AN EVALUATION METHOD FOR THINKING
IN TECHNOLOGY ECOLOGIES
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ABSTRACT

As technology progresses, we become surrounded with an ever increasing number of devices. Information can now be persistently represented beyond a single screen and a single session. In the educational context, we see a rapid adoption of the panoply of devices, but often without any careful thought. Devices in isolation are unlikely to enable effective learning.

This research explores how devices function in technological display and device ecologies or ecosystems to support human thinking, learning and sensemaking. Based on the theories of Vygotsky’s sign mediation triangle, we contribute a method that may allow one to evaluate how technology configurations support (or hinder) students’ thinking. Our method proposes the concept of objectification as a way to identify the potential or opportunity for learning in technology ecologies.

The significance of such an evaluation methodology is considerable, given the nascent field of sensemaking and the lack of consensus on evaluation in such contexts: our research advances a principled approach by which device ecologies can be examined for their potential to provide ‘learning experiences’, and enables one to articulate affordances for the design of technological spatial environments that can help to support higher thought. Our contribution thus is in terms of methodology, theory, evaluation and the design of technology ecologies.
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This dissertation is very meaningful to me as it represents the closure of a chapter of my life at Virginia Tech. It also engages a topic that is deeply fascinating, exciting and intriguing to me, although it has proved to be tremendously challenging at times.

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CHAPTER I: INTRODUCTION

I.1. Technology Ecologies

An influx of devices has been made available to the consumer in recent years. The reasons are multiple: advances in technology, spurts of innovation, rules of the marketplace, ... This era has been called a “gadget-overloaded world” (Madison, 2013). A recent online survey (Crosby & Conroy, 2013) indicates that the average person carries 2.9 devices at any one time. This is not too surprising if one understands that the devices are oftentimes not used as single, isolated devices, but in tandem for different purposes, different tasks, in different contexts and at different times. This phenomenon can be termed as the rise of technological ecosystems, whereby devices and software are interconnected and co-serving but all rallied around one purpose: providing a cohesive user experience. The experience desired depends on the domain. One can think, for instance, of the music ecology that includes listening to songs on one’s MP3 player, importing music from one’s iTunes library, downloading songs from the Internet, etc. As we shall see, we are concerned in this dissertation with an experience of learning.

We use the term ‘ecosystem’ and ‘ecology’ in this document as being synonymous, although nuances exist in their meanings. The term ‘ecology’ was coined by Ernst Haeckel in 1866 and is usually applied in the pure sciences to refer broadly to the study of how organisms relate with their environment (Stauffer, 1957).

A fair amount of work has looked at technology ecosystems or ecologies but each through a different lens. Many elaborate on the concept theoretically, philosophically or conceptually, several investigate methods for its technical designs and implementations, and a few offer empirical user studies. However, it is a difficult task for one to find an entirely coherent picture of the concept from the literature. Perspectives are not necessarily contradictory but previous work presents two main challenges: prior literature forms a cacophony of voices that requires much more research to integrate, and it leaves several gaps, especially when dealing with the issue of evaluation.
As the technological world becomes more complex, our desire for a less fragmented, less chaotic world increases. Technology and design that are more malleable nowadays open up greater opportunities for the study, understanding and experimenting of technology ecologies. This dissertation asks fundamental questions on the nature of technology ecologies predominantly in an educational context or for learning activities, and develops a theoretical foundation as to their role in human learning, thinking and sensemaking processes. Through doing so, it presents work that contributes to solving the two challenges of literature integration and of bridging the evaluation gap in research on technology ecologies.

I.2. Technology Ecologies in Education

From PDAs, laptops, mobile phones and tablets, new technological devices have been anticipated in many quarters as being beneficial tools for learning. Since the launch of the Apple iPad in 2010, for instance, many have touted the new device as having tremendous potential for education, both to enhance technology skills and to support curriculum learning. Many school districts are funding tablet distribution in low-performing schools. From the elementary to tertiary level, schools as well have been quick to launch pilot programs that hand out iPads to every student and teacher (Campbell, 2011; Hu, 2011; Seton Hill University, 2011).

However, these devices are often introduced into schools without full understanding of their effect on learning. Despite the pervasiveness of such computing devices in educational and personal contexts, we have limited understanding of how to effectively use them in education. The benefits of tablets, laptops, PDAs and others are often summed up merely in the value of the applications installed, e.g., Banister (2010). There seems to be an implicit assumption that mere connectivity and access to content through the devices is a sufficient condition for learning (Collins & Halverson, 2010). Much research has thus been carried out on the use of e-learning environments, e.g., (Raitman, Augar, & Zhou, 2005), the Web 2.0, e.g., (Williams, Karousou, & Mackness, 2011) or wireless connection through mobile devices, e.g., (Roschelle, 2003).
A major problem that arises from looking at the benefits of learning with technological devices as being placed mostly in the digital realm is that digital media is immaterial, invisible, and ephemeral. Yet, digital information is necessarily materialized into perceptible and accessible pixels into the world via devices that are physical, tangible artifacts. The role of interconnected devices in the learning process cannot be ignored. We thus define a technology ecology as a mesh of interacting displays and devices that enable the access to digital information, as well as its manifestation and manipulation to deliver a cohesive learning experience.

I.3. The Physicality of Information

It is inevitable that we stumble onto the issue of learning through digital pixels if our purpose is to investigate the nature of technology ecologies in educational contexts. It is simply too easy to ask ‘why does it matter?’. Why should we care about the multitude of devices? Apart from posing a problem of overload, they indeed provide us with choice, variety, convenience and comfort. After all, a document displayed on one’s tablet may be the same document displayed on one’s laptop.

We argue that such a perspective is problematic. The superficial similarity in appearance of the pixels encourages one to think of devices merely as ‘data straws’, portals that we reach in whenever and wherever we need the information stored ‘in the cloud’. In this line of thinking, devices function almost as simple transmitters of information (input/output devices) whose physicality has no or little impact on one’s thought processes. We do not mean the influences or adjustments dictated by differences in design aspects such as screen size, device weight or sensitivity of the trackpad. Those are mainly considerations of context or environment of use, primary function, conventions, and human aesthetic preferences. Instead, we mean factors or characteristics of the devices that enable the digital information to effectively participate in our process of thinking, to become ‘real’.

The paper ecology is perhaps the best example of a human designed artifact ecology that integrates in our thought processes, mediating it, supporting it and facilitating it. We readily appropriate sticky notes, paper napkins, random sheets, whiteboards, markers, staplers, and books during learning. We more often than not find ourselves resorting to
paper for scribbling, drawing, outlining, doodling, annotating, etc. to aid in our process of thinking and only thereafter transcribing digitally through a device. Even further, several of our entire environments from libraries to offices and classrooms have been designed to precisely act as effective mediators of human higher thought. Admittedly, the paper ecology has been developed over hundreds of years. We can work by analogy and attempt to apply principles of design of the paper world to the digital world and its devices. Some have in fact performed work in that direction, e.g., (Sellen & Harper, 1997). While valid, that approach however does not allow one to fashion possibilities beyond the original home of the analogy, i.e. the paper ecology. We propose an alternative approach that is grounded in a theoretical understanding of the role of digital devices in thinking, and supported by empirical research.

I.4. The ‘Real’ Bits: A Technology Tale

We have mentioned that digital information needs to have the quality of being ‘real’ to effectively participate in and mediate thought in-situ. We shall use a short tale from the TV Sci-Fi series, Star Trek Voyager, to clarify the concept of being ‘real’. This technology tale was first proposed by Dr. Francis Quek and can also be found in Chu and Quek (2013). We note that its relevancy is purely for explanatory purposes, and is in no way meant to be a picture of how we see the future of technology ecologies to be. The story of Star Trek Voyager begins with the spaceship being flung to the far corners of the galaxy with no way of returning home anytime in the near future. The spaceship was initially equipped with a virtual doctor in the form of an Emergency Medical Hologram (EMH). Through holo-emitters, the EMH doctor was designed to materialize in corporeal form only in the Sick Bay area of the ship and only when summoned for medical treatment. But as the inhabitants of the spaceship realized that they were not going to be able to go back to Earth, they soon developed mobile holo-emitters that allowed the doctor to materialize in more areas of the ship and for longer periods of time. Eventually, they ‘stabilized his matrix’ to such an extent that he was able to be materially present continuously throughout larger portions of the spaceship, participating in the life of the community and impacting the inhabitants beyond its core functional purpose of treating medical emergencies. For the inhabitants of Star Trek Voyager, he became ‘real’.
The Star Trek technology tale is used as an analogy to help us understand the role of devices with regards to digital information. The analogy is helpful because although located in the science fiction universe, it represents a meaningful, full-fledged scenario or context whereby each element of importance can be mapped to our situation of the use of digital information for learning, e.g., holo-emitters as technological devices, the doctor as digital information, etc. We also subsequently found it to be useful in helping us to derive an approach to answer our research question of evaluation.

Following the technology tale, our ecology of devices can be thought of as the network of mobile holo-emitters aboard the Voyager spaceship, and digital information as the EMH doctor. However, unlike in science fiction where the engineers of Voyager simply had to ‘stabilize the doctor's matrix’, we know little about the technological enablements required to allow digital information to materialize and function beyond its basic purpose of conveying and recording human thoughts. Neither do we understand how to consistently detect when a technology ecology is well-adapted to support the human thinking, learning and sensemaking experience.

I.5. Research Questions, Approach and Contributions

This leads us to the key questions that we pose in this research. These are two-fold:

1. How may technology ecology of devices make information ‘real’ enough for one to engage in higher thought?
2. How may we know when they do?

The focus of this dissertation is on the second question, but we aim to be able to contribute as well to the first during our investigation. The second question of ‘how may we know’ is inherently one of evaluation method. What kind of approach will allow us to assess the effectiveness of a technology ecology in fulfilling its mission of providing a learning experience to the student?

The research questions can be understood more simply if explained in the following way, as illustrated in Figure 1: If a researcher looks at a given situation where some form of learning is meant to occur (e.g., a classroom scenario, a brainstorming session, a report
writing situation), whereby a set of technologies are being used, (e.g., laptops and big displays, desktops and tablets, etc.) how may she identify whether learning is occurring? Can she determine whether learning actually happens? And further, what characteristics in the set of technologies being used support (or hinder) learning to occur?

Our investigation will tackle these issues in three main steps: (i) develop a *theoretical base* that can assist us to understand thinking and learning in a digital world; (ii) carry out an *exploratory study* that can help us to determine (design) factors that may make information ‘real’ in technology ecologies for learning; and (iii) develop a *method* that enables us to evaluate a technology ecology for its ability to support learning.

![Figure 1. Illustration of Research Questions](image)

In this regard, this dissertation will produce outcomes of three types: theory, design factors and evaluation method. We expect to contribute to the understanding of the nature of technology ecologies for learning, their design requirements, and methods to analyze and evaluate them.

A note has to be made about scope. Because of the vastness of the issues that are being addressed, this dissertation presents work that is exploratory in nature, set within a specific perspective of a fixed theoretical framework and within the boundaries of our definitions of the key concepts.
I.6. Concept Definitions

Several concepts central to this research are subject to great variety in interpretation. To minimize misunderstanding, this section elucidates the four key terms that will be used throughout this dissertation:

**Technology ecology of displays and devices:** A mesh of interacting displays and devices that enable the access to digital information, as well as its manifestation and manipulation to deliver a cohesive learning experience.

Although we have already presented the definition of the ecology earlier, it is repeated here for the sake of convenience and completeness. Alternative forms of the term that will be used throughout this dissertation include ‘ecology of displays and devices’, ‘ecology of devices’, ‘device ecology’, ‘display and device ecology’ and ‘technology ecology’. Displays and devices here refer to any kinds of artifacts that are capable of either displaying digital information, providing access to digital information, allowing a user to interact with digital information, or all of these.

