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A Collaborative Social Computing Model For Transdisciplinary Problem Solving

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A COLLABORATIVE SOCIAL COMPUTING MODEL FOR TRANSDISCIPLINARY PROBLEM SOLVING

by

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INTERDISCIPLINARY ENGINEERING

ABSTRACT

The capacity to address and solve today's complex problems is becoming exceedingly more difficult because of the transdisciplinary nature of our current system of knowledge. Innovative solutions are no longer the by-products of centralized offices and laboratories. In fact, crafting solutions for truly complex problems requires a collaborative sharing of knowledge that transcends the artificial boundaries of departmentalized offices and research facilities.

For decades, segmented information systems built on distributed platforms have kept transdisciplinary problem solving fragmented, without the ability to effectively share knowledge or data. This segmentation has stifled the progress of research reaching beyond the traditional boundaries of a single discipline. Sharing resources and information is slowed further by geography. Therefore, a growing need has arisen to expand current and create new methods and theories into a conceptual model that integrates acquisition, storage, management and analysis of data that transcends existing perspectives. Collaboration via social computing is needed to replace the existing knowledge exchange with a new one that reinforces the exchange of knowledge across disciplines and specializations. Furthermore, social computing provides an opportunity for an expanded collaboration and knowledge exchange. The second generation of web-based communities and hosted service, or Web 2.0, provides the perfect mix of technologies for enabling collaboration that garners community intelligence. These factors can only be addressed through the creation of a model that addresses the collaboration and knowledge integration gap.

The Transdisciplinary Problem Solving Model (TPSM) addresses these issues by utilizing techniques that are conducive to collaboration, which empower transdisciplinary problem solving. The result is the creation of a paradigm that provides scientists with the ability to seamlessly communicate and share intelligence. The TPSM provides the ability to disseminate insights gained through the use of common standards, vocabularies and systems that enable data integration and knowledge sharing in a systematic way. The TPSM also uses sophisticated techniques such as the use of concept maps, social bookmarking and wikis. These, in turn, encourage research that explores shared ideas and expands the application of scientific discoveries.

Keywords: Collaborative Social Computing, Collaboration, Transdisciplinary, Complex Problem Solving.

DEDICATION

I dedicate this dissertation to my family.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AI	Artificial Intelligence
CBR	Collaboration Based Research
CSC	Collaborative Social Computing
CPS	Complex Problem Solving
CM	Conceptual Model
HTML	HyperText Markup Language
IM	Information Management
IdR	Interdisciplinary Research
JS	JavaScript
JSON	JavaScript Object Notation
KI	Knowledge Integration
KS	Knowledge Sharing
KP	Knowledge Production
KM	Knowledge Management
KR	Knowledge Re-engineering
MdR	Multidisciplinary Research
NLM	National Library of Medicine
QA	Quality Assurance
REST	Representational State Transfer

RSS	Rich Site Summary
SC	Social Computing
TD	Transdisciplinary
T^4 FUNDAMENTALS	Four Transdisciplinary Fundamentals
TA	Transdisciplinary Assessment
TdR	Transdisciplinary Research
TdC	Transdisciplinary Collaboration
TdS	Transdisciplinary Science
TKI	Transdisciplinary Knowledge Integration
TKS	Transdisciplinary Knowledge Sharing
TKP	Transdisciplinary Knowledge Production
TPS	Transdisciplinary Problem Solving
TPSM	Transdisciplinary Problem Solving Model
UAB	The University of Alabama at Birmingham
W3C	World Wide Web Consortium
WWW	World Wide Web
XML	Extensible Markup Language

I. INTRODUCTION

This dissertation addresses the challenges of solving problems that possess a high degree of complexity by applying the transdisciplinary approach that utilizes collaborative social computing techniques. This approach is coupled together to form a problem solving model. By definition, a problem is considered complex if both the goal state and the initial state are clearly defined, if (a) there are no precise definitions of the problem solving space and, (b) there are no precise definitions of the operators that are available [1]. The "transdisciplinary approach" combines different fields of knowledge to offer a larger and more-complete solution to complex problems [2]. Knowledge is not solely defined within a single discipline. The knowledge needed to uncover the interplay and interconnection of factors that underlie complex problems transcends the boundary of discipline-based knowledge. This line of reasoning misses the point when considering the dynamics of a complex problem. Consequently, an approach to complex problem solving (CPS) that transcends artificial divisions of knowledge is needed. The ability to craft solutions for today's complex problems is becoming exceedingly more painstaking [3] [4]. Additionally, crafting solutions to complex problems requires significant knowledge sharing and integration. The core contributions of this dissertation are as follows:

1. First, the reasoning behind the development of a transdisciplinary problem solving model (TPSM) is identified as the need for an integrated model that

uses the four transdisciplinary fundamentals (T^4 FUNDAMENTALS) --system, process, design and metrics -- to craft solutions to CPS.

2. Second, the TPSM provides a path forward in the form of a set of collaborative social computing techniques that can be used to integrate and share knowledge, creating a unified knowledge base. The TPSM achieves knowledge sharing and integration by ensuring that properties and protocols of multi-agent communication are used. This validates the one-group knowledge transference, ensuring that all members of the transdisciplinary team receive the message.
3. Third, a three-phase approach is proposed as a means of providing intellectual control and structure to transdisciplinary problem solving (TPS).

The T^4 FUNDAMENTALS are engineering principles that form the foundation of the TPSM. The four fundamentals provide an overall structure to the complexity and deterministic chaos of TPS. The structuring of the transdisciplinary problem is based on the principles and properties of the system fundamentals, design fundamentals, process fundamentals and metric fundamentals.

Each of the fundamentals has a specific and key goal. The system fundamentals allow each transdisciplinary problem to be viewed as a system. This system view enables the utilization of system-of-system principles to TPS. This may call for the integration of the system to form a larger system or the decomposition of key processes into a system-of-systems view. Each of these techniques is used to provide a means for managing the overall complexity and understanding of a transdisciplinary problem.

The design fundamentals work together with the process fundaments. The design fundamentals provide a means for comparing the distributed model to the integrated model, while the process fundamentals seek to identify all processes and their points of integration within the integrated model. In this respect, the model represents the knowledge base or system of knowledge that must be operationalized using tools such as concept maps.

In the metrics phase, the concepts involving engineering measurement and quality assurance are developed. This provides a means of continuous feedback and validation during the transdisciplinary problem solving process. The knowledge base is an overlapping part of each of the T^4 FUNDAMENTALS that embodies the specific knowledge and skills related to a transdisciplinary problem. Additionally, the T^4 FUNDAMENTALS act as a strategy for sharing and integration with an emphasis on the interplay between tools, techniques, theories and methodologies. The TPSM offers a unified approach that is operational across domains.

The TPSM addresses two types of problems: (1) complex problems that are rooted in fields like biology and genetics, and (2) complex technical problems. These complex problems are defined by a set of characteristics as shown in Table 1 [53]. In times of increasing globalization and technological advances, many problems humans have to face in everyday life are quite complex, involving multiple goals as well as many possible actions that could be considered, each associated with several different and uncertain consequences, in environments that may change dynamically and independent of the problem solvers' actions [5].

The dissertation is organized as follows: In Chapter I, an overview of TSPM is given. This includes the challenges addressed by this dissertation and the motivation and approach for this body of work.

Chapter II addresses selected topics associated with collaborative social computing and transdisciplinary problem solving. In the survey of these topics, each is defined individually. An overview of social computing and collaboration is provided. The different types of research are evaluated. Complex problems and wicked problems are defined. Also, word maps are described as an alternate solution to knowledge production. Lastly, the alternative solutions that address complex problems are reviewed: (1) Deliberatorium, (2) DebateGraph and (3) Idiagrams.

TABLE 1

CHARACTERISTICS OF COMPLEX PROBLEMS

Complex Problems	Complex Technical Problems
No definitive problem boundary	Isolatable, boundable problems
The problem is relatively unique or unprecedented	Problems are of a universally similar type
Unstable and/or unpredictable problem parameters	Stable and/or predictable problem parameters
Multiple experiments are not possible	Multiple low-risk experiments are possible
There is no bounded set of alternative solutions	There is a limited set of alternative solutions
Involve multiple stakeholders with different and/or conflicting viewpoints and interests	Involve few of homogeneous stakeholders
No single optimal and/or objectively testable solution	There is a single optimal and testable solutions
No clear stopping point	The single optimal solution can be clearly recognized

In Chapter III, the key concepts of transdisciplinary problem solving are provided. The chosen concepts are a reflection of components of TPSM. A formal definition and overview of CSC is given, along with its traits and goals as used in the Web 2.0 framework. The complexity involved in TdR is discussed. TKS, TKI, and TKP are all defined along with the logical or mathematical model used when exploring multi-agent communication. Additionally, conceptual models are explained in conjunction with the TPSM. Also, concept maps are explained as a method for exploring knowledge socially.

In Chapter IV, TPSM is discussed in detail. Each component of the model is defined. The use of concept maps for knowledge integration is described. The case study demonstrates and validates that TPSM is provided. The collaborative social computing components that are key to TPSM are also described.

In Chapter V, concluding remarks are provided on the dissertation and a recommendation is made about future work related to TPSM.

A. Motivation – The Transdisciplinary Approach

The motivation for this dissertation is to address the central position of research within society today, which has intensified efforts to integrate separate bodies of knowledge. The U.S. National Academies defines transdisciplinary research as a mode of research that utilizes community intelligence to integrate information, data, techniques, tools, perspectives, concepts, and/or theories from multiple disciplines or bodies of specialized knowledge to solve complex problems where the solution transcends the scope of a single discipline or area of research practice. Using this definition as a foundation, two reasons for knowledge integration are established:

1. the advancement of a new and better fundamental understanding, and
2. the ability to address and solve problems that are transdisciplinary in nature.

In the last decade, the online research population has grown rapidly. Furthermore, studies show that it is becoming increasingly commonplace to perform research studies online. As this trend continues to grow, fueling transdisciplinary [6]-[12] studies, researchers must have an environment that provides a simple, straightforward model and that provides procedures for integrating, contributing, and using data [13]. As identified via the literature, our motivation can be traced back to four developments in the history of science, humanities, social sciences and engineering as seen in Table 1 [15][16].

TPSM seeks to provide a central and convenient repository for new transdisciplinary problem solving research exploration [14] that allows researchers from various disciplines to evolve knowledge and data gathered for different purposes [17]. The model makes the knowledge base available to members of a virtual community where researchers with various diverse backgrounds interact in social communities or sub-communities relating to their research problem while investigating their findings and data, which is ultimately shared among a broader audience. Figure 1 shows the elements of knowledge sharing and community intelligence as they are defined in TPSM. Knowledge sharing implies the exchange of information, skills, and expertise, while community intelligence assumes the collaboration of many that leads to innovation, discovery, and a more efficient decision making process. TPSM provides a unified mechanism for diverse applications and researchers to interact with scientific data.

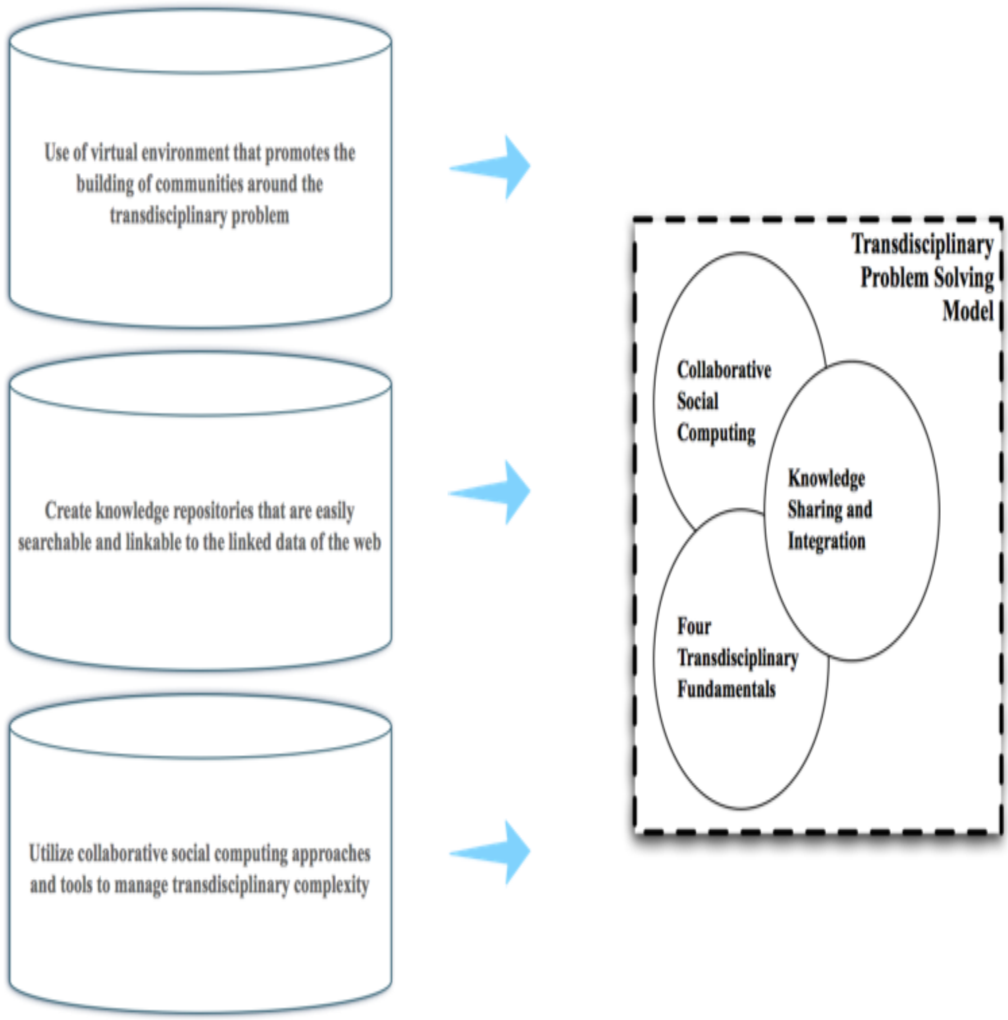

Figure 1. The flow of community intelligence in TPSM.

TPSM is built on the notion that TPS is increasingly a knowledge and information industry [18]. So it makes sense to draw on the success of various researchers. However, the benefit of using information technology to improve the translational nature of research is not realized without elements that empower the collection and integration of data. Oftentimes, knowledge re-engineering must occur as a function of information collection to remove bottlenecks that prevent integration. This is increasingly prevalent as the age of linked data continues to grow [18] [19].

The ability of researchers to address and solve today's complex problems is becoming exceedingly more difficult [3] [4]. Specifically, when referring to TPS, our focus is centered on three primary aims in relation to transdisciplinary research. First, at its simplest, transdisciplinary problem solving organizes data and knowledge in a way that enables access and integration of existing information in new innovative ways [20] [21]. This knowledge sharing or integration represents a system of knowledge. As a system, the following four transdisciplinary fundamentals (T^4 FUNDAMENTALS) are applied to the knowledge base:

1. System,
2. Process,
3. Design, and
4. Metrics

Establishing a knowledge base is an essential task. But any knowledge base must be coupled with meta-data to provide meaning to the data. Information becomes useless if it is not linkable to other sources of knowledge, which allows the data to be subjected to further analysis. Accordingly, the purpose of TPS extends much further. The second aim focuses on the developing tools and resources that assist in the analysis of the knowledge base. Here, utilization of collaborative social computing is critical.

The third aim is to validate the model to determine if it actually results in the interpretation of the results in a much more meaningful manner. TPS should provide the ability to conduct global analysis of the entire knowledge base. This includes the capability to unlock hidden mysteries within the knowledge base, as a result; uncovering common principles that are reusable across many systems and disciplines, leading to the discovery of innovative, yet novel features [22].

No one denies that there is a need to end the fragmentation within scientific research. There is a growing need to expand current and create new methods and theories into a conceptual model that integrates acquisition, storage, management, and analysis of data, which transcends existing perspectives [23][24]. Collaboration via social computing is needed to replace the existing knowledge exchange with a new one that reinforces the exchange of knowledge across disciplines and specializations [25] [26]. Furthermore, social computing provides an opportunity for an expanded collaboration and knowledge exchange. The second generation of web-based communities and hosted service, or Web 2.0, facilitates the perfect mix of technologies for enabling collaboration that capitalizes on community intelligence.

For decades, segmented information systems built on distributed platforms have kept transdisciplinary problem solving research fragmented, without the ability to effectively share knowledge or data [3]. This segmentation has stifled the progress of research that reaches beyond the traditional boundaries of a single discipline. Sharing resources and information is slowed further by geography. These factors can only be addressed through the creation of a model that addresses the collaboration and knowledge base integration gap. By utilizing techniques that are conducive to collaboration, which empower transdisciplinary problem solving, the result would be the creation of a paradigm that provides researchers with the ability to seamlessly communicate and share intelligence [4][23][25][26]. Such a model would provide the TR community with the ability to disseminate insights gained through collaboration [27] [9]. Current collaborative efforts have been slowed by the nonexistence of common standards, vocabularies and systems that enable data integration and knowledge sharing in a systematic way [9]. Increasingly sophisticated techniques are allowing researchers to probe deeper by using collaboration techniques, such as sharing knowledge by using concept maps, social bookmarking and wikis. Such collaboration encourages researchers to explore shared ideas and to expand the application of scientific discoveries, as well as educate the next generation of researchers [6] [7]. However, most of these advances have been interdisciplinary in nature [28].

Therefore, the impetus for defining a new approach stems from the need to build a transdisciplinary research collaboration environment that removes the segmentation found between scientific disciplines and research. Scientific research should increase knowledge sharing and discovery. To accomplish these two objectives, our approach classifies each component of the system as a whole, as a collection of interdependent knowledge systems.

Problem solving emphasizes the ability to accentuate the usefulness of knowledge for addressing real world issues, as opposed to the search for fundamental scientific understanding. Moreover, some scholars conceive of transdisciplinary research as a unifying principle for knowledge integration, which is determined by universal formal structures or patterns at the basis of pluralistic processes and their dynamics.

B. Brief Description of the Importance of Web 2.0 on Transdisciplinary Knowledge

The importance of Web 2.0 is usually considered in the form of social media and networking tools. However, CSC extends to the utilization of easy-to-use, lightweight, mostly open-source, computing tools. TABLE 2 provides a list of some common open-source tools, along with a brief description. The creation of these tools has revolutionized the individual user application development and participation paradigm. Their advent has increased the parity between browser based applications and desktop applications. This has been accomplished through the decentralization of processing load and scalability, which is an important characteristic of Web 2.0 technologies. Consequently, this creates an environment that empowers transdisciplinary knowledge sharing and integration that spans multiple domains. As transdisciplinary knowledge is made available it increases the collective intelligence of the community [44]. This increased collective intelligence can be directly attributed to the portability factor of Web 2.0 technologies. The knowledge of each user is liberated; setting the stage for a microcosm that leverages the intellect of the many. The production of transdisciplinary knowledge has always been a process where knowledge must be both shared and integrated. The measurable spike in innovation that has appeared over time indicates this fact. The Web 2.0 knowledge process has created significant value to the low cost facilitation of direct innovation. This can all be traced back to the open-source conventions prevalent in CSC, which keeps large numbers of inputs freely available to foster innovation [34] [44].

TABLE 2

COMMON OPEN-SOURCE COMPUTING TOOLS

Open-source Computing Tools	Description
AJAX	Asynchronous JavaScript and XML. The technique of exchanging data with a server, and updating parts of a web page - without reloading the whole page.
Python	An object-oriented, interpreted, and interactive programming language.
Perl	A general-purpose programming language originally developed for text manipulation and now used for a wide range of tasks including system administration, web development, network programming, GUI development, and more.
Ruby on Rails	An open-source web framework that is optimized for programmer sustainable productivity, favoring convention over configuration.
PostgreSQL	A powerful, open source object-relational database system.
MySQL	An open source relational database management system (RDBMS).
HTML5	A markup language for structuring and presenting content for the World Wide Web and a core technology of the Internet. It is the fifth revision of the HTML standard.
CSS3	Used to control the style and layout of Web pages. CSS3 is the latest standard for CSS
JavaScript	A scripting language is a lightweight programming language, programming code that can be inserted into HTML pages.
JSON	JavaScript Object Notation is a text-based open standard designed for human-readable data interchange. It is derived from the JavaScript scripting language for representing simple data structures and associative arrays, called objects. Despite its relationship to JavaScript, it is language-independent.
jQuery	A fast, small, and feature-rich JavaScript library. It makes things like HTML document traversal and manipulation, event handling, animation, and Ajax much simpler with an easy-to-use API.

Over the past decade, there has been a dramatic paradigm shift from more intelligent and powerful computers towards social or network-based computing. Accordingly, this paradigm shift principally enhances the knowledge base. The knowledge base represents the collective group knowledge, which is enhanced by human capabilities, both within individual and social contexts through the context of social computing. So the shift eliminates the need for sophisticated software built to mimic human intelligence and creativity replaces it with easy-to-use tools that allow users to express and communicate human intelligence and creativity more effectively [39].

In this sense, the social interaction of transdisciplinary knowledge to a social based model has been continuously and drastically changing. Many web applications are now being developed with participation, collaboration and openness built into them as a natural extension. These inherent features are the product of how people share knowledge. The networked environment is now closer to the user environment, which has empowered the users to make knowledge sharing and integration a natural part of personal expression and communal interaction. Web 2.0 has fundamentally changed characteristics of human social interaction, by allowing knowledge transference to be a less intrusive action. These characteristics define Web 2.0, as a participatory information sharing, interoperability, and user-centered design medium for collaboration on the World Wide Web [30][31]. Figures 2 and 3 display a programming snippet transferring a JSON object. JSON is a common medium used to transfer information across domains. In effect, Figures 2 and 3 show how simply knowledge can be shared. Additionally, it must be noted that the open-source computing tools scale quickly, facilitating the accommodation of extremely large and robust knowledge communities with masses of collective intelligence being exchanged. Furthermore, the collective intelligence can be validated in real-time by using client-side technologies like JavaScript. The fact is that open-source computing technologies have directly facilitated scalable channels that allow the new norm to be approached as part of normal human behavior, creating and delivering an online community experience that is a rich and fluid for developers and users alike. This attributes directly to the rise of collaborative social computing [32]-[35].

```
<cfcomponent output="false">
	<cfsetting showdebugoutput="false">
	<cfinclude template="application.cfm">
	<cffunction name="getResearch" access="remote" output="false" returnformat="json">
		…

		<!--- Calculate the Start Position for the loop query.
		So, if you are on 1st page and want to display 4 rows per page, for first page you start at: (1-1)*4+1 = 1.
		If you go to page 2, you start at (2-)1*4+1 = 5  --->
		<cfset start = ((arguments.page-1)*arguments.rows)+1>

		<!--- Calculate the end row for the query. So on the first page you go from row 1 to row 4. --->
		<cfset end = (start-1) + arguments.rows>

		<!--- When building the array --->
		<cfset i = 1>

		<cfloop query="records" startrow="#start#" endrow="#end#">
			<!--- Array that will be passed back as JSON --->
			<cfset arrresearchs[i] = #RESEARCHID#,#RESEARCH_TITLE#,#CONTACT#,#CATEGORY#,#CATEGORYID#,
			#RESEARCH_TYPE#,#RESEARCH_TYPEID#,#TEAM#,#OVERALL_PERCENT_COMP#,#DESCRIPTION#,
			#NOTES#,#PRESENTATION#,#PROCESS_FLOW#, #RESEARCH_PLAN#,#KEY_CONTRIBUTIONS#,
			#KEYWORDS#,#ACCOMPLISHMENTS_SUMMARY#,DateFormat(#TARGET_DATE#, "mm-dd-yyyy"),
			DateFormat(#DATETIME_MODIFIED#, "mm-dd-yyyy")]>
			<cfset i = i + 1>
		</cfloop>

		<!--- Calculate the Total Number of Pages for your records. --->
		<cfset totalPages = Ceiling(records.recordcount/arguments.rows)>

		<!--- The JSON return --->
		<cfset strReturn = {total=#totalPages#,page=#Arguments.page#,records=#records.recordcount#,rows=#arrresearchs#}>

		<cfheader name="expires" value="#GetHttpTimeString(Now())#">
		<cfheader name="pragma" value="no-cache">
		<cfheader name="cache-control" value="no-cache, no-store, must-revalidate">
		<cfsetting showdebugoutput="false">
		<cfcontent type="application/json" reset="true">

		 <cfreturn  strReturn />
	</cffunction>
...
</cfcomponent>
```

Figure 2. A module for formatting a JSON object.

{"ROWS":[[1,"Building Semantic Ontologies using Concept Maps","Dr. Varadraj P. Gurupur","Semantic Web",1,"Concept Maps",2,"",94,"The use of concept maps to build ontologies for the semantic web.","http:\/\/notes","http:\/\/presentation","http:// processflow","http:\/\/researchplan","Dynamic Ontologies","Ontologies, Semantic Web, Concept Maps","","12-31-2012","07-05-2011"]],"PAGE":1,"RECORDS":115,"TOTAL":6.0}

This is an example of a single JSON record as it would be processed within HScMed.

Figure 3. An example of a single JSON record.

C. *Dissertation Approach*

The object of this proposed model is to achieve collaboration under a transdisciplinary systems outlook by using social computing and networking techniques to dramatically revolutionize the way researchers collaborate and interact via the Internet. Given the enormous complexity of the contemporary world, characterized by a dynamic interrelation between processes of economic globalization, political reorganization, cultural integration and environmental degradation, it becomes necessary to design a collective inquiry process of participative action-research. Specifically, the hindrances to transdisciplinary problem solving may be viewed within the context of three distinct issues. First, current methods lack the ability to organize data and knowledge in a way that enables access and integration of existing information so that it may be viewed in a way that stimulates the creation of new knowledge. Secondly, there is a lack of integrated tools and resources that assist in the analysis of the knowledge base. Lastly, knowledge transference must be validated to determine if the system of knowledge is being interpreted in a meaningful way.

Figure 4 illustrates the complexity and chaos that is involved in attempting to control and structure a transdisciplinary problem and the transdisciplinary knowledge that is needed to craft complex solutions.

