Chapter 17
Beyond ‘Apps’ on Tablets: Making Sense of Learning Within Technology Ecologies

Sharon Lynn Chu and Francis Quek

Abstract The vision of Vannevar Bush and Douglas Englebart of using computers to augment the human intellect more than half a century ago has been taken to heart by technology designers and computer scientists. Much technological progress has been made that allows the rampant use of laptops, desktops, tablets and smartphones in daily tasks to help us in thinking and learning. However, the single device can only go so far to facilitate higher-level thinking. We advance that the possibilities of the augmentation of human intellect by digital technologies are limited unless we design for the various technologies to function together in ecologies. In this paper, we present a theoretical foundation using Lev Vygotsky’s sign mediation theory to articulate a design framework identifying key processes that should be supported to assist higher-level thinking. We also provide examples of affordances that can help the design of effective technology ecologies within our framework.

17.1 Introduction

At the very beginnings of the computing revolution, both Vannevar Bush in 1945 and Doug Englebart in 1962 presented visionary essays positing that machines may one day ‘augment the human intellect,’ extending the powers of the mind to make knowledge more accessible. Since then the computer has been developed to enable the manipulation of numbers, databases, texts, simulations, artificial intelligence, etc.

As Bush and Englebart contemplated at the dawn of our computing era, we are at a point of critical mass of development of computation and connectivity to revisit the question of how computation may extend our capacity to think and learn. If we look at the current landscape of computing technologies, the modern computer has taken on many different forms from the notecard-sized smartphone to the book-sized tablet and to the whiteboard-sized large screen displays. We propose in this paper that all

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of these technology and devices need to function in ensemble to truly augment the human intellect.

In her seminal book 'Inventing the new medium,' Murray listed four unique affordances or properties of the computer that characterize the power of this digital method of representation: procedural, participatory, encyclopedic, and spatial [1]. Modern computing devices and technologies vary on a spectrum of Murray's properties of procedural, participatory, encyclopedic, and spatial, but functioning together they can empower the user to think more deeply and learn more broadly in a pervasive fashion throughout daily life. We explore how computing devices, especially tablet and touch devices, functioning in concert in *technology ecologies* [2, 3] may augment the user's mental capabilities throughout the entire workflow of knowledge-based tasks. We present a theoretical and a design framework for how technology ecologies augment human thought based on our reflections, observations, and results of exploratory studies.

17.2 Technology in Education

Why is it so significant to understand and to design the next wave of computing technologies such that they function within technology ecologies? After all, we have already come a long way from Bush's vision of 'memex' and can already use our smartphone to look up a Wikipedia page whenever we want to know something and our laptop to store searchable databases of research papers. The problem we address is how operating singularly, each device or technology is limited to isolated instances of 'intellect augmentation,' that although still beneficial, does not necessarily extend across the broader panoply of our thinking. After each episode of technology use or information access, we go back to relying on the use of our human memory and inherent mental capabilities to make use of the information or knowledge gained.

Nowhere is this isolated use of computing technologies more apparent than in education and learning environments. The dominant current paradigm of using the computer in the classroom is characterized by learning within the confines of single devices. An embodiment of this paradigm is the one-on-one tablet programs that are rapidly gaining popularity across the country. School districts that are investing large amounts of resources on distributing an iPad to every student [4–9] face problems not only in the form of loss of devices, hacking [10], or loss of precious classroom time on tech support, but also in the failure of the transformative change in education that the devices were expected to bring.

Users of the various devices typically construct their own workarounds to transcend the bounds of single device silos. People email themselves and each other relevant files, keep their files on online services, discuss ideas on instant messaging. They use online storage not primarily as storage but as data bridges across devices, and use attachment features of social media to foster 'data dialogs' with themselves and each other to move data between laptops, iPads, android devices, smartphones and the like. For learners with single devices these workarounds are cumbersome and many students do not discover how to break the device silos. With well-designed and thought-out integration of technologies, the level of intellect augmentation that could result from the use of technologies designed to interact and function in concert can far exceed what is capable by the single computer.

17.3 Technology Ecologies

A range of research has hitherto applied the metaphor of a biological ecosystem to human activities with technology. However, this body of work does not always form a coherent whole, and it is a challenging undertaking to present either a commonly agreed definition or a comprehensive synthesized account of the work. The overall message underlying the different positions of technology ecologies 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. From our perspective, a technology ecology is characterized by three key principles:

- The technology engages all devices within the environment,
- The technology addresses the entire workflow of the task being undertaken,
- The technology provides an experience of flow to the user.

