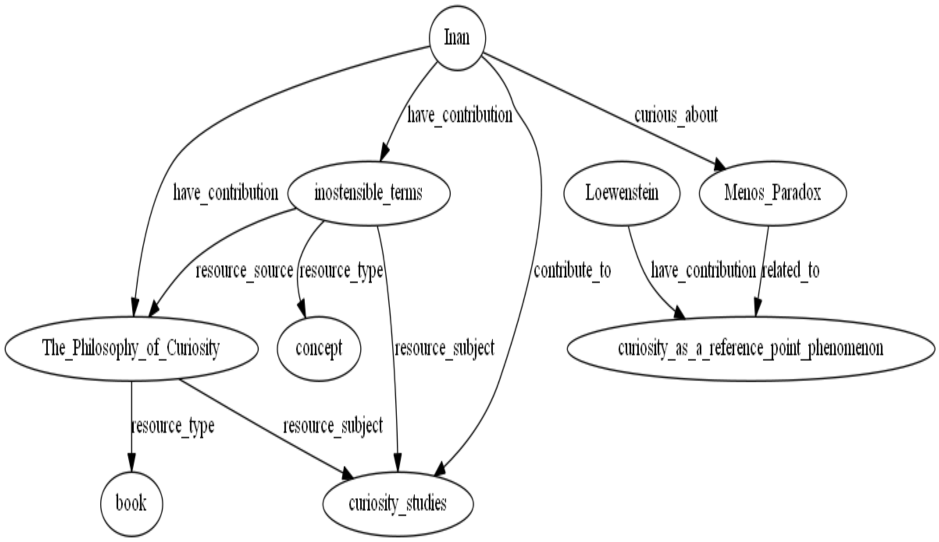

Figure13. Simple directed graph of statements about contributions of Inan enriched by resource type, resource subject and resource source as well as resources that the Inan is curious about or related to and some additional inference rules

17) The final graph became much more informative for Researcher E so much so that we not only has information about Inan's contributions to the field but also about his curiosities and even a resource named 'Loewenstein', who seems to have contributed to the field with an idea which is related to Inan's object of curiosity. That seems to be very enriching experience and a good example of augmented curiosity. However, here we need to stop and think about a new problem we are facing.
18) Researcher E was curious about Inan and now he has Loewenstein in front of him. Does he really care? Even if he would not be bothered by learning one more piece of information, if he had limited time, would he prefer to learn it or something else within the set of alternative statements? The answer depends on his curiosity traits that are defined by the relative influence of cognitive dynamics. Here are some of the possible answers:
    a. Researcher E might have an interdisciplinary spirit like Researcher C and the influence of expansion dynamics might be high. In this case, he will desire to expand his knowledge to the related areas. If his expansion dynamics is very powerful; if there are 3 statements about Inan and 2 statements about a related resource; and if he has to choose 3 among them, he might prefer to combine (1, 2) or (2, 1).
    b. If he has a type of personality that favors focusing on things and completing all the information gaps within any interest domain, then the completion dynamics is at work. In this case he is likely to choose all pieces of information from the closed interest-domain about Inan (3, 0). If although completion dynamics is a powerful influencer of his final curiosity trait, if his perception of the completeness of Inan-domain is satisfied, he might want to check what else to know in different contexts.

c. Even if Researcher E is a total specialist as opposed to being a generalist and he is only focused on philosophy and nothing else, his perfection dynamics might be influential and therefore he might prefer to learn things related to Meno's Paradox including Loewenstein. Actually, there is nothing in this graph saying that Meno's Paradox has collative value (in the sense of Berlyne's framework) except for the name itself. The resource itself could have another name but its content could as well be collative.
   Let us incorporate this point into our ontology as 'collative_status' and remake the graph:

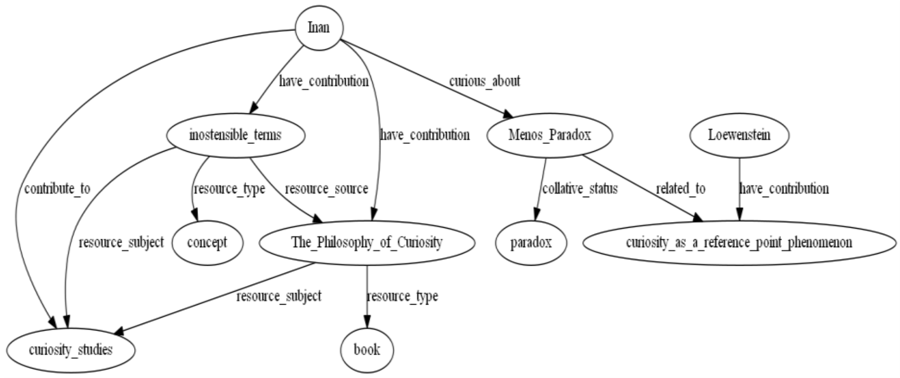

Figure14. Simple directed graph of statements about contributions of Inan enriched by resource type, resource subject and resource source as well as resources that the Inan is curious about or related to; some additional inference rules and collative status

d. Continuing with the scenario above, even if perfection dynamics is at work and Researcher E is willing to learn more about Meno's Paradox, now that he knows that it is a paradox he might still suffice with learning about Meno's Paradox itself. He can simply start reading about it so why would he care about Loewenstein as well? Actually this might still change based on the information about who Loewenstein is? If we had more information about Loewenstein such as his main field of study, this could be an input that would influence the results of his curiosity dynamics. Now we add this information as well:

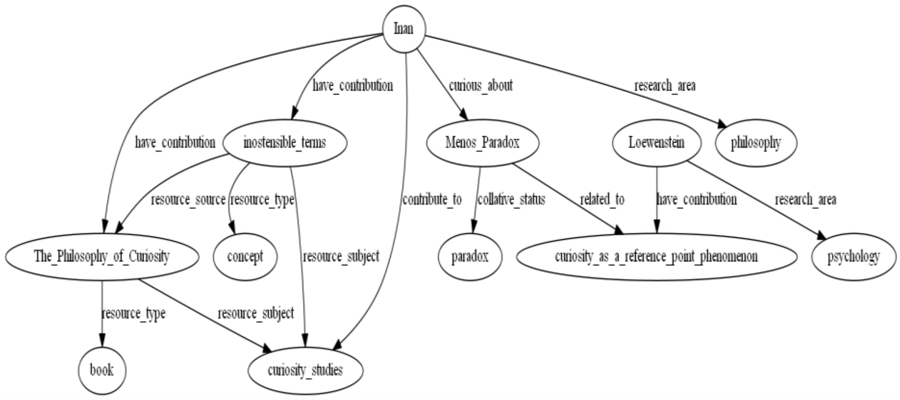

Figure15. Simple directed graph of statements about contributions of Inan enriched by resource type, resource subject and resource source as well as resources that the Inan is curious about or related to; some additional inference rules; collative status and contributors' research area

e. As now we have the research area as well, the interplay of Researcher E's cognitive dynamics becomes a little bit more complex. He is a specialist, who would not want to exceed the limits of his domain focus. Therefore, completion dynamics is a big influencer of his curiosity traits. However, he is also a perfectionist. He is attracted to paradoxes, problems, challenges and conflicts. As he learns that Meno's Paradox is actually a paradox his attention is drifted toward the meaning-cluster around Meno's Paradox. He is tempted to learn about Loewenstein as well but as he sees that he is a psychologist, his specialist spirit overrides and he focuses on Meno's Paradox itself.
f. Now let us put a final twist into our story and enter the explicative value of 'curiosity_as_a_reference_point_phenomenon' into our graph:

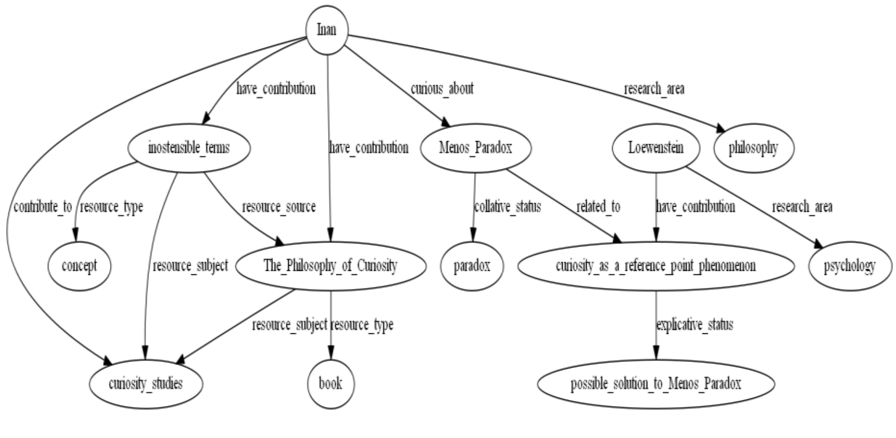

Figure16. Simple directed graph of statements about contributions of Inan enriched by resource type, resource subject and resource source as well as resources that the Inan is curious about or related to; some additional inference rules; collative status; contributors' research area and explicative status

g. In the previous case, if the personality-based curiosity dynamics of Researcher E differed such that perfection dynamics overrode completion dynamics in an attempt to find some useful information to solve the conflict, he could nonetheless have attended to Loewenstein. This did not happen. However, when we further enrich our ontology with 'explicative status' relationship we have one additional information about 'curiosity as a reference point phenomenon' such that it is said to be a possible solution to the paradox that Inan, coming from the same philosophy interest domain, is curious about. This can be a game changer and Researcher E might select this idea as well as its source, which is Loewenstein himself.