**Making ‘real’:** Providing digital information with a certain metaphoric sense of concreteness that allows it to be easily wielded in the process of thinking by a user.

We define ‘real’ here not so much by the actual definitions of the word, but by the actions and effects that it produces, i.e. the participation of digital information in the loop of thinking. It does not mean ‘true’, ‘existing’, ‘genuine’ or ‘objective’ per se.

Again, information is ‘real’ so far as it can participate in, and further thinking. This can be explained, perhaps more simply, in mathematical terms as in Figure 2. Let us say that a learner’s starting state of knowledge about a particular area is taken to be $X$, e.g., the history of Ancient Japan. He is in a situation where he comes in contact with new knowledge about the area, $Y$, for instance, reading a webpage about the Edo era. The resulting state of knowledge of the learner can then be represented to be $X + Y$ that we can encapsulate as being $Z$. Should the information be just absorbed in a static manner, one could say that this resulting state is the end state of knowledge of the learner in that area. However, if the new information again participates in the thought of the learner to further her thinking, then the learner uses $Z$ in an extension of her
knowledge, manipulating it, associating it with other pieces of information, dissecting it, deducing from it, synthesizing it, etc. These manipulations, following our mathematical analogy, could be of any form ranging from $Z \times W$, $Z^2$, $Z + b$, etc, e.g., creating a hypodissertation of why the Edo period was so critical to the development of modern Japan. Factors or characteristics of the tool or technology that allow information to participate in thought in such a way is defined as being ‘real’.

**Higher thought:** Abstract psychological processes such as learning, creating, sensemaking, reasoning are processes of higher thought

We borrow this term from the Russian psychologist, Lev Vygotsky (1986), who classifies the more complex forms of human thinking as higher thought.

**Learning:** A process by which the student engages in a mental activity involving any form of manipulation of information pieces

This dissertation uses the term ‘learning’ (as well as other terms, namely ‘thinking’ and ‘sensemaking’) as reference to or as representative of the broader category of higher thought or abstract psychological processes. We are not equating learning with higher thought, but rather using the term to denote the broader category of thinking processes for the convenience of referencing throughout the dissertation.

‘Learning’ in that sense is not restricted to only the uptake of new knowledge. One important caveat is that the process that we look at in this work can be best embodied in

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**Figure 2. Mathematical representation of information as participating and furthering thought**
the term ‘thinking’. However, because of the significantly greater amount of literature referencing ‘learning’ as a concept instead of ‘thinking’, the term ‘learning’ is used more frequently in this dissertation. Another term that has been used sometimes in the literature to refer to the kinds of mental processes that we are considering here is ‘cognizing’ (Dror & Harnad, 2008).

To recap, our research seeks to answer the questions of the design of technology ecologies for learning and the method to evaluate such ecologies for their support of learning. The following sections of this dissertation first present an overview of previous research that has been done in areas related to the issue being addressed, notably concepts of technology ecologies, evaluation methods of technology ecologies, and approaches of evaluating higher thought processes. Given the interdisciplinarity of the area, focus is maintained on literature in the field of Human-Computer Interaction and closely allied fields. The next sections then describe the theoretical foundation of our proposed approach, the exploratory study conducted to gain insights on the questions asked, and the development of a theoretically-driven evaluation method to assess thinking in technology ecologies. These are followed by a a description of findings from the study, and then a critical analysis of our proposed approach and evaluation method. We conclude the dissertation by drawing out again the significance of this research and laying out suggestions for future research.
II. 1. Technology Ecologies (TEs)

A range of research has hitherto applied the metaphor of a biological ecosystem to human activities with technology for illustrative purposes and to stimulate intellectual discussions. However, this body of work does not always form a coherent whole, and it is a challenging undertaking to present a comprehensive synthesized account. We review below technology ecology (TE) notions proposed in the literature, with emphasis on how they differ from our own concept of TE and the particular domain that they address. Table 1 and Table 2 show summaries of the TE work reviewed and points of distinctions for each.

The overall message underlying the different positions in the literature is that artifacts, devices, systems and products cannot be studied in isolation but can only be truly understood when seen in the broader perspective of the universe they inhabit. Depending on the position taken, the universe can consist of one's physical context, other artifacts used, or one's practices and culture using technology. We classify the perspectives into three categories: theoretical or philosophical positions, empirical study results and technical frameworks.

II.2. TE Theoretical Contributions

Among the earliest theoretical or philosophical positions taken on technology ecology concepts, one can find the ‘media ecology’ by Marshall McLuhan (Strate, 2008). McLuhan’s concept of a media ecology was not defined by precise principles but rather by a set of three key propositions:

(i) that media or media technologies function as environments that pervade human culture

(ii) that the media ecology does not determine or dictate human action. Instead it defines its possibilities and constraints

(iii) that the ecology does not result in direct, easily perceptible effects. It allows “particular forms of communication, consciousness and culture to emerge”.

Table 1 and Table 2 show summaries of the TE work reviewed and points of distinctions for each.
The media ecology concept is a much broader concept than our own and does not necessarily involve digital technologies. McLuhan’s work resides mostly in the field of communication and media studies, and he was mostly concerned with making sense of the influences and effects of media systems of the time. Similarly to others however, his concept reflects on the role of technology ecologies as enablers or disablers with regards to human action (and thought). His ideas have been very influential and has spawned directions of inquiry from which we ourselves draw. Yet, the challenges of applying his work are numerous: 1. He presents principles and not the specifics relating to modern media; 2. While visionary, he does not benefit from the hindsight of the devices, developments, and environments that have evolved in the intervening years since his writings; 3. He does not address the impact of ecologies on learning per se.; and 4. His work tends to have greater impact at the societal and cultural level, while our work seeks to understand the mechanisms of how technology ecologies impact learning within the psyche of the individual and society of learners.

Other TE concepts that relate closely to the field of media studies are Altheide’s (1994) ‘ecology of communication’ or ‘communicative ecology’ and the ‘information ecology’ by Nardi & O’Day (1999). They provide specific characteristics of ecologies as they define it. Both the ecology of communication and the information ecology emphasizes that an ecology is marked by critical relationships among its constitutive components. The information ecology concept, especially, remains closely aligned to the biological ecosystem analogy from which it originates. Characteristics that mark an information ecology include, for example, diversity, coevolution, the presence of keystone ‘species’, and locality.

Closer to the field of human-computer interaction (HCI), Tungare et al. (2006) have proposed the ‘personal information ecosystem’, which maps the biological ecosystem metaphor to technological devices used in a user’s personal environment. Krippendorf (2005) advanced the concept of the ‘ecology of artifacts’ in the context of his proposition of ‘the semantic turn’, a paradigm shift of design whereby designers should not only account for the function of devices but also for their meaning to users. In an ecology of artifacts, which can include any kind of informational, graphic, technological, architectural, social or industrial artifacts, the meaning of one artifact affects its interactions with all the other
artifacts placed in a large cultural complex. Krippendorf describes the ecology of artifacts in these terms that would be harder to paraphrase more eloquently: “an ecology of artifacts is fuelled by how populations of stakeholders experience and interpret artifacts relative to each other, particularly putting them to use selectively. The theory describes the ecological properties of the meanings that communities of stakeholders bring to populations of artifacts.”

Last but not least, Rick’s (2009) ‘classroom ecology of devices’ is a position paper that advocates the use of interactive devices, such as interactive tabletops, as part of a larger ecology of devices in the classroom to build up a ‘collaborative script’. A few others such as Gibson (1977), Suchman (2007) and Norman (1988) have also referred to the ecological metaphor in their writings to different degrees, although with no particular focus on the matter in the sense that we understand it here.

II.3. Empirical Studies on TEs

Research of technology ecologies that present an empirical study of some sort include Huang, Mynatt & Trimble’s (2006) ‘display ecology’, where they studied the use of a specific type of interactive large multi-user display systems, the MERboard, developed by NASA for the unique use of Mission science tasks. Their study was an intensive year-long field investigation of how the MERboard is used in an environment of multiple displays around the center. Three main observations were made: a) that large interactive displays are more suitable for ill-defined, unstructured tasks; b) that the use of the displays change according to collaboration styles and the other types of displays present in the environment; and c) evaluations of the displays should consider the whole ecology instead of the usefulness of individual displays. It is worthwhile to quote the authors on this point: “Evaluation should be based on how well and flexibly the entire ecology of displays supports work tasks, rather than a simple measure of use or disuse of individual displays or applications within the environment”.

Enquist, Tollmar & Corry’s (2007) ‘palpable interaction ecology’ incorporates “a pervasive computing presence and the ability to add and subtract devices and data as desired”. They embodied their ecology concept in a digital artifact that was designed to be “network-
enabled, modular, configurable” for purposes of communication with others and interaction with the environment by pregnant women. In the context of pervasive healthcare services, they conducted a pilot study testing the use of their digital artifact over a period of time. Their findings are mostly specific to the healthcare area. On a general level however, they conclude that a pervasive healthcare support system should not rely on design principles advocating e.g., simplicity and invisibility, but should consider the dependencies between users and devices, shifting needs of users and affordances of devices by looking at the “construction and deconstruction of devices and services”.

Dearman and Pierce’s (2008) paper on ‘computing with multiple devices’ begins with a similar premise as ours, that the number of devices per user is growing rapidly. They conducted interviews with 27 people from academia and industry to understand their practices. Their findings are three-fold: a) there is no one-to-one relationship between user activities and devices, i.e. a user performs an activity on different devices depending on context; b) the role that a device plays is user-specific, i.e. device use varies according to the user and constraints; and, c) the separation of work and personal activities across devices is important for users in industry. The authors recommend a change of focus on users rather than on devices for design.

Forlizzi (2008) presents the ‘product ecology’ as a theoretical design framework for helping researchers and designers to choose “qualitative research methods in flexible, non-prescriptive ways” to improve the user experience and evoke social behavior from products. Although it is not explicitly associated with any empirical user study, it is a more practical approach to the ecology concept. The product ecology framework is based on the social ecology theory, and is structured around five factors (product, system of products, person/people, roles, environmental and social context: place) that lead to a series of variables and questions designed to guide research and design.

Jung et al.’s (2008) ‘personal ecology of interactive artifacts’, and Coughlan et al.’s (2012) ‘device ecology’ describe interesting user studies on technology ecologies in educational contexts. We will expand on them later since they are particularly relevant to our work. From the management sciences, Bailey & Barley (2011) present an extensive ‘shadowing’ study of ‘teaching-learning ecologies’, tracking knowledge as it moves through six
engineering firms. Their focus however was on knowledge within people and not on technology use.

II.4. Technical Implementations of TEs

Some of the technical frameworks that have been proposed to implement technological ecologies are Loke & Ling’s (2004) use of petri nets to represent the state of devices, the ‘task migration framework’ by Pyla et al. (2009), and Pierce & Nichols’s (2008) framework based on instant messaging to enable multi-device user experiences. Since our work does not address the technical implementation of a technological ecology, an in-depth review of literature on this aspect is out of the scope of this dissertation.

II.5. Studying TEs in Education

Among the different conceptions of ecologies that we reviewed, only Coughlan et al. (2012) and Jung et al. (2008) presented formal empirical studies about technology use in a learning context. Rick (2009) points out the importance of a classroom ecology, but does not provide any supporting study. Coughlan et al.’s investigation informs the design of ecologies by studying transitions in foci across devices (a tabletop computer with a mirrored projection, laptops, a telephone) in three short controlled activities, carried out in a “technologically-enhanced indoor space”. Communication across devices was provided by a Central Management System and instant messaging. The focus of their study was on how device ecologies can support collaboration. Study results presented a set of “seams” that represent disconnects in a device ecology that can affect users’ behaviors. Their study however gave little indication of how one can understand whether or how learning has occurred within the context they constructed.