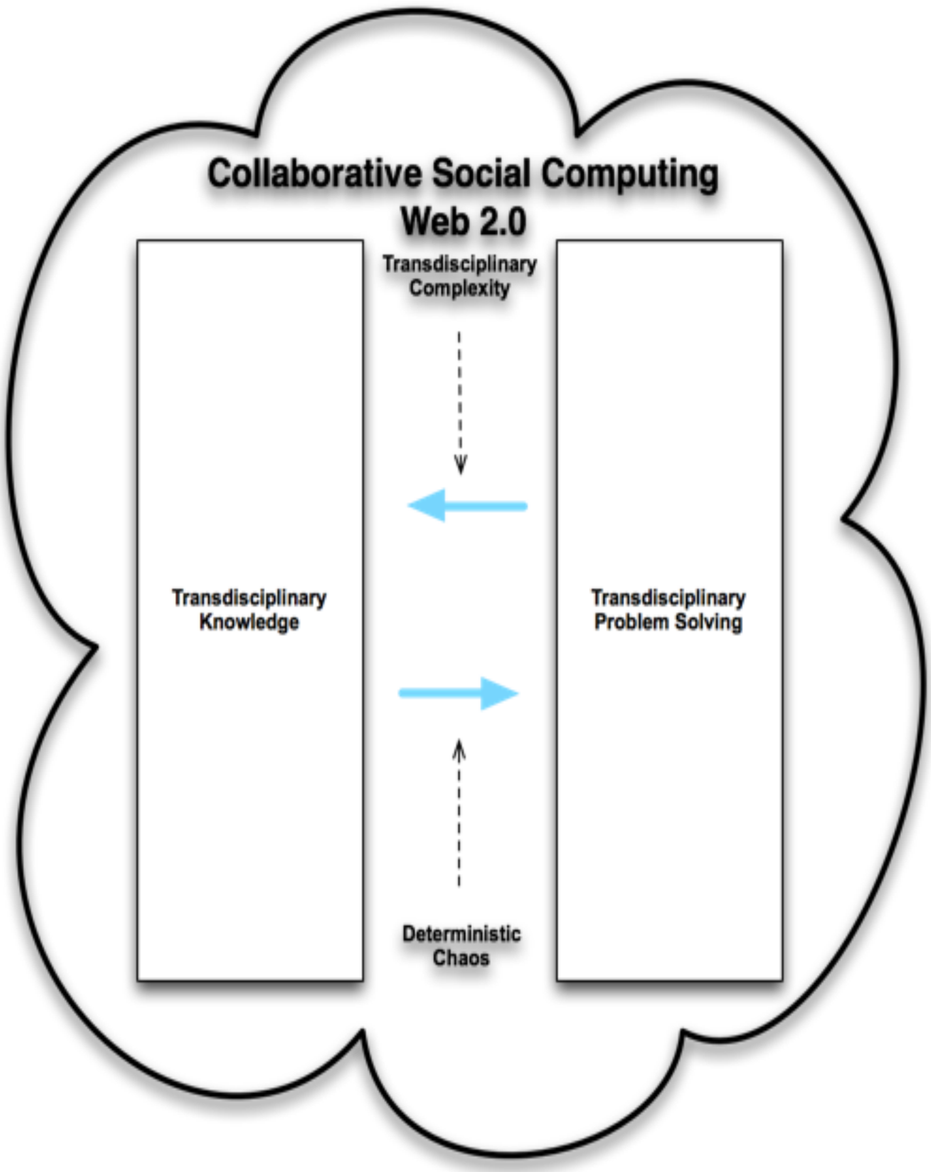

Figure 4. The need for intellectual control and structuring of TPS.

Advances acquired through information and communication technologies support these processes, and their application within the different realms of daily life, such as the familiar, educational and productive realms. Therefore, the incapability of theoretical and exclusively disciplinary approaches for constructing adequate and knowledgeable responses at the level of the relevant problems is increasingly becoming evident. Consequently, the quantity of interrelated factors that characterize current social phenomena need to be observed, studied, and constructed in a participative manner as complex cognitive models [36].

Essentially, collaborative social computing represents the collection of technologies that gather, process, compute, and visualize social information [11]. This new social structure has emerged, creating an array of loosely integrated social components. In fact, integration of social computing in scientific research (Science 2.0) and scholarly publishing have acted as enablers, bridging the principles of participation and collaboration across different points along the continuum of knowledge production and dissemination [27]. For example, medicine becoming one of the most information-intensive sectors of the economy, the National Library of Medicine (NLM)'s bibliographic database MEDLINE [9] added over 1 million new publications in 2010.

However, the proposed model involves bridging the systematic knowledge in a transdisciplinary way. Although the focus of the model is more on the connections between the knowledge base and the transdisciplinary team, emphasized collaboration, participation, and innovation are all embodied in the benefits gained [13]. The idea of a learning system that emphasizes data fluidity as information moves transparently through various levels of stewardship, is a key component of the model. An expansion of this methodology is used to create an environment that empowers scientists with the ability to combine the advances in various disciplines. This also requires engaging in experiments to connect data resources in ways that will accelerate discovery. These efforts originated from individual research and single discipline practices where scientific data is available in hundreds of public and private databases. These resources have been made accessible due to new technologies and the Internet [6]. The problem is finding an innovative way to take advantage of this influx of advanced techniques and increased access to data. Social computing provides a medium for sharing data, ideas, and computational techniques. Furthermore, it allows useful patterns and the knowledge base to become transferable commodities.

Today's challenge, then, is to harness the power that systematic knowledge integration provides, and then, to use collaboration to gather the benefits of community intelligence. Collaborative social computing is based on Web 2.0 methodologies, yet scalable and forward looking enough to incorporate the semantics of Web 3.0. This is the logical next step as we look at ways to add meaning to the data of the Internet. For example, in the industrial age of medicine, healthcare was a highly technologized [7]-[9] commodity offered to patients in a reactive, mass-produced way. In the information age, medicine must evolve to become predictive, personalized, preemptive, and participative [10]. TSPM provides a systematic approach that allows the utilization of the work of many scientific disciplines to effect the changes needed for promoting ongoing advances without causing unanticipated harm.

Innovation is required to create the architectures needed to promote social participation. This is why a paradigm shift is needed to adopt a social computing model that enables the social aspects of Web 2.0 and other social computing technologies to be viewed as individual systems. These systems would then have the ability to integrate in a variety of new ways that enhance the user experience like never before. By applying a system-of-systems framework, which treats each component as a separate system, these issues are addressed. Each system communicates as a set of defined processes with specific inputs and outputs. This creates a collection of social computing systems that are easily reusable and scalable, reducing the complexity involved in integrating these systems [37].

D. Conclusion

In this chapter, the need for an integrated research model for addressing transdisciplinary problem solving was identified. This dissertation addresses this need. The motivation and approach of this dissertation was also discussed.

II. SURVEY OF CORE TOPICS, METHODS AND TECHNOLOGIES

In this chapter, core research types are described to provide a clear understanding of the different types of research. Formal definitions of social computing, collaboration and problem solving are provided. The attributes and characteristics of complex problem solving and wicked problems are given. Word maps are discussed as an alternative to solutions for knowledge production (KP).

A. Definitions of Core Research Types

In this section, definitions for core research types are specified to clarify the theoretical assumptions underlying this dissertation and explicate the definitions as a point of reference. The definitions act as a comparative analysis of collaboration based research (CBR). This analysis is meant to show the contrast between the selected CBR types (Table 3).

TABLE 3

OVERVIEW OF TYPES OF RESEARCH

Disciplinary
Within one academic discipline
Disciplinary goal setting
No cooperation with other disciplines
Development of new disciplinary
Knowledge and theory
Multidisciplinary
Multiple disciplines
Multiple disciplinary goal setting under
One thematic umbrella
Loose cooperation of disciplines for exchange of knowledge
Disciplinary theory development
Crossdisciplinary
Crosses disciplinary boundaries
Dominant discipline
Dominant discipline integrates the knowledge of another discipline
Collaboration is based on dominant discipline attempting to solve problem within their domain
Participatory
Involves academic researchers and on-academic participants
Exchange of knowledge, knowledge bodies not integrated
May be disciplinary or multidisciplinary
Not necessarily research, goal may be academic or not
Interdisciplinary
Crosses disciplinary boundaries
Common goal setting
Integration of disciplines
Development of integrated knowledge and theory
Transdisciplinary
Crosses disciplinary and scientific/academic boundaries
Common goal-setting
Integration of disciplines and non-academic participants
Development of integrated knowledge and theory among science and society

Note: From "From Landscape Research to Landscape Planning: Aspects of Integration, Education and Application" by B. Tress, 2006, *Springer,* p. 16. Copyright 2006 by Springer. Adapted with permission.

- *Disciplinary research* addresses projects, which consider specific types of phenomena, which are particular to the bounds of a single, coherent, logically consistent knowledge base [45] [57]. This knowledge is associated with one academic field of study or profession. The research activity is orientated towards the use of expected skills and competences to answer a specific research question. This question is based on a shared vision that surrounds one specific goal or aim [45] [58]
- *Multidisciplinary research* (MdR) is when a number of disciplines exist concurrently, with the absence of any direct relationship. The members of the multidisciplinary team maintain their independence from the other involved disciplines; therefore, no theoretical structures will occur [58]. Although MdR has many forms that are based on the level of collaboration within the research disciplines, as well as the research study, there will be no change to the autonomy of the disciplines. Therefore, any KP will be limited to the disciplinary work. These multidisciplinary research types may be defined as follows [45]:
    - ***Additive:*** A type of MdR that is formed by various disciplines working independently, without any interaction between the disciplines and members of the MdR team are nonexistent. The study does not include a synthesis of the final results. However, a collective final report may include the independent findings.
    - ***Nondisciplinary**:* A type of MdR research that is used when a disciplinary approach is unable to address the study subject, therefore multiple approaches that are borrowed from various disciplines are used instead.

  - ***Integrated**:* A type of MdR where many disciplines take part in the study, developing a synthesis of disciplinary results. However, collaboration only occurs where there is a necessity.
  - ***Synthetic**:* When an MdR team utilizes deep interaction between disciplines, leading to a synthesis in a new discipline. The new discipline is based on its own principles and assumptions.

- *Crossdisciplinary* research (CdR) is when the axiomatic principles of a single discipline are used at the same hierarchical level, creating a polarizing effect across disciplines towards this axiomatic [58] [59]. This form of CBR involves the use of a dominant discipline collaborating in an attempt to solve problems within their own domain [60]. Existing knowledge is used and knowledge is processed across the disciplinary boundaries, allowing the dominant discipline to integrate the knowledge of another discipline [58].
- *Participatory studies* are CBR(s) that involve collaboration between academic researchers and non-academic participants working together to solve a problem. Academic researchers and non-academic participants integrate knowledge, creating new knowledge. Often, participatory studies are not considered research [45].
- *Interdisciplinary Research* (IdR) is when CBR is defined at the next higher hierarchical or sub-level and a common axiomatic for a group of related disciplines is guided by a sense of purpose [59]. In this case, IdR surmises any study or group of studies undertaken by scholars from two or more distinct scientific disciplines in which the study subject would be challenging for either

discipline alone. This form of CBR is based upon a conceptual model that links or integrates theoretical frameworks, methods and terminologies from those disciplines, uses study design and methodology that is not limited to any one field, and requires the use of perspectives and skills of the involved disciplines throughout multiple phases of the research process [47][45]. IdR similarly approaches the issue from a range of disciplines, while allowing the transference of methods from one discipline to another [45]. This exchange also represents contributions from the various disciplines, which are integrated to provide a holistic outcome (61).

- *[56]* distinguishes three degrees of IdR, namely:
    - ***degree of application:*** transference of the methods of one discipline to another, for example, using chemistry to develop new medicines;
    - ***epistemological degree*****:** transference of the methods of one discipline to another on the ontological level, for example, the use of formal logic in the area of general law;
    - ***degree of the generation*****:** new disciplines are created by the transference methods from one discipline to another to create new theories that transcend the parent disciplines. For example, transferring mathematical methods to meteorological phenomena to generate chaos theory.
- *Transdisciplinary Research* (TdR) is the most complex from of CBR [58]. TdR is defined as research efforts conducted by investigators from different disciplines working jointly use create new conceptual, theoretical, methodological, and translational innovations that integrate and move beyond discipline-specific

approaches to address complex problems [45]. These complex problems are project-centric and commonly concerned with finding solutions to real-world problems. TdR requires a shared theoretical understanding and an agreed interpretation of knowledge [63]. TdR defines a new mode of scientific research that coordinates all disciplines and interdisciplinary in the education and/or innovation system with a focus on the sharing and integration of knowledge around complex, heterogeneous domains, rather than disciplines and subjects [59] [61]. In other words, disciplinary methodologies and theories are homogenized into a combination of disciplinary components and perspectives that may represent the invention of an entirely new discipline, which has no obvious separation between the contributing domains [62]. TdR transcends separate disciplinary perspectives towards the epistemological goal of KP of a particular phenomenon [56] [62].

B. Social Computing: A definition

Most research defines social computing as some combination of the following three types of studies [37]:

- Studies on the computing systems supporting social behaviors in some cyberspace. The computing systems include Web 2.0 elements: blogs, Twitter, wikis, RSS, instant messaging, multiplayer gaming and open source development.
- Studies on the computing generated through or relying on a social crowd's intelligence.
- Studies on the law of a society in a computing cyberspace.

Social computing, by definition, culminates the aspects of Web 2.0 that, when used, have the potential to introduce organic collaboration. Historically, social computing is used as a general term in computer science to represent the intersection of social behavior and computational systems. The first aspect of social computing involves the magnification of social behavior through the use of computational systems. Normally, social computing tools and features are simply integrated as a function of an application. Social computing involves creating or re-creating social conventions and social concepts, referred to as social software, which centers on collaborative information technology. Often referred to as social media, social computing encompasses a wide range of tools, ranging from simple email and chat to much more elaborate social networking and collaboration tools.

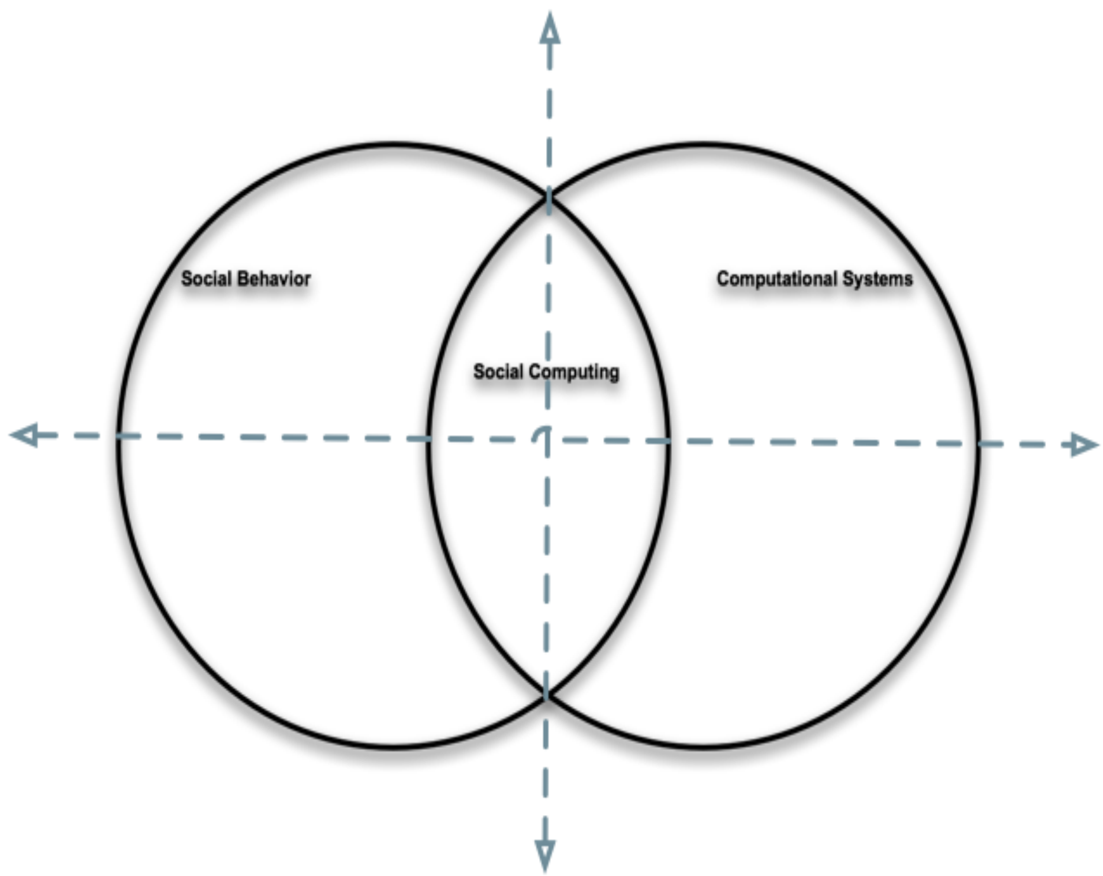

Figure 5. The intersection of social behavior and computational systems.

Figure 5 shows the concept of the intersection of social behavior and computational systems. The first aspect of social computing involves the magnification of social behavior through the use of computational systems [37].

C. Collaboration: A definition

In this dissertation, the term "collaboration" can be generally defined as two or more co-equal individuals sharing both their knowledge and experience, working to achieve a common goal. This sharing of knowledge and experience creates a process that enables each participant to see different aspects of a problem, while constructively exploring differences and searching for solutions that transcend the limited view that often accompanies non-collaborative environments. Generally speaking, collaboration is most well suited in the following instances [38] [39]:

- The problems are ill-defined, or people disagree on how the problems are defined.
- Different groups or organizations with vested interests depend on each other in some way.
- Those with a stake in a problem have yet to be identified or organized.
- Some stakeholders have more power or resources than others.
- Those with a vested interest have different levels of expertise and access to information about the issue.
- The problems are often characterized by technical complexity and scientific uncertainty.

- Differing perspectives on the problems lead to conflict or disagreement among the stakeholders.
- Incremental or unilateral efforts to address the issue have been ineffective.
- Existing processes for addressing the problems have proved unsuccessful.

D. Introduction to Tag Cloud

A tag cloud is a visual representation for text data, typically used to depict keyword metadata (tags) on websites, or to visualize free form text. Tags are represented by single words, and each tag's weight depicted by its font size or color. This allows the most important information to be quickly visualized. These weighted tags may also be hyperlinked, connecting the tag to associated knowledge.

Figure 6. Example of a word map.

In social software, there are three main tag cloud application types, which are distinguished by their meaning rather than appearance. Table 4 shows the three main types of tag clouds [64]-[66]. Table 5 displays a comparison of different tag cloud variations [64]-[66].

TABLE 4

THREE MAIN TYPES OF TAG CLOUDS

Tag Cloud Types	Description	Frequency
Type I	There is a tag for the frequency of each item. Useful for displaying metadata about an item when precise results are not desired.	Size represents the number of times that tag has been applied to a single item.
Type II	There are global tag clouds where the frequencies are aggregated over all items and users.	Size represents the number of items a tag has been applied, as a presentation of each tag's popularity
Type III	The tag clouds contain categories, with size indicating the number of subcategories. Some approaches allow the constructing of tag clouds by applying tag co-occurrences in documents.	Tags are used as a categorization method for content items. Tags are represented in a cloud where larger tags represent the quantity of content items in that category.

TABLE 5

COMPARISON OF VARIATIONS OF TAG CLOUDS

Type	Description
Data Clouds/ Cloud Data	A data display which uses font size and/or color to indicate numerical frequency. Similar to a tag cloud, but instead of word count, it displays data.
Text Clouds/Word Cloud	A visualization of word frequency in a given text as a weighted list.
Collocate Clouds	An extended version of the text cloud that provides a more focused view of a document. Instead of a complete document summation, the collocate cloud examines the usage of a particular word. Formatted to show frequency (as size) and strength (as brightness).

Font sizes are determined, one to maximum font size, directly with smaller frequencies. For larger values, a scaling should be made. In a linear normalization, the weight t_i of a descriptor is mapped to a size scale of 1 through *f*, where $t_{\min}$ and $t_{\max}$ are specifying the range of available weights.

$$s_i = \left\lceil \frac{f_{\max} \cdot (t_i - t_{\min})}{t_{\max} - t_{\min}} \right\rceil \text{ for } t_i > t_{\min} \text{; else } s_i = 1 \tag{1}$$

- s_i : display font size
- $f_{\max}$: max. font size

- t_i : count
- $t_{\min}$: min. count
- $t_{\max}$: max. count

Since the number of indexed items per descriptor is usually distributed according to a power law, for larger ranges of values, a logarithmic representation makes sense [66] [67].

E. Problem Solving

Problem solving is a term that used in many disciplines, creating various perspectives and terminologies when it comes to clarifying a definition. Mostly problem solving is considered to be a structured mental process for finding solutions to problems. These problems usually require the use of problem solving techniques when it comes to finding and shaping solutions. These problem solving techniques constitute a variety of approaches that involve the decision-making process. Table 6 shows a list of common problem solving strategies [68]. Table 7 provides the generally accepted problem solving process.

TABLE 6

COMMON PROBLEM SOLVING STRATEGIES

Problem Solving Strategy	**Description**
Abstraction	Solving the problem in a model of the system before applying it to the real system
Analogy	Using a solution that solves an analogous problem
Brainstorming	A group activity involving a large number of solutions or ideas and combining and developing them until an optimum is found
Divide and conquer	Breaking down a large complex problem into smaller, solvable problems
Hypothesis testing	Assuming a possible explanation to the problem and then trying to prove (or disprove) the assumption
Lateral thinking	Approaching solutions indirectly and creatively
Means-ends analysis	Choosing an action at each step to move closer to the goal
Method of focal objects	Synthesizing seemingly non-matching characteristics of different objects into something new
Morphological analysis	Assessing the output and interactions of an entire system
Proof	Attempting to prove that there is not a solution to the problem. The point where the proof fails will be the starting point for finding a solution
Reduction	Transforming the problem into another problem for which solutions exist
Research	Employing existing ideas or adapting existing solutions to similar problems
Root cause analysis	Identifying the cause of a problem
Trail-and-error	Testing possible solutions until the right one is found

TABLE 7

GENERAL PROBLEM SOLVING PROCESS

Seven Steps to Problem Solving
Define and Identify the Problem
Analyze the Problem
Identify Possible Solutions
Select the Best Solutions
Evaluate Solutions
Develop an Action Plan
Implement the Solution

F. Define Complex Problem Solving

Problem solving is as an area of cognitive science [83] that includes both complex problems and complex technical problems. CPS occurs to overcome variations between a given state and a desired goal state by means of behavioral and/or cognitive, multi-step activities. The given state, goal state, and barriers between given state and goal state are complex, changing dynamically during problem solving, and are transparent. The exact properties of the given state, goal state and the barriers are unknown to the solver at the onset. CPS implies the efficient interaction between a solver and the situational requirements of the task and involves a solver's cognitive emotional, personal, and social abilities and knowledge [82]. When assessing a problem three attributes must be considered [69] [70]:

- *Complexity*: a review of the problem must be done to determine if a large number of diverse, dynamic, and independent elements exist*;*

- *Measurability:* what is the practicality and difficulty of obtaining sound quantitative data;
- *Novelty:* while attempting to identify and structure the problem is it determined that the issue is evolving or does it require action in the way of an innovative solution.

Where complex problems require broad, systematic perspectives, technical problems require a narrow, detailed focus. Although complex technical problems are easier to solve, they do benefit from the innovative product that TdR produces. Both types of problem solving have been addressed throughout history, however theories have not progressed accordingly in the cognitive sciences [1] [73]. The lack of theories is further complicated by the necessity of a shared glossary and a classification of tasks when researching problems that are transdisciplinary in nature. Although problem solving is deeply rooted in the psychology, it is operationalized in many different ways, which provides no psychological theories to measure complexity [71] [72].

When combined with TdR, complex problem solving seeks to address the complexity of intellectual functions that are defined as higher-order cognitive processes that utilize the integrated, systematic knowledge base that transcends the modulation and control of a routine or fundamental skill set [74]-[77]. True problem solving, as defined and used in transdisciplinarity occurs when an organism or an artificial intelligence system needs to move from a norm to innovation.

G. Characteristics of Complex Problems

Dietrich Dörner's theory of complex problems [75], which was later expanded upon by Joachim Funke [78] [79], concluded that complex problems typically have characteristics that can be summarized. This is a summarization of problem theory, which attempts to classify complexity types. However, no single dimension can be considered necessary and sufficient to identify a task as complex. In fact, it takes the consideration of multiple formal descriptors to define and classify a CPS task. This is in part due to the unbound nature of complex problems. Also, the systematic nature of the knowledge that is produced for transdisciplinarity requires a system-based point of view [71].

Complex problem solving is a factor of many jobs. It can be difficult to come up with ideas and solutions to complex or multi-layered problems when a person experiences difficulty with problem solving and associated decision-making. Additionally, complex problem solving can be understood by contrasting it against a set of principles that seek to differentiate "complex" with "simple," noncomplex problem solving as depicted in Table 8 [79][82]. Table 9 lists a set of features that can be used to characterize CPS [79].

TABLE 8

COMPLEXITY MEASUREMENT FACTORS

Measurement	Explanation
Availability	What is the access level associated with knowledge retrieval? Measured by the transparency of the problem situation.
Precision of goal definition	Is the goal well defined? Are there multiple goals? Are the goals contradictory?
Complexity Level	Is the problem defined by numerous variables? What is the connectivity between variables? Is the functional relationship of the variables linear or nonlinear?
Stability properties of the problem	Are there time constraints or dependencies involved as part of the problem solving process?
Richness	Is there semantic embedding of knowledge? Rich semantic embeddings often reduce the uncertainty to a large degree.

TABLE 9

CHARACTERISTICS OF COMPLEX PROBLEM SOLVING

Complexity Features	Explanation
Intransparency	In complex problem solving situations, knowledge about "symptoms can be limited, which leads to a state of inference. Variables typically lend themselves to direct observation only.
Polytely	Complexity is increased by multiple, sometimes-contradictory goals. Reasonable trade-offs must be addressed.
Complexity of the situation	This feature is concerned with the number of processes that can be identified and regulated. While a large number of variables increase complexity, their connectivity pattern adds additional complexity. This is the attribute of the control system versus the dynamic aspects of the system. As this complexity grows the situational demands cause conflict with the limited capacity of the problem solver.
Connectivity of variables	Complex problems are plagued by high degrees of connectivity in which changes in one variable affect the status of many related variables. Complex problems often contain so high a degree of connectivity that is impossible to anticipate all possible consequences of a given situation.
Dynamic developments	Dynamic changes occur unexpectedly during the complex problem solving process. Due to time constraints, additional pressures arise. These changes can induce spontaneous changes in other aspects of the problem. This adds a certain level of unpredictability.
Time-delayed effects	Consequences within the action space may not be immediate. Delays may occur, causing long unforeseen wait times.

H. Characteristics of Wicked Problems

Wicked problems are termed as “divergent” as opposed to “convergent” problems. For a so-called ‘tame’ problem, the problem definition is – though it might be very complicated – well understood and promises a solution. The more it is studied, the more answers sooner or later converge. A divergent problem isn’t well defined and does not promise a solution. The more it is studied, the more people inevitably come to different solutions and interpretations. The process to tackle tame problems is assumed to be fundamentally linear, comprising a sequence of steps leading to a desired outcome/solution. In a complex environment not even a shared problem understanding can be taken for granted. We don’t know what we don’t know.

Horst and Webber [84] constructed a list of ten characteristics associated with wicked problems that were initially derived as a means for addressing the planning of complex policy (TABLE 10).

TABLE 10

CHARACTERISTICS OF WICKED PROBLEMS

Characteristics of Wicked Problems
Defining wicked problems creates a wicked problem in itself. Difficulty in creating a definitive formation around the problem.
Wicked problems have no stopping rule.
Solutions to wicked problems are not right or wrong and generally accepted as better worse, good enough, or not good enough.
There is no immediate or ultimate test for solutions to a wicked problem.
Solutions to wicked problems are considered to be a "one-shot operation"; Wicked problems lack trial and error because each solution attempt is significant.
There is not an enumerable or exhaustive set of solutions, nor is there a well-defined set of permissible operations that may be incorporated into an action plan.
Every wicked problem is unique.
Every wicked problem is a symptom of another problem.
The existence of discrepancy representing a wicked problem can be explained in numerous ways. The chosen explanation determines the nature of the problem's resolution.
Wicked problems have no given alternative solutions.

Conklin later generalized the concept of problem wickedness to areas other than planning and policy. The defining characteristics are [76]:

- The problem is not understood until after the formulation of a solution.
- Wicked problems have no stopping rule.
- Solutions to wicked problems are neither right nor wrong.
- Every wicked problem is essentially novel and unique.
- Every solution to a wicked problem is a ‘one shot operation.’
- Wicked problems have no given alternative solutions.

In 2000, Roberts categorized strategies solving wicked problems as shown in Table 11 [85].