19) At this stage we will stop and focus on a problem that has been occurring slowly in our toy model development. As the ontology is enriched it becomes a better fit with the dynamics of scientific curiosity, which is good for our model and the user. However, as the number of entries increase as well as the inferred statements, we start to have problems to do with the 'time budget'. We have limited time and therefore limited resources to consume. However, the collaborative system is designed to grow and growth makes it more difficult to consume. Therefore, we need some optimization as envisaged by our theory of curiosity. Before discussing how we can do it in our toy model, we will review some of the figures.

20) The total number of statements entered by the whole collaborative community so far is 31. We will call the total space of resources within a domain 'curiospace' and all of the resources in all domains of the system 'universal curiospace' (for the universal curiospace of the toy model see Appendix A; for the graph of universal curiospace see Appendix B). After Researcher E informs the system that he is exclusively interested in Inan, the resulting Curiospace-1 (including the inferences of Interest Dynamics Rule-1 and Rule-2 and Curiont Rule-1) is reduces down to 15:

1. Inan->curiosity_studies[label=contribute_to];
2. Inan->inostensible_terms[label=have_contribution];
3. Inan->The_Philosophy_of_Curiosity[label=have_contribution];
4. The_Philosophy_of_Curiosity->book[label=resource_type];
5. The_Philosophy_of_Curiosity->curiosity_studies[label=resource_subject];
6. inostensible_terms->concept[label=resource_type]
7. inostensible_terms->curiosity_studies[label=resource_subject]
8. inostensible_terms->The_Philosophy_of_Curiosity[label=resource_source]
9. Inan->Menos_Paradox[label=curious_about];
10. Menos_Paradox->curiosity_as_a_reference_point_phenomenon[label=related_to];
11. Loewenstein->curiosity_as_a_reference_point_phenomenon [label=have_contribution];
12. Menos_Paradox->paradox[label=collative_status];
13. Inan->philosophy[label=research_area];
14. Loewenstein->psychology[label=research_area];
15. curiosity_as_a_reference_point_phenomenon-> possible_solution_to_Menos_Paradox[label=explicative_status];

This is actually an extremely basic example of ambient intelligence. Remember that we have made such a formulation while discussing interest dynamics:

Interest Dynamics Formula-3: All the rest being the same about resources A and B, if A is related to one's interest domain while B is unrelated, A is preferred over B, unless universal curiosity overrides interest dynamics.

And then we formulated two inference rules that clarified 'relatedness' notion in terms of the ontology such that as Contributor A is related to her Contribution, then Formula-3 should be at work.

Interest Dynamics Rule-1: If A is curious about Contributor A, then A is likely to be curious about the contributions of A.

Interest Dynamics Rule-2: If A is curious about any resource X, then A is likely to be curious about the other resources that X is curious about or related to X.

Therefore, although Researcher E was only curious about Inan, we could also offer him his contributions as well as other resources such as Meno's Paradox, which he is curious about.

This ends our initial toy model. Our toy model proved that we can design a collaborative platform which stores ontological statements about resources in a standard format, enables an ontological structure within which cognitive dynamics and their interactions can be clearly described, applies formulas of cognitive dynamics theory as simple rule engines working over the ontologies, simply optimizes the curiospace output based on personalized inputs and curiosity-augmenting rules ('I am interested in Inan' -> Interest Dynamics Rule-1 and Rule-2 -> then the resulting graph), which reduces 31 resources into 15 (time-budget constraint).

4.6. ENHANCING THE MODEL WITH REVISED ONTOLOGY, RULES AND CALCULATION

In the previous section, we have described some of the alterative resource selections of Researcher E in relation to the possible interactions within the cognitive dynamics vector space. However, we need some mathematics to be able to incorporate all these interactions into a single model. Before getting into the mathematics of calculating maximum expected satisfaction based on our theoretical formulations, we need to focus a little bit on our ontology.

The current ontology we have reached at the end of the last section is below:

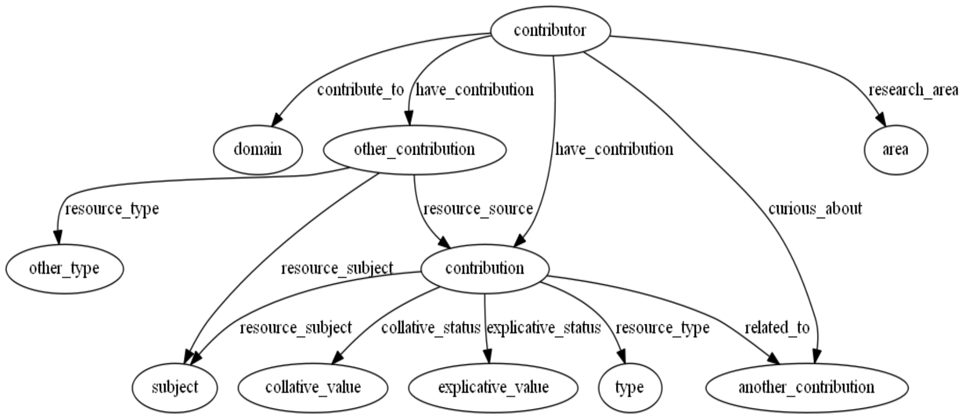

Figure17. The ontology of Curiospace-1

The ontology hierarchy starts with the contributor node and at the bottom we have values that we need to calculate maximum expected satisfaction. Actually this ontology has not been designed at the first hand for facilitating such calculations and although it is instructive for theory-based descriptions or some very simple curiosity trait modeling, it might not be the best fit for a comprehensive mathematical model. In the rest of this section, we will try to develop an ontology that can be utilized for such a model. And, as a starting point, we will refer back to the 5th assumption of our Cognitive Dynamics Theory as given in the section 3.5:

- There are cognitive forces that interactively determine the cognitive motions toward content-bearing resources. They optimally influence cognitive universal scientific curiosity to make cognitive selections on the basis of maximum expected satisfaction under time constraint.

Therefore, given time-budget constraint, any reliable ambient semantic intelligence system must be able to select a limited number of resources that can maximize the expected satisfaction, which can only be measured on the basis of a motivational model of curiosity traits. What we have achieved with our Cognitive Dynamics Theory is that we have identified the cognitive forces (dynamics) that influence the selections and formulated those selections. If we have enough data about the selections of the system users, we can also draw conclusions about the relative weight of each curiosity dynamics component. If we obtain those weights, we can use them for predicting future selections just like taking a vector sum to determine the final direction of an object. The most critical contribution of Cognitive Dynamics Theory to such a model is not just its descriptive power, but also the concrete formulations we can use for extracting data, which, in turn, helps us generate the vector space of the person's curiosity traits.

Now let us revisit the formulations of each cognitive dynamics in a numbered Curiosity Formula List (CFL):

1. <u>Expansion Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A varies from what one already knows more than B, A is preferred over B.
2. <u>Expansion Dynamics Formula-2:</u> All the rest begin the same about resources A, B and C, if one has no prior information related to A, B and C and if one has to pick two of them due to time constraint, if A and B is close to each other in terms of content and C has the highest variation, A and C is preferred to A and B and B and C is preferred to B and A.
3. <u>Completion Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem, while B does not, A is preferred over B, provided that completeness perception is not already satisfied.
4. <u>Completion Dynamics Formula-2:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem with greater effect than B, A is preferred over B, provided that completeness perception is not already satisfied.
5. <u>Explication Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem at the core (has explicative status), while B does it at the periphery, A is preferred over B, unless there is a specific reason to collect peripheral information or the meaning-subsystem is in an initial (child-like) stage.
6. <u>Explication Dynamics Formula-2:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem at the core (has explicative status) with greater effect than B, A is preferred over B, unless there is a specific reason to collect peripheral information or the meaning-subsystem is in an initial (child-like) stage.
7. <u>Perfection Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A is incongruous to a meaning-system (has collative status), while B is not, A is preferred over B, unless there is a specific reason to avoid this.
8. <u>Perfection Dynamics Formula-2:</u> All the rest being the same about resources A and B, if A is incongruous to a meaning-system (has collative status) with greater effect than B, A is preferred over B, unless there is a specific reason to avoid this.
9. <u>Interest Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A is under the interest domain of one, while B is not, A is preferred over B, unless universal curiosity overrides interest dynamics.
10. <u>Interest Dynamics Formula-2:</u> All the rest being the same about resources A and B, if A is a greater interest for one compared to B, A is preferred over B, unless universal curiosity overrides interest dynamics.

11. <u>Interest Dynamics Formula-3:</u> All the rest being the same about resources A and B, if A is related to one's interest domain while B is unrelated, A is preferred over B, unless universal curiosity overrides interest dynamics.
12. <u>Interest Dynamics Formula-4:</u> All the rest being the same about resources A and B under one's interest domain, if A has a higher total weighted average score of prestige, popularity and participant evaluation (PPP value) than B, A is preferred over B, unless there is an exclusive reason determined by the person.