Jung et al. studied one’s network of personal artifacts through the lens of ‘factors’ and ‘layers’ within a ‘personal ecology of interactive artifacts’, described as a “set of all physical artifacts with some level of interactivity enabled by digital technology that a person owns, has access to, and uses”. They make use of two methods called the Personal Inventory, based on a simplified version of the Repertory Grid Technique, and the Ecology Map, which consists of sketching using sticky notes to probe about a person’s device ecology. Their
exploratory study with ten graduate students found that perceived attributes of an artifact can be classified into two categories, designed properties (physical, functional, informational, interactive aspects) and subjective values (experiential, emotional, social). They further specify the different types of relations that artifacts in a personal ecology can have, based on: purpose of use, context of use, or subjective meaning. Their study results, although very helpful to understand the nature and types of technological ecologies, again do not consider the process of learning.
Table 1. Theoretical or philosophical contributions on the TE concept

<table>
<thead>
<tr>
<th>Concept</th>
<th>Author(s)</th>
<th>Characteristics of the Ecology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology ecology of displays and devices</td>
<td>Chu and Quek (2012)</td>
<td>• <strong>What:</strong> Mesh of interacting displays and devices</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Why:</strong> Deliver a cohesive learning experience</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>How:</strong> Enable access to digital information, its manifestation and manipulation</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Concept</th>
<th>Author(s)</th>
<th>Characteristics of the Ecology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media ecology</td>
<td>McLuhan (1962)</td>
<td>• Media (technologies) function as environments that pervade human culture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Media do not determine human action, but they define its possibilities and constraints</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Media do not cause linear effects, but enable particular forms of communication, consciousness and culture to emerge</td>
</tr>
<tr>
<td>Ecology of communication</td>
<td>Altheide (1994)</td>
<td>• Relationships related through process and interaction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• A <strong>spatial and relational basis:</strong> characteristics of a medium depends on a certain arrangement of elements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relations are not haphazard or wholly arbitrary: connections emerged because they are fundamental for the medium (technology) to exist and operate as it does</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>There are developmental, contingent and emergent features:</strong> a change in any portion is likely to influence another portion</td>
</tr>
<tr>
<td>Information ecology</td>
<td>Nardi &amp; O'Day (1999)</td>
<td>• <strong>System:</strong> Marked by strong interrelationships and dependencies among its parts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Diversity:</strong> Its complexity ensures niches for many different roles and functions that complement each other</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Coevolution:</strong> Dynamic change and adaptations occur as system adjusts to new constraints and possibilities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Keystone species:</strong> Presence of certain species is crucial to survival of the ecology</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Locality:</strong> Local participants construct the identities of each component by assigning it a 'name' and a 'habitation'</td>
</tr>
<tr>
<td>Personal information ecosystem</td>
<td>Tungare &amp; al. (2006)</td>
<td>• <strong>Organisms:</strong> Distinction among components of ecosystem is based on ability to transform or transmit information</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Energy flow:</strong> Equivalent of information flow. Some devices are producers of information, others consume information</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Variety and Diversity:</strong> With respect to capabilities of devices to transform and transmit information</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Interdependencies:</strong> Devices have different types of relation among them, e.g., symbiosis, commensalism, parasitism</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Environment:</strong> Changes in support infrastructure in ecosystem affect devices within, e.g., advances in available infrastructure spur innovation in devices; parts of the ecosystem move towards environments that can better sustain the system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Processes:</strong> Continual internal processing and inter-device communication occurs in the devices in an ecosystem</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <strong>Equilibrium:</strong> When user’s information needs are met and information flow and interdependencies remain stable over time. Components may be added to or removed from the ecosystem at any time.</td>
</tr>
</tbody>
</table>

| Classroom ecology of devices                  | Rick (2009)                      | • Scripted learning activities should not be unduly limited in effectiveness by the limited number of devices |
|                                              |                                  | • Application suites should be able to utilize multiple different devices                      |
|                                              |                                  | • Data should be able to be shared seamlessly between devices inside and outside the classroom |
|                                              |                                  | • New devices should be able to be integrated into the classroom                                |
Table 2. Empirical studies related to the TE concept

<table>
<thead>
<tr>
<th>Concept</th>
<th>Author(s)</th>
<th>Characteristics of the Ecology</th>
</tr>
</thead>
</table>
| Technology ecology of displays and   | Chu and Quek (2012)              | • **What:** Mesh of interacting displays and devices  
• **Why:** Deliver a cohesive learning experience  
• **How:** Enable access to digital information, its manifestation and manipulation |
| devices                               |                                  |                                                                                                                                                        |
| Display ecology                      | Huang, Mynatt & Trimble (2004)   | • *Uses of large displays may not be constant over time:* both interactive and passive use, e.g., as ambient displays, have to be accounted for  
• *Value of large displays in display ecologies is in terms of ease and level of support for task and collaborations that call for such surfaces:* the fluid migration of tasks among display surfaces is characteristic in multi-display environments  
• *The nature of work changes over time, from exploratory to streamlined and routinized:* support for undefined tasks and proceduralization allows artifacts to be continuously valuable |
| Interaction ecology                  | Enquist, Tollmar & Corry (2007)  | • Users are in continuous dialogue with each other and with distributed physical artifacts  
• The ideal state is one of harmonic interplay, where relations between actors are smooth  
• The state of balance between people and artifacts is characterized by a state of awareness of the status of surrounding resources and control over attentional demands of artifacts  
• People and artifacts have mutual dependencies  
• Balance of an ecology results from ongoing and dynamic interaction between people and artifacts  
• Focus is the everyday meaning people ascribe to things and strategies for how to act accordingly |
| Computing with multiple devices      | Dearman & Pierce (2008)          | • Focus on users, not devices  
• Awareness of roles and context of use  
• Lighter-weight information transfer  
• Improvement of file synchronization |
| Personal ecology of interactive      | Jung et al. (2008)               | • *Connection through information sharing:* However people appropriate digital artifacts based on customized needs regardless of initial design intents of artifacts  
• *Connection through functional compatibility:* People augment the use of a single artifact flexibly through customized combinations with different devices  
• *Contextual affordance and commonality:* Diverse affordances of context and physical properties render some artifacts more important to users when selecting one device to use  
• *Ecological values changing behavior:* Value criteria influence user’s behavior, perception and general experience with artifacts |
| artifacts                             |                                  |                                                                                                                                                        |
| Device ecology                       | Coughlan et al. (2012)           | • *Physical seams* distinguish between devices, and the space between them  
• *Information seams* occur when certain information is available only in certain places  
• *Sensory seams* where something cannot be seen or heard from another part of the device ecology  
• *Interface seams* where devices have the same functionality, but provide it in different ways |
II.6. Evaluating Thinking, Learning and Sensemaking in TEs

Few or any work on technology ecologies in education evaluate their effects on learning or other higher thought processes in relation to the devices used. The focus of Coughlan et al. (2012)’s study, for example, emphasizes collaboration and foci transitions. Jung et al. (2008)’s focuses on elucidating the relationships and interplay among the different devices in one’s personal ecology. One of the obvious reasons is that the evaluation of learning represents a tremendous challenge. Generally in HCI, learning appears to have been most commonly measured by the administration of pre-post questionnaires of factual knowledge or information to study participants to detect some sort of change. Apart from the decontextualized, very contrived and rigid nature of this type of tests, it also does not reveal much in terms of how the method, process or tools used during the activity have helped or hindered learning. They are therefore mostly useful only for a blanket statement of whether the piece of technology in question was effective or not in transmitting the desired information.

It is important to note that we are only interested in how to evaluate learning (thinking, sensemaking or other higher thought processes) for the purpose of scientific discovery or understanding about technology ecologies. Our research is not concerned directly with the assessment of students’ learning or performance. Many methods such as examinations, portfolios, presentations and peer assessment (e.g., see Macdonald and Savin-Baden (2004)) have been developed for this purpose in education research and in the learning sciences. Kennewell (2001) summarizes the problem that we address well: “The challenge remains to design a metric for affordances and constraints which allows for the relativity of these features to the learners’ abilities.”

Apart from HCI, the field of educational technology (edutech) perhaps then is the closest area with research that is relevant to our question of how to evaluate technology ecologies for learning activities. Much Edutech research has decried the study of technologies in isolation (e.g., how useful is a computer or particular software for learning?) and has emphasized the need to study particular technologies in the context of other factors of the educational ecosystem (e.g., the role of teachers, the school system, classroom setting, etc.). The ecosystem referred to in these work however include the community, infrastructure
and institutional system in which the particular technology is being used. Our conception of the ecosystem conversely relates to the network of other technologies used around the particular one under study. This distinction will be made clearer in the next section on ‘Theoretical Model’.

Another critical distinction to highlight in the evaluation of learning is that of outcome-based versus process-based assessment. The use of pre-post test scores, for instance, considers outcomes to determine the effectiveness of a technology. However, as described by Kennewell (2001), because of the multitude of factors that can influence results, “it may thus be preferable to consider how to ‘measure the learning process’ rather than how to ‘evaluate Information Technology’”. Vygotsky (1978) also emphasized the importance of studying the process of higher thought: “To encompass in research the process of a given thing’s development in all its phases and changes...fundamentally means to discover its nature, its essence, for ‘it is only in movement that a body shows what it is’”. We follow a process-based approach to evaluation in our work, heeding Kennewell’s and Vygotsky’s perspectives.

II.7. Summary of Related Work

Despite the large number of different conceptions of technology ecologies, comparatively few have focused on the educational domain or the learning activity. Among work that have looked at learning contexts, most assess factors with respect to the design of TEs but not necessarily in relation to optimizing the process of learning. In the next section, we present a review of theoretical models that have commonly been used as foundation for the process-based evaluation of technologies for learning, thinking and sensemaking.
CHAPTER III: A THEORETICAL MODEL OF TECHNOLOGY MEDIATION

The use of technologies to support higher thought processes is by default a mediated activity. Users interact with information needed to catalyze thinking through a particular technology or technology ecology. The idea that technologies, tools or artifacts provide mediation has been advanced by many including Vygotsky, Polanyi, Merleau-Ponty, Heidegger, Piaget and Papert.

Vygotsky and others following in his stride such as Leont’ev and Engestrom called for “a serious study of artifacts as integral and inseparable components of human functioning” (Kuutti, 1996). According to their mediation theory, artifacts, acting as externally-instantiated signs called ‘material carriers’, have a mediating effect on higher-level processes such as thought. Polanyi (1967) and Merleau-Ponty (1962) argue that we gain a certain awareness of tools by physically manipulating them using bodily actions, leading to an internalization process of experiences. Heidegger (1962) proposes that our existential engagement with the world only becomes meaningful through our interaction and experience with tools in the world, and that the tools can act in different capacity from being ‘present-at-hand’ to ‘ready-to-hand’. Last but not least, Piaget and Papert (Ackermann, 2001) inform us that learning is actively constructed through interaction with the world, and that it is transformed when expressed or actualized in different media and contexts.

All these perspectives point to the fact that the study of the physical manifestation of digital media in the form of artifacts and tools as actualized in an educational context is a worthy effort. It provides a motivation for us to ask “To what extent can mediating technologies help to make information ‘real’ for the learner?”. We review below three of the more common theories based on the mediated model of cognition that have been adopted into the field of HCI in recent years to conduct process-based user evaluations of technology.
III.1. Models of Mediated Cognition

Distributed cognition

The theory of distributed cognition, first proposed by Edward Hutchins (1995) based on his study of airline cockpits, sees cognition (thinking) as being spread across tools, artifacts, people and processes. The use of distributed cognition to analyze activity systems has been called cognitive ethnography and is guided by a set of four core principles (Hollan, Hutchins, & Kirsh, 2000):

1. People establish and coordinate different types of structure in their environment
2. It takes effort to maintain coordination
3. People offload cognitive effort to the environment whenever practical
4. There are improved dynamics of cognitive load-balancing available in social organization

One of the concepts in distributed cognition that is key to our context is that of offloading or externalization. As embodied beings, people make use of their environment to reduce their cognitive workload. In the words of Wilson (2002), “we make the environment hold or even manipulate information for us, and we harvest that information only on a need-to-know basis”.