TABLE 11

STRATEGIES FOR SOLVING WICKED PROBLEMS

Strategy	Description
Authoritative	This is a strategy that seeks to lessen the problem complexity through the creation of a small agile group, thus, decreasing the number of competing viewpoints at the offset of the project. The disadvantage is that the small group may not have an appreciation for all of the intricate perspectives needed to address the problem.
Competitive	This is a strategy that attempts to craft a solution around the "completive nature" of the group. Opposing points are constructed against each other in an attempt to find preferred solutions. Additionally, solutions are weighted against each other in order to arrive at the optimum solution. The disadvantage, however, is that this adversarial approach can lead to a confrontational environment in which knowledge sharing and integration is discouraged. Moreover, participants may not be motivated to craft the best possible solution.
Collaborative	This is a strategy aimed at involvement and engagement amongst all participants. The goal is to find the best possible solution. Typically, meetings characterize these approaches where issues and ideas are discussed. Agreement is formulated around common, agreed upon approaches.

I. Deliberatorium

The Deliberatorium is a large-scale argumentation approach developed by Klein of MIT. The theory behind the Deliberatorium formalizes an approach of utilizing social media techniques to make decision making better. Additionally, the simple approach calls for members of a community to make their contributions in the form of a deliberation map, a tree-structured network of posts each representing a single unique issue (question to be answered), idea (possible answer for a question), or argument (pro or con for an idea or other argument) [108] [109]. Figure 7 is a screenshot of the Deliberatorium tool developed by Klein.

Figure 7. The Deliberatorium.

Note: From “How to Harvest Collective Wisdom on Complex Problems: An Introduction to the MIT Deliberatorium” by M. Clemens, 2011. Copyright 2011 by CCI working paper. Reprinted with permission.

The Deliberatorium is designed around the principle of large numbers of people, distributed over time and space, combing their insights in an attempt to find well-founded solutions to complex or wicked problems (e.g. sustainability, climate change policy, and complex product design) [108]. The Deliberatorium is a software tool designed to help organizations better harvest their collective knowledge so that it can be incorporated from various perspectives as solutions to complex problems. This is an attempt to avoid the dysfunctional behaviors (such as noise, disorganized content, and polarization), which are considered as hindrances of other forms of social media when they are applied to challenging topics. Figure 8 provides the layout for a typical deliberation [108] [109].

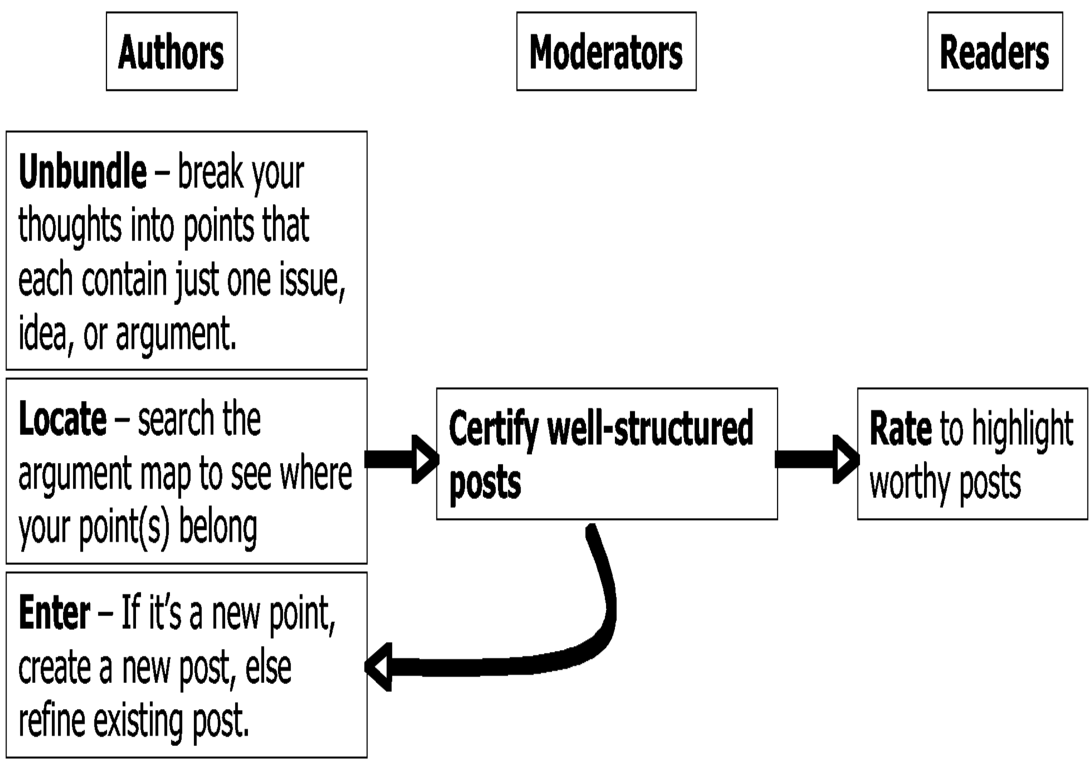

Figure 8. Layout of a Deliberatorium.

Note: From "How to Harvest Collective Wisdom on Complex Problems: An Introduction to the MIT Deliberatorium" by M. Clemens, 2011. Copyright 2011 by CCI working paper. Reprinted with permission.

J. DebateGraph

DebateGraph is a cloud-based service offering that provides individuals or groups a way to process information. Additionally, the DebateGraph communicates a way to learn, deliberate, and decide on complex issues (Figure 9).

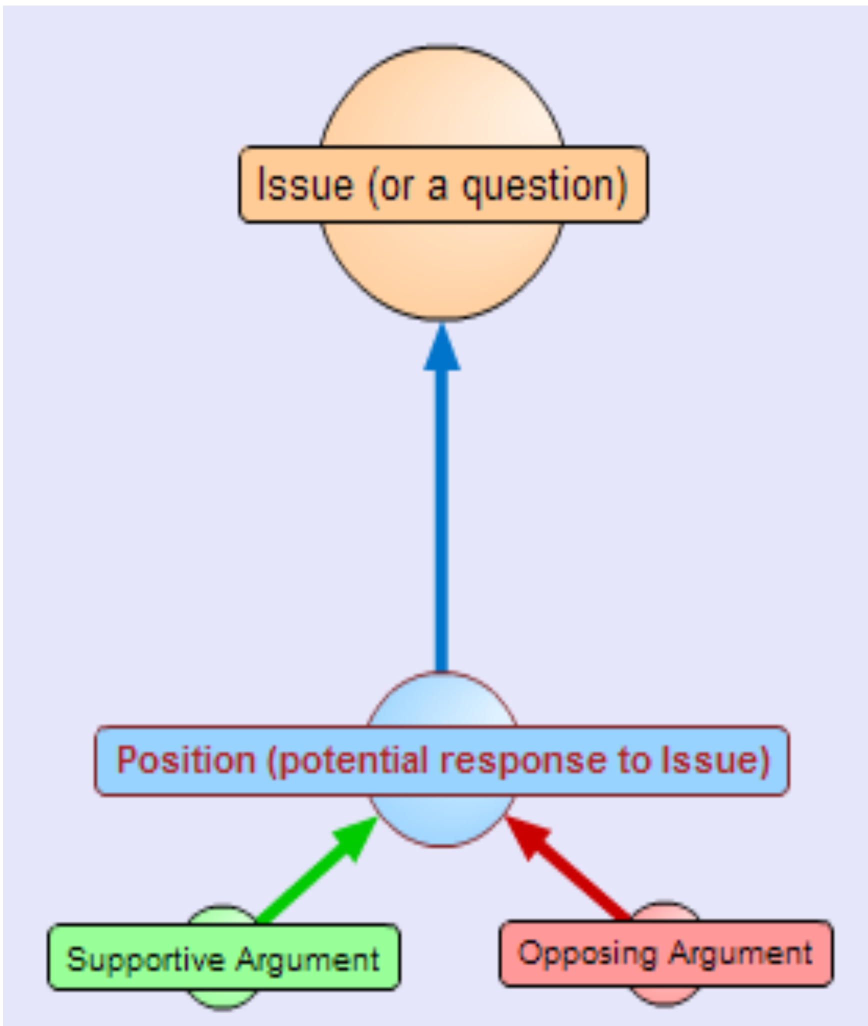

Figure 9. Example of showing the components of a DebateGraph.

Note: From "DebateGraph" by M. Clemens, 2012, http://debategraph.org/ [Online] Available. Copyright 2012 by DebateGraph. Reprinted with permission.

- This service allows any size community to externalize, visualize, question, and evaluate all of the alternatives relevant to the topic at hand. By promoting intelligent, constructive dialogue within the community around a set of issues [97].
- Each public map contributes to an accumulating graph of structured understanding, augmenting the community's knowledge across a growing range of topics being addressed [97].
- Expressing knowledge in a structured and transparent form acknowledges that individuals are understood and delineated in context, to fill any gaps, and to expand upon, improve, and challenge any of the points considered directly and avoids unnecessary duplication and character attacks, and is accessible and advancing in light of new evidence and ideas [97].
- As people increase their contribution of insight to the public graph: all the communities' network benefits are worthier and whether the communities are small teams, organizations, networks of stakeholders, or societies as a whole, having the capability to enhance our power of perform decision making in the face of complex problems today has never been more pressing [97].

In essence, building the maps involves three steps [97]:

1. breaking down the subject into meaningful ideas;
2. figuring out the relationships between those ideas; and,
3. expressing the ideas and relationships visually.

K. Idiagrams

Idiagrams provide systemic analysis, systems mapping, and strategic consulting services to help clients:

1. Think clearly and systemically about complex problems
2. Engage diverse stakeholders who must be part of the solution
3. Communicate effectively with the people who must act on those problems

According to the Idiagram website, the product works well for teams facing complex multi-faceted problems to:

- Build a sophisticated systemic understanding of complex issues and opportunities
- Develop broad strategic insight
- Design more creative solutions
- Build shared vision, ownership, and enthusiasm
- Communicate effectively with others

Excelling at the above and in general collaboration can have an unfathomable impact on team knowledge, morale, and coordination. For better thinking, communication and coherent action the approach is centered on systems thinking and mapping [53].

The visual modeling process serves as a tool to help Idiagram clients:

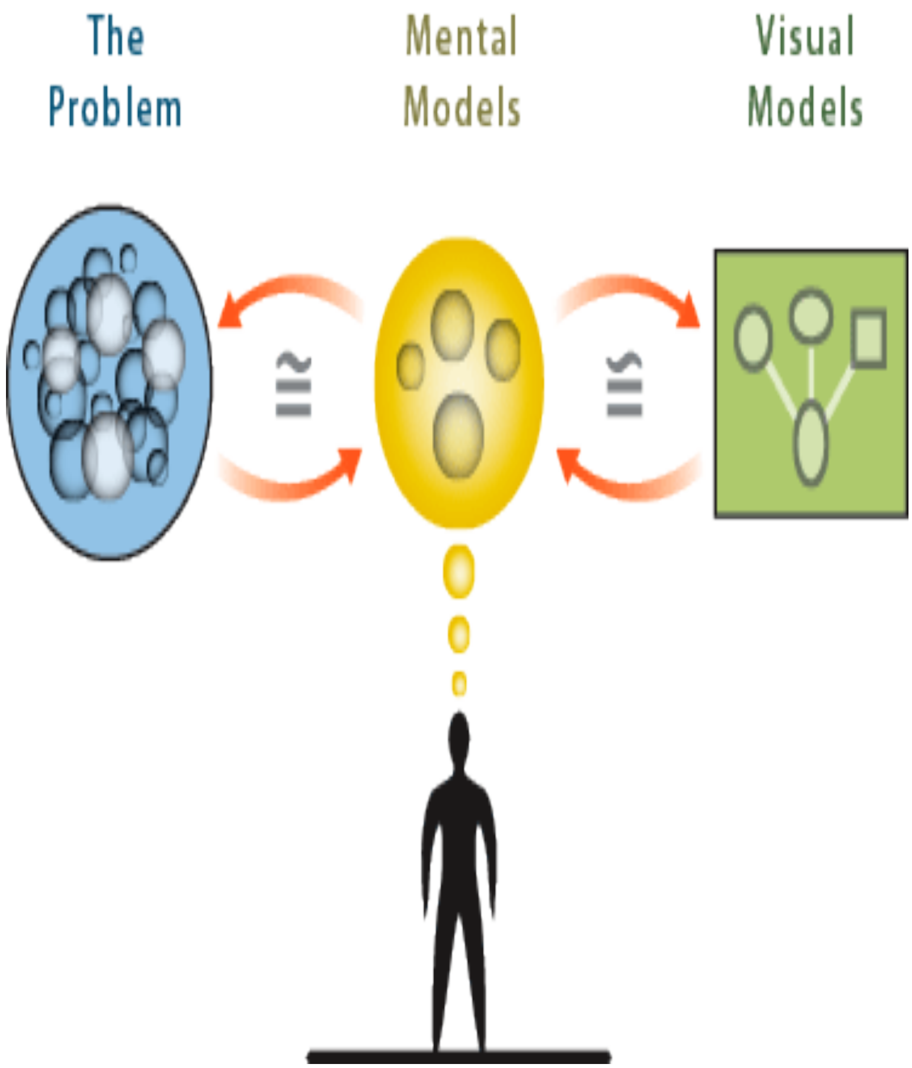

Figure 10. Thinking clearly.

Note: From "Idiagram" by M. Clemens, 2012, http://www.idiagram.com/ [Online] Available. Copyright 2012 by Idiagram. Reprinted with permission.

Clarify any complex issues hindering progress. A broader, clearer and deeper understanding appears with mapping the element of the problem and visual models guiding the system in need of change. By giving us a tangible model to work with, visual models can empower us to design more creative and effective solutions [53].

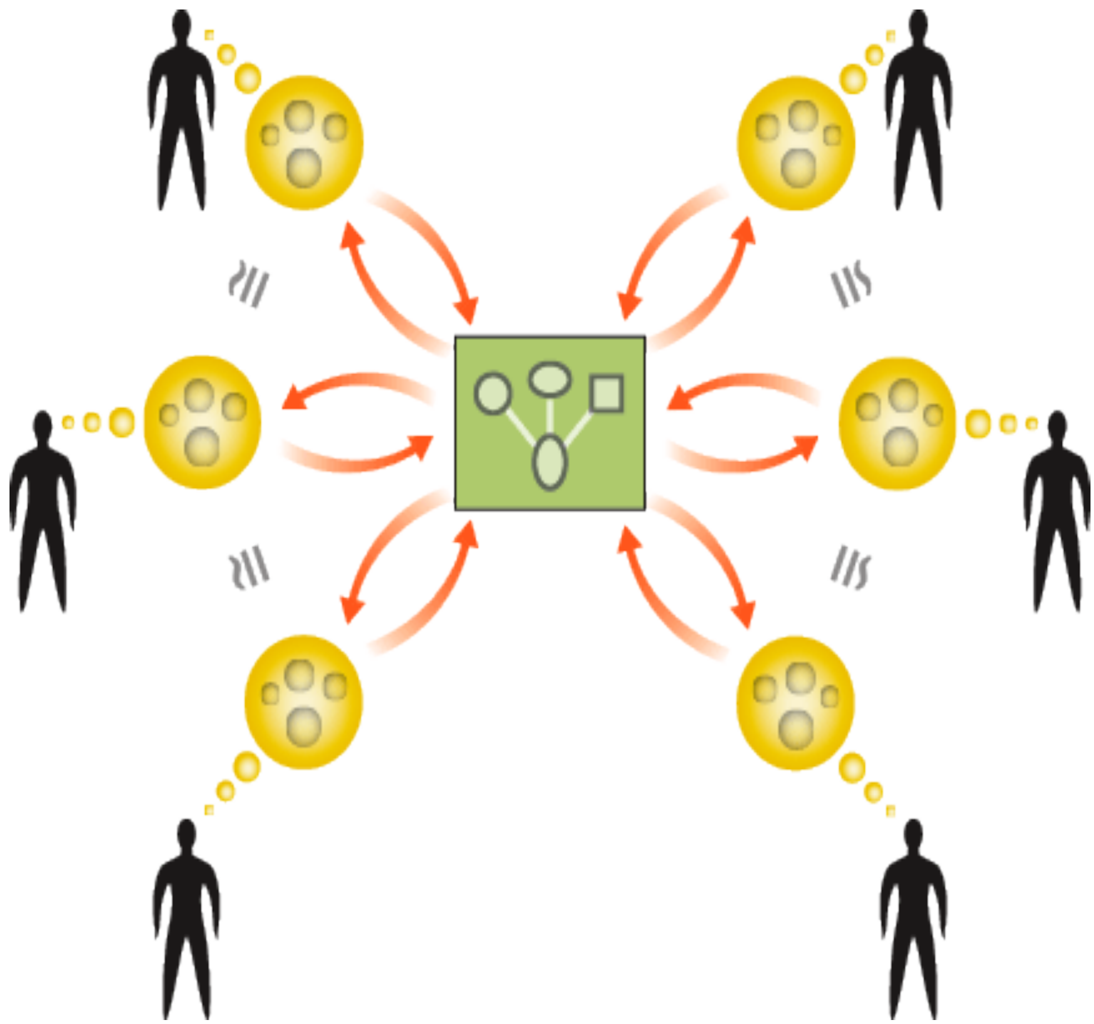

Figure 11. Think Together.

Note: From “Idiagram” by M. Clemens, 2012, http://www.idiagram.com/ [Online] Available. Copyright 2012 by Idiagram. Reprinted with permission.

Encourage teams to merge a logical and consistent picture of their diverse knowledge and perspectives. Visual models initiate more adequate conversations and offer a universal map of the issue. The process of visual modeling of thinking together supplies the group with a sense of teamwork, sharing their collective knowledge and encourages them to forge ahead with a mutual sense of understanding, ownership and purpose [53].

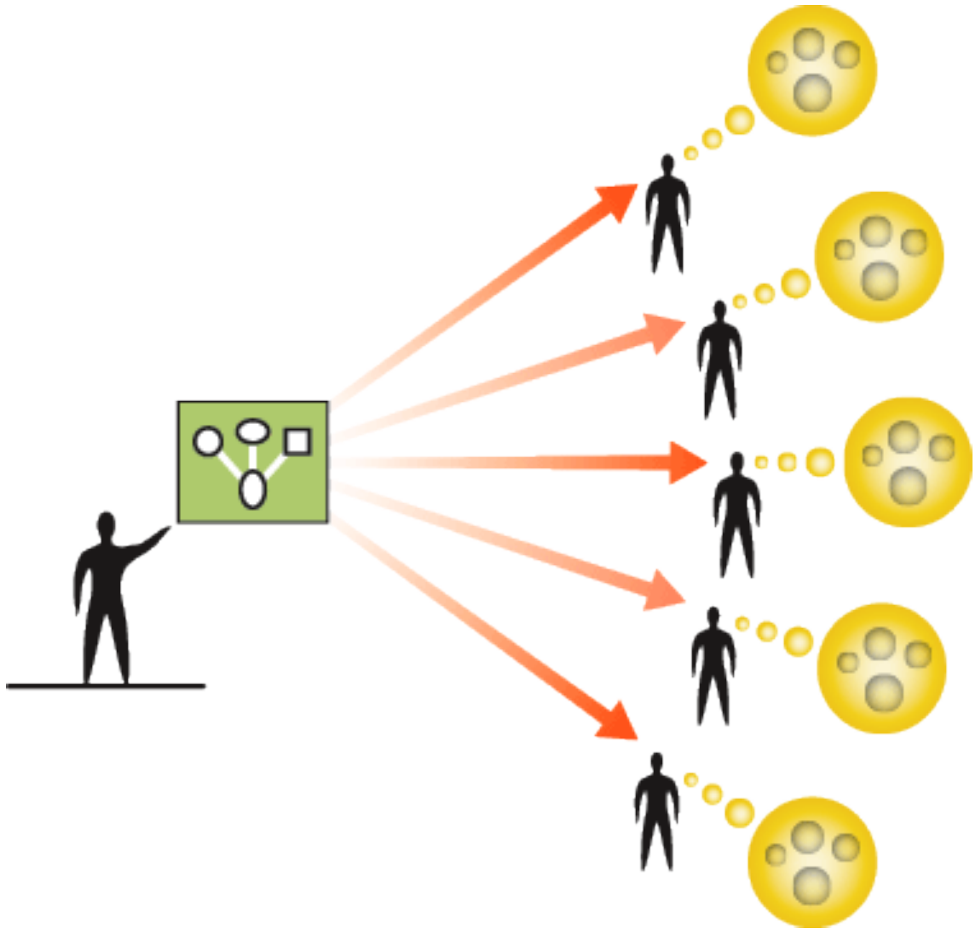

Figure 12. Communicate effectively.

Note: From “Idiagram” by M. Clemens, 2012, http://www.idiagram.com/ [Online] Available. Copyright 2012 by Idiagram. Reprinted with permission.

Depending on how well they are communicated; ideas can thrive or be eliminated. Visual stories assist in conveying your ideas in a simple and convincing way, if structured appropriately. Well-constructed graphs center the attention on ideas as visual concepts: creating images that take hold of core ideas [53].

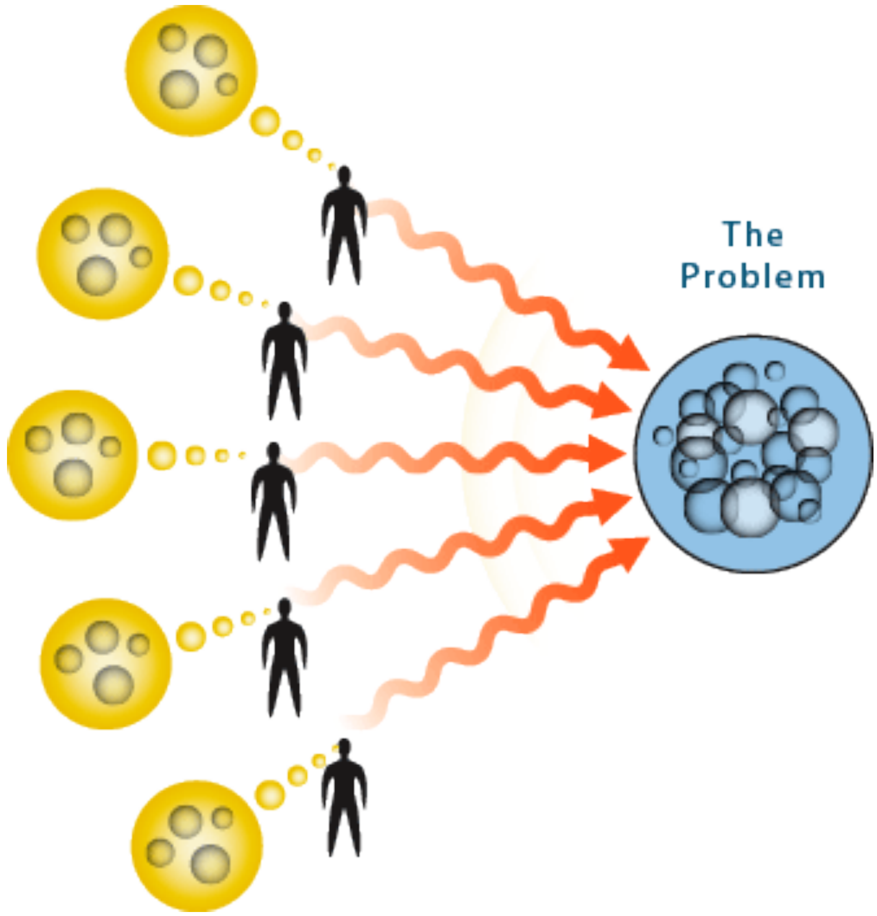

Figure 13. Generate shared vision and coherent action.

Note: From “Idiagram” by M. Clemens, 2012, http://www.idiagram.com/ [Online] Available. Copyright 2012 by Idiagram. Reprinted with permission.

Systems maps are means for building understanding and action, not ends in themselves. To inspire people to work toward the common goal with coherent action and self-organization, the group must share the vision. The source should be manageable and coherent action flows so a shared vision and common understanding of issues, goals and the means to achieve them is determined [53].

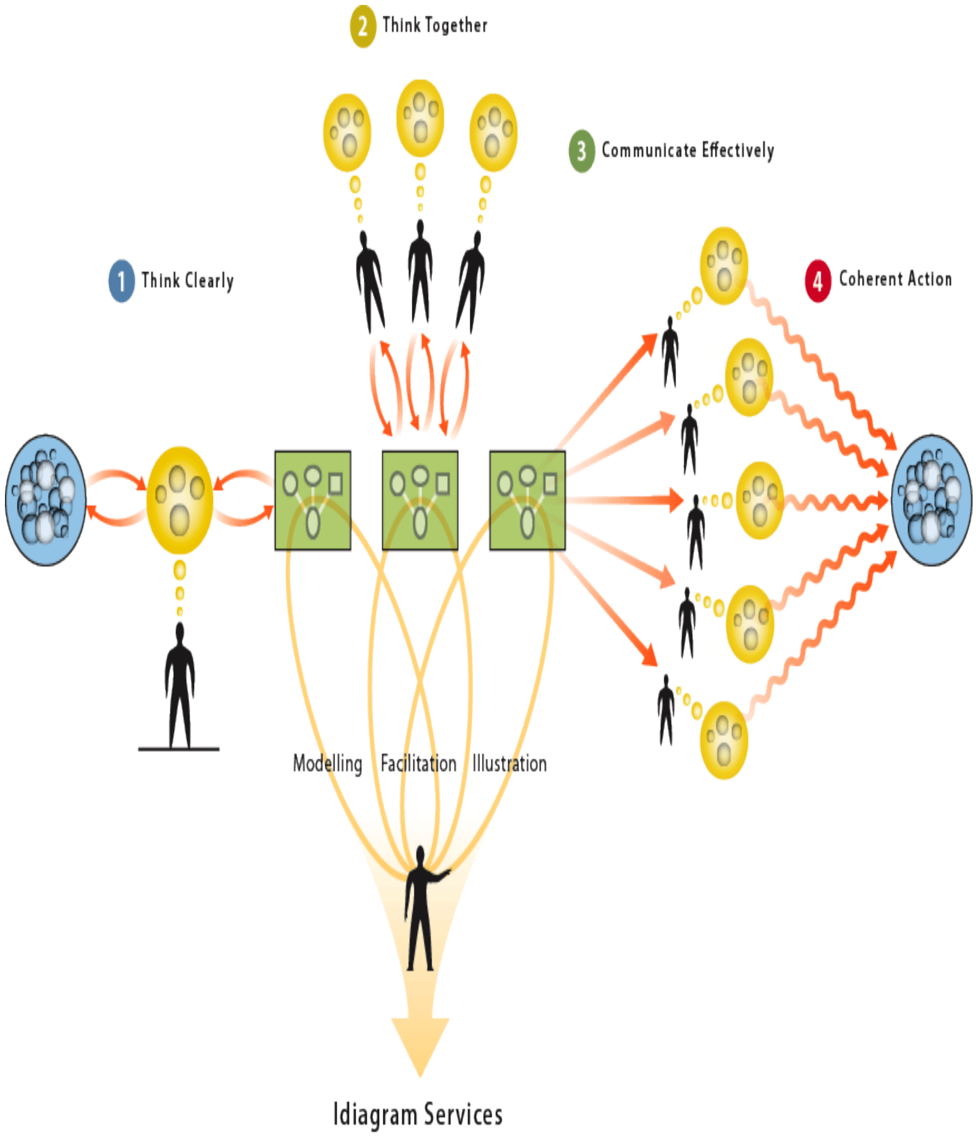

Figure 14. Put it all together.