Now we will start a step-by-step design of a simple and working curiosity ontology which can incorporate these dynamics into a mathematical model, which, in turn, will enable our system to analyze curiosity traits. The ontology will also be designed for collaborative features that are needed for ambient connectivity.

1. Our curiosity ontology model will start with a curious Scientific Researcher (SR).
2. Scientific researcher have one or more interest domains and is linked to his domains with the predicate 'curious_about'.

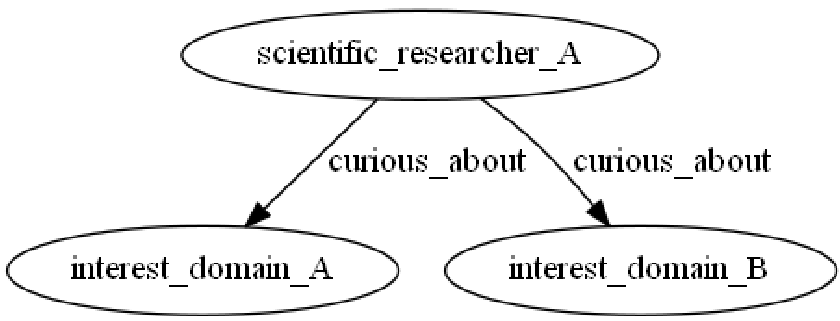

Figure18. Step-by-step construction of theory-driven ontology model.
Curious researcher and interest domains

3. He is embedded into a collaborative community of curious researchers with overlapping and non-overlapping interest domains:

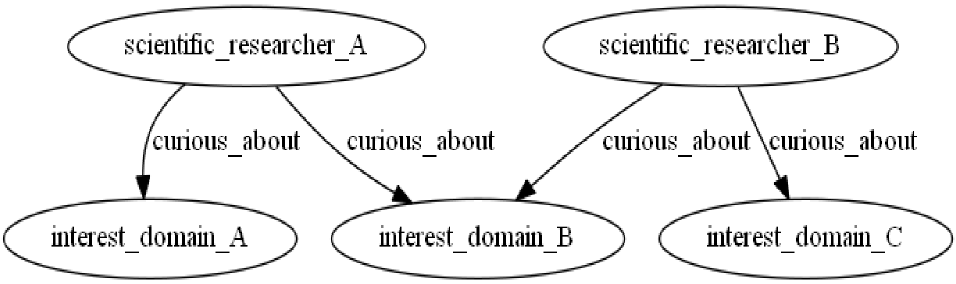

Figure19. Step-by-step construction of theory-driven ontology model. Collaborative community of curious researchers with overlapping and non-overlapping interest domains

Collaboration Rule-1: If Scientific Researchers A and B are curious about same interest domain, they will be part of a 'Broad Interest Domain Community' (BIDC).

4. Each interest domain has contributions as the domain resources. This time our ontology will be contribution-centric rather than contributor-centric. Contributors will gain importance through their contributions, i.e. contributors will not have independent value as resources but only through their works.

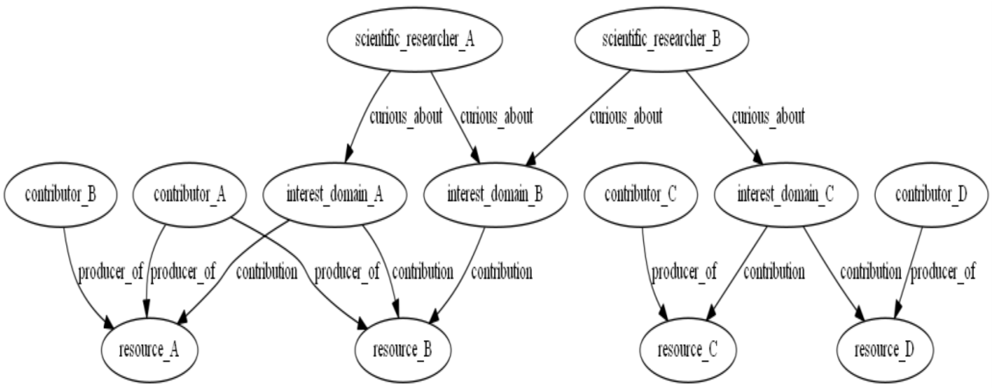

Figure 20. Step-by-step construction of theory-driven ontology model. Scientific Researcher, interest domain, contributions and producers in a contribution-centric architecture

This is the simple skeleton of the ontology. SR goes to interest domain and interest domain goes to the contributed resource. Contributor information is there but it is secondary.

5. Now we will feed the ontology with data that allows for measuring the influence of each cognitive dynamics such as collative_value (perfection dynamics), explicative_value (explication dynamics) and PPP_value (interest dynamics) of the resources. PPP value includes three values:

   a. Popularity: The total number of entries done for this resource by the collaborative community.
   b. Prestige: Significance score given to the resource by a high-profile subset of the collaborative community.
   c. Popular score: Significance score given to the resource by all participants of the collaborative community.

6. Completion and expansion dynamics are polar forces, the former forcing the cognition to stay within the boundaries of a specific domain, while the latter is forcing the cognition to start new ventures and expand its boundaries. The data about those items will come from the analysis of how much time budget a user spends on selecting intra-domain items as opposed to near and distant items.
7. The minimal ontology design that can incorporate these points is as follows:

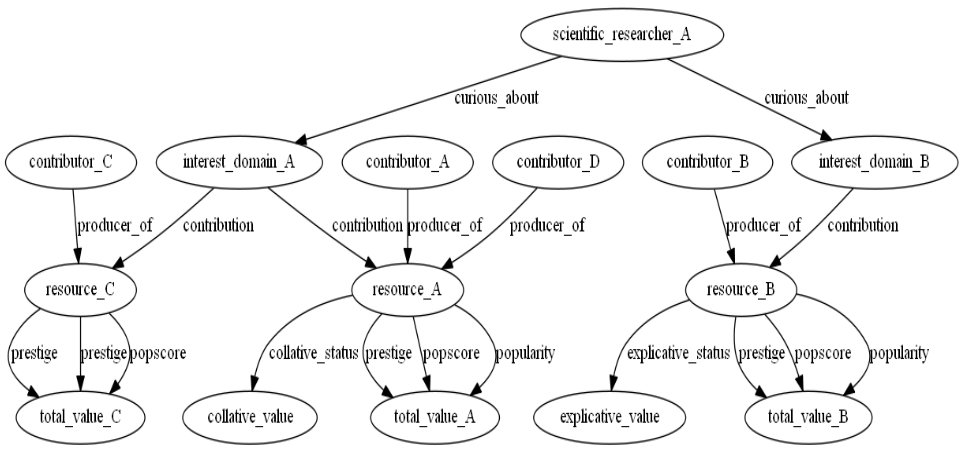

Figure 21. The minimal ontology design that can incorporate the modeling components

8. Now we will populate the ontology with the statements below and start developing the mathematical model.

   - Ahmet_Subasi->curiosity_studies[label=curious_about];
   - Ahmet_Subasi->extended_mind[label=curious_about];
   - curiosity_studies->The_Psychology_of_Curiosity[label=contribution];
   - curiosity_studies->The_Philosophy_of_Curiosity[label=contribution];
   - curiosity_studies->curiosity_as_a_reference_point_phenomenon[label=contribution];
   - curiosity_studies->reference_to_the_unknown[label=contribution];
   - curiosity_studies->Menos_Paradox[label=contribution];
   - extended_mind->coupling[label=contribution];

- Inan->The_Philosophy_of_Curiosity[label=producer_of];
- Loewenstein->The_Psychology_of_Curiosity[label=producer_of];
- Loewenstein->curiosity_as_a_reference_point_phenomenon[label=producer_of];
- Inan->reference_to_the_unknown[label=producer_of];
- Clark->coupling[label=producer_of];
- Plato->Menos_Paradox[label=producer_of];
- curiosity_as_a_reference_point_phenomenon->explain_how[label=explicative_status]
- reference_to_the_unknown->explain_how[label=explicative_status]
- coupling->challenging_idea[label=collative_status]
- Menos_Paradox->paradox[label=collative_status]
- curiosity_as_a_reference_point_phenomenon->77[label=PPP_value]
- reference_to_the_unknown->64[label=PPP_value]
- Menos_Paradox->82[label=PPP_value]
- coupling->78[label=PPP_value]
- The_Psychology_of_Curiosity->91[label=PPP_value]
- The_Philosophy_of_Curiosity->90[label=PPP_value]

The resulting ontology is:

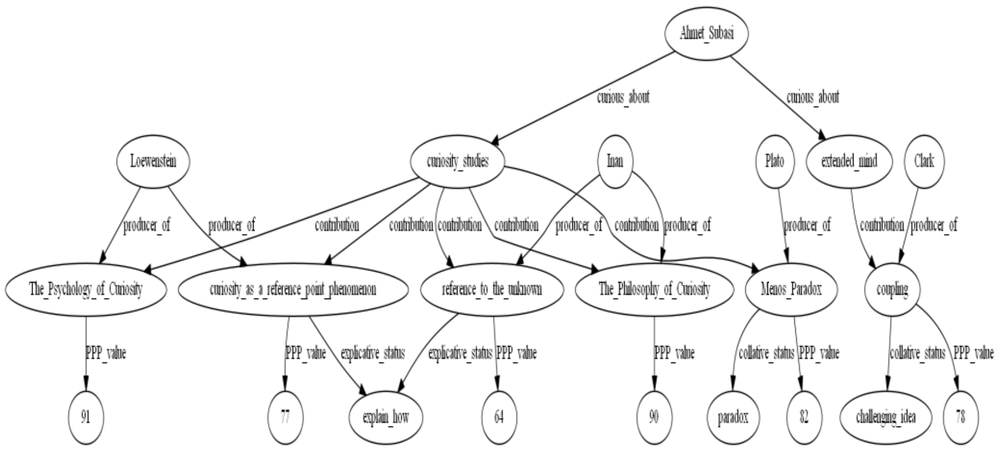

Figure 22. The minimal ontology design that can incorporate the modeling components populated with statements

The first step is the entry of the interest domains by the user. In our example Ahmet Subasi (SR) enters 'curiosity_studies' and 'extended_mind' as two interest domains. The total number of resources that the system will display as a graph is in Figure 22. There are 6 resources 5 from curiosity studies domain and 1 from extended mind domain:

- The_Psychology_of_Curiosity (curiosity_studies)
- curiosity_as_a_reference_point_phenomenon (curiosity_studies)
- reference_to_the_unknown (curiosity_studies)
- The_Philosophy_of_Curiosity (curiosity_studies)

- Menos_Paradox (curiosity_studies)
- coupling (extended_mind)

Now SR wants to select some resources for research and he chooses 'curiosity_studies' domain and as he only has a little time he limits the number of resources to 3.

9. In our new curiosity ontology the initial pruning will start with the interest domain. In our example the likelihood that Ahmet picks 1 of 3 from extended mind seems to be low since Ahmet explicitly chose 'curiosity studies' as an object of his curiosity, but this conclusion still has to be informed by some data. The reason is that by our model there is a certain level of independence from interests influenced by the expansion dynamics. If 5 items that fall under 'curiosity studies' carried almost the same content, Ahmet might be happier to get one from the 'extended mind' domain. We still do not know that. Yet, it is not easy to know something like that without actually reading the content of the resources. If all the resources were articles or books, we could also apply some machine learning algorithms to see which one has differential content. These might be some of the viable solutions but in our simple example there is a more visible pattern. The fact is that if someone reads The Psychology of Curiosity he will also know about curiosity as a reference point phenomena and if someone reads The Philosophy of Curiosity he will already know a lot about how Meno's Paradox is related to curiosity and what reference to the unknown is. Therefore, if the ontology gave enough level of information such as the source of a resource, then maybe Ahmet would like to pick two resources and something more interesting. Now we will do this addition to the ontology.

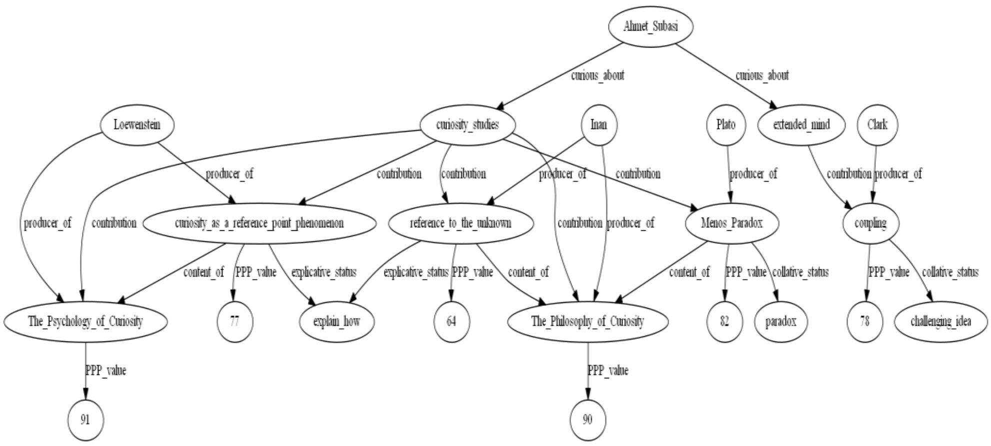

Figure 23. The minimal ontology design that can incorporate the mathematical modeling populated with statements and enhanced with content_of relationship

As seen in the new graph we actually have three interesting things all along the way. If Ahmet reads The Psychology of Curiosity, The Philosophy of Curiosity and the definition of 'coupling', it would be the most satisfying experience for him given limited time. Yet, please do not forget that Ahmet will not know that 5 resources under curiosity studies collapsed into two, this is a conclusion by the ontology.

Expansion Dynamics Rule-1: If resources in a domain are sourced by another resource in the same domain, they are treated as one resource and the containing resource will be addressed.

If we take this rule as absolute, then the system will only present the following resources to Ahmet:

- The_Psychology_of_Curiosity (curiosity_studies)
- The_Philosophy_of_Curiosity (curiosity_studies)
- coupling (extended_mind)

Although the rule seems to be intuitively valid for increasing the utility of research by avoiding non-informative repetitions, from a user experience stand point, a person might want to see something twice in different forms rather than jumping to another interest domain although there is no visible link between the two except for being the interests of the same person. After all, seeing a resource dedicated to an idea rather than the book containing this idea may have its own merit such as drawing attention to this idea and highlighting it within many ideas within the book that contains it. If this objection is taken seriously, we can offer a revision to the rule above.

Expansion Dynamics Rule-1 Revised: If resources in a domain are sourced by another resource in the same domain, they are treated as one resource and the containing resource will be addressed, if there is any other interest domain the contributions of which are linked to the contributions of the initial interest domain.

To translate the rule above, even if the system is going to bundle same-content resources, it should do it with the justification that the other interest domain of the user has some related resources. For covering such a scenario we are adding another statement to our model:

- extended_mind->curiosity_studies[label=related_to]

Although we started with the intention to come up with a mathematical model, we are still dealing with ontology rules and logic. However, the following example will demonstrate why this is needed. We will use the following maximum expected satisfaction function for calculating the total satisfaction expected from any set of choices:

- **Maximum Expected Satisfaction = (Curiosity Dynamics Influence Probability x Resource Value) + (Curiosity Dynamics Influence Probability x Resource Value)**

Curiodynamics Calculation-1:

Curiospace Size: 6 resources

Time Budget: 3 resources

Influence Probabilities:

- Interest Dynamics: .95
- Completion Dynamics: .80
- Expansion Dynamics: .20

Applying Curiodynamics Rules:

- Container bundling
- Interest expansion

PPP Values of Resources:

- The_Psychology_of_Curiosity -> 91
- curiosity_as_a_reference_point_phenomenon –> 77
- The_Philosophy_of_Curiosity -> 90
- reference_to_the_unknown -> 64
- Menos_Paradox -> 82
- Coupling -> 78

Calculation:

- The_Psychology_of_Curiosity (curiosity_studies) -> (0.95 x 91) + (0.8 x 91) = 159.25
  - curiosity_as_a_reference_point_phenomenon (curiosity_studies) -> (.95 x 77) = 73.15
- The_Philosophy_of_Curiosity (curiosity_studies) -> (0.95 x 90) + (0.8 x 90) = 157.5
  - reference_to_the_unknown (curiosity_studies) -> (.95 x 64) = 60.8
  - Menos_Paradox (curiosity_studies) -> (0.95 x 82) = 77.9
- coupling (extended_mind) -> (0.05 x 78) + (0.2 x 78) + (0.95 x 0.8 x 78) = 78.78

Result:

- The value of each resource is defined by a weighted average of Popularity, Prestige and Popular Scoring (PPP value or alternatively 'curiovalence score').
- As intrinsic motivations with their intrinsic rewards, the influence of each cognitive dynamics is given as probabilities previously obtained by user statistics.
- Due to a grasp of those dynamics, we have defined a sensible rule which bundled same-content resources under their containers.
- This removed the 'completion' property of some of the items from the calculations, since they are already contained by some other resource.
- As completion dynamics has not been at work for those contained items, there is no corresponding reward mechanism that adds up to Maximum Expected Utility function.
- 'coupling', on the other hand, has lower score than the score of the first level interest domains (as a secondary relational interest domain), but it has some extra score from expansion, and as it has a direct relationship with the interest topic it gets some more score from 'second-level interest' contingent.
- The calculation for this second-level interest is the multiplication of the influence probabilities of interest dynamics and completion dynamics. Just to remind, completion can happen in two ways: inward and

outward. As ‘coupling’ is a related interest domain of Ahmet, he is happy to complete the picture at one step above.

At this stage, there may surely be objections about the validity of this calculation. Why is summation a justified calculation in this case? Why did we multiply interest dynamics probability with completion dynamics probability? Why completion dynamics and expansion dynamics sum up to 1? Why the curiovalence of ‘coupling’ is multiplied by 0.05 (1 – .95 interest probability)?