That is important as it reinforces our premise that the environment, things around us, and tools that we use interact with our thoughts. However, the concept of offloading has the connotation of a one-way ‘information dump’. The reuptake or ‘harvesting’ of the information back from the environment leaves the information unchanged and static.

Situated cognition

The theory of situated cognition has been significantly influenced by the work of Lave & Wenger (1991) in situated learning and apprenticeships. Situated cognition holds that people can only act and learn in context. Their actions respond to instantaneous, real-life situations instead of following planned scripts. This perspective argues against learning as an accumulation of knowledge. Rather, it perceives learning as an interactive process that occurs in situations. The principles of situated cognition can be grouped into four categories (Choi & Hannafin, 1995):
• The role of context (Everyday cognition, Authenticity, Transfer)

• The role of content (Knowledge as tool, Content diversity and transfer, Cognitive apprenticeships, Anchored instruction)

• The role of facilitation (Facilitation methods, e.g., modeling, scaffolding, coaching, advising, fading)

• The role of assessment (Problems and issues, Trends in situated learning environments – self-referencing, flexible and transferable knowledge and skill, diversity and flexibility of learner-centered measures, etc.)

Our interest in situated cognition is mainly in the recognition of the inextricable link between thinking and the contexts in which it occurs. This helps us to understand how the characteristics of the technology ecologies in which we function may affect how we think and learn. This puts into perspective, Lewin, quoted in Ross & Nisbett (1991), who proposed the idea of channel factors as “small situational forces that either increase impelling forces or reduce constraining forces to move individuals toward a specific behavior”. Channel factors catalyze behavior in a particular direction whenever “small but critical facilitators or barriers” are encountered. We posit that device affordances or characteristics may guide decisions in-situ on the appropriation and manner of use of devices for learning and cognitive tasks.

**Activity theory**

Activity theory (AT) provides a framework to understand the basic units in an activity system. Its core premise is that any activity is goal-directed and mediated through the use of tools or artifacts. Although AT attempts to describe the activity of the single individual, it does not see the individual action as being isolated. The individual action is embedded in cultural practices, social rules and communities of practice. Activity theory thus frames its entire analysis around the concept of the human ‘activity’ and sees the individual as “situated in a social, cultural, historical, and artifactual world” (Halverson, 2002).
The origin of Activity theory is from Lev Vygotsky’s theory of the sign triangle. Vygotsky was a Russian psychologist and is considered the father of the cultural-historical psychology tradition. His work was popularized and developed in the form of AT mostly by his students Leont’ev and Engeström. We shall come back to Vygotsky’s theories in the later sections of this dissertation.

AT is typically represented by the diagram shown in Figure 3. The theory spells out six guiding principles:

1. Unity of consciousness and activity
2. Object-orientedness
3. Mediated activity
4. Hierarchical structure
5. Internalization/externalization
6. (Historical) Development

Due to well-named theoretical constructs, AT thus has strong descriptive power (Halverson, 2002), but evidence of its usefulness as a practical evaluation framework to generate concrete system improvement guidelines has so far been limited. Work that tries to do so finds itself employing theoretical jargon for intensely qualitative descriptions of problems (e.g., Fjeld, Morf, and Krueger (2004)), and benefits gained are often in a form that is difficult to use.

Figure 3. Activity theory triangle
A number of attempts have been made to render AT more accessible as a design and evaluation tool. Quek & Shah (2004) reviewed five of the common ones: the ActAD method, the Activity Checklist, the AODM method, the Jonassen & Rohrer-Murphy framework, and the Martins & Daltrini framework. Their findings suggest that the ActAD method (Korpela, Soriyan, & Olufokunbi, 2000) and the Activity Checklist (Kaptelinin, Nardi, & Macaulay, 1999) are the only two having potential for use during the evaluation phase of development. Nevertheless, we found these as being still too contrived for our purpose of understanding the mechanism of thought processes in the learning activity.

III. 2. Vygotsky’s Theory of Mediated Action

Our aim was to find a method that allows for the study of thinking in a multi-device environment. To do so, we needed a theoretical foundation that will provide us with a lens to start from. The theories of distributed cognition, situated cognition and activity theory reviewed above all share the importance of context and external representations in cognitive processes. The context referred to in situated cognition tends to include mostly environments, practices, interactions or cultural representations. According to distributed cognition, the external ‘agents’ can include things as well as people. Similarly, context in activity theory may be seen as both physical tools and social actors but contrary to in distributed cognition, humans and artifacts are not functionally equivalent.

Therefore while all these theories may provide an appropriate foundation for our mission of developing a method to investigate thinking in TEs, we found that Vygotsky’s theory of mediated action provides the most depth in terms of its understanding of higher thought processes and interactions with external representations. Vygotsky (1978; 1987) proposes a way by which things in the environment may be brought into the very process of thinking. The mechanism that he proposes is to a certain extent very similar to David Kirsh’s ‘Thinking with external representations’ (2013).

Following, we first explain Vygotsky’s original theory of mediated action, and then describe our extension to it that allowed us to formulate an initial approach to studying thinking in TEs.
According to sign mediation theory, language is conceived of as a psychological tool by which both cultural (interpersonal) and psychological (intrapersonal) thought are ‘mediated’ (L. S. Vygotsky, 1978; Vygotsky, 1987). Signs are self-generated linguistic stimuli (L. S. Vygotsky, 1978) that extend the operation of human cognition beyond the confines of the strictly biological system. Figure 4 illustrates Vygotsky’s sign mediation theory. For example, a student in algebra may be introduced to the summation concept: \(a + b + c\) ... She understands and is able to perform the operation. However, if she had to think of details of the concept each time she applies it, the limits of her memory, attention, and mental processing would make further advancement untenable. Thus, she encodes this concept as a mental ‘sign’ – the concept of ‘summation’. She is able to think of the operation simply as \(\Sigma\), and to employ this in further learning (e.g., \(\sum_{n=1}^{5}(n - 2)^2\)). As the sign becomes ‘internalized’ it becomes in essence the object in her thinking. She can ‘unpack’ the sign as needed to attend to the details.

We use a modified version of Vygotsky’s sign mediation triangle as our theoretical basis to analyze data collected from our study. Vygotsky’s theory talks about the subject, or student in our case, engaging in an activity, which for us is a thinking/learning activity with the object(ive) of processing a certain unit of thought or piece of information, through the use of signs or tools, for example, a concept or a technological device.

![Figure 4. Vygotsky’s sign mediation theory](image)

In Vygotsky’s model, signs may take the form of both internal or external symbols (a stick between a child’s legs becomes his horse, and a block represents an idea (L. S. Vygotsky,
1978), or as an abstract entity grounded in language. Externally instantiated signs are referred to as ‘material carriers’ (MC) of thought (McNeill, 2005) (see Figure 4). Any perceivable object (spatial location, gestures, objects or even sounds) in the environment can opportunistically and temporally be appropriated for use as MCs to assist thinking by bringing spatial ability and perception into play. In theory, the MC can be anything that may or may not resemble the mental object. In our example in the diagram, the MC for convolution can be a specific hand gesture or a written * symbol.

**A Model of the Theory of Mediated Action**

In the context of our definition of a technology ecology of displays and devices (a mesh of interacting displays and devices that enable the access to digital information, as well as its manifestation and manipulation to deliver a cohesive learning experience), we present a high-level model of how thinking can be understood with regards to interactions with digital information through physical technological devices. Figure 5 illustrates our model.

![Figure 5. High-level model of thinking in TEs](image)

People’s thoughts (what we label as Thought objects, TOs), can be encoded into information, that we describe as digital objects (DOs). Through technology in the ecology, DOs can be externalized as Manifest Objects (MOs) that are perceptible to the human senses. Examples of MOs can be displayed documents, images, or file icons. These MOs, however, also have the capacity to mediate further thinking – a process we call objectification. Externalization of TOs as MOs allows the user’s perceptual and spatial abilities to participate in the thinking process. This idea is related to that of ‘distributed cognition’
(Hollan et al., 2000), which, as we described earlier, states that human knowledge and cognitive processes are offloaded into the environment as external representations. Our contribution is that we suggest the mechanism by which cognition is distributed into the environment through the ecology.

We now use Vygotsky’s sign mediation theory to describe a mechanism by which the different processes in our high-level model may take place.

*Extension to the Sign Mediation Triangle*

In the early 1900s, Vygotsky obviously never encountered the magic of computation and modern display technology. The number of MCs one can entertain at any one time is limited by the meanings one can assign and recall for amorphous objects and space. We advance a theoretical framework, in Figure 6, that extends the model of the *sign* and MC, to include the ‘magic’ of digitality. The top of Figure 6 from *thought object* (TO) to mental *sign* and *material carrier* (MC) replicates Vygotsky’s mediation theory. In the information world, a TO can be *encoded* in a *digital object* (DO). The DO can at times even *extend* the TO, such as with information about how the convolution formula was derived. The mental *sign*, as well, thus becomes *associated* with the DO. Through technology ecologies, the DO is *expressed* as a MO, e.g., as a website displayed in a browser on a mobile device. If one mentally appropriates this MO in the process of thinking, in essence shedding ‘intentional regard’ (Dourish, 2004) to the object, the MO becomes synonymous with the MC, i.e. the binding process of *objectification*. Objectification, we purport, is a concept that can be used to identify when one has entered into a situation where one has potentially learned or engaged in higher thinking. In other words, these can be called situations with potential for learning, or opportunities for learning.

Our model expands the power of MOs to support thinking through MCs in two ways. First, MOs are iconic and provide mnemonic reference in ways that arbitrary objects and space cannot. This potentially expands the number of MCs one can employ over longer periods of time. Second, digital media that are encodings of one’s *thought objects* (and hence associated with one’s mediating *signs*) can serve as an external long-term detailed representation of a piece of knowledge, thus extending the depth of thinking one can
handle. Our model describes a thinking process that is different from simply opening a document on a screen to refresh one’s memory about an idea because then the document simply becomes something one queries for information rather than wields in the process of thinking. With multiple users, the MO, being the perceivable component of the model, becomes (in co-located situations) or may be made (in remote scenarios) the shared object among all users (Figure 7). We envision users taking advantage of the broader interactions made possible by a technology ecology to place, organize, and possibly step back and view networks of MCs, as shown in Figure 7.
Figure 6. Digital extension to the sign mediation triangle

Figure 7. Extended sign mediation triangle in groups
Ill. 3. ‘Let’s Follow-the-Doctor’ Approach

The theoretical model that we presented above allows us to understand more clearly the different elements that are involved in activities focusing on intellectual output. Table 3 shows a summary of all the key concepts that are used in our extended theoretical model based on Vygotsky’s sign mediation triangle.

It is helpful to think of the model using the analogy of our Star Trek technology tale, told in Section I.4. The ‘Real’ Bits: A Technology Tale. Recall that just like the Voyager crew ‘stabilized the matrix’ of the hologram doctor to give him a quality of ‘realness’ for the inhabitants of the ship, our aim is to understand what ‘real’ means in the context of digital information and to find the design process by which information may be made ‘real’ for students. In other words, what is the equivalent of ‘realness’ and of ‘stabilizing the matrix’ for the design of technological digital devices for learning?