Note: From "Idiagram" by M. Clemens, 2012, http://www.idiagram.com/ [Online] Available. Copyright 2012 by Idiagram. Reprinted with permission.

Idiagram services include research, systemic analysis, and mapping, facilitation of group strategic thinking, and design of communication materials. The function of Idiagram services is to provide the clients with thinking-partners on multifaceted issues and create multiple stakeholder involvement and alliance. Visual models contribute to knowledge and people coming together [53].

L. Conclusion

In Chapter II, an overview was provided of social computing. A definition of collaboration was given. Tag Clouds were reviewed, as a solution for social computing and an option for knowledge sharing and integration. Problem solving was defined. Characteristics were provided for complex problem solving and wicked problems. Alternate problem solving solutions were discussed in detail: (1) Deliberatorium, (2) DebateGraph, and (3) Idiagram.

III. INTRODUCTION TO TOPICS RELATED TO TRANSDISCIPLINARY PROBLEM SOLVING

In this chapter, core components of the TPSM are discussed. The following sub-sections introduce CSC, identifying its associated goals, traits, and tools. A brief overview of TdR as a mechanism for managing complexity is introduced. The ideas around transdisciplinary knowledge sharing, integration, and production are all developed. The validation metric used to ensure that shared knowledge is integrated correctly is discussed. This chapter ends with a discussion on conceptual models and concept maps. Each topic discussed in this chapter represents key components of the TPSM.

A. Introduction to Collaborative Social Computing

Collaborative social computing shifts computing and collaboration to the edges of the network, and empowers collaboration through social computing, which provides a promising alternative to the ad-hoc approaches that have previously facilitated the exchange of knowledge [40]-[42]. By combing collaborative and social computing a paradigm shift is manifested that provides a controlled exchange of knowledge and creativity. This paradigm shift fosters engagement in social interaction, contributions of expertise, sharing of content, the ability to collectively build new tools, and disseminate knowledge, as well as assimilates collective knowledge systems. Collaborative social computing represents a new research frontier for the sharing of knowledge systems.

This research allows collaboration that works to empower the scientific community with the ability for multidisciplinary or even transdisciplinary engagement [40] [41] [43]. Researchers from various disciplines would all have the ability to share and collaborate. Recent literature indicates that the creation of such an environment would improve innovation and transform scientific transdisciplinary problem solving by reducing the amount of time involved in solving complex research problems. Moreover, there does not exist an integrated mechanism that facilitates collaboration for knowledge sharing and data integration.

B. Common Traits and Goals of Collaborative Social Computing

Several common traits may be observed among collaborative social computing platforms that differentiate them from traditional computing and content sharing environments. CSC relies on the creation of communities that are structured horizontally. This horizontal structure is key to the way that content is driven. CSC relies on a loose structure that is highly adaptive, yet inherently creative, which is optimal for the dynamic and continual refinement that is necessary with online content. This dynamic nature is an important characteristic because it creates communities enveloped by shared interest [38].

CSC expands the organizational boundary to be much more fluid, often spanning multiple communities, and on occasion anchored around a single individual or an associated interest group. Ideas are cross-fertilized, and collective knowledge is developed, creating an environment that is ripe for collective intelligence and innovation. Altruistic and community-oriented motivational factors act as dominant behavioral drivers behind community building, which bring people and information together in constructive ways [38]. Table 12 outlines the common traits of CSC by displaying a direct comparison between the attributes of traditional versus collaborative methods of interaction [44]. Table 13 list provides a list of collaborative social computing communities (CSCC), along with their descriptions [93].

TABLE 12

COMMON GOALS & TRAITS OF COLLABORATIVE SOCIAL COMPUTING

Attribute	Traditional	Collaborative Social Computing
Organization	Most Centralized	Mostly decentralized
State	Less dynamic	Highly dynamic
Membership	Relatively static	Highly transient
Structure	Well defined	Minimal, loosely defined
Scope	Organization	Fluid boundaries, overlaps with other stakeholders like customers
Preference knowledge	Limited content	Rich content, enhanced by dissemination structures and peer influence mechanisms
User identity	Limited mobility	Highly mobile
Scalability	Limited	Very high
Content	Relatively static	Rich and highly dynamic
QA	Standardized procedures	Peer feedback, unstructured
Developments tools	Mostly proprietary, require expertise	Mostly open-source, easy-to-use, lightweight
Interoperability	Limited	Highly interoperable
Portability	Limited	Highly portable
Reusability	Limited	Can be integrated with other applications/networks to create new systems
Focus of control	System-level	Close to user
Ease of use	Relatively low	High

Note: Adapted from "Research Issues in Social Computing" by M. Parameswaran and A. B. Whinston, 2007, *Journal of the Association for Information System, 8:6,* p. 338. Copyright 2007 by JAIS. Adapted with permission.

TABLE 13

COLLABORATIVE SOCIAL COMPUTING COMMUNITIES (CSCC)

CSCC	Website	Description
Open Biomedical Ontologies	http://www.obofoundry.org/	The OBO Foundry is a collaborative experiment involving developers of science-based ontologies who have established a set of principles for ontology development with the goal of creating a suite of orthogonal interoperable reference ontologies in the biomedical domain.
National Cancer Institutes	http://www.cancer.gov/	A component of the NIH, NCI conducts and supports research, training, health information dissemination, and other programs with respect to the cause, diagnosis, prevention, and treatment of cancer, rehabilitation from cancer, and the continuing care of cancer patients and their families.
W2C Health Care Life Sciences Interest Group	http://www.w3.org/2001/sw/hcls/	HCLSIG is chartered to develop and support the use of Semantic Web technologies and practices to improve collaboration, research and development, and innovation adoption in the of Health Care and Life Science domains.
Biomedical Informatics Research Network	http://www.nbirn.net/	Among other things, BIRN hosts a collaborative environment rich with tools that permit uniform access to hundreds of researchers seeking to advance diagnosis and treatment of disease, enabling communication and cooperation on multi-institutional investigations.
CTSA Informatics Community	http://www.ctsaweb.org/index.cfm	The CTSA is a consortium that is transforming how clinical and translational research is conducted, ultimately enabling researchers to provide patients with new treatments more quickly and efficiently.
Neuroscience Information Framework	http://neuinfo.org/	The NIF enhances neuroscience research by enabling discovery and access to research data and tools worldwide.

The term social computing incorporates the idea of computer-mediated interaction. The social impact of such interaction within the Internet is tremendous, not only for connecting individuals, but also for connecting their knowledge. Table 14 depicts the goals of collaborative social computing.

TABLE 14

GOALS OF COLLABORATIVE SOCIAL COMPUTING

Description
Initiating new ways of knowledge transfer.
Information centric.
Simulated knowledge system environment.
Group collaboration.
Reflective collaboration.
Collation of knowledge systems.
Virtual environment.
Social engagement.
Community building.

C. Collaborative Social Computing Tools and Components

The next generation of new applications and services that facilitate collective action and social interaction can be categorized as collaborative social computing tools and components (CSCTC). These applications tap into social intelligence via a rich exchange of multimedia information and evolution of aggregate knowledge [94] [95]. CSCTC seek to present knowledge within a unified data processing model in which services, processes and people collaboratively gather and work on collective intelligence. The tools and components of CSC are categorized by technologies that include Web 2.0, online communities and social computing. Examples include blogs, wikis, social bookmarking, peer-to-peer (P2P) networks, open source communities, image and video sharing communities, and online networks [44] [94]. CSCTC build on a number of critical capabilities found in Service Oriented Architecture, Event Driven Computing, and Structured Data Management.

Although the collaborative model overlaps a number of disciplines, it is not an architectural style or an approach to system design. Rather, the term defines a paradigm that incorporates aspects of social computing and personal collaboration tools into a unified data processing model. These virtual worlds and the Web are pushing social computing into cyberspace and closer to full realization of the augmented human intellect and social behavior [3] [4] [29] [39] [69]. Table 15 divides the evolution of CSC in three distinct phases, which encompasses a wide range of CSCTCs.

TABLE 15

THE EVOLUTION OF COLLABORATIVE SOCIAL COMPUTING

1st Phase	2nd Phase	3rd Phase
e-Mail	Virtual workspaces	Blogs
Calendar	Enterprise portals	Wikis
Group scheduling	Instant messaging	XML feeds (RSS, Atom)
Network file shares	Presence	Tags & social bookmarks
Discussion forums	Web conferencing	Social networks
Groupware	P2P systems	User-generated content/media
Audio conferencing	Search	Virtual worlds
Video conferencing	Content management	Life streaming Reputation systems Open source software Synchronous editors Asynchronous editors

D. Using Transdisciplinary Research to Manage Complexity

Attempting to manage problems with a high level of complexity requires that the problem solving approaches are able to deal with both interlinked processes and multiple social perspectives. The complexity of a transdisciplinary problem is identified by both social and scientific problems that are intertwined. This is why TdR is more about the sharing and integration of transdisciplinary knowledge to produce high quality transdisciplinary knowledge production (TKP). This knowledge trajectory is used to solve the problem through the creation of collective intelligence that consists of the culmination of various knowledge systems and disciplinary knowledge that all work together to lessen the complexity. In the TPSM, transdisciplinarity is used as an approach to complex problem management, shifting the focus away from the entanglements of the problem itself, but rightly focusing on KS and KI to facilitate the appropriate KP. Moreover, the TPSM uses transdisciplinary approaches that exploit collective processes that facilitate dialogue across knowledge systems, and holistic, contextualized frameworks [47].

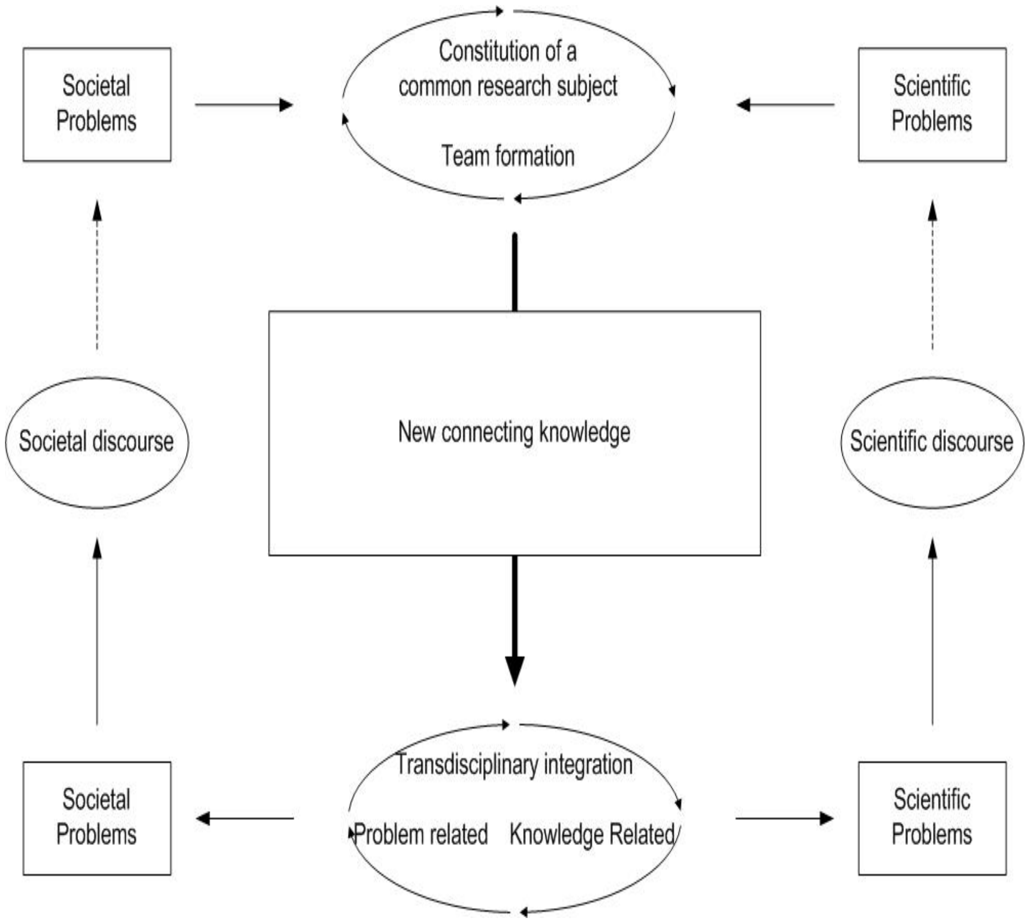

Figure 15. Transdisciplinary Integration Model

Note: Adapted from "CITY:mobil: A Model for Integration in Sustainability Research. In G. Hirsch Hadorn, H. Hoffmann-Riem, S. Biber-Klemm, W. Grossenbacher-Mansuy, D. Joye & C. Pohl, et al. (Eds.), *Handbook of transdisciplinary research*" by M. Bergmann and T. Jahn, 2008, *Handbook of transdisciplinary research,* p. 89. Copyright 2008 by Springer. Adapted with permission.

Figure 15 shows the flow of information TKI model. Notice how transdisciplinarity evolves to deal with both complex societal problems and scientific problems in parallel. Any solution requires broad KS and KI across multiple research disciplines, communities, civil society, and governments [47]. TdR already recognizes the need to include multiple knowledge spheres for managing complexity and finding solutions [47]-[49]. This inclusion includes three key sources of knowledge: (1)

knowledge experts from academia, (2) knowledge experts from non-academia and (3) stakeholders. Transdisciplinarity manages complexity by ensuring effective participation among all members of the transdisciplinary team. As depicted in Figure 16, effective participation is achieved by transgressing the boundaries between groups. Transdisciplinary approaches do this by first recognizing the complexity and then using KS and KI techniques to produce knowledge for decision-making and action as part of the problem solving process [47][50][96].

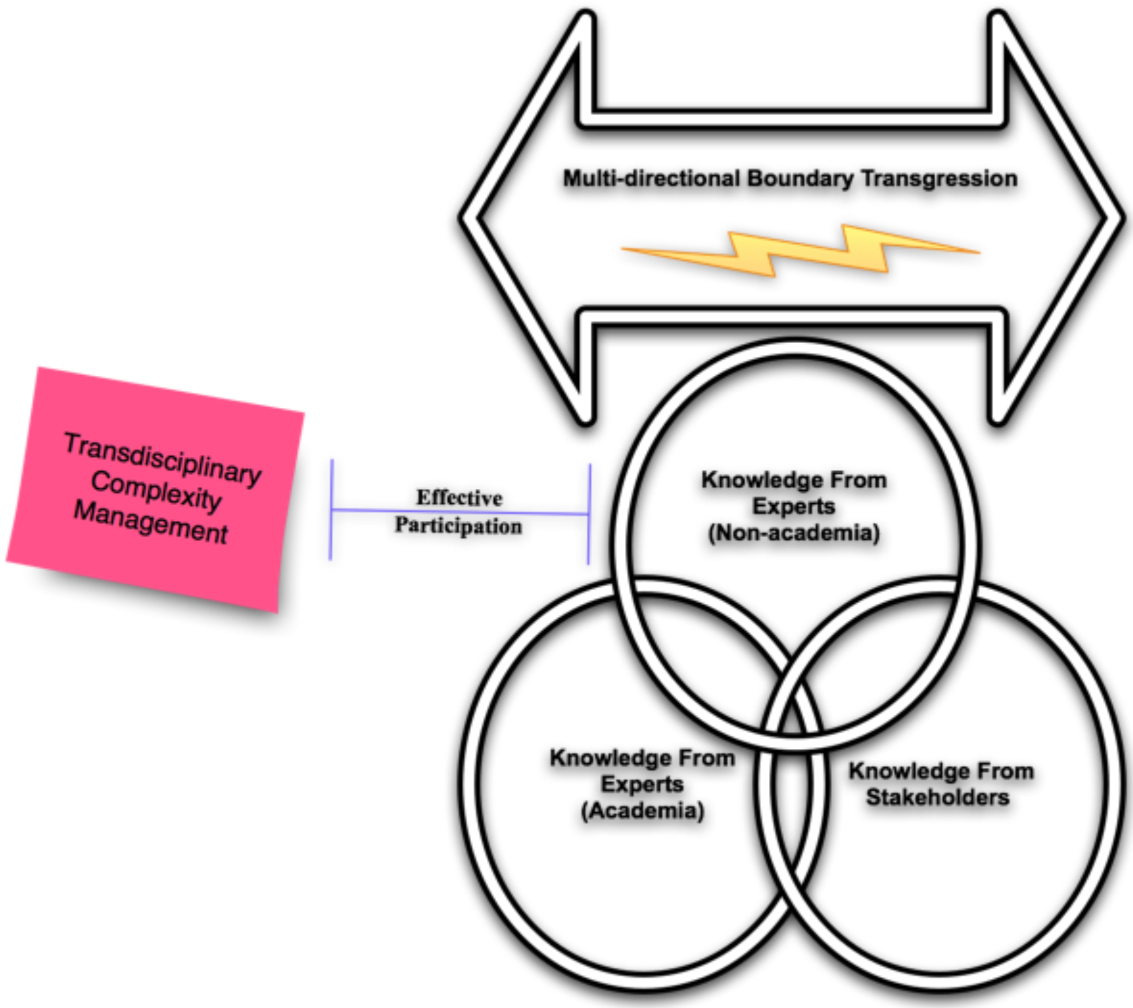

Figure 16. Boundary transgression in knowledge spheres.

There are three primary factors involved in using transdisciplinary research methods to manage problem complexity; the research is problem driven, the focus is on KS and KI as a means of creating multi-directional participation across the recognition knowledge spheres when dealing with complex problems, and the creation of effective participation amongst all members of the transdisciplinary team [47][51][52]. The goal of TdR is to address the knowledge demands for both societal problems and scientific problems congruently. These two concepts should not be addressed in isolation. TdR therefore has the metric of KP as the key metric of absolution.

TdR is intended to overcome these obstacles of problem complexity that are often introduced through the use of one-dimensional, discipline-bound research. Specifically, the reasons for using TdR can be summarized as follows [97] [98]:

- to answer complex questions;
- to address broad issues;
- to explore disciplinarity and professional relations;
- to solve problems that are beyond the scope of any one discipline;
- to achieve unity of knowledge, whether on limited or grand scale.

E. Transdisciplinary Knowledge Integration

Transdisciplinary knowledge integration (TKI) is composed of the integration of people, knowledge and artifacts that pertain to different scientific and non-scientific knowledge domains [99]. Before TKI can occur, a transdisciplinary assessment (TA) must take place to determine the quality of knowledge inputs [100]. Traditionally, knowledge integration suffered from knowledge loss because its primary goal was to simply make a single quantitative whole. However, TKI seeks to acknowledge the diversity of the transdisciplinary knowledge, thus acceptable and appropriate tradeoffs are constructed. Additionally, the TA seeks to establish meta-concepts to create a shared language or glossary. Again, special care is taken to ensure that the diversity of knowledge is represented by the inclusion of all concepts. The shared glossary is a tool that is created to enhance understanding; therefore, all relevant concepts are included. Moreover, this ensures a complete understanding is formed across the transdisciplinary knowledge realm.

After the completion of the TA, TKI, which is distinguished within three formal dimensions, occurs as the illustrated in Table 16 [101]:

TABLE 16

THREE DIMENSIONS OF KNOWLEDGE INTEGRATION

Dimensions of Transdisciplinary Knowledge Integration	**Attributes**
Social Integration	Integration of the members of the transdisciplinary team. Here the transdisciplinary team seeks to integrate interest, motivations and goals that are present and need to be considered. Members of the transdisciplinary team must have formal interaction.
Cognitive or knowledge integration	Integration of the transdisciplinary team's participants into a single knowledge base. The heterogeneous knowledge from the different domains, various concepts, perceptions, and theories used to create explanations and methods must be combined into an adequate methodology.
Technical integration	Integration of artifacts that are/have been produced by the transdisciplinary team. Transdisciplinarity calls for (1) inclusive experimentation; (2) joint papers; (3) joining of data; (4) and/or computer systems.

F. Transdisciplinary Knowledge Sharing

Transdisciplinary knowledge sharing (TKS) is a concept that illustrates unobstructed knowledge flow. TKS is rooted in CSC, with the goal of delivering proper alignment and a seamless flow of knowledge between groups [103]. TKS is about the facilitation of group learning, through sharing, into usable ideas, products, processes, theories and methodologies [102] by using CSC mechanisms. Table 17 [105] compares common KS behaviors with KS that is CSC centric. Notice that the use of TKS strategy implies a focus on KS that is directed towards complex problem resolution. TKS is an extension of contemporary KS. TKS is based on multi-agent theories of learning and communication. TKS in itself offers a more robust form of KS because it facilitates the transfer of knowledge from the knowledge source: person-to-person; person-to-group; person-to-document; group-to-document; and group-to-group, to recipient of knowledge via CSC. The efficacy of TKS depends on not only the social environment but also the source of knowledge, ability of recipient & type of message [104].

There are two major KS approaches or strategies. Most KS behaviors are based on one of the two strategies. These approaches are formalized as codification and personalization [103]-[105]. The codification strategy offers a formalization of explicit knowledge. The expression of codified knowledge can be difficult representing processes, which allow knowledge to be documented, and objective [104]. The personalization strategy, on the other hand, offers the formalization of tacit knowledge, which is based on direct person-to-person interactions [104]. TKS offers a strategy that formalizes by codification and personalization congruently, therefore, creating a cross association between explicit and tacit knowledge.

TABLE 17

KNOWLEDGE SHARING BEHAVIORS COMPARED TO TKS

	Written contributions	Organizational communications	Personal interactions	Communities of practice	Transdisciplinary Knowledge Sharing
Channel	Person-to-document, for example posting ideas to online database	Person-to-group (social), for example, brainstorming meetings	Person-to-person (social, informal), for example talking face-to-face over lunch	Person-to-group (social, informal), for example, meeting with community members to discuss problems	Person-to-group, Person-to-document, Person-to-person, Group-to-document, Group-to-group, (social, informal, formal) uses social computing mechanisms
Motivation	Extrinsic: high Intrinsic: moderate	Extrinsic: high Intrinsic: moderate	Extrinsic: low Intrinsic: high	Extrinsic: moderate Intrinsic: high	Extrinsic: high Intrinsic: high
Rewarding strategy	Individual rewards	Rewards at both individual and team levels	Procedural and distributive fairness of rewards	Intrinsic rewards such as building relationships with colleagues	Intrinsic rewards based on solving complex problems
Affecting factors	Knowledge sharing rewards	Commitment to the organization	Personal networks and relationships	Trust between two parties	Based on complex problem resolution
Knowledge shared	More explicit	More tacit	More tacit	More tacit	Both explicit and tacit
Knowledge sharing strategy	Codification strategy	Personalization strategy	Personalization strategy	Personalization strategy	Personalization and Codification strategy

By expanding traditional KS with CSC, TKS enables empowers KS by combining the once separate paradigms codification and personalization, into a unified knowledge system. However, it is important that these two strategies may only be integrated in socially conducive environments. Because of the complexity level of TdR, both strategies are needed, since TKS eliminates the normal technological tension that usually dominates the interpersonal dynamics reflected in KS [104].

TABLE 18

KNOWLEDGE SHARING DOMAIN COMPARISON

Knowledge Sharing Domains	Attributes
Fundamental or basic research, also termed classic or Mode 1 research	Knowledge sharing is highly systemized and organized along disciplinary lines. The primary function of the knowledge sharing is to conduct scientific investigations that primarily serve the advancement of understanding rather than the saving of specific problems.
Applied or Mode 2 research (Transdisciplinary Knowledge Sharing)	Knowledge sharing is transdisciplinary, heterogeneous and directed at solving complex problems. Knowledge sharing is driven by the desire to achieve knowledge production. The perception is that the knowledge is useful and highly contextual. Successful knowledge sharing requires a process and design phase in which the knowledge is packaged to address the needs of potential adopters.
Policy formulation and strategy development	A domain of knowledge sharing that includes statements of intent, operating principles, frameworks, guidelines, plans and desired outcomes at various levels of centralization and/or decentralization. In this domain, knowledge sharing requires a lot of synthesis of inputs from many domains, while meeting high adoption and diffusion needs. The knowledge base must be well codified (made explicit) for the implementation to be successful.
Operational management	A knowledge sharing domain that combines explicit-tacit knowledge domains that deal with infrastructure and organizational capability. Explicit knowledge comes in the form of guidelines and manuals. Tacit knowledge is based on experiential learning and verbal sharing of good practice and failures.
Local communities "own" local, indigenous or traditional knowledge	A knowledge sharing paradigm that evolves over time though generations of hands-on learning while meeting day-to-day challenges. This knowledge is transferred over time in folklore, societal norms, management systems, and social memory.

Using KS enabled technologies, such as intranets, knowledge repositories, and databases, which are emphasized by codification to be intertwined by social networking.

By socializing KS, individuals, groups, and organizations are more knowledge connected using both personalization and codification strategies combined. This idiom is true, as long as KS occurs in the correct KS domain as depicted in Table 18.

G. Transdisciplinary Knowledge Production

TdR research is more than the pure interaction of different research and/or societal partners, but it remains a research activity. TKP is a characteristic of TdR. At an abstract level, TKP is a new paradigm in KP, which signifies knowledge that is socially trusted, application-oriented, transdisciplinary, and subject to multiple accountabilities [113]. TdR contains processes of knowledge creation, application, and reflection, as well as feedback to science. These processes go hand in hand and mutually influence each other.

In [114] Bereiter and Scardamalia formalized two theoretical models of the composing process, the knowledge-telling model, and the knowledge-transforming model [114][115]. The knowledge-telling model is a formalization of knowledge generated through written text. The basic steps include the mental representation of a written task, the generalization of topic identifiers, and the use of these topic identifiers as contextual clues for information retrieval through the process of "spreading activation" [114][115]. Here writing down all ideas produces an exhaustive sum of knowledge. Congruently, identifiers are matched to tasks.

In the knowledge-telling model, connections between content elements and discourse knowledge are made. This increases the knowledge acquisition through content processing and discourse processing interaction [114][115]. TKP extends these two models to contents shared and integrated through CSC. By establishing project specific goals, and applying social computing interaction, knowledge creation takes on a new form. The knowledge production, therefore occurs as part of a two-step process that is formalized as part of the process depicted in Figure 17:

- Existing knowledge or discourse knowledge is used to develop a solution to a specific problem. This knowledge comes directly from the transdisciplinary team and is a by product of existing scientific knowledge. If this knowledge is shared and integrated correctly, the transdisciplinary team generates new knowledge in order to solve the complex problem. Existing knowledge must first be shared and then integrated where possible to produce newly generated knowledge to solve complex problems. The term is used here to underline that the solution of a complex problem does not automatically allow the results to be used to solve other problems of a similar kind.
- Generic knowledge is knowledge that is generally applicable to answer similar kinds of problems [116]. Science is interested in the nature and behavior of observable phenomena, which is amplified in the context of CPS. Therefore, true knowledge production seeks knowledge that has relevance and validity beyond a specific context. Through reflective processes, transdisciplinary teams expand existing methods and theories, generating newly defined methods and theories that may be applied to the problem in context. The transdisciplinary team draws conclusions of general relevance and in this sense develops generic knowledge. Generic knowledge is then pushed back into the science community in the form of a book or paper. This creates the natural expansion of TKP. The knowledge process creates a natural sharing of knowledge throughout the scientific

community, making it available for future complex problem investigation. Generic knowledge increases the knowledge base within the scientific community, broadening the knowledge applicable to societal problems. This further expands the flow of information depicted in Figure 17.