First of all it gives a good mathematical description of what is going on in our cognition at least introspectively and secondly it has a strong grounding in the literature pioneered by Loewenstein. I invite the reader to think about what ‘adds up’ to their satisfaction. As a personality trait you are either generalist or a specialist. If in 80 percent of the cases you would select a content that sticks to your current interest, then it would mean in 20 percent of the cases you would explore territories out of the bounds of your interest (the reason why expansion and completion sum up to 1). If you will know something that is related to your interest topic that makes you satisfied (.95 probability). However due to universal curiosity there might be times where you would enjoy to explore any interest domain independent of your current interest (therefore the remaining .05). If you are going to learn something else from the same domain which is already covered by a previous resource that you are already familiar with, that may not make you very happy (unsatisfied completion dynamics), but nonetheless you might prefer to have it rather than some unrelated item of information. As your interest currently focuses your attention to one domain, you might not want to be distracted from it but if you have already covered what is interesting to you right now and all the rest to come from this same domain is already contained by them, you might be more open to knowing something else (container bundling rule). If this ‘something else’ is among your interest topics (be it secondary to your current focus), that is a plus. If it is closely related to your current interest topic than it might still make you excited for some additional reason, which is the possibility of completing the picture one level above (therefore multiplying the interest probability with completion probability and curiovalence). If this Ahmet was actually me, yes I would be very happy to know about ‘coupling’ since that might give me the chance to complete my overall picture where I start thinking about extended curiosity. If no one has so far established a link between extended cognition and curiosity including me, then this excitement could go away and I might prefer to have something else from the same domain despite it is contained in one of the other resources, especially if the system provides any additional information about these items such as links between this resource and any other resource.

If we continue this line of reasoning, theoretically your ideal sum of pleasure would be a piece of information that falls under our interest domain (interest dynamics) and in addition to that it completes a very critical piece of the puzzle (completion dynamics and explication dynamics) and is very surprising and paradigm shifting (perfection dynamics). Now let us incorporate these dynamics into a second calculation to come up with an example that brings together all the dynamics including perfection and explication dynamics (which will change the results above).

Curiodynamics Calculation-2:

Curiospace Size: 6 resources

Time Budget: 3 resources

Influence Probabilities:

- Interest Dynamics: .95
- Completion Dynamics: .80
- Expansion Dynamics: .20
- Perfection Dynamics: .60
- Explication Dynamics: .70

Applying Curiodynamics Rules:

- Container bundling
- Interest expansion

PPP Values of Resources:

- The_Psychology_of_Curiosity -> 91
- curiosity_as_a_reference_point_phenomenon–>77 (Explicative value)
- The_Philosophy_of_Curiosity -> 90
- reference_to_the_unknown -> 64 (Explicative Value)
- Menos_Paradox -> 82 (Collative value)
- Coupling -> 78 (Collative value)

Calculation:

- The_Psychology_of_Curiosity (curiosity_studies) -> (0.95 x 91) + (0.8 x 91) = 159.25
  - curiosity_as_a_reference_point_phenomenon (curiosity_studies) -> (.95 x 77) + (.70 x 77) + (.40 x 77) = 157.85
- The_Philosophy_of_Curiosity (curiosity_studies) -> (.95 x 90) + (0.8 x 90) = 157.50
  - reference_to_the_unknown (curiosity_studies) -> (.95 x 64) + (0.7 x 64) + (0.4 x 64) = 131.2
  - Menos_Paradox (curiosity_studies) -> (.95 x 82) + (.60 x 82) + (0.3 x 82) = 151.7
- coupling (extended_mind) -> (.05 x 78) + (.20 x 78) + (.95 x .80 x 78) + (.60 x 78) + (.30 x 78) = 133.38

Result:

- The selection probabilities of collative versus non-collative; explicative versus non-explicative; interest versus non-interest; completion versus expansion sum up to 1. Coupling has second order interest relation with the current interest domain and it is represented as a multiplication of the interest probability and completion probability since it presumably completes the picture at a super-level, which is the researcher-level itself.

- The inclusion of collative and explicative values to ‘ideas and concepts’ changed the selection set from (The Psychology of Curiosity, The Philosophy of Curiosity, coupling) to (The Psychology of Curiosity, curiosity_as_a_reference_point_phenomenon, The Philosophy of Curiosity) due to the addition of perfection dynamics and explication dynamics.

In our final graph (Figure 23) there is no explicit link between curiosity_studies and extended_mind domains. We have inferred a relationship by the assumption that if a single researcher has two interest domains they might have a relationship. Alternatively, however, the model might exclude such inferences but only operate if there is an explicit statement regarding the relation or it might make a further calculation based on the number of entries expressing such a relation, the score given to the relation statement or the profile of the users that do it (prestige) to justify the validity of the data for its second-order interest calculation.

Also, the decision not to add collative and explicative status scores into ‘article’ resources is also just an option. The model might want to add the overall collative and explicative scores of all the ideas and concepts that are sourced by another resource into that resource, but this might cause the containers to have the highest scores all the time overriding the ideas and concepts. These are areas to be tested and redesigned based on the user experience to turn the toy model into a real production system.

This final calculation completes our toy model development. We have incorporated a basic maximum expected satisfaction (utility) calculation including influence probabilities and curiovalence scores into our theory-informed ontology resources and rules. In the next session we will discuss how we can obtain those probabilities and how should such a model be interacting with the user.

4.7. GATHERING INITIAL DATA FOR THE GRAPH AND USER PROFILING

In order for our model to be functional an initial amount of resources must be populated into the system and it must have a seed ontology with a hierarchy of interest domains. Also there must be a list of initial rules that will automatically generate new resources based on the current ones with regards to curiosity dynamics. For the initial user profiling, again, certain amount of input must to be collected from the user for extracting curiosity behavior patterns. The initial entries can be made by the users in a self-descriptive way and the system can fine-tune its model with the subsequently accumulated data such as user selections and ratings of the resources. Other methods such as click-stream analysis, the amount of time spend for a specific document, content analysis of the reading list of the user and machine learning methods of text categorization and clustering can also be utilized for user profiling. For example, as interest domain specification is a critical element of the ontology-based resource recommendations, the system may interact with word processors and categorize what is being written in the research paper of the researcher in real-time and match the content against the most relevant interest domains by utilizing machine learning algorithms and immediately start generating recommendations. Yet, such a practice would nonetheless require a background corpus and an ontology of interest domains. Online resources such as Wikipedia can also be used for associating interest-domains designed by the ontology designer and related textual corpus.

Some of the features of resources such as collative value and explicative value can also be extracted automatically with the help of machine learning algorithms applied onto the text content. For example, even if there is no metatag related to an idea statement such as ‘making sense, cause_of, curiosity_motivation’, the system can infer from the ‘cause_of’ predicate that this resource has some explication value. This can also be a rule-based inference if the statement is logically formulated. If it is just a textual expression without a logical form, again, machine learning and information retrieval techniques can be used, especially if there is any other related textual content of the resource such as a link to a Wikipedia page or a textual description of the resource.

Having Prestige, Popularity and Popular Score (curiovalence score) attached to the resources is another critical requirement of the system as our recommendation calculations are based upon these curiovalence scores as well as curiosity dynamics probabilities. Valence, in psychology, refers to the intrinsic attractiveness of a situation, event or object especially in the context of emotions. Prestige stands for the score given by a high-profile sub-set of the collaborative community; popularity stands for the total number of entries made for a specific resource; and popular score means the score given by each and every participant of the community. In our model, PPP value (curiovalence score) is defined through a calculation over the personalized parameters entered by the users through the user interface as well as statistics. If there is no current PPP value for a given resource, the system can use the average score of the most related resource and start changing the value after a statistically significant amount of scoring is done by the collaborative community. The weights for the total calculation of PPP value can also change with respect to the personality of the users, which is either explicitly stated by the user herself or inferred by the system based on the selections of the user.

Finally for a better ambient experience, the user must be ideally embedded into the community of researchers. Common Interest Domain Communities can be divided into further groups based on some further data provided by resource selections and group based interaction can be increased by social media interactions. The system should also relate people with complementary areas of research and collaboration teams should be able to form their customized graphs. All community related data can be used as an additional source of information for collaborative filtering and user profiling.

This section ends the chapter as well as our Ambient Semantic Intelligence Model for Scientific Research toy design. We have covered key components of such a system in a proof-of-concept model, which is only a simple attempt especially when compared to the potential designs implicated by the possibilities of the theory. We will make some further discussions and draw final conclusions in the next chapter.

CHAPTER 5

5. DISCUSSION AND CONCLUSIONS

We attempted to do four things so far in our dissertation: (1) discussing the concept of scientific curiosity and its relevance to cognitive science; (2) offering a unified cognitive theory of scientific curiosity; (3) discussing the concepts of ambient intelligence and semantic intelligence and emphasizing their relevance to the findings of curiosity studies; and (4) offering a computational model to demonstrate that the unified cognitive theory provides a good grounding for an ambient semantic intelligence model aiming at augmenting scientific curiosity and aiding scientific research.

While doing the first one, we had to construct a framework within which all the insights coming from different disciplines and sources make a coherent sense, but more importantly all the insights needed to be formulated such that they can provide a grounding for a functioning model. The value of this unification should not be underestimated. One can find all the components of our curiosity theory in a variety of works and one can even find similar attempts to unify the findings such as that of Loewenstein's. Although Loewenstein makes a good effort in offering a mathematical description of curiosity in the form of expected maximum utility, he does not give clear formulations of how curiosity traits can be extracted by an analysis of selection patterns. Also he does not give clear distinctions between what we called completion, perfection, explication and expansion dynamics as well as an explanation of how those dynamics interact. Independence from interests is another point that Loewenstein's model totally exclude. In our model, however, all of those dynamics are described as well as their interactions.