We can think of the thought object (TO) in a learning-oriented activity as being all the medical knowledge needed onboard the Voyager ship to treat patients. The sign is the idea of the doctor embodying the medical knowledge. The digital object (DO) is the program that allows the doctor to be materialized. The manifest object (MO) is the actual embodiment of the doctor as can be seen by the inhabitants of the ship. The doctor becomes a material carrier (MC) when the crew uses him to advance or restore their health.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Short Form</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thought Object</td>
<td>TO</td>
<td>The idea or concept</td>
</tr>
<tr>
<td>Mental Sign</td>
<td>Sign</td>
<td>Psychological encapsulation of the TO</td>
</tr>
<tr>
<td>Digital Object</td>
<td>DO</td>
<td>Digital representation of the TO</td>
</tr>
<tr>
<td>Manifest Object</td>
<td>MO</td>
<td>Perceptible representation of a DO</td>
</tr>
<tr>
<td>Material Carrier</td>
<td>MC</td>
<td>Perceptible object used as psychological tool</td>
</tr>
</tbody>
</table>

Table 3. Summary of concepts in theoretical model
on the ship.

In devising a method that may allow us to detect whether thinking is being promoted in a particular technological environment and to associate thinking with devices in such a way that it helps us in design, there are two main questions that we must ask. These questions should define the approach and guide the method that we develop. The questions are as follows:

1. Is there a manifest object of the thought object?
2. Does the manifest object become a material carrier at any point? (i.e. does objectification occur?)

These questions recognize that even as researchers, we unfortunately have access only to the external and to what is perceptible to the senses. Thus, even as we attempt to investigate thinking and how it is supported by external representations, we can only aim to identify external representations and their perceptible effects.

With the two questions in mind, our approach is inspired by the idea of ‘following-the-doctor’ around the Voyager starship. Can we identify when, where and how the doctor is used by the inhabitants of Voyager? Or in our case, if we ‘follow the digital object’, can we identify when, where and how the DO, through an MO, becomes an MC?
CHAPTER IV: KNOWLEDGE DISCOVERY STUDY

To allow us to develop our evaluation method based on the approach outlined in the previous section, we needed a concrete scenario that is flexible enough to allow us to experiment with our approach. We conducted a qualitative study of the manifestation of the thinking process in technology ecologies of devices. Adopting the hermeneutic perspective, the inquiry was to seek “understanding rather than explanation” and to uncover systems of meaning from the participant’s vantage point (Patterson & Williams, 2002). We follow the methodology specified by Patterson & Williams (2002) who advance that a hermeneutic approach begins with establishing a point-of-view (our ‘objectification framework’), from which an ‘organizing system’ is derived to meaningfully organize, interpret and present data (Tesch, 1990).

IV.1. Study Methodology

The study asked a set of students to experience a technology ecology for the purpose of doing a knowledge discovery assignment over a two-month period. Their experience was captured through self-reports and interviews. The participants were 12 computer science students in a graduate class. The assignment, to be completed in teams of three, was to research and write a report about the emergent field of ‘Physical Computing’.
The students were each given a 'testbed suite' of devices comprising an iPod Touch, an iPad, and a 27" iMac to use as their own throughout a semester. The iMac, embedded in a custom casing that allowed it to be laid on the table horizontally or at an angle, was endowed with a touch overlay to enable touch interaction (see Figure 8). The rationale for the dissemination of devices of various form factors was that we wanted to provide the students with an experience of a heterogeneous ecology. Additionally, to provide a basic information architecture that crosses devices in the ecology, we installed the free file sharing service Dropbox\(^1\), the notetaking service, Evernote\(^2\), with a paid subscription, and the paid PDF reader GoodReader\(^3\) on the iPad. The first two services are stationed in the cloud, and GoodReader can be paired with Dropbox to allow data synchronization and transfer. We provided the students with a tutorial session on how to use the three services/applications prior to the study.

The class was held in our research center, which contains several large display screens spread out in different meeting rooms, and a large interactive vision-based touch screen prototype (Verdie, Fang, & Quek, 2009). All students had constant access to the building.

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\(^1\) www.dropbox.com
\(^2\) www.evernote.com
\(^3\) http://www.goodreader.net/goodreader.html
They were asked to use technology as much as possible while doing the assignment, including the device suite given to them, the large display screens around the center, and any other devices that they own such as laptops and other desktops. They could also use the devices freely for any other purposes.

**IV.2. Data Collection**

We conducted semi-structured interviews and surveys to capture the students’ experiences with technology before they were given our suite of devices (pre-experience), and after they have used them for the semester (post-experience). Each interview lasted for about an hour and was audio recorded. The purpose of doing a pre- and post-interview was not to perform an experimental comparison, but rather, to be cognizant of the initial conditions under which our participants joined the study.

The pre-experience interviews and surveys collected data about the students’ behaviors and ‘strategies of use’ of the devices, as well as their attitudes toward and perceptions of the devices and processes. More specifically, the survey, which was completed in the presence of the interviewer, asked about the list of devices used and owned, the duration and frequency of use, familiarity with devices, purpose of use, perceived usability of devices (measured on a 7-point likert scale by adapting the IBM usability questionnaire (Lewis, 1995) with dimensions like ease-of-use, comfort, efficiency, satisfaction), and data sharing methods. Qualitative comments were also encouraged during the completion of the survey. The interview addressed similar themes as the survey, and added questions about the role of devices in their idea generation and paper writing processes, and device interactions in their existing ecologies.

The post-experience interviews asked about the process of assignment completion; impact of the devices on practice; problems with devices, information sharing, and the writing process; context/situations of devices use; influencing factors of information use; personal sensemaking; work distribution and team coordination; use of file/data sharing services; longer term device use; general assessment of the ecology; desired changes; meeting contexts; idea generation process; and, information presentation.
CHAPTER V: PROPOSED EVALUATION METHOD

We used the data obtained from the knowledge discovery study conducted to develop our evaluation method. All pre- and post-interviews were fully transcribed with timestamps. Survey data were imported into a spreadsheet for analysis.

V.1. Analysis of Study Data

To separate relevant from irrelevant verbiage in the transcripts, two coders did a first round of analysis of all the transcripts to identify ‘thinking episodes’. Following Barker’s (Barker (1963) in Bailey and Barley (2011)) concept of “behavioral episodes”, we define a thinking episode as a “coherent run of [thinking] in which the constituent [processes] have a constant direction, a purpose”. Some examples include ‘filtering out important keywords’, ‘searching for information’, and ‘annotating papers’. We acknowledge that thinking is a process with no explicit end point or necessary resulting outcome. However, the method of tracking thinking episodes allowed us to identify possible situations when the students engaged in thinking, and was thus presented with opportunities for learning. The evaluation of the uptake of knowledge or retention per se is out of the scope of this dissertation.

In order to make sense of our data on the students’ experiences of their ecologies, we engaged in what we call a ‘DO (Digital Object)-path analysis’ that emerged from our ‘follow-the-doctor’ approach. The steps involved in our analysis, illustrated in Figure 9 together with an example analysis (Figure 10), were as follows: each thinking episode was analyzed to distinguish the different components of TOs, DOs, MOs, and technologies used. We noticed that certain objects had a high frequency of occurrence in our collated list. To focus our analysis thus, we decided to trace the use of three of the common DOs: GoogleDocs documents, Evernote notes, and PDF documents. We shall call these our three focus objects for our study. All thinking episodes where any of the three DOs were manifested as MOs were copied to a separate spreadsheet for analysis. We then analyzed the different technology configurations in which the DO in question was used in each of the relevant thinking episodes.
By tracing the model components in context of use, we determined whether there were indications that objectification had occurred in any form for the particular task at hand. Two separate coders identified objectification indicators by making a judgment as to whether the MO (e.g., Evernote note displayed on a tablet screen) brought spatial ability and perception into the process of thinking. Subsequently, a feature extraction was done, whereby we identified the characteristics of the technologies, or technology configurations, that seemed to have supported or hindered the objectification process. The characteristics were further categorized along uncovered themes. A sample of the analysis carried out in a spreadsheet is shown in Figure 11.

![Diagram](image_url)  

**Figure 9. Method to identify and associate thinking episodes and device affordances in technology ecologies**
V.2. The DO-Path Analysis

The method that we developed based on the ‘follow-the-doctor’ approach and grounded in the study data that we obtained can be easily generalized and applied to other types of learning tasks, other types of data collected and other types of technology.
ecologies. The method, which can be considered as a kind of data ethnography, is basically made up of four parts, as illustrated in Figure 12:

**Part 1: Preparation**
Part 1 includes the selection of a data source (interview transcripts, meeting videos, conversation recordings, etc.), extraction of coherent pieces from the data source that are indicative of ‘thinking episodes’, and deciding on the DO to follow.

**Part 2: Thinking Process Identification**
Part 2 involves analyzing each thinking episode to identify the thinking process in focus, the TO being pursued, and the MO (if any) to which the TO is matched.

**Part 3: Objectification Occurrence**
Part 3 entails coding the analyzed episode for indicators of objectification, and using those to determine whether objectification has occurred in the specific episode. The presence of

![Figure 12. Four-part method for thinking in technology ecologies](image-url)
at least two indicators should be sufficient to rule in favor of objectification in any one particular episode. If objectification is determined to not have occurred, the episode in question may be discarded from future analysis, depending on the goal of the researcher.

**Part 4: Technology Support**

Part 4 involves the identification of the various pieces of technology/devices that have been used in the specific episode. For each technology piece, a coding process is performed to analyze how different features of the technology supported or hindered the objectification process in that episode.

**V.3. Objectification Indicators**

One of the key parts of the DO-path analysis is to determine whether objectification has occurred during the thinking episode. Keeping watch for objectification indicators helps one to reach a judgment on that. The indicators are basically evidence of objective references to the thought object (TO) via the manifest object (MO). They may vary in nature depending on the type of data source being used for analysis. Some examples of objectification indicators are:

- Pointing to the MO (e.g., laptop screen) while talking about the TO (e.g., a paper idea)
- Holding the MO in hand (e.g., holding the tablet in the air) while talking about the TO (e.g., a particular paper)
- Glancing at the MO (e.g., PDF opened on the tablet) and then processing the TO (e.g., writing down a related paragraph)
- Manipulating the MO (e.g., circling a keyword on the whiteboard) while discussing the TO (e.g., the keyword)

**V.4. Examples of Objectification Storylines**

Using data from our knowledge discovery study, we present examples of how we saw objectification manifested in our testbed technology ecology. Recall that our analysis traces three kinds of ‘focus objects’ (PDFs, Evernote notes and GoogleDocs) used by our participants as DOs. Our DO-path analysis of the post-interviews brought to light different
ways in which the objectification process occurred in the ecologies that the students experienced. We follow one of our three ‘focus’ objects as it was involved in two example storylines extracted from thinking episodes.

**Storyline 1: Identifying relevant sources for the assignment**

One team employed a strategy by which they brainstormed a set of keywords and organized these on a whiteboard as a concept map, after attempting to use the vision-based interactive touch screen and failing. From this, they selected a subset of keywords to explore, and used these for literature searches. One of our participants related the following process, which we map to our model:

1. He searched for sources using the keywords and left these in tabs in his laptop browser. These were not saved to disk nor named. The browser tabs served as a ‘bag of finds’ whose relevance was yet to be determined (“I didn’t save them on my computer. They were opened in my browser actually, because I wanted to filter what I have and see if I need to take these or not.”).

2. He brought his bag of finds on his laptop to the next meeting and presented them to the team, and selected some to take (“I just renamed the paper to keep track of which is which. If I saw robotics ... so this is the robotics paper. If there is a lot of robotics papers, I will say robotics 1, 2, 3, and or I would tie it to the name of the author.”). It is at this point that the participant associates particular PDFs with signs. Relating this to Figure 3, the ‘concept of robotics paper as relevant to physical computing’ was the thought object, the sign was the name of the file, and the manifest object was either the displayed PDF document or the named file icon in the folder.

3. He would copy the PDFs to his iPad for further reading, and refined the naming of the PDF according to his understanding of the paper (“So after you read the paper ... OK ... this paper is about this. A way I used to do is to just rename the paper to keep track of which is which.”).