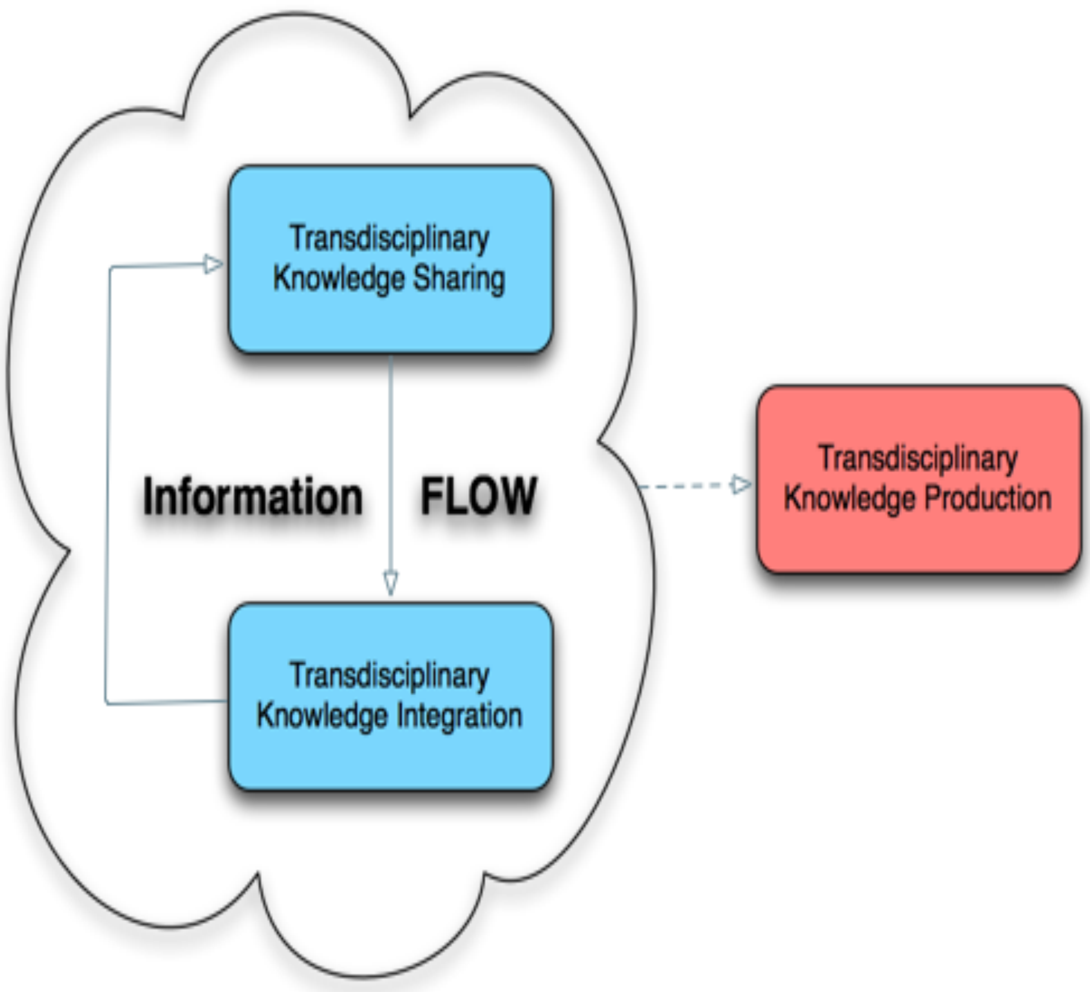

Figure 17. Transdisciplinary Information Flow

H. Logical Properties of Knowledge

In [112] Stulp and Verbrugge extended the knowledge based approach to the Transmission Control Protocol (TCP), which is a set of rules (a protocol) used along with the Internet Protocol (IP) to send data in the form of message units between computers over the Internet. In [110][111] Baars and Verbrugge extended the knowledge-based approach to create a multi-agent communication algorithm. The algorithm focused on knowledge and knowledge creation within a group operating in the framework of cooperative problem solving in multi-agent systems [111]. In their formalism agents are represented S (senders) and R (receivers) and the communication channel represents the environment [112].

The TPSM utilizes CSC or collaboration achieved through social computing techniques and tools. Therefore, the algorithm for multi-agent communication as formalized in [112] is applied to all knowledge and knowledge production in the TPSM. TPS calls for the use of a transdisciplinary team structure that includes multiple agents. The communication of knowledge is done within the context of shared dialogues with an emphasis on collective goal achievement. This follows the definition as defined in the subsection of Chapter II. Transdisciplinary knowledge sharing and integration requires several forms of communication:

1. Person-to-group,
2. Person-to-document,
3. Person-to-person,
4. Group-to-document (component of collaborative social computing),
5. Group-to-group (shared dialogue).

According to [112], each of these forms of knowledge distribution has local and shared states, actions, and protocols that can be modeled. These states form a global state in the Kripke model [112]. All of the knowledge relations are equivalence relations forming the well-known epistemic logic $S5_n^C$ [113][112]. Here are the axioms and rules of knowledge that are applied to transdisciplinary knowledge for $i = 1, \ldots, n$ [112]:

$K_i\varphi \subseteq K_i(\varphi \subseteq \psi) \subseteq K_i\psi$	(Knowledge Distribution)	(1)
$K_i\varphi \subseteq \varphi$	(Veracity of Knowledge)	(2)
$K_i\varphi \subseteq K_iK_i\varphi$	(Positive Introspection)	(3)
$\neg K_i\varphi \subseteq K_i\neg K_i\varphi$	(Negative Introspection)	(4)
From φ infer $K_i\varphi$	(Knowledge Generalization)	(5)

Here follow the axioms governing general knowledge $E_G\varphi$ (the knowledge φ is known by all members of transdisciplinary G) and common knowledge $C_G\varphi$ (φ is common knowledge amongst transdisciplinary group G). Let G ⊆ {1,…,n} [112]:

$E_G\varphi \subseteq \wedge_{i\in G} K_i\varphi$	(General Knowledge)	(6)
$C_G\varphi \subseteq E_G(\varphi \subseteq C_G\varphi)$	(Common Knowledge)	(7)
$C_G\varphi \subseteq \varphi$	(Truth of Common Knowledge)	(8)
From $\varphi \subseteq E_G(\psi \subseteq \varphi)$ infer $\varphi \subseteq C_G\psi$	(Induction Rule)	(9)

The full explanation of multi-agent communication is defined in [112] and used here with direct permission from Baars and Verbrugge.

I. Conceptual Model

In the transdisciplinary problem space conceptual models represent the mental model of how a process works. The conceptual model is explicitly chosen to be independent of design or implementation concerns, for example, concurrency or data storage. The aim of a conceptual model is to express the meaning of terms and concepts used by domain experts to discuss the problem, and to find the correct relationships between different concepts. The conceptual model attempts to clarify the meaning of various, usually ambiguous terms, and ensure that problems with different interpretations of the terms and concepts cannot occur. This allows specific relations to be tested for their correctness and completeness. Conceptual modeling uses notations such as UML or OMT to describe these mental models. With the TPSM conceptual models are used within the context of multi-agent communication for sharing and integrating knowledge within a team. This signifies the advances in the Internet, which has caused mental models to be more elaborate and complex. Now it is possible for conceptual models to contain huge amounts of diverse information. This possibility has stimulated a growing demand for understanding how to integrate multiple and heterogeneous conceptual models. However, this can add additional complexity to the task of creating conceptual models.

Because this can be true, the TPSM simplifies the process by making conceptual modeling part of the structuring and investigation of the complex problem. Conceptual models seek to express abstractions, while visualizing interoperability, modularity and dynamism within the problem domain. These qualities are particularly useful in that they can help to promote open systems, which are typically dynamic, yet predictable and highly heterogeneous [14]. In these types of application domains, the interoperability offered by the CSC enables a back and forth flow of knowledge. Furthermore, conceptual models are used to link or integrate theoretical frameworks across various disciplines. This makes their use a must within the TPSM because of their ability to describe individual components and interacts. Additionally, conceptual models provide a robustness and flexibility of the interfaces between both the disciplines and the problem space.

Each of the knowledge domains is likely to be characterized by different views of the world that are explicitly defined by discipline specific views of the complex problem. However, conceptual models offer a means of identifying explicit relationships and constraints [3]. Figure 18 shows a conceptual model that depicts the exploration, socialization and collaboration of knowledge within the framework of CSC.

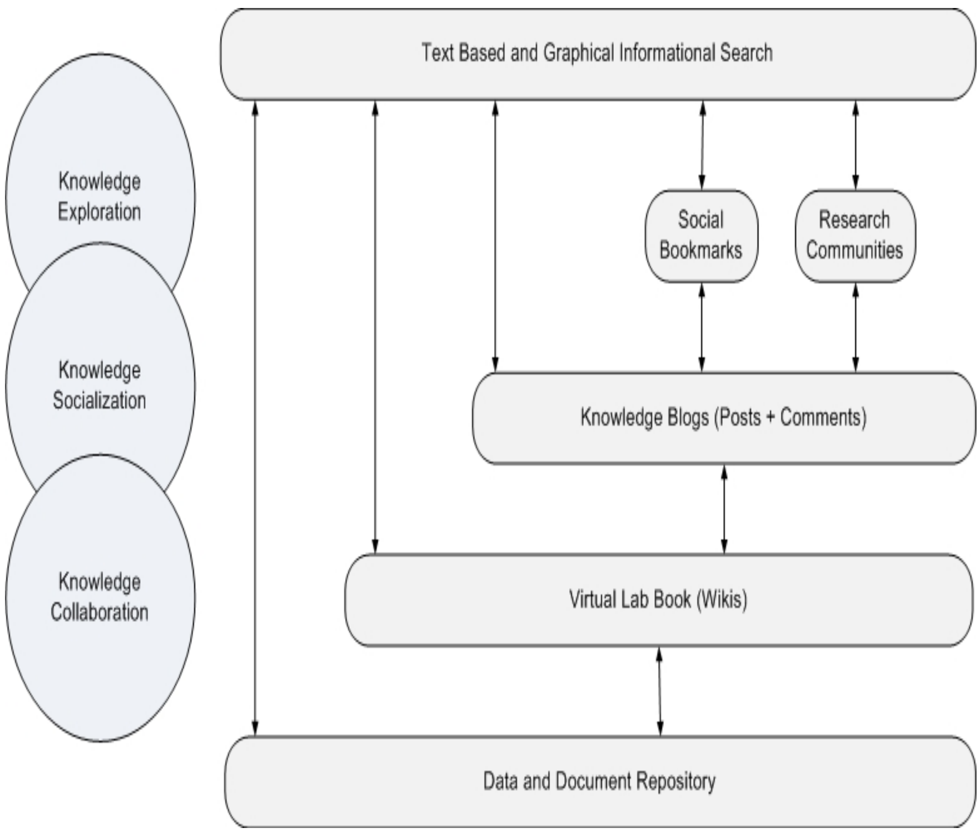

Figure 18. Knowledge collaboration within virtual communities

In a conceptual model, associations between knowledge sources enable an organic vetting of domain specific depictions of ideas. These conceptual models can be diverse in nature, making the embedded knowledge sources within the models dynamic. The merging and integration of diverse conceptual models has to be accomplished, bearing in mind that some models may be incapable due to the vast differences in domain knowledge that exist. Additionally, this highlights the differences in disciplines and their ability to fully understand each other; therefore both syntactic and semantic inconsistencies can arise and thus need to be reconciled.

The following list provides a detailed explanation for using conceptual models:

1. Conceptual models allow the development of more detailed quantitative models.
2. Conceptual models are very effective for developing concrete ideas around obscure problems that are rooted in complexity.
3. Conceptual models enable the effective communication of detailed technical concepts by allowing them to be summarized in a non-technical way.
4. Conceptual models provide a physical background upon which the knowledge derived from various scientific disciplines can be integrated and shared.
5. Conceptual models increase understanding by enabling the development of ideas around obscure processes that are rooted in complexity, as well as displaying the links between these processes.
6. Conceptual models can help to identify gaps in knowledge and understanding.
7. Conceptual models help with decision-making and resource planning.

8. Conceptual models can facilitate participation between all members of a transdisciplinary team.

J. Concept Maps

A concept map is a diagram with hierarchical nodes, labeled with concepts. The nodes are linked together with directional lines and are arranged from general to specific. The concepts are linked using these names showing the connection between the concepts and ideas. In addition, arcs can be directional, i.e. one could use arrows instead of lines. Building concept maps is a way to examine how completely you understand the principles, and the relationships between a specific subject and the formal context. The following list represents the reasoning behind concept map use:

- A concept map is a graphical representation of existing knowledge that can be linked to new knowledge [106].
- Concept maps are tools for organizing and representing knowledge. They include concepts, usually enclosed in circles or boxes of some type, and relationships between concepts or propositions (indicated by a connecting line and linking word) between two concepts. Linking words on the line specify the relationship between the two concepts. [106]
- The arrangement of major concepts from a text or lecture into a visual arrangement. Lines are drawn between associated concepts, and relationships between the connected concepts are named. These concept maps reveal the structural pattern in the material and provide the big picture. [107]

- Concept mapping is a technique for visualizing the relationships between different concepts. A concept map is a diagram showing the relationships in between concepts. Concepts are connected with labeled arrows, in a downward-branching hierarchical structure. The relationship between concepts is articulated in linking phrases, e.g., "gives rise to", "results in", "is required by," or "contributes to". [106]

A Knowledge Soup is a mechanism that allows users to collaborate in the construction of individual concept maps. A Knowledge Soup on a particular topic is a collection of propositions from the various participants building concept maps on that topic. Users never see concept maps that are built by other users, but collaborate through shared propositions within the Knowledge Soup. Knowledge Soups have many applications. For example, collaboration by groups of scientists or other professionals, by accumulating the propositions from all participants, the Knowledge Soup becomes an aggregation of the knowledge of the participants [106][107].

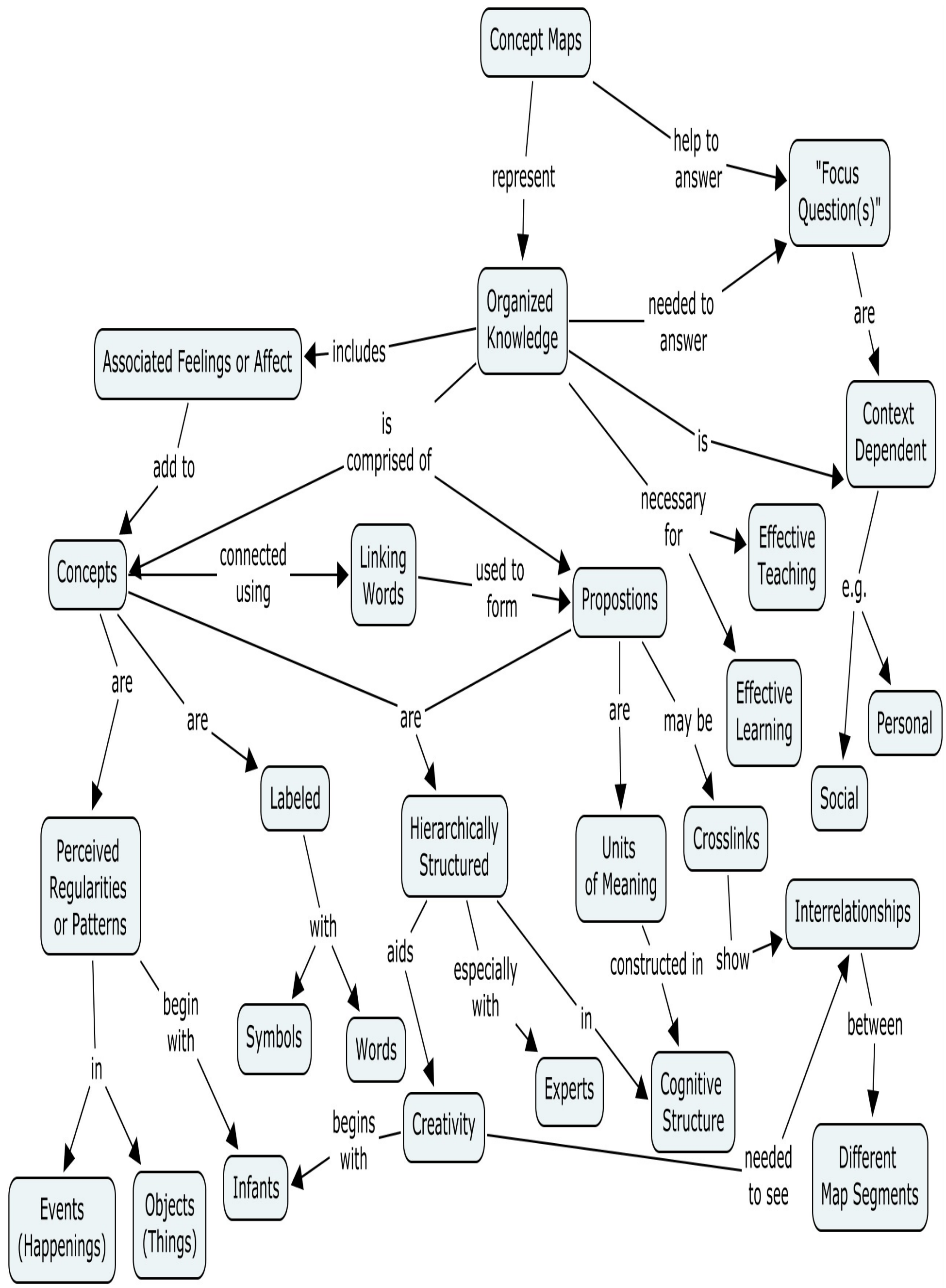

Figure 19. Concept map example.

Note: Adapted from "The Theory Underlying Concept Maps and How to Construct and Use Them" by J. Novak and A. J. Cañas, 2008, *Technical Report IHMC CmapTools 2006-01 Rev 01-2008, Florida Institute for Human and Machine Cognition,* http://cmap.ihmc.us/Publications/ResearchPapers/TheoryUnderlyingConceptMaps.pdf [Online] Available. Copyright 2008 by Florida Institute for Human and Machine Cognition. Adapted with permission.

K. Conclusion

In Chapter III, an overview was provided of CSC. A review was given of the traits and goals of CSC. The tools and components of CSC were introduced. An overview of how transdisciplinary research may be used to manage complexity was provided. A formal discussion of TKI, TKS, and TKP were given, along with the logical properties of knowledge. Finally, conceptual modeling and concept maps were introduced.

IV. TRANSDISCIPLINARY PROBLEM SOLVING MODEL

In this chapter, an in-depth explanation of the TPSM is provided. The TPSM outlines a guide for addressing the issues associated with crafting complex problems. The knowledge base is described as a means for dealing with TKS, TKI, and TKP. Also, the role of CSC as part of the model is explained along with a case study that demonstrates the model. The T^4 FUNDAMENTALS are aligned with their use within the TPSM. Figure 20 provides an overview of the TPSM and the components that are discussed.

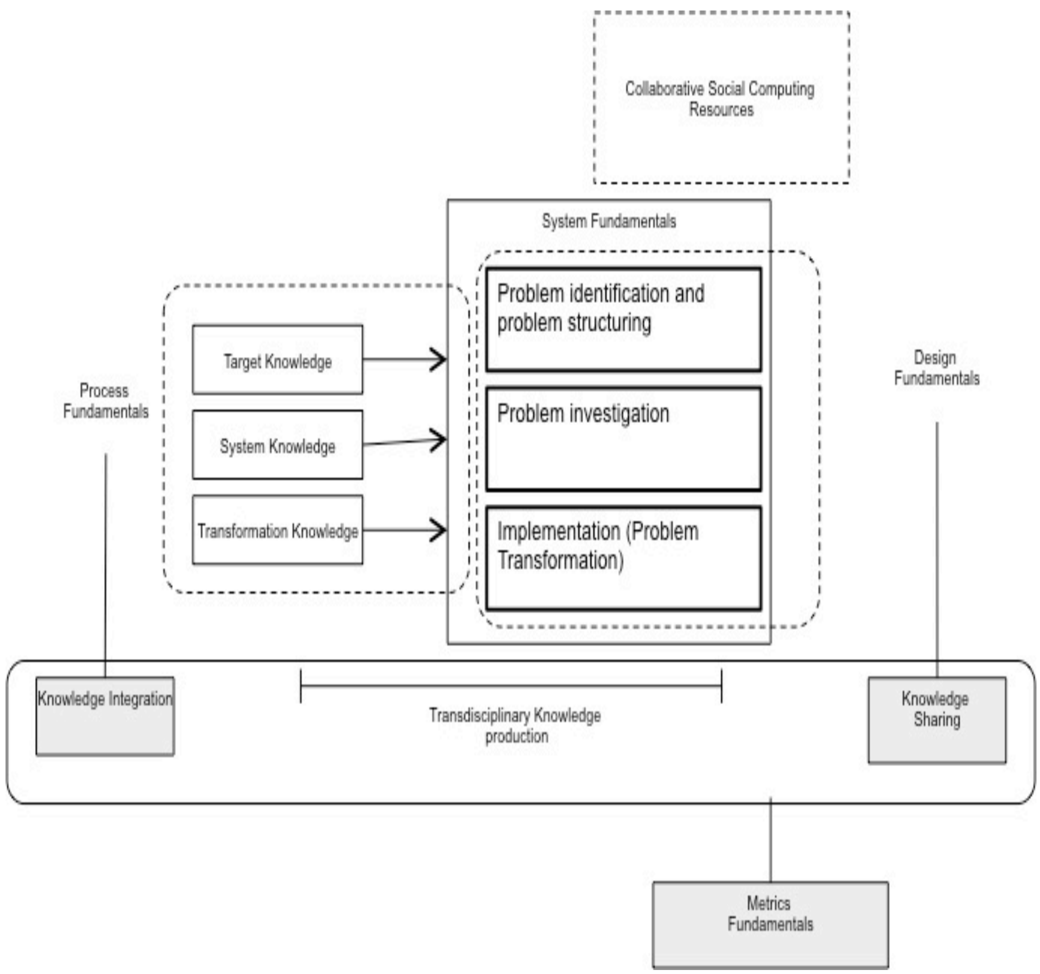

Figure 20. Transdisciplinary problem solving model.

A. Overview of the Dissertation Contribution

The TPSM outlines a model for addressing problems that cannot be solved by single disciplinary methodologies. Likewise, the complexity of transdisciplinary problems oftentimes requires thinking beyond science alone. First, transdisciplinary problem solving (TPS) is the scientific treatment of complex problems, which denotes real world connotations. This creates a challenge because the research design must be embedded into the real world context. Secondly, transdisciplinary knowledge management is crucial to the successful implementation of any solution that seeks to address CPS. People from different disciplines and from outside of science all possess unique knowledge about distinct aspects of the problem and need to collaborate to design and implement effective solutions.

TABLE 19

TRANSDISCIPLINARY FUNDAMENTALS.

T^4 FUNDAMENTALS	Explanation
System fundamentals	The integration of each system to form a larger system using System-of-systems principles.
Design fundamentals	Comparison of distributed model to the integrated model.
Process fundamentals	Identification of all processes and their points of integration within the integrated model.
Metrics fundamentals	Testing of all data and process integration.

Regarding the model's methodology and organization, the TPSM is defined within the scope of the T^4 FUNDAMENTALS (Table 19):

1. System Fundamentals
2. Design Fundamentals
3. Process Fundamentals
4. Metrics Fundamentals

These T^4 FUNDAMENTALS are the foundation that outlines the basic framework of the model. In each fundamental, special attention is paid to handling the sharing, integration and production of transdisciplinary knowledge. These tasks are cooperative and accomplished in the form of system knowledge, target knowledge and transformation knowledge.

Table 20 [15][55] provides details of the interdependencies between the three forms of knowledge.

1. Systems knowledge confronts the difficulty of how to deal with uncertainties. The difficulties in transferring the abstract model or theory to a concrete case with underlying specific conditions are a result of these uncertainties. Usually, the empirical or theoretical knowledge about a transdisciplinary problem is lacking, so depending on the accepted interpretation of the problem the uncertainties may be assigned different degrees of importance, which leads to a diverging TA of the need for action and of target knowledge and transformation knowledge. Uncertainty in the system knowledge can often be used to block attempts to transform a problem situation [55].

2. Target knowledge questions what the multiplicity of the social goals means for the research, form the society of practice-related problems and for transdisciplinary collaboration between science and actors [55].
3. Transformation knowledge establishes technologies, regulations, practices and power relations that must be taken into account when addressing the transdisciplinary problem. This constitutes what can be called the consequences of pragmatism, since options for change have to rely on existing infrastructure, current laws, and current power relations and cultural preferences, to be effective. These social, cultural and technological givens must be considered or a discrepancy between knowledge and practice will take place [55].

TPSM provides a sequential process for transdisciplinary problem solving. Table 21 illustrates the sequence or flow of a typical transdisciplinary project. The data/resource is the catalyst between some researchers while the social profile is the method for others. This model therefore has the potential to dramatically improve resource sharing and transdisciplinary scientific collaboration by bringing together both conventional and unconventional collaborations [17][18][19]. The TPSM aims to better align TKP to the societal needs for solving, mitigating or preventing problems. The TPSM strives to grasp the relevant complexity of a problem, taking into account the diversity of both the everyday world and scientific perceptions of problems, linking abstract and case-specific knowledge, and developing descriptive, normative and practical knowledge for the common interest. Intellectual control and structuring are vital to the model's ability to mitigate the deterministic chaos associated with TPS (Figure 21).

TABLE 20

INTERDEPENDENCIES BETWEEN THE THREE FORMS OF KNOWLEDGE

<table>
<tr><th>The Three Forms of Knowledge</th><th>Description</th><th>Research Questions</th><th>Challenge</th><th>Questions to help with Positioning</th></tr>
<tr><td>System knowledge</td><td>Knowledge of the current status or current state of understanding of knowledge</td><td>Questions about the genesis and possible development of the problem and about interpretations of the problem</td><td>Reflecting on and dealing with uncertainties with the help of real-world experiments</td><td>2, 3</td></tr>
<tr><td>Target knowledge</td><td>Knowledge about the target status</td><td>Questions related to determining and explaining the need for change, desired goals and better practices</td><td>Clarifying and prioritizing diverse perceptions of targets and values, taking into account the common good as a regulatory principle</td><td>1, 3</td></tr>
<tr><td>Transformation knowledge</td><td>Knowledge about how to make the transition from the current to the target status</td><td>Questions about technical, social, cultural, legal and other possible means to transform existing practices and introduce desired ones</td><td>Learning how to make existing technologies, regulations, practices and power relations more flexible</td><td>1, 2</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5">To what understanding of the genesis and possible development of a problem and life-world interpretations of it does the transdisciplinary problem question refer?</td></tr>
<tr><td colspan="5">To what kind of need for change, desired goals and better practices does the transdisciplinary problem question refer?</td></tr>
<tr><td colspan="5">To what technical, social, cultural, legal and other possible means of acting does the transdisciplinary problem question refer?</td></tr>
</table>

Note: Adapted from “Principles for Designing Transdisciplinary Research” by C. Pohl and G. H. Hadorn, translation by A. B. Zimmermann, 2007, *Swiss Academies of Arts and Sciences,* p. 38-40. Copyright 2008 by Swiss Academies of Arts and Sciences. Adapted with permission.