The second important point is the coherence between the unified cognitive theory and the offered model. For instance, in our Explication Dynamics Formula-1, there is a reference to the 'completion of a meaning subsystem at the core'.

> <u>Explication Dynamics Formula-1:</u> All the rest being the same about resources A and B, if A completes a meaning-subsystem at the core (has explicative status), while B does it at the periphery, A is preferred over B, unless there is a specific reason to collect peripheral information or the meaning-subsystem is in an initial (child-like) stage.

To be able to signify a selection among two things where one 'completes at the core' and one 'completes at the periphery' we need a corresponding ontology within which such distinctions can be formally represented. In our ontology-based model, we are using metadata to signify whether a resource has the attribute of 'being a core information' or not. This metadata based modeling may have its own disadvantages such as relying too much on user entries. There are components of the model such as Explication Dynamics Formula-1 that can be handled in a more formal and automated fashion. One such method is using graph theoretical functions such as calculating betweenness-centrality score of any resource node to determine whether they are central or not.

> [Betweenness-centrality] Calculates the *centrality* of the node. Centrality is defined as the percentage of shortest paths in the graph that pass through that node—that is, when a message is passed from one random node to another random node, what is the chance that it will have to go through this node? Centrality is sometimes considered a measure of the importance or influence of a node, since it tells how much information must pass through it or how much the network would be disrupted if the node was removed. In this example, node b is the most central. Node e is much more central than node d, even though they both have two neighbors (Segaran, Evans, & Taylor, 2009).

Similarly, if the user does not enter any or sufficient information regarding her interest domains, the system can automatically define the interest domains of the user using text categorization and clustering techniques. Such type of functions can also be used to automatically determine the relatedness of interest domains, which was a decisive factor in our Curiodynamics Calculation-1 example.

We also need to justify the basic choices regarding our model construction. A basic choice regarding the knowledge base is using a graph rather than a standard database model. The power of graph representation is that it is to most intuitive and practical representation of ontology-based predicate logic statements and connected data. It should be reminded that Ambient Semantic Intelligence Model is not only a knowledge base with logical statements and a new recommender system that builds its personalization upon a theory of curiosity. It is also a system that automatically augments its knowledge resources through theory-driven ontology-rules and logical operations. Especially after a significant size, graph databases become the most practical and feasible model of storing and transforming such knowledge structures.

> For data of any significant size or value, graph databases are the best way to represent and query connected data. Connected data is data whose interpretation and value requires us first to understand the ways in which its constituent elements are related. More often than not, to generate this understanding, we need to name and qualify the connections between things (Robbinson, Webber & Eifrem, 2015).

Graph databases also allow for many useful graph-theoretical analysis methods such as centrality and cliquishness, which are not possible with conventional databases.

Another choice made in the model is the usage of directed graphs. Directed graphs have higher expressive power to represent logical operations that are by their semantic structure directional. For example, if any interest domain has an idea such as 'curiosity, caused_by, the_desire_to_make_sense' we cannot represent this idea in a non-directional representation without losing or distorting some information. However, there is also a space for non-directional graph in our model, especially when connectedness of the graph is used for functions such as centrality calculation. Many specific relation types can be abstracted through 'related_to' predicates for converting a directed graph into a non-directed one. For the example given above, we can translate it as 'curiosity, related_to, the_desire_to_make_sense' and now it becomes a relation valid in both directions.

The example graphs we have given in our toy model are mostly acyclical graphs. There is no specific reason for that. The graphs in our model can have cyclical resources as well. For example, our system can infer that two interest domains have second-order relatedness if they both belong to the same researcher, but this n can also be explicitly represented in the graph via 'curiosity_studies, related_to, extended_mind' type of a statement. This type of a relational abstraction allows for a connectivity graph, which, in turn, can be used for the graph theoretical functions mentioned.

Another question about the model would be how the ranking and recommendation methods and techniques of the model differentiate from that of current recommender systems. Below is a list of differentiators:

1. Firstly, recommendations are only a component of Ambient Semantic Intelligence model. The system not only filters the current set of resources but also provides an ontology-based platform for collaboratively generating new resources as well as rule-based automation that augments the resources.
2. Current content-based recommendation systems rely heavily on string-based information retrieval functions. A previously selected content that is used for characterizing user interest is either interesting or not interesting. If a subset of the alternative content items matches with the historically specified interest items, the system recommends them. However, being interested is not the only dynamics that define overall curiosity as our cognitive theory suggests. There are many other dynamics at work. Our system introduces the current recommender literature new features such as collative value, explicative value and probabilistic calculation of interest over independence from interest, completion versus expansion dynamics, which enable a more sophisticated personalization.
3. Over specialization is a big shortcoming of the current recommenders, whereas our model enables users to interact with the 'unknown' items effectively in a way that is in sync with their natural curiosity patterns. The 'unknown' resources can be collaboratively entered into the system as a coherent ontology or automatically inferred by the ambient intelligence system by the use of defined curiosity rules and their recommendation is made possible via theory-based curiosity traits personalization:

   > Content-based recommenders have no inherent method for finding something unexpected. The system suggests items whose scores are high when matched against the user profile, hence the user is going to be recommended items similar to those already rated. This drawback is also called *serendipity* problem to highlight the tendency of the content-based systems to produce recommendations with a limited degree of novelty. To give an example, when a user has only rated movies directed by Stanley Kubrick, she will be recommended just that kind of movies. A "perfect" content-based technique would rarely find anything *novel*, limiting the range of applications for which it would be useful (Lops, Gemmis, & Semeraro, 2011).

   Serendipity lacked by recommenders is ideally realized in ambient semantic intelligence system, because it enables the calculation of 'independence from interests' as well as enabling a balance between completion and expansion dynamics.
4. Current recommenders do not utilize graph analysis methods such as centrality and cliquishness. In our model, our system can differentiate among two resources based on their centrality. Such type of operations are motivated by the unified cognitive theory of curiosity. It is known by empirical studies that if an information item completes a knowledge domain more effectively than any other item, then it would be preferred by the system. Graph theory enables the recommendation algorithm of our model to incorporate centrality calculations by using its graph structure. Similarly, the expansion dynamics can be reflected into the rating algorithm by assigning a novelty score of a new domain.

Another discussion point of our model is that it basically relies on the idea of a standard ontology model. One of the basic shortcomings with ontology engineering is the practical infeasibility of a universally accepted ontology, although the departure point of this technology is semantic interoperability. For the concept of curiosity ontology to have a real impact, if there are more than one widely accepted curiosity ontologies, they must be mapped against each other, which is a daunting task. There are NLP techniques used for such tasks and they have a certain degree of success, but this is obviously one of the problems that has to be addressed. Another way to overcome this problem could be using curiosity ontologies within private domains such as a specific platform, which has the downside of weakening the effect of crowdsourcing.

While constructing our toy model in the previous chapter, we said that although we had the intention to come up with a mathematical model, but were still dealing with ontology rules and logic. Although we could come up with an expected satisfaction calculation that is consistent within the model, it is highly intertwined with a complex curiosity ontology requiring to incorporate intricate relationships such as 'being second-level interest of the person but having more completion influence due to a connection between inter-domain resources'. When we compare such ad hoc strategies with the simplicity and elegance of Bayesian Networks, it might raise questions about the effectivity of the offered method. When we analyze Bayesian Networks we see certain simplifications that makes the elegant mathematical model possible. First of all, BNs are based on conditional dependencies and the relationship among the nodes are represented with a single predicate indicating influence. In other words, every Bayesian relationship can be reformulated with a single-predicate as "node_A, conditionally_dependent_on, node_B'. The simplicity of the ontology makes it possible to remove hardcoding and focus on probabilities between nodes. Such an ontology is a good fit, for instance, for representing probabilistic causal relationships between symptoms and diseases. In a multi-predicate ontology model such as ours, however, the required level of expressiveness is much higher as can be seen in the descriptions and calculations of the toy model. BNs per se, on the other hand, cannot provide such level of expressiveness:

> BNs provide an elegant mathematical structure for modeling complex relationships among hypotheses while keeping a relatively simple visualization of these relationships. Yet, the limited attribute-value representation of BNs makes them unsuitable for problems requiring greater expressive power (Costa, Laskey, & Ghazi, 2006).

This, however, does not change the fact that our model still has the challenge of better matching with the open world environment. The level of reliance on deterministic relationships represented in a classical logical formalism may pose a challenge to its practical value.

> A major shortcoming of ontologies is their inability to represent and reason with uncertain, incomplete data. Due to various factors (see Costa 2005) virtually all current ontology formalisms are based on classical logic, and thus provide no support for plausible reasoning. In the example above, a standard ontology might enumerate several possible senses for the word "Washington," but would have no ability to grade their relative plausibility in a given context. This is inadequate for an open world environment in which noisy and incomplete information is the rule (Costa, Laskey, & Ghazi, 2006).

A new line of research addressing the need to represent uncertainty within the expressive power of ontologies focuses on Bayesian ontologies, which extends OWL to incorporate probabilistic information such that it becomes compatible with the Bayesian method.