In this storyline, we observe the formation of signs and the use of manifest objects as MCs to help the participant make sense of how each paper (representing a specific concept) fits in ‘Physical Computing’. This strategy was seen in two other participants. One had put her
‘bag of papers’ on her *iPad* and had them open in tabs to share and discuss with her teammates (“... papers that were open on it ... since we were talking about what we researched. I was able to say *I found this paper, it talks about this and this*”). She was using the *iPad* on which the PDF was materialized as an MO to support her discussion and thinking (the team did not actually read the paper on the *iPad* screen, the participant merely used it as an objectified *sign* to reference the information the PDF contained). A third participant employed an almost identical strategy with a slight difference in that he did an initial filtering of his ‘bags of finds’ on his laptop browser tabs, and winnowed these to 15 - 20 papers that he saved and named in his Dropbox. He copied these to his *iPad* for further reading and annotation. There was also evidence of his employment of filenames as meaningful *signs* to give him mnemonic access to the PDFs, and his use of the displayed PDFs as MCs in the process of reasoning about ‘Physical Computing’.

**Storyline 2: Creating the assignment report**

One of the participants organized his paper building from an outline written in a GoogleDocs document. This outline served as the conceptual frame on which he worked: “I have the outline and each point I know which PDF is linked to what, so I would read the PDF and while I am reading, I get an idea, and I start writing on the paper.” He read the paper on his *iPad* and wrote in GoogleDocs on his laptop simultaneously. He mentally associated each outline item in his GoogleDocs outline with several PDFs.

Here, we see that he has a two-level conceptualization of the PDF paper he is reading. The idea of an outline item is a thought object. Both the mnemonic name of the PDF and the concomitant name of the outline point serve as signs for the TO. The TO has two different simultaneous MOs. The outline item in the opened GoogleDocs document is a MO with which he associates the TO, but it is also clear that he “knows which PDF [it] is linked” to. A second MO is thus the display of the PDF on his iPad. Further, since the PDF summoned to the *iPad* is open to reading and inquiry, the contents of the PDF themselves become another level of TOs, signs, and MOs. At each level, objectification may occur to allow the use of the MO as an MC for reasoning. It is precisely this nature of signs that are able to hold entire concepts for thinking, and be unpacked into its contents for inquiry at a finer degree.
of abstraction that makes the theory a potent vehicle to understand thinking in technology ecologies.

This same two-level strategy was employed by another participant who used PDFs in Dropbox folders to support conceptualization. The mnemonic names of the PDFs served as the signs and the preview display of the PDFs (quick look feature in the Macbook laptop) in the Dropbox folder served as the MO or MC when he referred to it while writing. The participant wished he could add more information to the sign at the level of the whole PDF, stating “Originally we discussed annotating them (the PDFs), but we found that it was kind of difficult to actually do it because we just wanted to have a summary of each paper but Dropbox on the iPad would not let us create a text file [of the same name] next to the papers.” This shows that the participant was thinking at the level of the PDF as a whole, and wanted to associate meta-information at the level of PDF within the folder structure.

Another three participants exhibited the same two-level conceptual structure using yet other methods to provide overarching structure of how the sign associated with each PDF relates to the paper as a whole. Two of them employed a citation manager, (e.g., Endnote, Mendeley) to maintain citations and to add an annotation at the level of the whole citation for each PDF. An entire PDF thus could be used as a contained unit of thinking for paper writings. Our last participant recorded to use this strategy employed Evernote for her higher-level organization. She had an Evernote note for each PDF document, describing its contents at the level of its place in the whole ‘Physical Computing’ paper. Evernote allowed her to attach the PDF directly to the note, enabling the same two-level sign-MC strategy.
CHAPTER VI: OTHER STUDY FINDINGS

Although the focus of this dissertation is on the methods of evaluation, we present insights and findings that were gained from the use of the DO-path analysis to give an idea of the type of results that could be obtained from our proposed method. The findings on device affordances provide important insights as to the design of technology ecologies for learning. To frame our findings, we will first describe the starting context of our participants from results of the pre-interviews/surveys, with an emphasis on processes of thinking with devices. This also conveys an understanding of the work strategies of the participants in the testbed TE of the study, since practices, as we anticipated, did not change significantly over the two months.

VI.1. Initial Experience of Testbed TE

It was evident that some of the students already had a rather extensive ecology of devices prior to the study. The most common devices that they possessed were laptops, desktops and smartphones. Fewer owned tablets, music players and large displays (Figure 13). Among those who owned them, laptops and tablets were used daily. Desktops were mostly used only two to three times per week. All, apart from two, indicated that they used their smartphones everyday. The use of music players and large displays was more sporadic.

![Figure 13. Distribution of devices in initial ecologies of the students](image)

Laptops and smartphones were mostly ranked first in familiarity, followed by tablets and music players. Students were generally least familiar with desktops and large displays. Their use of the devices can be classified into three types:
• *Instantaneous* use, e.g., checking email, calendar, news, social networks (tablet, smartphone)
• *Extended* use, e.g., reading papers, video streaming (laptop, tablet, large display, music player);
• *Long-term* use, e.g., backup of work, managing Internet (desktop, music player).

All except one had experience with Dropbox prior to the study, with an average duration of use of a year. Only three of the students had used Evernote, with an average of two months of use. All of the others however made use of other notetaking applications such as GoogleDocs and TextMate. Among those who already had a tablet, only one of them made use of GoodReader. The other students used other PDF readers/annotators such as Adobe Reader and QuickOffice. In terms of usability, the laptop \( (M = 2.57) \) was ranked the highest, followed by the tablet \( (M = 2.41) \), the desktop \( (M = 2.39) \), the smartphone \( (M = 1.92) \), the music player \( (M = 1.88) \), and finally the large display \( (M = 1.85) \).

In the existing technology ecologies of the students, the thinking process for assignments mostly followed the standard loops of foraging and sensemaking (Card & P., 2005), with the prominent use of the laptop and desktop throughout. Actions in which a thinking process was evident on these devices included for instance, “just open[ing] up Microsoft Word and start typing in ideas”, taking notes in a text file on Dropbox “when I’m surfing and I find something interesting”, “categorizing my papers through...folders”, and “start[ing] to kind of do a treelike structure from the cited references”.

Those who had a tablet reported making use of it only occasionally for purposes of work. We could not identify many thinking episodes in their accounts of use of tablets. Among the few that we found such as for annotating readings, reading information in the browser or notetaking in the native ‘Notes’ application, the annotations were only “like an intermediary step to a final annotation”, the website was “just [to take] a look at”, and the notes (e.g., “on page X second paragraph is interesting”) would remain on the tablet.

The use of non-digital materials, such as sticky notes, notebooks and pieces of paper, was evident mostly in the ‘foraging’ part of the process. Paper materials appeared to have been used only as quick, temporary MCs and rarely had their content transferred to digital in the
same exact form. One participant, for instance, recounted that she would write down ‘idea fragments’ on paper, and then “when I finally get my idea, I would put it on TextEdit”, after which she would throw away the paper pieces. Or for reading papers, another participant “tend to print them out”, “take some notes on it. And then turn it into some thrash”. A number of the participants also reported relying only on memorization, “I remember some keywords of it, so I can get it when I want to”, without the use of any devices.

**VI. 2. Affordances of Testbed Technology Ecology**

To recap, our theoretical framework used for analysis is that digital objects may be materialized through technology ecologies into manifest objects, and that these MOs may be appropriated through a process of objectification to serve as material carriers that support thinking. We extracted 50 thinking episodes that related to GoogleDocs documents, Evernote notes, and PDF documents. Our DO-path analysis traced the three ‘focus’ MOs in terms of thinking processes, TOs, DOs, MOs, technologies used, relevant quotes relating to affordances and experience, and the occurrence of an MO-MC binding (coded as hindrance or support).

![Objectification instances in testbed technology ecology](image)

The fourth part of the DO-path analysis coded the quotes extracted in the first part of the analysis for objectification indicators and ‘support’ (in the moment or/and in the long-term) or ‘lacking’ characteristics of the technology configurations used. Indicators included for example referencing materials as thoughts, reports of pointing to objects as ideas, and use of space as an organizing structure. Figure 14 shows the distribution of thinking episodes in which the MO was able to be coded as either having a support or hindrance role in relation to the students’ thinking processes. The syndissertation of the technology
affordances that we found supported, were lacking, or hindered objectification to occur is presented in Figure 15. The features were derived from storylines like Storyline 1 and 2 that we described in Section V.4. Examples of Objectification Storylines.

Storyline 1, for example, shows evidence of the creation of mental signs as part of the reasoning workflow, and how objectification may have occurred by which MOs, materialized from the PDFs, served as MCs to support thinking. The persistence of the ‘bags of finds’ in the laptop browser allowed the participants to think of these finds as ‘stuff I found’ without necessarily forcing them to a premature commitment to meaning or interpretation. The mobility of the iPads supported opportunistic action so that the bags of finds and the named PDFs could be used to support thinking. The transparency of action between searching, renaming, and reading allowed for “a complete experience”.

![Figure 15. Affordances of technology ecologies to support objectification](image)

In Storyline 2, all the participants regarded the entire PDF as the DO related to a particular TO at the level of the organization of the entire paper being written. The participants all employed a strategy of encapsulating this level of conceptualization of the paper with a very short description that served as the MO. This allowed the participant to bring perception into the process of thinking by using the MO to serve as an MC. The extent at which this objectification process occurred however was highly dependent on the transparency of interaction to annotate/associate meta-data to the high-level description of the TO, and the persistence of the display of the MO. The immediacy of being able to quickly...
drill down to the content of the PDF document as well supported the unwrapping of successive layers of abstraction and encapsulation.

**The Design of Learning Spaces**

We believe that there is a lack of designed support to optimize technology’s role of augmenting humans’ higher thought. From our findings, we proposed technology affordances that appear to help the process of objectification. These can be classified into seven groups, although they are all interrelated at certain levels. Below, we discuss the central theme of each group, while providing considerations for system design features that can potentially embody each theme. It must be noted however that our proposition of technology affordances in technology ecologies for learning does not imply that one can design such a complete ecosystem for learning. Variations in individual learning styles and the diversity of subject matter to be learned would preclude such rigidly constructed ecosystems.

Drawing insight from the inveterate paper ecology that has supported learning since Gutenberg’s printing press, we suggest that learning ecologies, be they physical or digital, have to remain ad-hoc but with designed support. The paper ecology, that includes writing implements, tables, bookshelves and libraries, books, and the myriad paper clips, staplers, rulers, and folders, has evolved over more than half a millennium and provides a vast set of components that are flexible enough for the individual to appropriate them to construct his/her environment for specific learning experiences. The digital ecology as well, needs to evolve technologies that possess affordances but yet are malleable enough to support learning.

We present below the main groups of affordances from our testbed ecology that we found allowed information to become ‘real’ for the students. These are represented more legibly in the star diagram in Figure 16:
Affordance 1: **Expectation of interaction (includes transparency, shareability):** It is key that components of technology ecologies are able to not only interoperate in some way, but also provide an expectation of interaction to users. Our writing implements for example can be expected to write with few impediments on paper. Of course, the paper ecology is constrained by materials and physical laws (e.g., we do not have to worry about book 2.0 falling through the surface of table 3.1 because of incompatibilities) while all interactions in TEs have to be designed and implemented. Also, the cultural longevity of paper has built expectations and constraints (e.g., pencils do not work on leather portfolios) into the user community that digital technologies cannot always rely on.

In our study for instance, the students reported that they decided to use the whiteboard for brainstorming particularly because they knew that they would be able to take a picture of it with their iPad cameras later on. Conversely, a clear example of failure of this aspect in our study is one instance where the students spent one entire meeting only to set up shared
Dropbox folders and Evernote notebooks. Work in middleware and system interoperability, as well as direct interaction methods, are important to enable this affordance of ‘expectation of interaction’ to take place.