TABLE 21

TRANSDISCIPLINARY PROBLEM SOLVING MODEL

General Transdisciplinary Project	Steps in Collaborative Social Computing Approach	Knowledge types mainly involved in the specific step	Transdisciplinary Fundamental Involved in the specific step
Problem identification and problem structuring	Conceptual Modeling	Target knowledge System knowledge	System Fundamentals
Problem investigation	Concept Maps	System knowledge System knowledge	Design Fundamentals Process Fundatmentals
Implementation (Problem Transformation)	Multi-agent communication	System knowledge Target knowledge Transformation knowledge	Metric Fundamentals

Note: Adapted from "Constructing Regional Development Strategies: A Case Study Approach for Integrated Planning and Synthesis: A Case Study Approach for Integrated Planning and Systhesis. In G. Hirsch Hadorn et al. (Eds.), *Handbook of transdisciplinary research*" by A. I. Walter, A. Wiek, and R. W. Scholz, 2008, *Handbook of transdisciplinary research,* p. 228. Copyright 2008 by Springer. Adapted with permission.

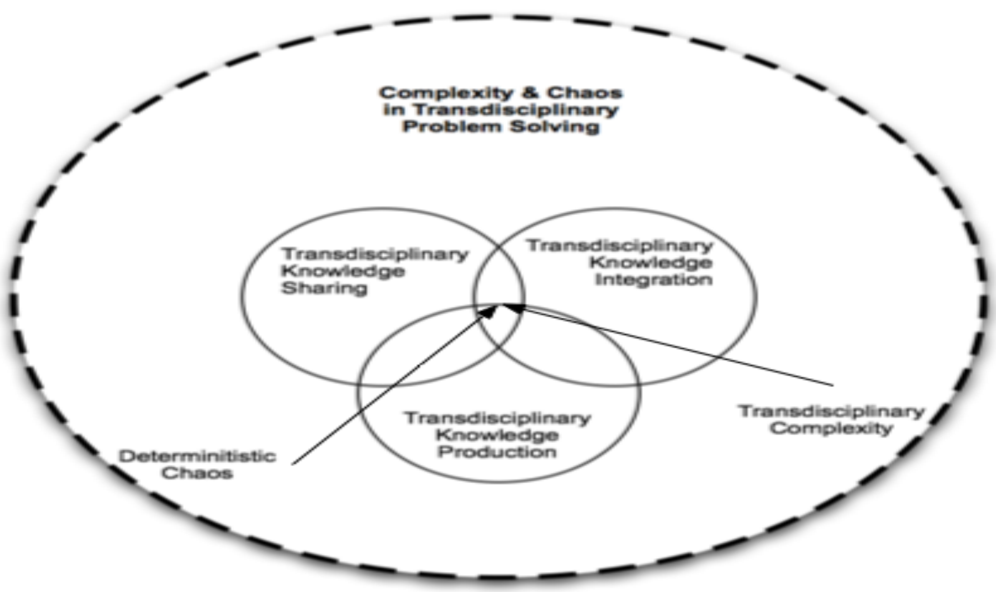

Figure 21. Transdisciplinary complexity and deterministic chaos associated with TPS.

B. Three Phases of Transdisciplinary Problem Solving

Due to complexity, TPS calls for a recursive approach, focusing on problem identification and structuring, problem investigation and problem transformation. The TPSM translates this recursive approach into the three phases of the TPS process (Table 22). The next three sub-sections will provide detail about the three phases used in the TPSM.

TABLE 22

THE THREE PHASES OF THE TPSM

The Three Phases of the TPSM	**Description**
Problem Identification and structuring	Define the problem, identify important aspects, and determine the research questions and who should be involved. Use conceptual modeling techniques to gain a clearer understanding of the process.
Problem Investigation	Knowledge from the transdisciplinary team is gathered and shared. This knowledge is then integrated into the knowledge base. Concept maps are used to operationalize the problem and knowledge space.
Implementation (Problem Transformation)	Produced knowledge is linked to an implementation and validated.

C. Problem identification and structuring

In problem identification and structuring, researchers and actors from the public or private sector or civil society jointly work on identifying and understanding the nature of specific problems in a problem field. A broad range of participants and competencies should be involved in order to frame and structure the unclear issues jointly, identify properly the relevant scientific disciplines and actors in the real world, evaluate the existing knowledge about problems in academia and in practical life, and learn about the needs and interests at stake. This information provides the knowledge base for problem solving, the questions that need to be addressed in research and the competencies required for the investigation of and deliberation about results [15].

For a given transdisciplinary problem, the first two components of the conceptual model are an attempt to properly understand the problem to be solved. Here the TPSM's use of the T^4 FUNDAMENTALS applies the engineering principles of system fundaments framing and viewing the transdisciplinary problem as a system. A transdisciplinary problem can contain several moving parts that will simply add to the chaotic nature the attempt to provide a solution. There the system fundaments seek to integrate part of the problem or system so that it can be conceptually described as a single system. Within- and between-concept systems the underlying problem structure is identified as a concept. The third component includes a variety of qualitatively different systems for representing these understandings–using written symbols, spoken language, static figural models like diagrams or images, manipulative models using concrete material. The idea is to get a complete real-world understanding of the transdisciplinary problem. The fourth component of the conceptual model contains processes for (a) changing the real situation to fit existing understandings, (b) changing existing understandings to fit the situation, and (c) changing the model to fill gaps, eliminate internal inconsistencies, and resolve conflicts within the conceptual model.

One outcome of problem identification and structuring could be that all the knowledge required for designing and experimentally implementing measures is already there and that phase three should be launched. Another possible outcome is that competencies and participants different from those initially expected are required, so the problem identification and structuring has to be repeated. Furthermore, problem identification and structuring, on the one hand, and problem analysis, on the other, can overlap. All this makes a recursive treatment of phases a more rational approach for achieving valid results than a sequential treatment.

D. Problem Investigation

In order to grasp the relevant complexity of relations in detailed problem analysis, the way in which diverse aspects and perspectives are integrated needs to be adequately understood. In addition, quality assurance of knowledge has to take into account mutual influences between systems knowledge, target knowledge and transformation knowledge, giving rise to conceptual, epistemological, and methodological uncertainties. Instead of defining standard conditions for idealisation, generalisation of knowledge has to be achieved by transferring models and methods from the context in which they have been developed to other contexts, while carefully validating the conceptions of each setting [15]. Therefore, problem analysis and bringing results to fruition are best conceived as recursive and integrated steps. For instance, in Held and Edenhofer's [15] development of integrated assessment methods for climate change mitigation, they combined approaches from natural science, economic growth theory, engineering, and ethics to identify climate policies that integrate both knowledge of the climate and economic systems as well as competing values of interest groups.

As part of the problem investigation phase, the T^4 FUNDAMENTALS require the utilization of the engineering principles associated with both the design and process fundaments. During the problem investigation phase, knowledge of the transdisciplinary problem is compiled from the transdisciplinary team. This knowledge is used to create concept maps based on the problem definition. Here concept maps are used to provide the following:

1. To operationalize the problem by integrating the heterogeneous knowledge of the transdisciplinary team [54].
2. To communicate the transdisciplinary problem.
3. To assess the understanding or diagnose the misunderstanding of the complex problem.
4. To define the process and flows of designated by the process fundamentals.
5. To share knowledge and understanding amongst the members of the transdisciplinary team.

The goal of operationalizing the transdisciplinary problem is to ensure that the transdisciplinary problem is clearly distinguishable or measurable and to make sure it is understood in terms of empirical observations. The design fundamentals require that a comparison be performed of distributed model and the integrated model. The design fundaments abstract the various parts of the problem definition that were collected during the problem identification and structuring phase. The design fundamentals are used to validate that the problem is being addressed in its entirety.

Additionally, during the investigation phase the process fundamentals are applied to identify all processes and their points of integration within the integrated model. This is a key engineering function that should be performed in an iterative manner. With each iteration the transdisciplinary team recognizes points where additional knowledge sharing and integration may be performed. Also, corrections are made to process points that may be deemed to be found to be incorrect later. Knowledge from this phase is maintained in repositories such as wikis that are linked to the concept maps. All knowledge should be represented on a node within the concept map.

E. Problem Transformation

Bringing the results to fruition, as a phase of the transdisciplinary process, also relies on the production of new knowledge. It is important the transdisciplinary team jointly learn about the strengths and weaknesses of problem solving strategies and develop competences for implementing and monitoring progress in order to be able to adapt strategies and purposes. This is important because two things must occur during the problem transformation phase based on TKP:

1. Metric fundaments are applied to validate the results. Validation is key because it ensures that appropriate action is taken to correct any errors in understanding and interpretation that may exist. If proper validation is not performed the results will not implement properly.

2. The newly produced knowledge must be communicated. Here the multi-agent communication metric is applied. This handles one-to-group transference of the knowledge base.

3. Lastly, an implementation plan is created that determines the direct and formal course of action that will be taken. This implementation plan should be prioritized so that it is not reduced to a list of desirable measures [54].

F. TPSM Utilization of Collaborative Social Computing

The TPSM uses CSC approaches to facilitate all KS and KI. Within the TPSM the CSC's approach is based on five core concepts, a set of five methods, and an overall framework for describing and planning sharing and integration. The concepts are:

1. a systems approach,
2. attention to problem framing and boundary setting,
3. attention to shared vision and shared vocabulary,

4. a sophisticated understanding of ignorance versus uncertainty to avoid knowledge uncertainty, and
5. understanding the nature of collaborations with respect to the CSC approaches that are applied.

The methods are dialogue-based, model-based, product-based, vision-based, and common metric-based. Collaboration must be measureable to be deemed effective. Using CSC technique processes to create the knowledge base is based on a focus of aims, process, actors, context, and outcomes. CSC is used to complement the transdisciplinary team by ensuring that information can be shared on a global scale, giving the transdisciplinary team the ability to make informed decisions, while making social connections with one another based on their common interests and goals. To facilitate these collaborations we have developed TPSM, which promotes collaboration in a manner that preserves the scientific process and interests while mitigating geographic and social barriers [32][35]-[39]. TPSM provides a centrist means for a transdisciplinary team to collaborate and share resources throughout the transdisciplinary development process. Social driven networking is combined with data driven categorization to facilitate collaborative based research (CBR), where collaborations are based on shared interests [17][20][21]. Figure 22 shows the transdisciplinary knowledge production model used in TPSM.

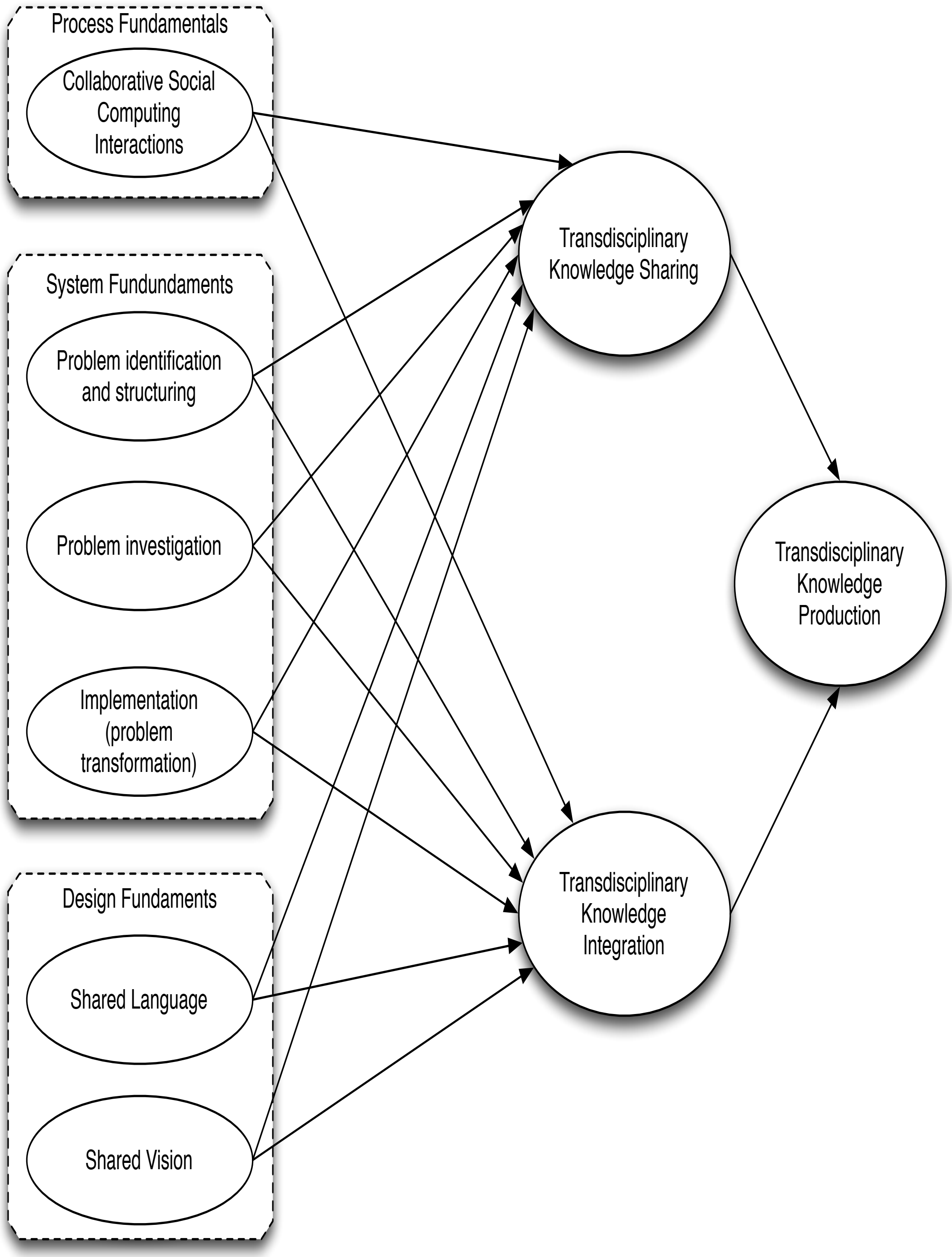

Figure 22. Transdisciplinary knowledge production in TPSM.

G. Case Study – Application Programming Interface (API) Manager

This section provides an in-depth discussion of the API Manager case study, which demonstrates and validates the TPSM. The API Manager case study represents a complex technical problem as characterized in Chapter I. The case study constitutes a real-world TdR project that was completed using the TPSM to provide intellectual control and structuring to the project, while reducing and managing complexity. Table 23 displays the multiple variables that were part of the case study.

TABLE 23

COMPLEX TECHNICAL PROBLEM ADDRESSED IN CASE STUDY

API Manager Case Study
Build an application programming interface (API) that enables the exposure of API(s) to Developers
Creation of a communication system that allows enablers (API developers) to collaborate and communicate with the developers using the API(s). API developers and API users should have a web based communication interface.
Provide an integrated API storage mechanism.
Provide an integrated application creation mechanism. Application development to be open source and social allowing other developers to install and use and extend existing applications.
Backend High Availability (HA) failover database replication solution.
Solution should operate within multiple datacenters.
Solutions should be built using cloud infrastructure.
Infrastructure management should be automated.

The structure of the transdisciplinary team is depicted in Figure 23, along with the elements of the TPSM. Table 24 that follows illustrates the organization of the expert members of the transdisciplinary team and their functions. Figure 19 below shows the CSC wikis, diagrams, online chat, concept maps, and flows. Notice how KS and KI iterate through the TPSM.

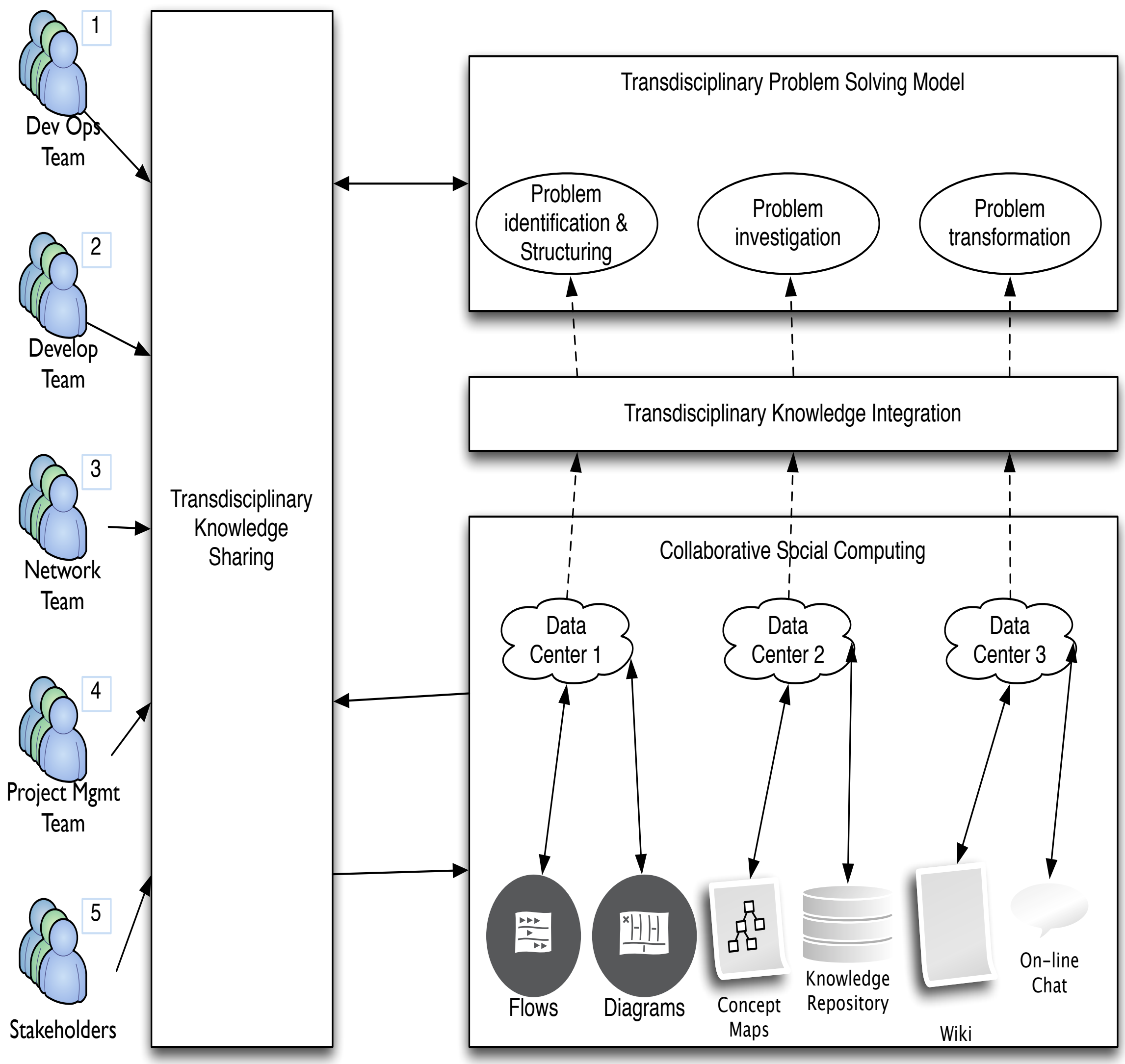

Figure 23. Transdisciplinary team and TPSM flow.

TABLE 24

ORGANIZATION OF TRANSDISCIPLINARY TEAM INVOLVED IN CASE STUDY

Experts	Function	Number of Members on Team
Dev Ops Team	Build the physical environment that will be used by the application and all of its components. Set up the database (db) replication. Set up the infrastructure automation. Set up continuous integration (CI).	10
Development Team	Primary responsibility is to perform the code development and write all tests.	25
Network Team	Build out the clouds and the associated datacenters.	10
Project Management Team	Manage the deliverables of the project. Manage the deliverables of each team.	7
Stakeholders	The idea people. They ensure that the project matches the initial vision. Stakeholders are involved throughout the process.	5

Figure 23 depicts the process of using the TPSM to build the API Manager application. The following steps were taken to build the application:

1. The problem is identified and structured and the team is defined.
2. Conceptual models are created. System fundaments are applied.
3. The problem is investigated and operationalized using concept maps. Process and design fundamentals are applied.
4. The problem is implemented. Selected and relevant aspects of the implementation are included. Metric fundaments are applied to validate the implementation.

5. All meetings and communication and knowledge exchange were done using CSC.

The results of the problem identification and structuring lead to the development of the conceptual models. Figure 24 shows the cloud implementation along with its components as defined within the case study. The conceptual model developed was the result of problem identification and structured input from all team members. This included a TA to create a shared vision of what would be needed in a final network build. In the TPSM all final components start as a conceptual model that has to be approved through KS and KI inputs of the entire transdisciplinary team.

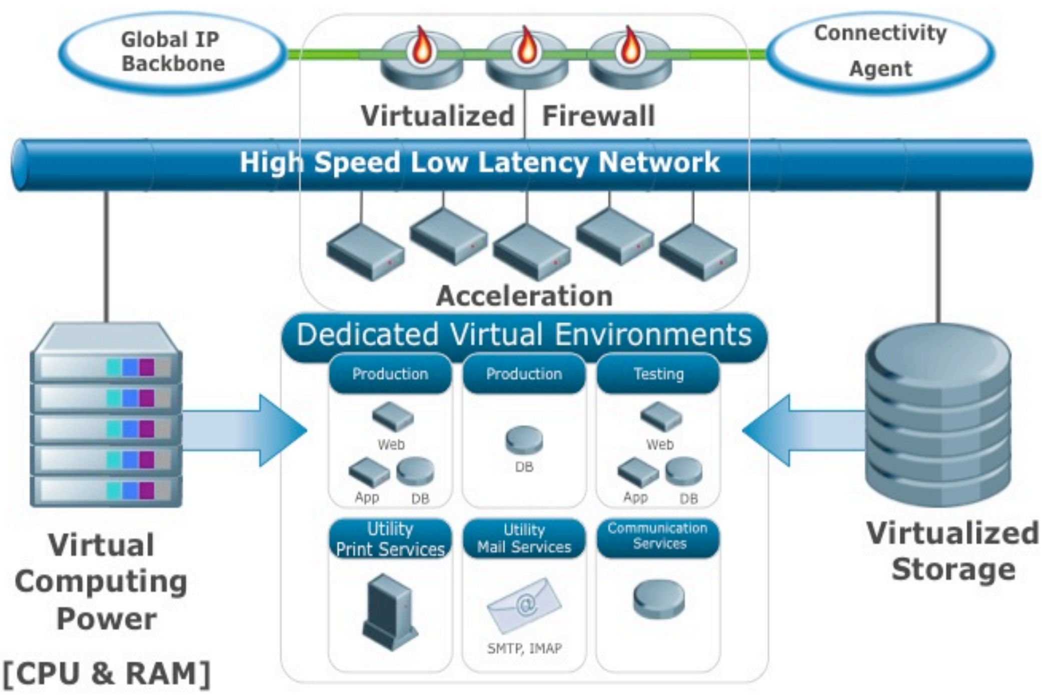

Figure 24. Conceptual graphical model of the cloud build and components.

The conceptual models created by the Dev Ops team show the replication setup across the datacenter model. The conceptual model allowed the transdisciplinary to get a full grasp of the system fundamentals associated with the overall system. Figure 25 shows the application of the conceptual model with drivers from the system fundamentals.

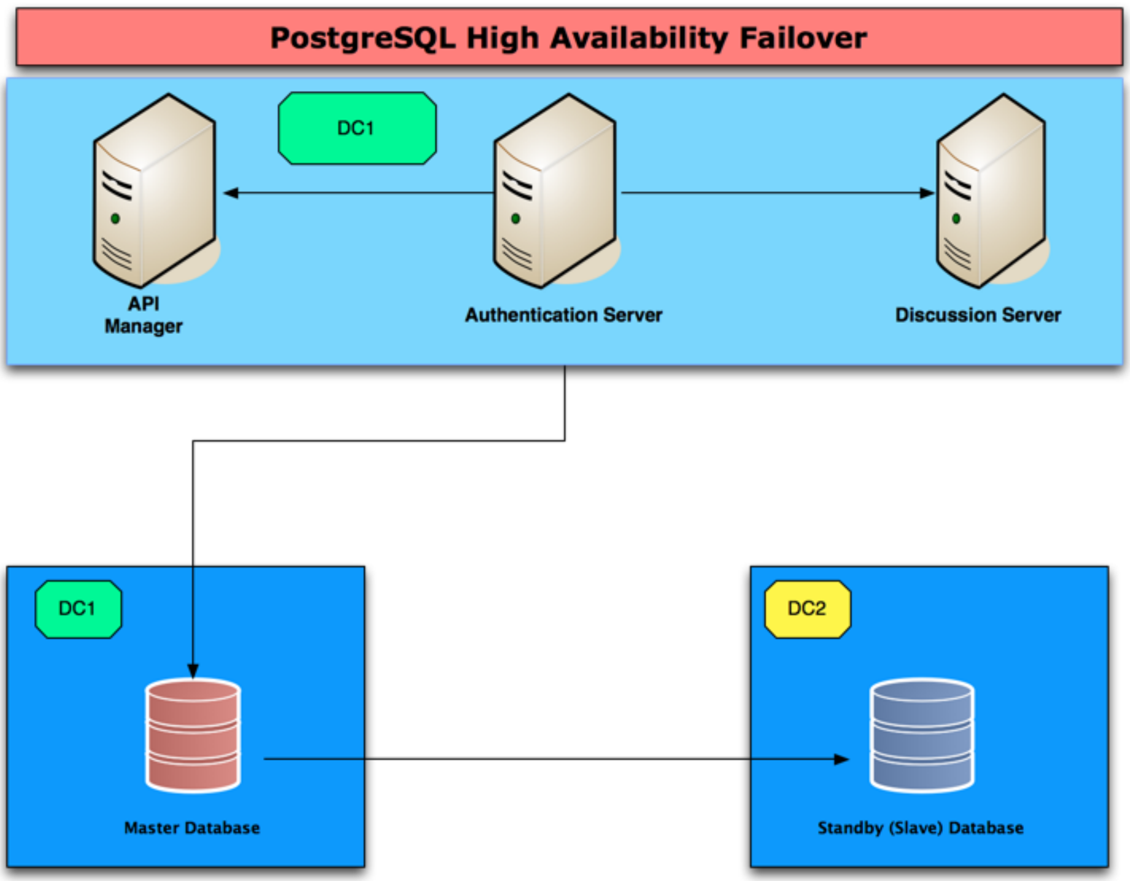

Figure 25. Conceptual model of the HA failover developed using system fundamentals.

The API Manager functionality offered an unusual technical challenge. The challenge was determining how to integrate the API Manager functionality. Problem investigation revealed that a server-side component was needed to query for the API(s) stored in the manager. There was increased complexity about how the calls to the API(s) should be structured. Figure 21 shows the conceptual model for application creation. Figure 27 displays the conceptual model for editing an application. Figure 29 illustrates the step involved in making an API service call. Each of the conceptual models is in its final approved state and represents current functionality.