> One of the main reasons why research in ontology languages is still focused on deterministic approaches has been the limited expressivity of traditional probabilistic languages. There is a current line of research focused on extending OWL so it can represent probabilistic information contained in a Bayesian Network (e.g. Ding & Peng 2004, Gu *et. al.* 2004). The approach involves augmenting OWL semantics to allow probabilistic information to be represented via additional markups. The result would be a probabilistic annotated ontology that could be translated to a Bayesian network (BN). Such a translation would be based on a set of translation rules that would rely on the probabilistic information attached to individual concepts and properties within the annotated ontology (Costa, Laskey, & Ghazi, 2006).

The idea of augmenting OWL semantics to allow probabilistic information is obviously an exciting one and has the potential to cover some of the gaps posed by our model. For example, with such an approach even if the description of an unknown concept may be uncertain we will be able to represent is in a form such as "Resource X is under domain A and moderately likely to be related to Resource Y under domain B." Ability to represent and reason with uncertainty would contribute to the overall reliability of an ontology and it would also help ontologies to map when the conceptual links between ontologies are not complete.

> Semantic similarities between concepts are difficult, if not impossible to be represented logically, but can easily be represented probabilistically. This has motivated recent development of ontology mapping taking probabilistic approaches (GLUE [7], CAIMAN [11], OntoMapper [19], and OMEN [13]) (See [14] for a survey of existing approaches to ontology mapping, including those based on logical translation, syntactical and linguistic analysis). However, these existing approaches fail to completely address uncertainty in mapping (Pan, Ding, Yu, & Peng, 2005).

These newer approaches extensively use methods such as text classification, translating OWN ontology into a BN structure (a directed acyclic graph) and generating conditional probability tables by utilizing the available constraints about classes and interclass relations, which enables ontology reasoning within and across ontologies in the form of Bayesian inferences (Pan, Ding, Yu, & Peng, 2005). Although promising and very much relevant to our research area, this new line of research is still on progress and its applicability and scalability is still under examination.

5.1. SIGNIFICANCE OF THE MODEL

In his renowned work *Sciences of the Artificial* Herbert A. Simon neatly describes the greatest challenge of the Digital Age:

> As of the mid-1990s the lesson has still not been learned. An "information superhighway" is proclaimed without any concern about the traffic jams it can produce or the parking spaces it will require. Nothing in the new technology increases the number of hours in the day or the capacities of human beings to absorb information. The real design problem is not to provide more information to people but to allocate the time they have available for receiving information so that they will get only the information that is most important and relevant to the decisions they will make. The task is not to design information-distributing systems but intelligent information-filtering systems.[4] (Simon, 1996)

Today we can find many useful scientific collaboration tools and designs that enable collective data sharing and organization as well as digital repositories with endless information resources and recommendation engines. However, we still do not have good solutions that address the problems of the modern 'attention economy'. In an age of information overload, optimizing human attentional resources becomes a key requirement of any good informational design. The study of human curiosity from a design perspective has a lot to contribute to this area.

What our model particularly achieves is that it gives us clear insights about how a theoretically informed model of curiosity can help to achieve truly personalized 'information-filtering systems' and recommendation engines through clear formulations of the curiosity selection patterns and an ontology-based maximum expected satisfaction calculation. Our efforts to unify the insights coming from different disciplines and resources echo Newell's attempts to construct unified theories of cognition in the smaller domain of curiosity:

> A single system (mind) produces all aspects of behavior. It is one mind that minds them all. Even if the mind has parts, modules, components, or whatever, they all mesh together to produce behavior… If a theory covers only one part or component, it flirts with trouble from the start. It goes without saying that there are dissociations, interdependencies, impenetrabilities, and modularities… But they don't remove the necessity of a theory that provides the total picture and explains the role of the parts and why they exist (Newell, 1990).

We believe that any comprehensive cognitive modeling for scientific collaboration would require a unified theory of curiosity for a reliable grounding. Such efforts has always been part of the artificial intelligence field such as SOAR project and many others, but curiosity itself as a specific motivational force has never been a central subject of inquiry as it is the case in many other fields. Therefore, we would like to underline the relevancy of our efforts regarding such a unified theory.

Another contribution of our model is the way it leverages available semantic technologies to represent semantically rich domains such as curiosity ontology, which provides an effective platform for the collaborative accumulation of resources while automatically augmenting those resources via reasoners, and gives working examples of how ontology-based reasoning capabilities can align with the underlying mechanisms of curiosity such as inostensible referencing. Just as the human capacity to refer to the unknown makes what is unknown discussable, the machine capacity to reason over logical representations within the ontology based on curiosity rules makes 'the unknown' available for the human curiosity beyond his current level of information. In a way, the system enables the collaborative formulation of the unknown and making those unknowns a probable object of curiosity for the related candidates. The implications of a functionality cannot be underestimated. Human beings can formulate the inferences of the unknown based on what they already know and this limits them to what they already know. Through semantic interoperability, collaborative resource space enables the formulation of otherwise impossible unknowns. This actually combines the insights of Inan's reference to the unknown and Loewenstein's curiosity as a reference point phenomenon concepts in a particular way. The ambient semantic model enriches our reference points and therefore enables a richer set of formulated unknowns, i.e. objects of curiosity. These are some of the significant contributions of our study that have the potential to shed light onto the future of the research area.

5.2. FUTURE OF THE RESEARCH AREA

The future of the research area, we believe, is in focusing on information systems that effectively meet the challenges of the attention economy. Curiosity studies is one of the fields that will nourish the efforts toward such a goal. The concept of ambient semantic intelligence deserves a good deal of attention since it bridges the gap between what we already have and what we can design based on the available technology and literature of today. Curiosity studies will help to bridge this gap by offering increasingly more comprehensive and formalized descriptions of the dynamics of human curiosity, which is a fundamental requirement of truly personalized information systems, i.e. of ambient semantic intelligence.

The obvious challenges posed by uncertainty and lack of a universal ontology are already addressed by initial studies on Bayesian ontologies, which is obviously an exciting field of future research. There will also be contributions to this specific problem area by other lines of research focusing on other techniques such as graph theoretical constructs. Formalizing the curiosity dynamics vector space and its rules in a way that better reflects the complexities of human curiosity and fine tuning the calculation of maximum expected satisfaction based on the statistical information of curiosity selection patterns are significant areas of improvement. The unified theory and the model have the potential to nourish each other, where the model provides platforms to test the assumptions and predictions of the theory and provide statistics based on the data generated by actual users and the theory continuously revises itself based on such data. Another exciting subject would be designing more adaptive human-computer interfaces that connects the human intellectual activity with the rest of the collaboration space in a seamless and natural way. Also the problem of populating high-quality data into the system without too much manual effort and how the structured and unstructured data freely floating in the cyberspace can be exploited for the model by the help of machine learning and information retrieval methods are very significant areas of research for the success of any such model.

All such efforts will have the single goal of designing ever-improving scientific research collaboration systems that not only gather and optimize the contributions of each collaborator, but also augments them by the support of semantically interoperable and personalized ambient semantic intelligence systems.

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APPENDICES

APPENDIX A UNIVERSAL CURIOSPACE OF TOY MODEL

1. Loewenstein->curiosity_studies[label=contribute_to];
2. Berlyne->curiosity_studies[label=contribute_to];
3. James->curiosity_studies[label=contribute_to];
4. Plato->curiosity_studies[label=contribute_to];
5. Lahroodi->curiosity_studies[label=contribute_to];
6. Schmidhuber->curiosity_studies[label=contribute_to];
7. Gomez->curiosity_studies[label=contribute_to];
8. Wierstra->curiosity_studies[label=contribute_to];
9. Loewenstein->The_Psychology_of_Curiosity[label=have_contribution];
10. Berlyne->collative_variables_instigate_curiosity[label=have_contribution];
11. James->scientific_curiosity_arises_from_inconsistency_or_gap_in_knowledge[label=have_contribution];
12. Plato->Menos_Paradox[label=have_contribution];
13. Lahroodi->independence_from_interests[label=have_contribution];
14. Schmidhuber->curious_robots[label=have_contribution];
15. Gomez->formal_interpretation_of_interestingness_focus_on_information_that_increase_predictability[label=have_contribution];
16. Wierstra->Curiosity_Driven_Optimization[label=have_contribution];
17. Inan->curiosity_studies[label=contribute_to];
18. Inan->inostensible_terms[label=have_contribution];
19. Inan->The_Philosophy_of_Curiosity[label=have_contribution];
20. The_Philosophy_of_Curiosity->book[label=resource_type];
21. The_Philosophy_of_Curiosity->curiosity_studies[label=resource_subject];
22. inostensible_terms->concept[label=resource_type]
23. inostensible_terms->curiosity_studies[label=resource_subject]
24. inostensible_terms->The_Philosophy_of_Curiosity[label=resource_source]
25. Inan->Menos_Paradox[label=curious_about];
26. Menos_Paradox->curiosity_as_a_reference_point_phenomenon[label=related_to];
27. Loewenstein->curiosity_as_a_reference_point_phenomenon[label=have_contribution];
28. Menos_Paradox->paradox[label=collative_status];
29. Inan->philosophy[label=research_area];
30. Loewenstein->psychology[label=research_area];
31. curiosity_as_a_reference_point_phenomenon->possible_solution_to_Menos_Paradox[label=explicative_status];