**Affordance 2: Immediacy (includes persistence, reference, situatedness, accessibility, multitasking, opportunistic action):**

*Immediacy* concerns features that allow the user to display, manipulate, and use DOs across devices without going through one or more indirect actions. For example, if a user has a physical paper that she wants a friend to read, she drops it on the table in front of him. However, if she had the document on her laptop, she may have to put it into Dropbox and tell him where to get it before they can discuss its contents. The lack of *immediacy* in this scenario hinders the *opportunistic* use of the document as a focus of discussion or thought. *Immediacy* is closely associated with *transparency*. Transparent interoperability across platforms supports immediate action as do *consistency* of interaction techniques (consistent ways to move and manipulate MOs across platforms is critical to support their use as MCs). In our study, participants used *persistence* to allow information to stay immediate and more easily participate in their thinking: on the laptop, they aligned their *Word* document and the PDF papers side by side. Others used their *iPad* as a ‘persistent’ secondary display for the PDFs.

**Affordance 3: Concreteness (includes dedicated use, spatiality, tangibility):** Components that possess the characteristic of ‘concreteness’ in a form appears to better support objectification. In our study we saw that the whiteboard that affords the use of space and the *iPad* that opens applications using the full screen real estate, for example, aid information to become what Heidegger (1962) calls a ‘thing’, something tangible for the student to grasp in her thinking process. A technological environment that requires the user to hold thoughts in mind while looking for the appropriate device to record them offers little support for objectification.

Work on embodied interaction, physicality, and tangible user interfaces that address how to enable the user to easily assign thoughts to concrete materials contribute to this affordance.
Affordance 4: Iconicity (includes structure, mnemonicity, atomization, customization):

Objects to which we have assigned meaning become more easily internalized than neutral objects. We have seen the use of file renaming and organization of folder structure as instances when *iconicity* has enabled MOs to be used as MCs of thought. The few works in HCI that have looked at familiarity of interfaces are potent informants of this affordance. *Atomization* is a related feature that supports the association of DOs to TOs. A TO is typically an atomic idea at some level of abstraction, in the same way that a ‘unit of analysis’ specifies an entity that is a coherent whole at a certain level. Take the idea of convolution in our earlier example. A Wikipedia page on convolution would be an apropos DO for the concept, but a whole book on signal processing would not (even if it contains a section on convolution). Features to support *atomization* (e.g., bookmark individual components of larger text documents) have been investigated for example in hypermedia research.

Affordance 5: Common ground (includes simultaneous focus and control):

To be able to focus on thinking in groupwork, the technology should provide support for students to easily create shared MCs. A common MO may not necessarily lead to the same mental *signs* for two different people. This is essentially the question of inter-subjectivity (Gillespie & Cornish, 2010). Physical things inherently allows for several users to have simultaneous focus and control. A page on the table can be seen by everyone around the table; several users can write on the whiteboard at the same time. In digital technologies however, the students always needed a separate ‘situating channel’ (e.g., speech, instant messaging, comment lines) to set common ground together with the ‘information channel’, where work is carried out. This factor also appeared to have prompted the more intensive use of GoogleDocs, which has a simultaneous editing capability, over Evernote for notetaking.

Work in computer-supported collaborative would be relevant to further inform the design of this affordance into technologies.
CHAPTER VII: CRITICAL ANALYSIS OF EVALUATION METHOD

The DO-path analysis method may be thought of as a kind of data ethnography whereby we track particular data objects so as to see its transformation throughout its 'life' while the learning activity lasts. It is by far an information-centric method, instead of a person- or device-centric one. It is also not a single data collection or analysis technique but rather, it borrows from different traditional techniques (e.g., qualitative open coding, video analysis, discourse analysis, observations) and specifies guidelines to detect the effects of data wielded as psychological tools.

We performed a SWOT analysis on the proposed evaluation method. SWOT analysis is a commonly used method in the business field to evaluate a company's competitive advantage in a particular marketplace. It has been used fruitfully outside of the business realm and in the HCI field (e.g., Rizzo and Kim (2005)). The general question asked was how well does the DO-path analysis method satisfy its purpose of evaluating thinking in technology ecologies. *Strengths* typically ask about the advantages of the organization/method/product, its unique selling point, what it does better, etc. *Weaknesses* ask about improvements that can be made to the organization/method/product, negative factors that can impact its use, actions to be avoided, etc. *Opportunities* and *threats* look at external factors that could affect the organization/method/product. The first asks about the trends and benefits to the greater community that the method could bring. The second asks about the potential obstacles, criticisms by others, etc.

To reiterate, the two main goals of this dissertation was to provide a viable solution to the following problems:

- How may technology ecology of devices make information ‘real’ enough for one to engage in higher thought?
- How may we know when they do?

Table 4 shows the strengths, weaknesses, opportunities and threats of the DO-path analysis based on our observations during the use of the method for our knowledge discovery study.
The use of our method in particular provides a way to analyze the \textit{process} of learning. As compared to the outcome-based method of pre-post knowledge tests commonly used by HCI researchers to measure learning or to test the effectiveness of a piece of educational technology, it gives a better understanding of the development of knowledge acquisition and processing as mediated by signs and tools. In the words of Vygotsky, one studies the live animal, the other the fossil. We know of no other method that precisely attempts to analyze the mechanism of learning with technology. Activity theory and distributed cognition that we described in Section III.1. Models of Mediated Cognition may perhaps be the other commonly known methods to analyze process in mediated situations. However, the theories underlying these two approaches are much less specific and harder to use. Often, findings from these are in the form of ‘thick descriptions’ that are difficult or not possible to be quantified or parsed for design themes.
Table 4. SWOT analysis of the DO-path analysis method

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<td><strong>Strengths</strong></td>
<td>- Flexible in terms of type of data source, i.e. not data type-specific</td>
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<td>- Provides clear stages and steps that can be systematically followed</td>
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<td>- Based on a solid theoretical foundation</td>
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<td>- Provides a language to make sense of the thinking process</td>
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<td></td>
<td>- Easy to associate thinking processes with technology features</td>
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<td>- Provides qualitative results that can be subjected to quantified analysis if desired</td>
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<td><strong>Weaknesses</strong></td>
<td>- May be labor-intensive and time-consuming</td>
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<td>- Subjective to a certain degree</td>
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<td>- May require a basic level of training to code for objectification indicators</td>
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<td><strong>Opportunities</strong></td>
<td>- Pave the way for a principled method that can provide some consistency to the evaluation of technology ecologies for learning</td>
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<td>- May catalyze discussion on the effectiveness of technologies to support learning</td>
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<td>- May allow for more in-depth and substantive analysis of higher thought processes</td>
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<td><strong>Threats</strong></td>
<td>- Thinking is a complex process and it is necessarily simplified to a certain extent</td>
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<td>- Objectification is an internal process, yet we can only do our best to detect external indicators of it</td>
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CHAPTER VIII: SIGNIFICANCE AND LIMITATIONS

VIII. 1. Significance

The extent of the significance of the work that this dissertation represents can be judged by considering the amount of contribution made. Our contribution is at least four-fold:

A. Methodology
The DO-path analysis is a method proposed to both evaluate thinking in a technological environment with regards to affordances of devices, and to evaluate devices in ecologies with regards to their use for thinking. We know of no other work in the literature that attempts to provide a clear evaluation or analysis method for thinking in technology ecologies. In that regard, this dissertation contributes significantly to the area of technology ecologies, focusing on how they may help us to think and to learn. We identified a gap in the literature of the plethora of technology ecology/ecosystem concepts previously proposed in terms of investigating learning.

B. Theory
We advance the relevancy of Vygotsky’s sign mediation theory to the study of higher thought in the areas of ubiquitous computing, pervasive computing, interactive surfaces and general HCI. We extend his theory to the digital world by proposing how thought objects may relate to digital objects, and their manifestation through technology ecologies.

C. Evaluation
We propose a way through the concept of objectification and method of DO-path analysis to examine device ecologies for their potential for learning. While we do not directly evaluate whether the students have learnt, we help to identify instances where students have possibly learnt, i.e. opportunities for the occurrence of learning. We believe that this in itself is a significant step toward measuring technology-mediated learning.
**D. Design**

We articulate affordances that can inform either design guidelines or evaluation metrics for the development of device and display ecologies that allow us to think effectively. The themes uncovered during our study provide a good starting point for designers, developers and researchers to ask ‘what should we develop for to support learning?’. This contributes not only to the design of interactive technologies, but also to the design of entire learning spaces, environments and architecture.

**VIII. 2. Limitations**

Although the work in this dissertation is limited in a number of ways, none of the limitations voids or lessens the significance that the work represents. The main limitations are as follows:

- The knowledge discovery study used as grounding for the development of the DO-path analysis method was conducted with computer science students who may have had a different perspective on technology. Researchers from other domains like history may require additional support to piece together fragmentary information. Such extension can be a rich domain for future research.

- Although we do not claim to propose a holistic explanatory theory of cognition, we do believe that the objectification framework manages to uncover basic thinking processes irrespective of the student’s domain expertise. Knowledge discovery is foundational to any form of learning.

- The evaluation method used to analyze the study data was developed in an iterative, interactive fashion during the analysis process itself. Therefore, though the general approach to be taken was known, the data analysis method to be used was not known beforehand. While this is not a problem in and of itself, a clear and streamlined posthoc analysis of the study data may reveal more detailed and nuanced findings.
CHAPTER IX: FUTURE RESEARCH

Through the contributions made in the four areas of methodology, theory, evaluation and design, we have opened up a large number of avenues for future research. There are also further research that may be done to improve upon the work that has already been carried out. We list a few possibilities for both further and future research below:

IX. 1. Further Research

Development of method
With repeated usage, the DO-path analysis method could be tremendously improved. The four steps of the method could be refined and streamlined to be simpler and more direct. Moreover, it would be helpful to provide a blank template for researchers to use when identifying the different components of the thinking episodes, e.g., the DOs, MOs. Another worthwhile approach to develop the method further is to create an application that can partially automate the analysis process by aiding in the identification of components, objectification indicators and the judgment of objectification. This, however, is a challenging undertaking that will require great effort.

Validation of method
The DO-path analysis method is still in need of both content and ecological validation. Further research may entail the use of the method across different types of technology ecologies for learning and by groups of people with differing characteristics (e.g., people who are not full-time students, casual learners, etc.)

Variations of data source
We made use of mostly interview data and self-reported in-situ speech to perform the analysis. Further research should employ our model and method to make sense of students’ in-situ speech and videos on top of their self-reported experiences of learning using technology.
IX. 2. Future Research

**Operationalization of design themes**

Each of the design themes that we uncovered in our study findings can be the subject of a whole new area of research in terms of how they can be applied to the design of new devices and interaction methods. Some work have already been done related to some of the themes by others. Three examples of the operationalization of the affordances are presented below:

*Example 1: Immediacy*

Chung et al. (2013) have looked at providing immediacy in the sharing of information across devices by implementing a gesture-based interface whereby the user can ‘flick’ an information piece directly from one screen to another, hence eliminating all mediation in information transfer.

*Example 2: Common ground*

Miller et al. (2008) conducted research on how PDAs coupled with a large interactive tabletop system can function to provide common ground to a group of history students engaged in a sensemaking task. In the integrated system called ‘CardTable’, the PDAs acted as an ‘information pickup and control device’ for each individual student while the tabletop ensured that common focus was maintained throughout the group and the task.