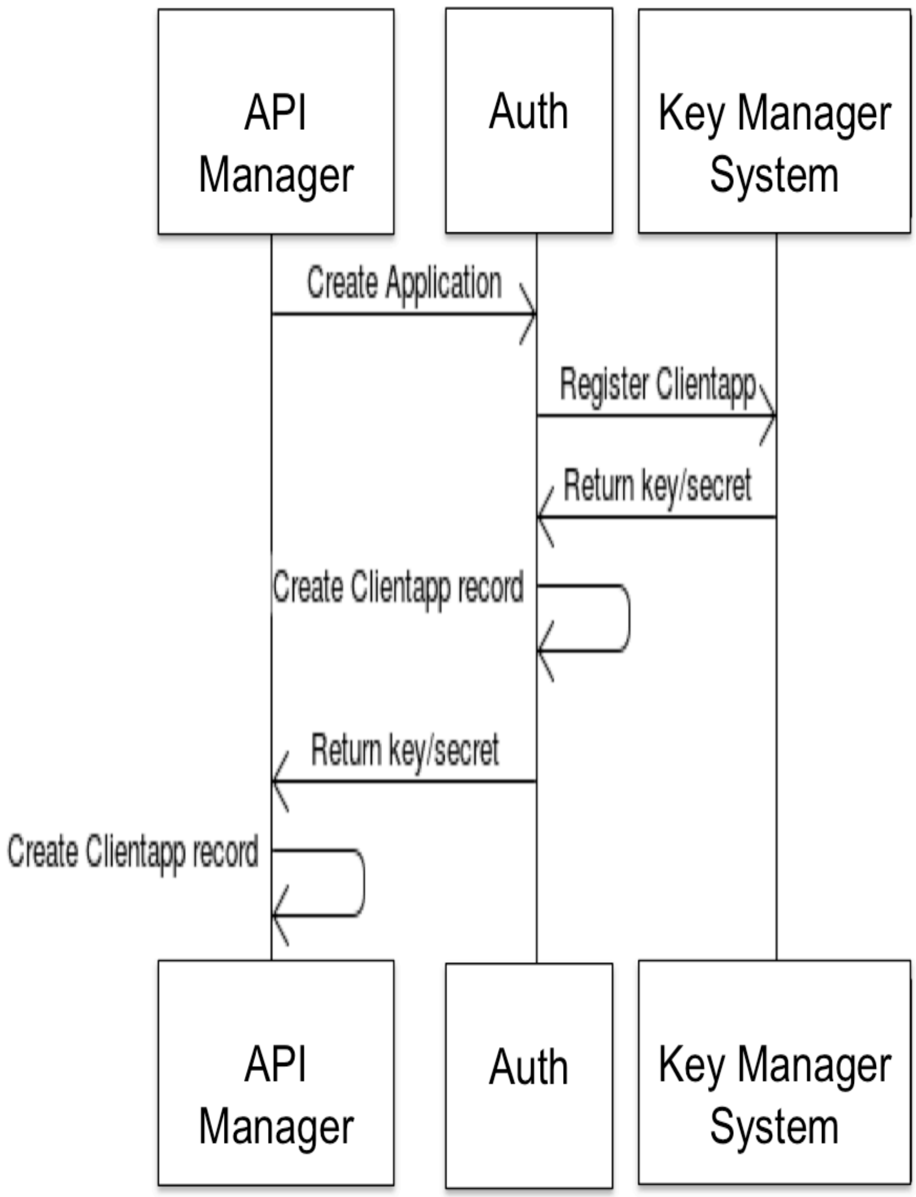

Figure 26. Create Application.

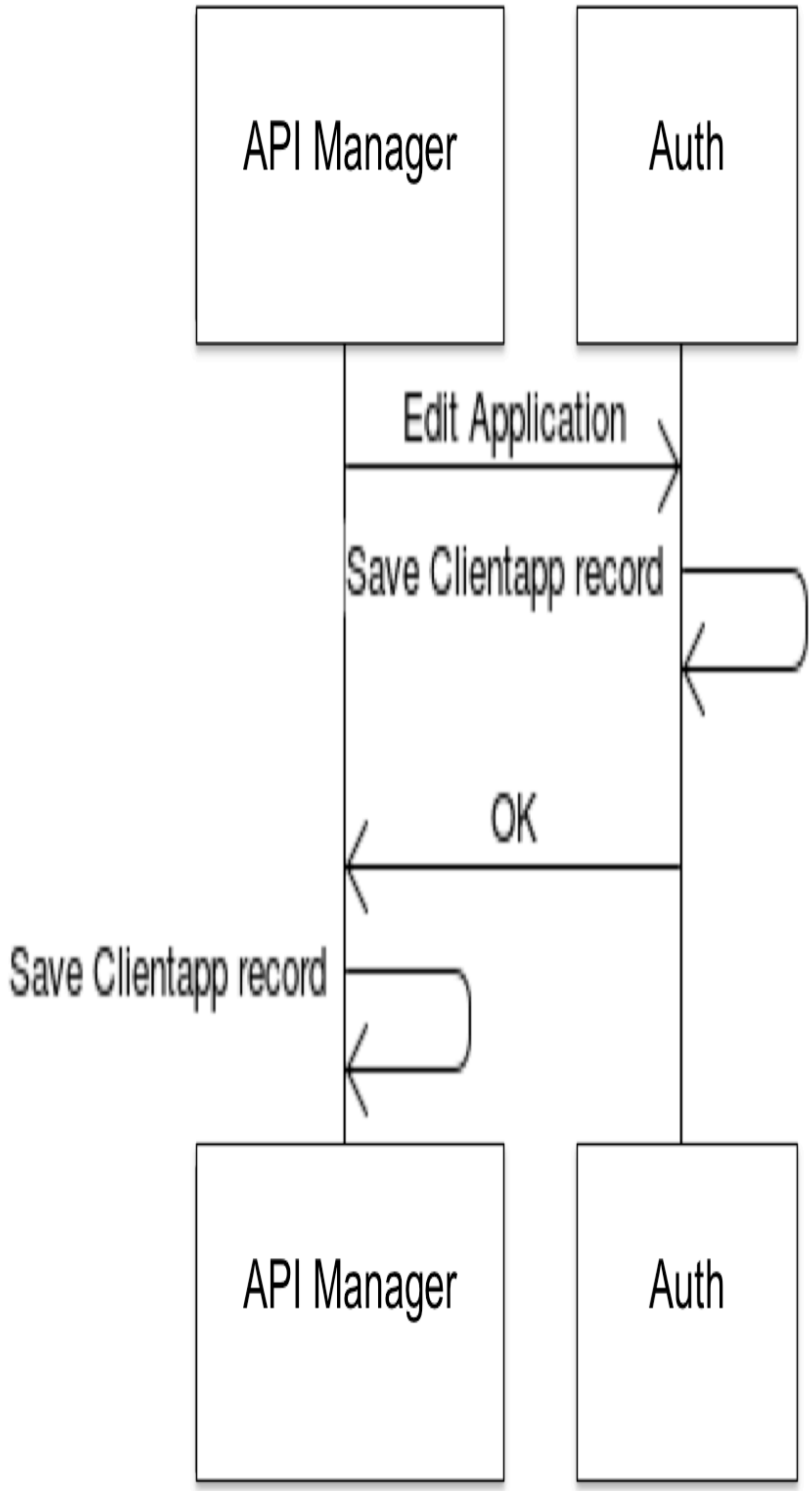

Figure 27. API Manager edit application.

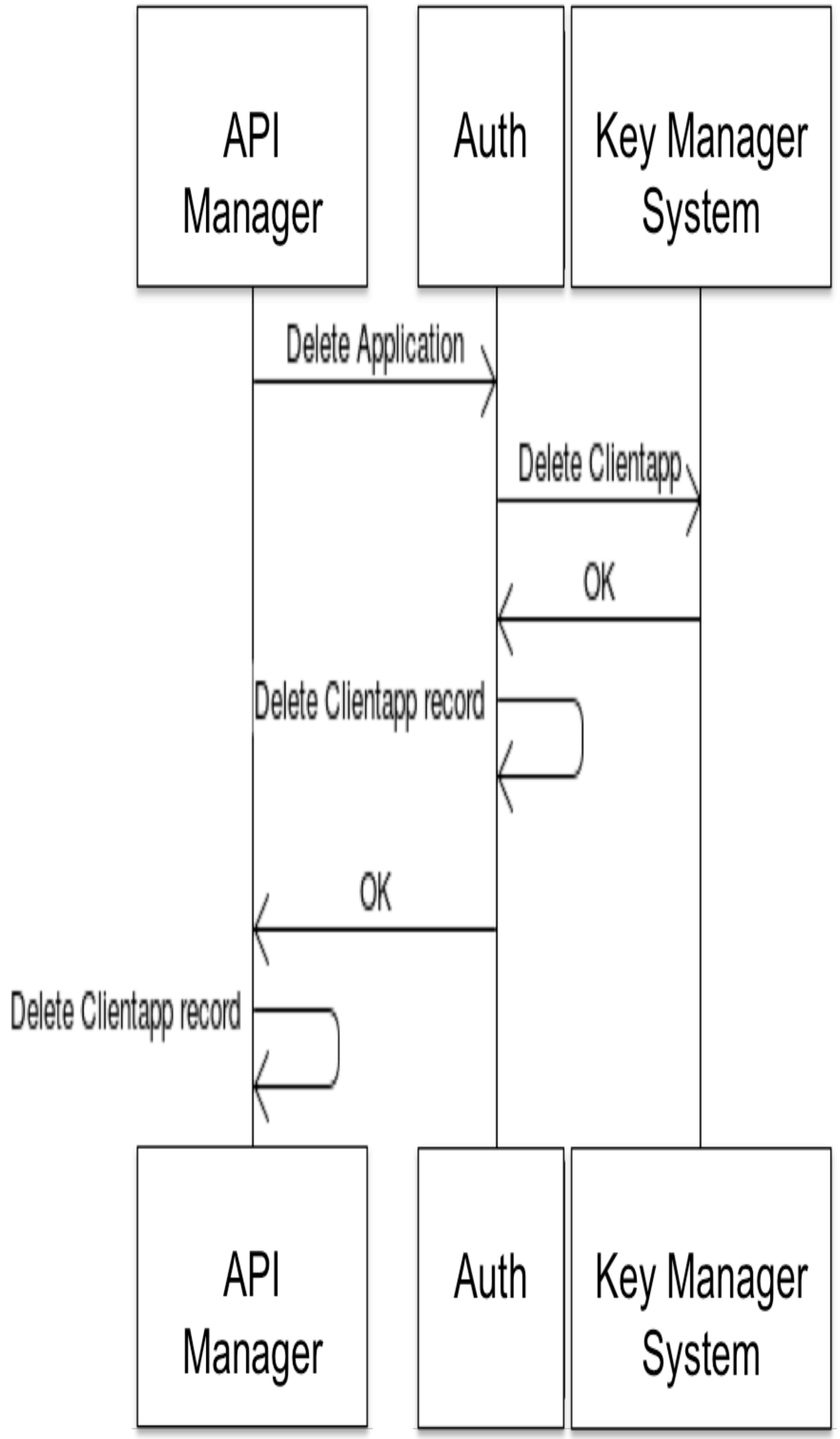

Figure 28. API Manager delete application.

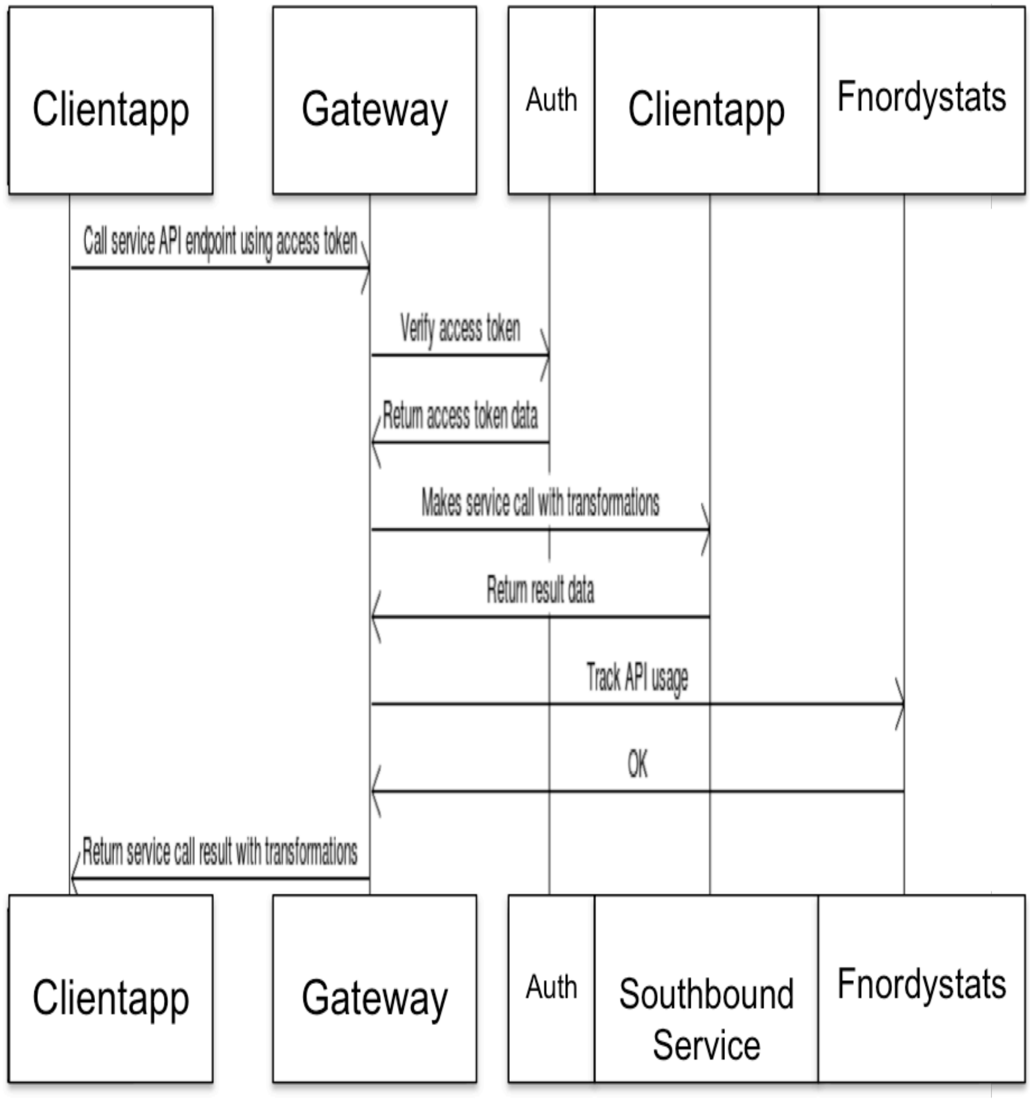

Figure 29. API Manager call service API.

The next phase of the TPSM is involved with using the process and design fundamentals to perform problem investigation. Complex technical problems are bound, therefore, concept maps were not required as part of KS and KI. Instead, concept maps were used to map the KS and KI process. Figure 30 shows the concept map depiction of transdisciplinary knowledge model using for processing TKP in the case study.

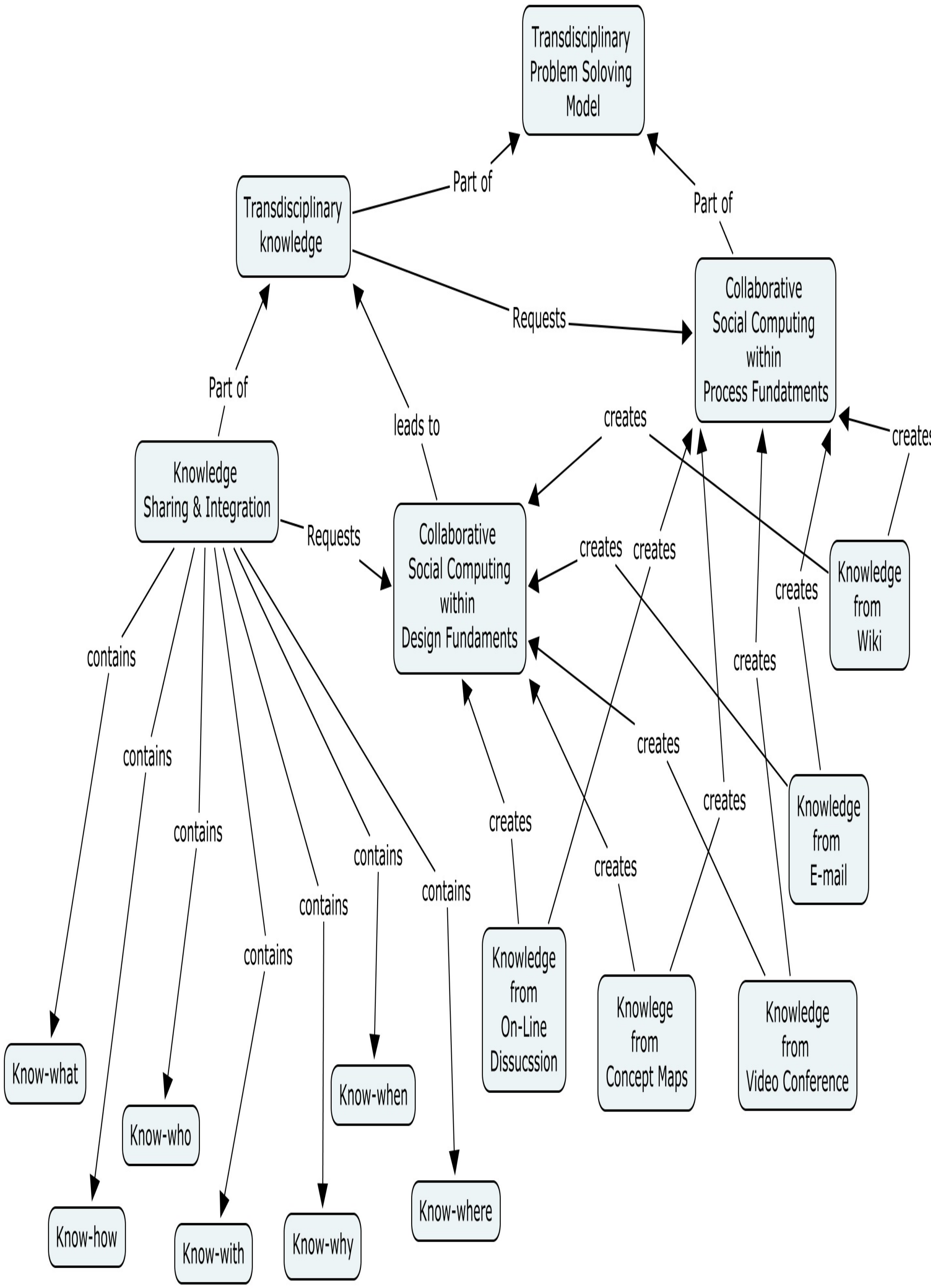

Figure 30. Concept map of knowledge process used in case study.

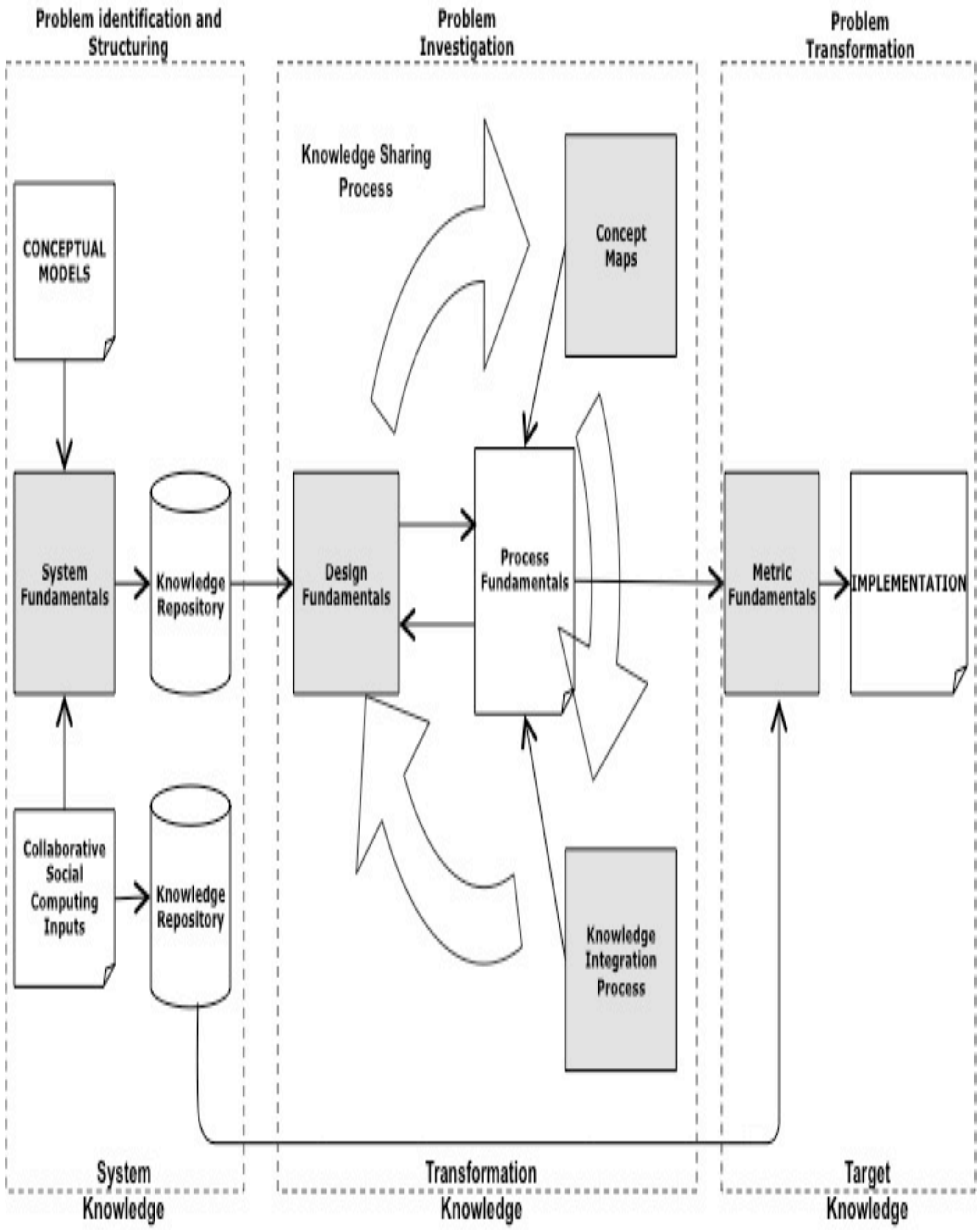

Figure 31. TPSM flow used to build API Manager.

Table 25 shows the problem implementation phase. Metric fundamentals were used to validate all solutions. This is a list of the most challenging problems. Some represent new problems that grew out of the original request, as is the nature of solving complex problems.

Table 25

LIST OF CHALLENGES IN THE TRANSDISCIPLINARY PROCESS

Challenge	**Description**	**Solution**	**Result**
Build an API Manager	Need to create, edit, and delete application within the API Manager.	A token configuration was created enabling tractable service calls.	This made control more fluent and eliminated service call collisions.
Build HA Failover Replication	Had to determine the appropriate setup and configuration for automating replication and failover.	Had to build a custom solution to handle the configuration as an add-on.	Wrote agent watchers that reconfigured the master/standby on fail.
Managing Data Volume	Need to push large chunks of data to backup and shared file locations. Data must stay in sync.	Data is sent in smaller check by sending and retrieving only the data that has changed.	Data was broken down and bundled less often, making the process more efficient.
Create Table Based Persistent Storage	Need to understand data structure. Understand where data is being created and how it can be pushed to the datacenter.	Data retrievals were represented as a table and the number of columns is programmed. Column names determine what data is pushed.	Used vectors and added the vectors into persistent storage. This enabled the creation of written methods to pull data by column or row.
Managed Infrastructure automation	Need to create architecture for automating infrastructure. Solution must be scalable and facilitate multiple environments.	Set up infrastructure using open source tools. Created a framework for handling multiple environments (development, staging, production).	Set up separate instances for each environment server. Created environment variables that controlled version of software.

H. Conclusion

In this chapter, the elements required to address the intellectual control and structuring problems in solving transdisciplinary problems were outlined. The TPSM is used to manage the complexity and deterministic chaos that are inherently a part of the TPS process. The TPSM was described and validated. The T^4 FUNDAMENTALS were used to inject engineering principles into the model.

V. CONCLUSION AND FUTURE WORK

A. Summary

In this section, concluding remarks of this dissertation are provided.

B. Motivation and Approach

Rapid technological advances, regulatory issues, and an aging population have introduced progressively more complex problems into transdisciplinary research [21] [22]. It has been widely accepted that there is a need for a comprehensive model [34] to resolve the fragmented solutions to information systems challenges across research involving TPS. Moreover, methods, theories, and conceptual models must integrate transdisciplinary perspectives into the systems developed for problem solving [23]. The desired solution must also address the ability of researchers to share and integrate the knowledge base.

CSC is the shared and interactive aspect of content over the web, such as blogs. Frequently, this strategy provides focus on applying knowledge socially through the use of applications designed to enable computer-supported collaborative and interactive work. Another aspect of CSC is more social science-centric and closely related to the emerging discipline of web sciences [3] [4] [69]. Based on these supporting principles of social computing, the model, which was developed using the T^4 FUNDAMENTALS, is referred to as the TPSM or transdisciplinary problem solving model. The main reason for the TPSM is surmised in the following approach as clarified in Chapter I and explained with detail in Chapters III and IV.

First, the reasoning behind the development of a transdisciplinary problem solving model (TPSM), is identified as the need for an integrated model that uses the four transdisciplinary fundamentals, T^4 FUNDAMENTALS, system, process, design and metrics to craft solutions to CPS.

Second, TPSM provides a path forward in the form of a set of collaborative social computing techniques that can be used to integrate and share knowledge, creating a unified knowledge base. TPSM achieves knowledge sharing and integration by using the properties and protocols of a multi-agent communication algorithm. This validates the various forms of group dialogue that are necessary to achieve transdisciplinary knowledge sharing and integration, ensuring that all members of the transdisciplinary team are part of the communication challenge.

Third, a three-phase approach is proposed as a means of providing intellectual control and structure to the TPSM. This three-phase approach is defined in the following phases:

1. Problem identification and structuring.
2. Problem investigation.
3. Problem transformation (implementation).

An inherent part of the TdR is embedded in the knowledge interdependencies. These knowledge independencies define the understanding for the knowledge in TdR:

1. System knowledge: existing knowledge.
2. Target knowledge: desired knowledge.
3. Transformation knowledge: moving from existing to desired knowledge.

This dissertation used the API Manager case study to demonstrate the TPSM. The case study examines the end-to-end solution by using the engineering principles in an established foundation.

C. Background

To address the effects of this lack of collaboration, the second generation of web-based communities has hosted services that facilitate [41] and offer an ideal mix of technologies for collaborating and sharing among participants. These technologies enable diversified communities of researchers to interact with each other and the knowledge systems.

Since its inception, the Internet has been a progressively significant tool for the distribution of content. The emergence of Web 2.0 elevated the communication modality by making the Internet social and allowing a new level of interactivity. The collaboration prototype described in this paper provides the opportunity to exchange complex documents, experiences, as well as many other forms of information. Knowledge sharing and community intelligence via the social web presents a powerful means of disseminating complex content. Similar to the tenants of Shannon's information theory, social computing creates multiple communication channels across various life science disciplines. The TPSM is a platform that is based on the principles of engineering rooted in the T^4 FUNDAMENTALS. The T^4 FUNDAMENTALS coupled with CSC increases information channels available among problem solvers. In the TPSM, collaboration is needed to assist with developing advanced theories and methodologies that can be used to solve complex problems.

Effective CSC requires integration, aggregation and analysis of data and information across multiple sub-fields of disciplinary research [1]. Therefore, the TPSM adheres to a defined process for data and resources that are associated with a transdisciplinary problem. The principle requirement of standalone data is that it advances the organization of knowledge on the web. Most large-scale projects follow a very basic flow: data is collected at multiple sites, combined, and processed. However, before this data is accessible and useful to others outside its origination; the meaning, purpose, and context of use must be well defined through the use of a TA. This effectively bridges and maps the research meaning across the multiple sub-fields of disciplinary research, through the TPSM's concept map implementation [1] [13] [43].

Researchers are also able to submit supporting documentation that may be used to help provide greater understanding about their domain of discourse. This may include presentations, publications or even team meeting notes. Since science produces vast amounts of data subdivided by sub-specialties, it is essential that a minimum amount of metadata be also provided. For example, it is common for biologists in different sub-specialties to be completely unaware of the key literature and vocabulary across domains.