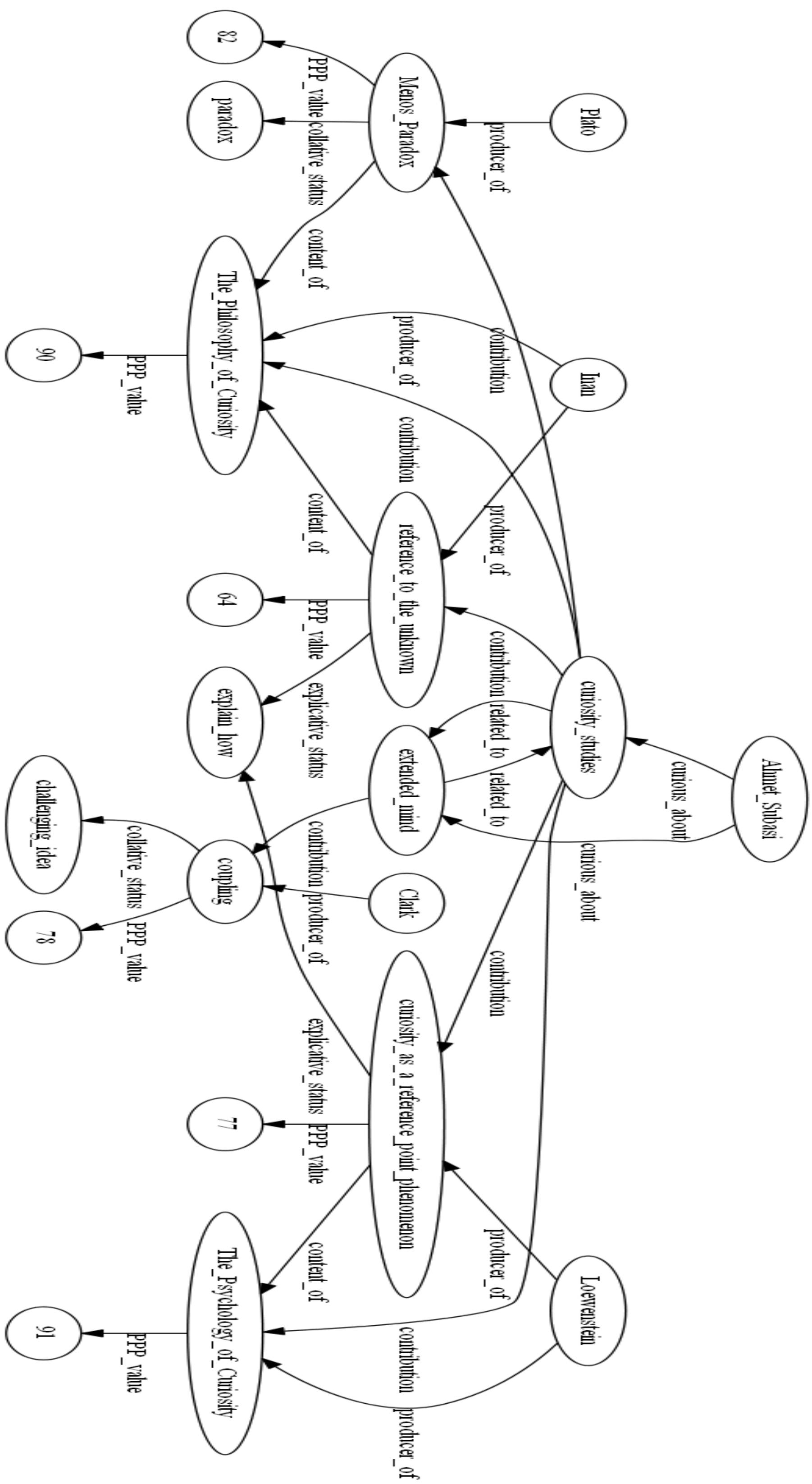
APPENDIX B THE GRAPH OF UNIVERSAL CURIOSPACE-1

APPENDIX C FORMULAS AND RULE SETS

- Expansion Dynamics Formula-1: All the rest being the same about resources A and B, if A varies from what one already knows more than B, A is preferred over B.
- Expansion Dynamics Formula-2: All the rest begin the same about resources A, B and C, if one has no prior information related to A, B and C and if one has to pick two of them due to time constraint, if A and B is close to each other in terms of content and C has the highest variation, A and C is preferred to A and B and B and C is preferred to B and A.
- Completion Dynamics Formula-1: All the rest being the same about resources A and B, if A completes a meaning-subsystem, while B does not, A is preferred over B, provided that completeness perception is not already satisfied.
- Completion Dynamics Formula-2: All the rest being the same about resources A and B, if A completes a meaning-subsystem with greater effect than B, A is preferred over B, provided that completeness perception is not already satisfied.
- Explication Dynamics Formula-1: All the rest being the same about resources A and B, if A completes a meaning-subsystem at the core, while B does it at the periphery, A is preferred over B, unless there is a specific reason to collect peripheral information or the meaning-subsystem is in an initial (child-like) stage.
- Explication Dynamics Formula-2: All the rest being the same about resources A and B, if A completes a meaning-subsystem at the core with greater effect than B, A is preferred over B, unless there is a specific reason to collect peripheral information or the meaning-subsystem is in an initial (child-like) stage.
- Perfection Dynamics Formula-1: All the rest being the same about resources A and B, if A is incongruous to a meaning-system, while B is not, A is preferred over B, unless there is a specific reason to avoid this.
- Perfection Dynamics Formula-2: All the rest being the same about resources A and B, if A is incongruous to a meaning-system with greater effect than B, A is preferred over B, unless there is a specific reason to avoid this.
- Interest Dynamics Formula-1: All the rest being the same about resources A and B, if A is under the interest domain of one, while B is not, A is preferred over B, unless universal curiosity overrides interest dynamics.
- Interest Dynamics Formula-2: All the rest being the same about resources A and B, if A is a greater interest for one compared to B, A is preferred over B, unless universal curiosity overrides interest dynamics.
- Interest Dynamics Formula-3: All the rest being the same about resources A and B, if A is related to one’s interest domain while B is unrelated, A is preferred over B, unless universal curiosity overrides interest dynamics.
- Interest Dynamics Formula-4: All the rest being the same about resources A and B under one’s interest domain, if A has a higher total weighted average score of prestige, popularity and evaluation than B, A is preferred over B, unless there is an exclusive reason determined by the person.

- Collaboration Rule-1: If curious researchers A and B are curious about same interest domain they will be part of a 'Broad Interest Domain Community' (BIDC).
- Expansion Dynamics Rule-1: If resources in a domain are sourced by another resource in the same domain, they are treated as one resource and the containing resource will be addressed.
- Interest Dynamics Rule-2: If A is curious about any resource X, then A is likely to be curious about the other resources that X is curious about or related to X.
- Interest Dynamics Rule-1: If A is curious about Contributor A, then A is likely to be curious about the contributions of A.
- Curiont Rule-1: If X has contribution Y, then A is related to Y.

APPENDIX D FINAL GRAPH



CURRICULUM VITAE

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EDUCATION

Degree	Institution	Year of Graduation
PhD	Middle East Technical University Cognitive Science/Informatics Institute	2016
M.A.	Istanbul Technical University Information Technologies	2012
M.B.A.	Istanbul Bilgi University MBA	2011
M.A.	Bosphorus University Cognitive Science	2009
B.A.	Sabancı University Social and Political Sciences Program	2004
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WORK EXPERIENCE

Year	Place	Enrollment
2013-...	SESTEK	Product & Business Development Director
2009-2013	AssisTT	MIS Manager

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English (Advanced) and German (Intermediate)

TEZ FOTOKOPİ İZİN FORMU

ENSTİTÜ

Fen Bilimleri Enstitüsü ☐

Sosyal Bilimler Enstitüsü ☐

Uygulamalı Matematik Enstitüsü ☐

Enformatik Enstitüsü ☒ X

Deniz Bilimleri Enstitüsü ☐

YAZARIN

Soyadı : SUBAŞI

Adı : AHMET

Bölümü : BİLİŞSEL BİLİM

TEZİN ADI (İngilizce): AN AMBIENT SEMANTIC INTELLIGENCE MODEL FOR SCIENTIFIC RESEARCH

TEZİN TÜRÜ: Yüksek Lisans ☐ Doktora ☒ X

1. Tezimin tamamı dünya çapında erişime açılsın ve kaynak gösterilmek şartıyla tezimin bir kısmı veya tamamının fotokopisi alınsın. ☐
2. Tezimin tamamı yalnızca Orta Doğu Teknik Üniversitesi kullancılarının erişimine açılsın. (Bu seçenekle tezinizin fotokopisi ya da elektronik kopyası Kütüphane aracılığı ile ODTÜ dışına dağıtılmayacaktır.) ☐
3. Tezim bir (1) yıl süreyle erişime kapalı olsun. (Bu seçenekle tezinizin fotokopisi ya da elektronik kopyası Kütüphane aracılığı ile ODTÜ dışına dağıtılmayacaktır.) ☒ X

Yazarın imzası .... Tarih ....