*Design of learning spaces*

Our work provides a stepping stone to the foundation required for the design of whole learning environments. Interest is growing rapidly in research to design both formal and informal technology-enhanced spaces that are particularly conducive for studying and learning. Such environments may include classrooms, libraries, museums, studios, study rooms, play rooms, etc.
That technological devices are now ubiquitous in education is a fact in the context of both institutions and the individual learner. The multitude of devices however are often used in technology ecologies to achieve a coherent and substantive experience. But ecologies of devices and displays is a phenomenon that we have yet to understand fully. Much research that investigate the benefits of devices for learning places emphasis on the framing of educational content from the point of view of digitality. We question instead how may the physicality of devices and the effects of interaction that it brings with it make digital information ‘real’ so as to positively affect processes involved in thinking, sensemaking and learning. Our focus was on the development of an evaluation method for studying thinking in technology ecologies and on affordances of devices that may support higher thought.

By extending Vygotksy’s theories of the sign mediation triangle to the digital world, we advanced the mechanism of objectification as one that helps us to understand the process of thinking, and an approach similar to data ethnography for the study of thinking. We conducted a longitudinal study involving the distribution of different devices making up a testbed technology ecology to graduate students to examine their use and appropriation throughout the completion of a semester assignment. The knowledge discovery study provided us with data to ground the development of our analysis method called the DO-path analysis. Using the method, we uncovered from our study several design themes that may support objectification. Our contributions in this dissertation are in the form of methodology, theory, evaluation and design.

The work in this dissertation provides an exciting stepping stone for further research to be done in the area of technology ecologies for learning. We do leave the philosophical debate as to what the ‘realness’ of information may mean to future work and to others, but we present a way to determine what is ‘real to the mind’ by looking at the effect of information to the extent that it can be wielded as a psychological tool.
Especially in the face of changing perspectives in education, HCI researchers should begin investigating and designing technologies that help us think, or in our Star Trek tale, that make the doctor ‘real’.
The following work have been published wholly or partially based on work conducted in this dissertation:


REFERENCES


APPENDIX A: Participant’s Consent Form

PARTICIPANT’S CONSENT FORM

PROJECT TITLE: Digital Ecologies for Learning

INVESTIGATORS: Sharon Lynn Chu, Blake Sawyer, Alex Endert, Haeyong Chung, Thomas Martin, Ph.D., Francis Quek, Ph.D., Christopher North, Ph.D., Steve Harrison, Michael Evans, Ph.D.

I. PURPOSE OF THE STUDY: The purpose of this study is to understand how digital information is objectified for learning through the use of different types of devices. This research is being conducted by Virginia Tech.

II. PROCEDURES:

Description

Prior to the start of the study proper, you will go through a pre-interview of about half an hour, where you will be asked simple questions about your current use of digital information and devices that you already own.

For the study, you will be given a set of devices that may include for instance an iPad, an iPod Touch, and an iMac fitted with a touch screen overlay. The set of devices that you receive will be determined by drawing lots.

The researchers will introduce each device and explain the key features of all the software required to you. You will then have one week to get used to the devices, and ask any questions about problems that you encounter.

You will be free to use the devices however you wish (including installing new software, bringing the devices home, etc) to complete a class assignment that involves the writing of a report on the nature of physical computing. The assignment has to be done in groups of three, and you are free to choose your own group members. More details about the assignment will be given by the class instructor.

The study will last one month, during which you can use the devices to complete the class assignment. During that study period, you will have to fill in a brief survey that should take no more than 10 mins to complete, nightly, to report about your daily use of information with the devices. The survey link will be emailed to you every afternoon.

At the end of the study, you will go through a post-interview of about one hour, where you will be asked about your use of the device set given to you and about your use of information to complete the class assignment. Note that both the pre- and post-interviews will be audio recorded.
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Virginia Tech Institutional Review Board: Project No. 11-788
Approved October 13, 2011 to October 12, 2012
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APPENDIX B: Pre-Study Interview Prompts

DIGITAL ECOLOGY for LEARNING

Pre-Interview: Interviewer’s Prompts

1. Say you have to write a paper for a class. What would be your usual procedures and processes?

2. When you have to generate ideas, do you make use of any of your devices? If so, how?

3. If participant did not list (macbook, iPod Touch, iPhone, iMac, iPad) Qs 1 (in online questionnaire):
   a. Do you use (rotate between devices not listed)?
   b. How long have you been using the (rotate between devices not listed)?
   c. How frequently do you use the (rotate between devices not listed)?
   d. On a scale of 1 to 6, with 1 being Very Unfamiliar and 5 being Very Familiar, how would you rate the extent to which you are familiar with (rotate between devices not listed)?
   e. What do you use (rotate between devices not listed) mainly for?
   f. How satisfied are you on the overall with (rotate between devices not listed)?

4. If you are having a meeting with some project members in the same room, and you find something relevant to your project while surfing the Internet on your laptop. How would you share it with the other members present?

5. Do you synchronize your devices so that you can share information across them?
   [Try to identify the ad-hoc ecologies (connections) that the participant has already set up]
   a. If so, when and in what situations do you synchronize?
1. What do you use [insert each service from Qs 3 here] mainly for?

2. [If Dropbox was not mentioned in Qs 3] Do you use Dropbox?
   0. [If yes] On a scale of 1 to 5, with 1 being Very Unfamiliar and 5 being Very Familiar, how would you rate the extent to which you are familiar with Dropbox?
      1. [If yes] How long have you been using Dropbox?
      2. What type of files do you usually store in it?

3. What software do you use to produce or create information?
   0. On a scale of 1 to 5, with 1 being Very Unfamiliar and 5 being Very Familiar, how would you rate the extent to which you are familiar with [insert each software from Qs 5 here]?
      1. How long have you been using [insert each service from Qs 5 here]?
      2. On which device do you use [insert each service from Qs 5 here]?
      3. How do you use each software? Do you each them differently?

4. Do you synchronize your device so that you can share information across them?
   [Purpose is to try to identify the ad-hoc ecologies that participant has already set up]
   a. If you, when and in what situations do you synchronize?

7. We would now like to know your perceptions and attitudes towards each device mentioned before. Please complete this Subjective satisfaction survey for each device.
APPENDIX C: Pre-Study Survey

DIGITAL ECOLOGIES FOR LEARNING

We are interested in your use of information. What devices do you use for producing and consuming information in any form?

a. How long have you been using the [insert each device from Qs 1 here]?

b. On a scale of 1 to 5, with 1 being Very Unfamiliar and 5 being Very Familiar, how would you rate the extent to which you are familiar with [insert each device from Qs 1 here]?

c. Rank all the devices you mentioned in order of frequency of use.

d. What do you use [insert each device from Qs 1 here] mainly for?

e. When or in which context/situation do you mainly use [insert each device from Qs 1 here]?

f. How much and how do you use each device [in Qs 1] for the following: (‘how much’ includes degree of use; ‘how’ includes strategies of use)
   . Information retrieval/access (for previously stored information)
   i. Storing information (whether self-produced or not)
   ii. Reading
   iii. Note-taking
   iv. Information seeking
   v. Writing
   vi. Information presentation

b. What role does each device play in your idea generation process when creating new information?

b. What role does each device play in your decision-making process when selecting information?

5. [If (macbook, iPod Touch, iPhone, iMac, iPad) was not mentioned in Qs 1] Do you use (rotate between devices)?

0. [If yes] On a scale of 1 to 5, with 1 being Very Unfamiliar and 5 being Very Familiar, how would you rate the extent to which you are familiar with [insert each device from Qs 2 here]?
   1. [If yes] How long have you been using the [insert each device from Qs 2 here]?
   2. What do you use [insert each device from Qs 2 here] mainly for?

6. Do you use any cloud services?

0. How long have you been using [insert each service from Qs 3 here]?
   1. On a scale of 1 to 5, with 1 being Very Unfamiliar and 5 being Very Familiar, how would you rate the extent to which you are familiar with [insert each service from Qs 3 here]?
   2. What do you use [insert each service from Qs 3 here] mainly for?
APPENDIX D: Post-Study Interview Prompts

DIGITAL ECOLOGIES FOR LEARNING

POST-INTERVIEW

IN GENERAL
You have already been recording your activities regarding the paper assignment throughout the semester. I will now ask you some general questions pertaining to the process as a whole. Please feel free to tell me points about any part of the study that you feel were significant.

Behaviors and Strategies

1. Steps for assignment completion
   Can you tell me about the broad phases or steps that your group took to complete the assignment?

2. Problems encountered with devices, information sharing, writing process, etc.
   In general, what are the main problems that you encountered? It can be with use of the devices, sharing information, the writing process or anything else?

3. Direct impact of devices on practice
   Did the devices change your practices in any way? (for the assignment and in your life generally)

4. Context/situations in which each device is used
   When and where did you use each of your devices?

4. Frequency of use of each device
   How frequently did you use each of the devices given to you?

5. Use of devices
   - What did you use each device mainly for?
   - Did you use any other devices apart from the ones given to you?
6. Other influencing factors that determined digital information use on particular devices
Are there any other factors which determined when you would use each device and for what?

7. Personal sense-making of information
How did you organize and made sense of information that you collected for the assignment?

8. Work distribution and coordination
   - How did your team distribute work for the paper?
   - Did roles change throughout the semester?
   - How did your team coordinate activities (incl. information sharing, syncing, organization, actual writing) for the completion of the assignment?

9. Use of Evernote, DropBox
   - Did you personally use Evernote/Dropbox?
   - Did your group make use of Evernote/Dropbox? If so, how? If not, why not?
   - How personally satisfied are you with Evernote/Dropbox?

Attitudes and Perceptions

1. Continued use of devices on a longer term
Would you be willing to continue using the devices on the long term?

2. Participant’s general evaluation of each device and of ecology
   - What is your general assessment of using all of the devices at one time?
   - Based on your experience, do you feel that having devices readily available to you were beneficial in any way?
   - What would you change to make the devices integrate better into your workflow and work practices?
DURING MEETINGS

I will now ask you a few questions concerning your activities specifically during project meetings.

1. Frequency of meetings

How many meetings did you have to complete the paper?

2. Meeting context
   o Where were your meetings held?
   o Any online meetings? How did the devices support (if at all) the online meetings?

3. Problems encountered
   o Did you meet with any problems during your meetings?
   o If so, how did you and your group resolve them?

4. Meeting discussion
   o What was the discussion mainly about during meetings?
   o Did the content change according to context, time period, people present, devices used, etc?

5. Materials used
   o What materials/devices/services did you use during your meetings?
   o What were you using each material/device for?
   o Did the materials/devices that you used vary based on the context that you were in?
   o Did you use any large display? In what way do you think the large display could become useful?

6. Idea generation
   o How did you generate ideas as a group?
   o Was there a need to look up any sort of information during meetings?
   o How did you decide on which ideas were going to actually be used in the paper?
   o How were these ideas recorded?

7. Information conveyance

How did you share information with your teammates during the meetings, and made sure that they understood what you were conveying?

8. Role distribution
   o Were there different roles that each group member assumed during the meetings?
   o Did roles change throughout the meeting?
APPENDIX E: Daily Diary Survey

Each participant of the study was asked to fill in a ‘daily diary’ in the form of an online form, accessed through a link emailed to them everyday at a fixed time in the evening.
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Did you use the devices for any other assignment-related activity?

- Yes
- Maybe
- No

Describe the following below:

a. Type of information you used or dealt with today (e.g., papers, rough notes, websites)

b. Your intention/ reason/ purpose in using it (e.g., reading to get ideas, skimming to get overview of a paper)

c. The context/ situation/ location in which you did the activity (e.g., at home lying on the bed, in the restroom, in kitchen while eating breakfast)

d. Any other comments about your feelings or opinions if any

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Did you do anything significant with digital information but NOT related to the assignment today? E.g. Wrote a paragraph of a report for another class

- Yes
- Maybe
- No

Describe the following below:

a. Type of information you used or dealt with today
   (e.g. papers, rough notes, websites, newspaper)
b. Your intention/ reason/ purpose in using it
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Write down any other things that you would like to report, or Submit the survey.

Thank you for your time and help in this study! You are very much appreciated.