The core functionality of the TPSM is centered on providing built-in visibility to information change, provenance, and explanation. Because it is done through the context of information, both the use and meaning of data is established, which, once available, provides a clear path to understanding the information content. For example, applying data integration to research designed for curing and preventing diseases requires an integrated understanding across sub-specialties. Therefore, it is necessary to ensure that knowledge sharing and integration is seamlessly embedded into the knowledge content model [1] [13]. This provides greater structure when creating back conceptual models and concept maps. As the complexity of the problem increases, the deterministic chaos increases, making it more and more difficult to adequately support the current information ecology of science. Seemingly, this is also applicable in rapidly evolving areas of TdR [1] [43].

D. Contribution

CSC must be organized for it to be effective. Transdisciplinary knowledge cannot be shared and integrated unless intellectual structuring of ideas takes place. The TPSM utilizes T^4 FUNDAMENTALS to offer structure to the CPS paradigm. The T^4 FUNDAMENTALS are defined as the following:

1. System Fundamentals
2. Design Fundamentals
3. Process Fundamentals
4. Metrics Fundamentals

The T^4 FUNDAMENTALS represent a collection of engineering principles that are used to provide structure within the TPSM. The system fundamentals provide guidance for system integration. The problem is represented as a system and structured using system-of-system principles. The design fundaments provide the comparison of the distributed model to the integrated model. The model integration of the design fundamentals is used in conjunction with the process fundamentals to identify all processes and their points of integration within the integration model. These steps correlate with the problem investigation phase of the TPSM. Throughout the TPSM, metric fundamentals are used to test all data and process integration to ensure correctness.

The TPSM uses CSC to facilitate transdisciplinary knowledge sharing and integration. CSC techniques and tools that are used with TPSM can be defined as follows:

1. Web 2.0 tools and techniques (e.g. wikis, blogs, collaborative environments).
2. Collaborative concept maps (These are vetted by the transdisciplinary team for completeness).
3. Collaborative conceptual models (These are vetted by the transdisciplinary team for completeness).
4. Open source software (e.g. Ruby on Rails, PostgreSQL, repositories).

E. Future Work

Expansion of the TPSM could occur in the following ways:

1. Development of artificial intelligence (AI) agents to automate knowledge production.
2. Development of an integrated virtual environment for performing research.
3. Development of transdisciplinary standards for abstract creation.
4. Extending the model into a formal or complete framework.

AI is a process that could be used to examine complex processes. Knowledge acquisition could be automated by creating knowledge agents. These intelligent knowledge agents could crawl through complex processes and interpret and translate knowledge sources. The knowledge agent could systematically remove knowledge bottlenecks by automating the re-engineering of knowledge. This would make knowledge acquisition conceptually straightforward. Currently the complexity rooted in knowledge sharing and integration is based around the complexity of the process itself. AI knowledge agents could minimize this process by making the process smart and efficient. Often researchers are overwhelmed by the amount of information that is available. Significant time and energy is required to review documents. AI automation could be key to eliminating inexactitude and the uncontrollable nature involved in structuring intelligence.

The creation of virtual research environments also provides the opportunity for extending the TPSM by making data-driven collaborations simple and efficient. Data integration is important in research for achieving a comprehensive understanding of various phenomena. The virtual research environments could be coupled with technologies like the semantic web to provide data integration over heterogeneous datasets distributed on the Web. In the semantic web each data item is identified by a globally unique identifier, i.e. a URI, and a relationship between two data items is described as a statement including a triple of subject, predicate, and object. It provides Representational Service Transfer (REST) Web service that retrieves data, as described in the lightweight JSON format.

In virtual environments the data/resource is typically the catalyst between some researchers while the social profile is the method for others. This has the potential to dramatically improve resource sharing and transdisciplinary collaboration by bringing together both conventional and nonconventional collaborations [17] [18] [19]. For example, virtual research environments could have the ability to search through listings of projects associated with various scientists. Once selected, scientists are able to view the full details of provided project information.

The development of transdisciplinary standards for abstract creation is key to obtaining information interoperability. At the same time, the standards cannot be so robust that they add to the complexity. Transdisciplinary standards should bring formalization to the practice of tasks (e.g. problem identification and structuring). The transdisciplinary standards could provide a model offering common standardization techniques. By using a specific set of rules this would guarantee abstract interoperability while allowing for as much specificity as necessary. This could be illustrated through different conceptual models, which could be generated to create seamless object models.

The TPSM is in the form of a model. Both models and frameworks are considered as the meta architecture to describe the structure of a process. As a framework, TPSM would provide guides in the form of a system of rules, ideas or beliefs that would be used to plan or decide supporting structure around how transdisciplinary problems are solved. However, as a model, the TPSM only acts a representation of a set of criteria that is loosely followed.

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APPENDIX A

CONCEPTUAL MODELS FOR API MANAGER

This appendix contains the complete list of conceptual models that were used as components of the TPSM.

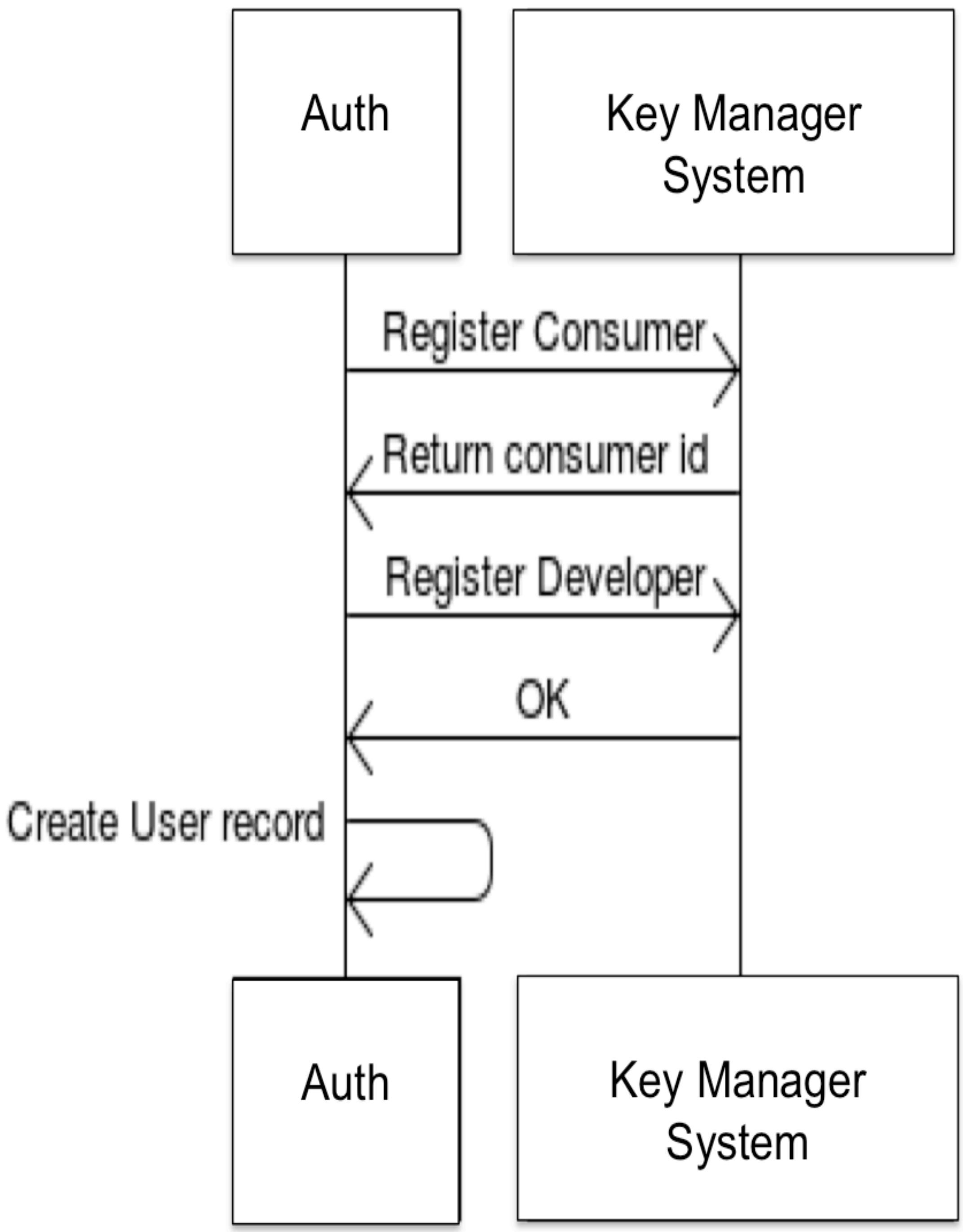

Figure A.1 shows the API Manager create user.

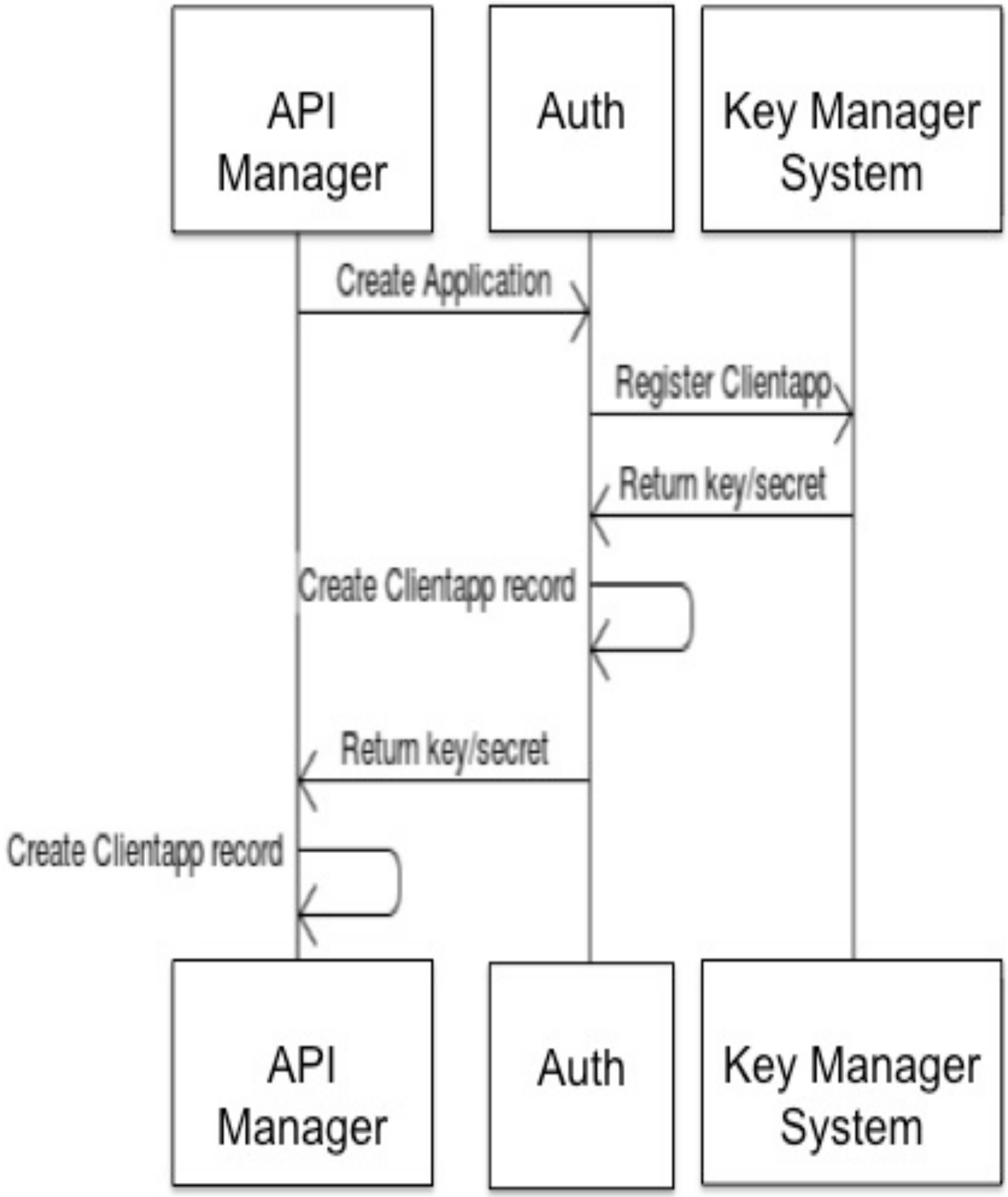

Figure A.2 shows the API Manager create application.

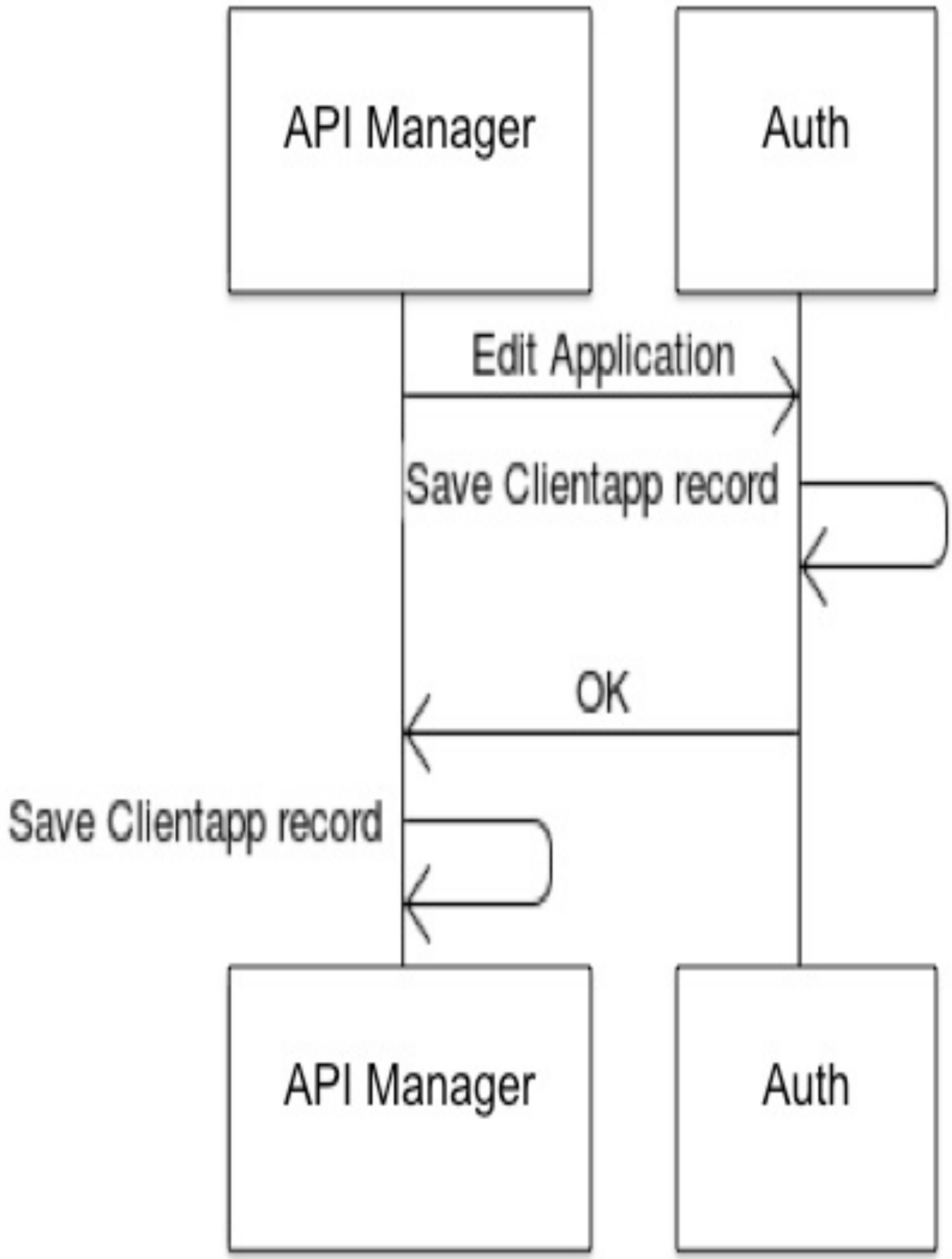

Figure A.3 shows the API Manager edit application.

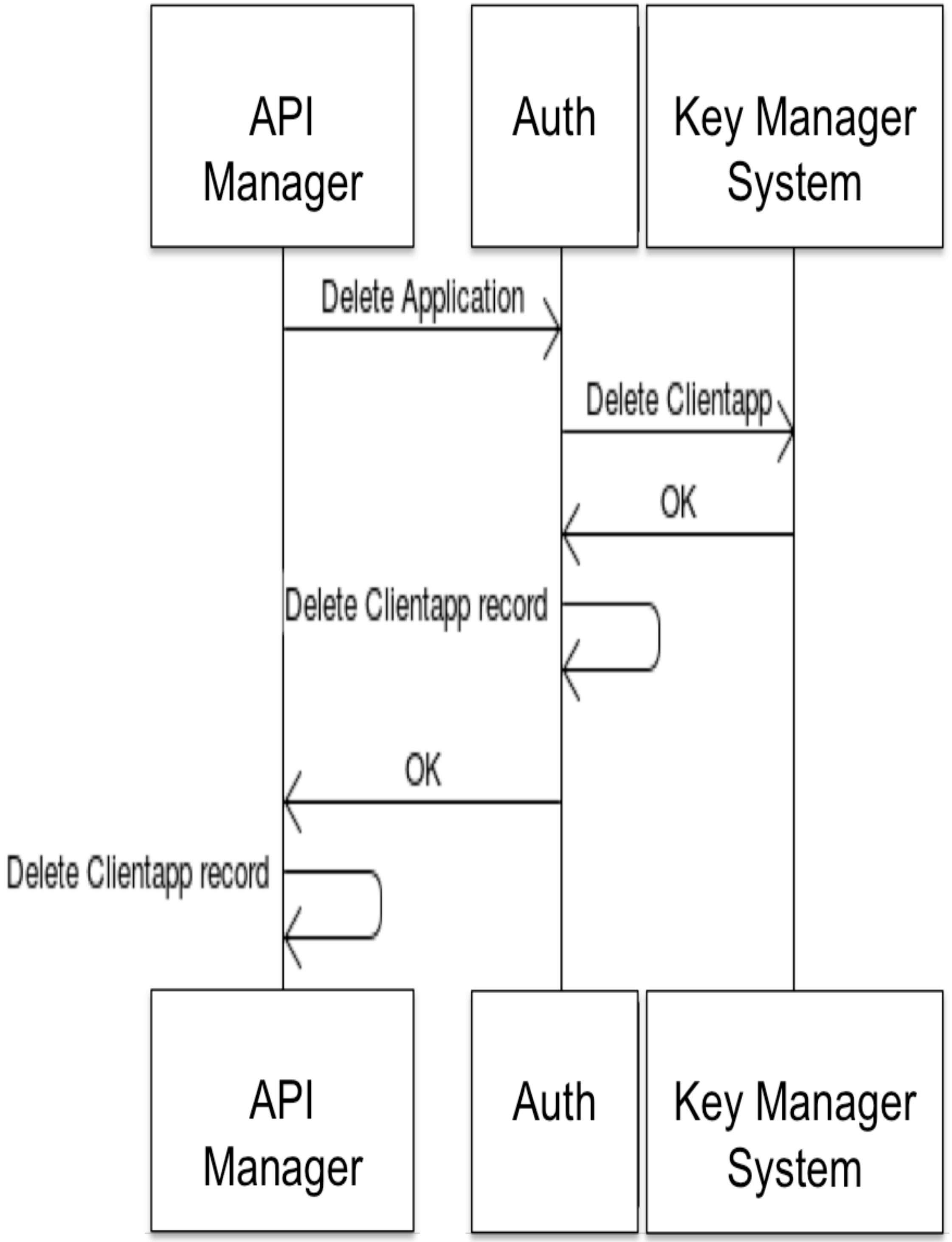

Figure A.4 shows the API Manager delete application.

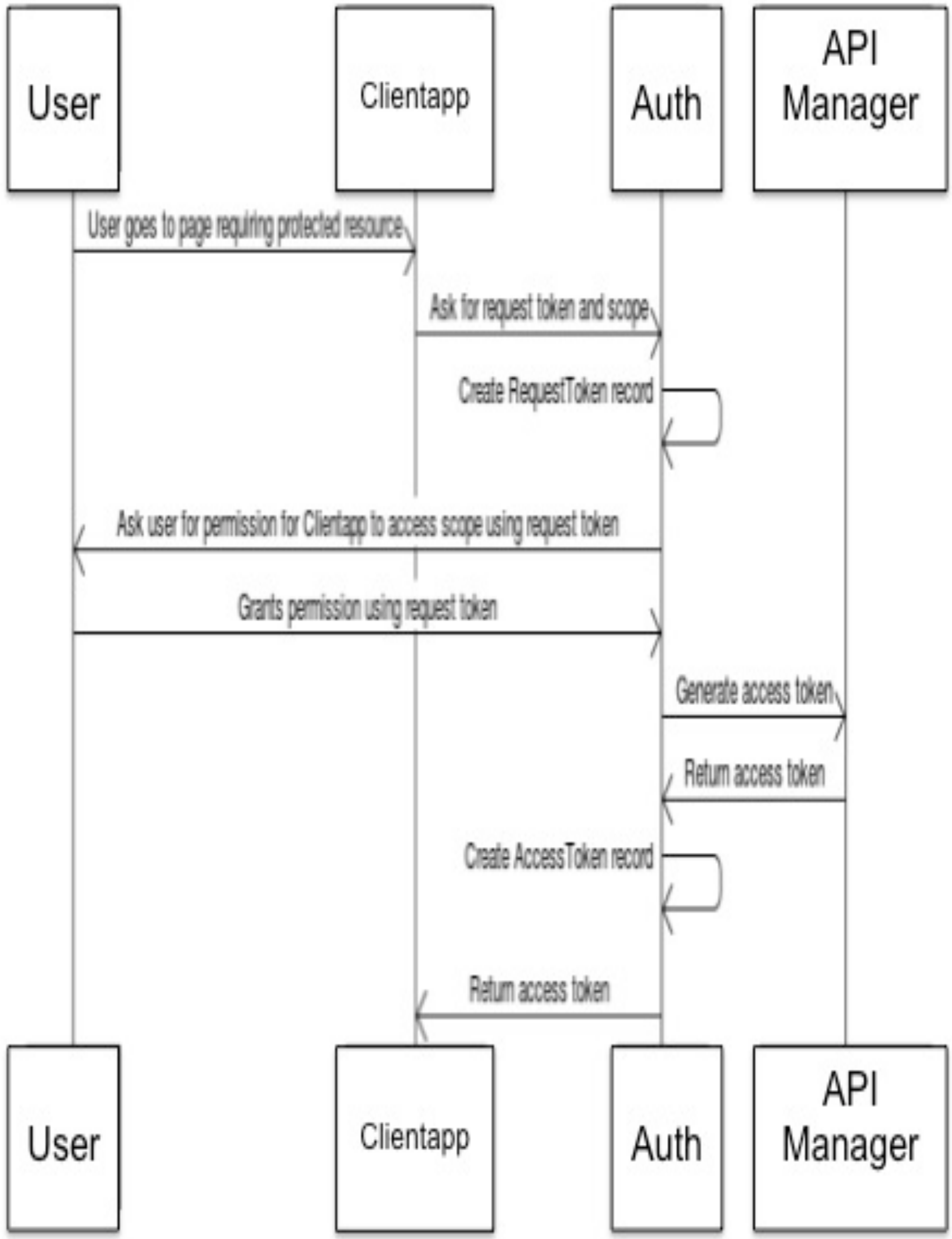

Figure A.5 shows the API Manager get access token.

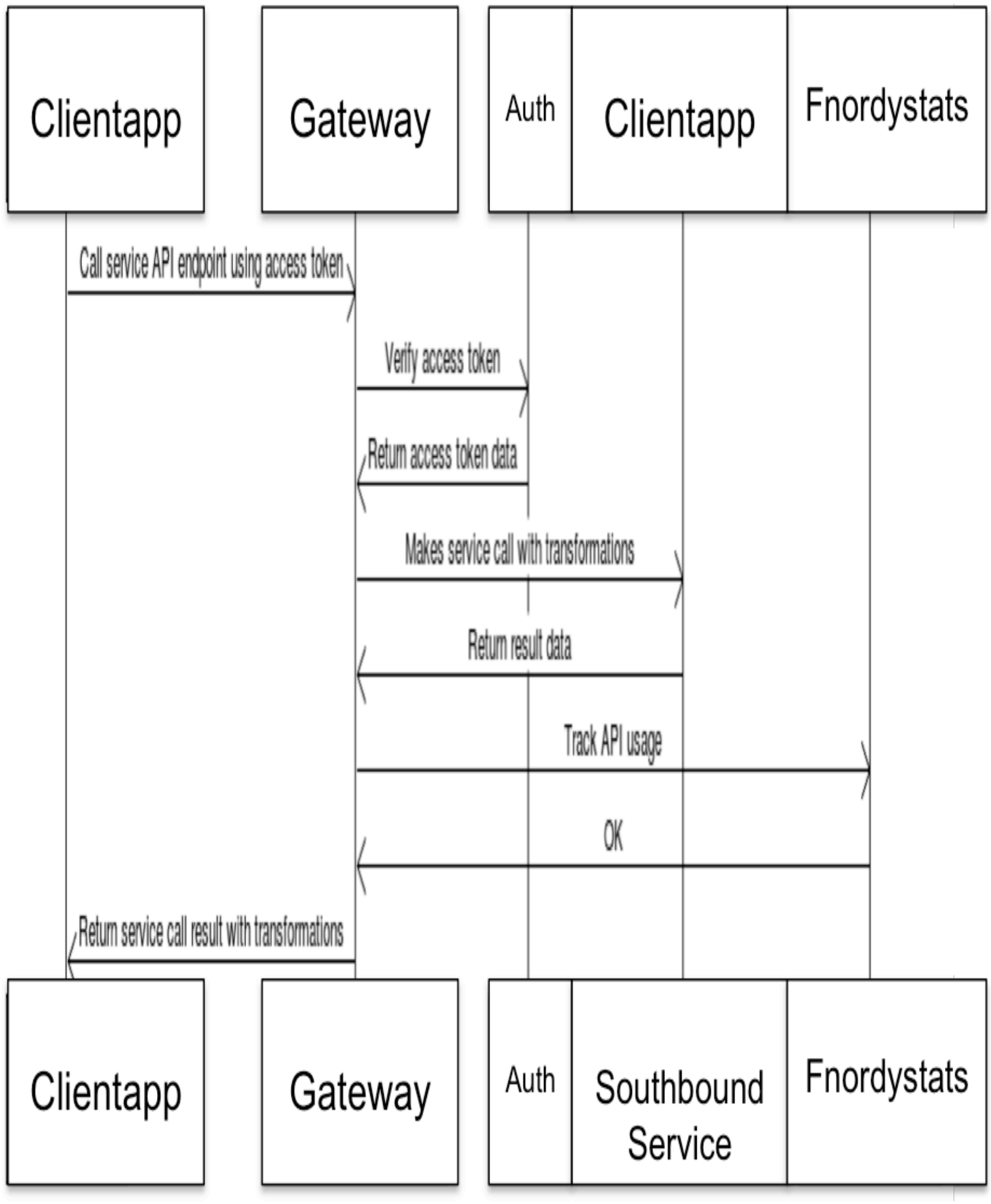

Figure A.6 shows the API Manager call service API.