Prior notions of technology ecologies can be classified into three categories: theoretical or philosophical positions, empirical study results, and technical frameworks enabling the implementation of ecologies. Figure 17.1 summarizes some of the main concepts of technology ecologies in prior research. Our conception of technology ecologies distinguishes itself in three ways. First, it specifies not only interrelationships among devices to be important, but also the support of human thinking as it deals with digital information from one subtask to another across space and time. Second, we think of technology ecologies as the environment inhabited by information and information objects. The technology ecology supports the manipulation, manifestation (through display and outputs), and movement of these information objects. Third, we emphasize that this engagement of the user with the various devices has to occur within flow—seamless interaction with digital information.

Our task of focus in this paper is learning. There has been little research that evaluates the effects such ecologies on learning or other higher thought processes in relation to the devices used. Rick [11] points out the importance of a classroom ecology, but does not provide any supporting study. Coughlan et al.'s [12] 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. Their study results presented a set of "seams" that represent disconnects in a device ecology that can affect users' behaviors. Their study however gave little

	Author	Year	Concept
THEORETICAL	McLuhan	1962	Media ecology
	Altheide	1994	Ecology of communication
	Nardi & O'Day	1999	Information ecology
	Krippendorf	2005	Ecology of artifacts
	Tungare & al.	2006	Personal information ecosystem
	Rick	2009	Classroom ecology of devices
EMPIRICAL STUDIES	Huang, Mynatt & Trimble	2004	Display ecology
	Enquist, Tollmar & Corry	2007	Interaction ecology
	Dearman & Pierce	2008	Computing with multiple devices
	Jung et al.	2008	Personal ecology of interactive artifacts
	Forlizzi	2008	Product ecology
	Bailey & Barley	2011	Teaching-learning ecologies
	Coughlan et al.	2012	Device ecology
	Chu et al.	2012	Technology ecology of displays and devices

Fig. 17.1 Concepts of technology ecologies

indication of how one can understand whether or how learning has occurred within the context they constructed.

Jung et al. [13] 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 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.

Perhaps the area that comes the closest to studying the process of higher level thinking in an environment of multiple devices is that of visual analytics. Visual analytics [14] aims to understand how people make sense of and integrate (digital) information from various sources to solve a problem or to gain insight to a particular scenario, most often an intelligence analysis task. Research in visual analytics has resulted in interesting models of the human sensemaking process that may help us to understand how levels of thought at each stage is augmented by current technologies, for instance, the well-known Pirolli and Card's [15] sensemaking loop. However there remain two large gaps: First, what is the exact mechanism by which the user interacts with a device to augment cognition in a learning context? Second, in what ways can various devices work together to reinforce the augmentation of cognition? In this paper, we draw on psychological and learning theories to answer the first question, and present a design framework that illuminates the second.

17.4 The Thinking Process

17.4.1 Sign Mediation Theory

Vygotsky [16, 17] proposes a way by which things in the environment may be brought into the very process of thinking in the form of the sign mediation theory. Similar to Kirsh's 'Thinking with external representations' [18], that posits that human thinking may be mediated or enhanced by psychological tools called signs or symbols [16, 19]. Signs may be defined as self-generated linguistic stimuli [20] that extend the operation of human cognition beyond the confines of the strictly biological system.

While thought is distinct from language, Vygotsky conceived of language as a tool for thought. 'Signs' are language units that relate to units of thinking to allow the building of higher-level and more abstract thinking. Signs are more than just encapsulations of thought objects or idea chunks that support more effective use of human short-term memory [21]. Signs are a kind of psychological 'handle' that allows the learner to grasp and manipulate concepts mentally or through such externalizing mechanisms as the sound of words either covertly or overtly expressed. Hence, they can function as building blocks with which we can build more complex thought objects. Figure 17.2 illustrates Vygotsky's sign mediation theory and an example of a student learns the concept of 'Average' or 'Mean' of *N* numbers: $\sum^{\mathrm{N}} a_i/\mathrm{N}$. 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 'Average.' She is able to think of the operation simply through the sign, and to employ this in further learning (e.g., *Average* of sample means). 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.

Signs may take the form of both internal (e.g., the word *Average* that represents the mental concept of the sum of a set of numbers divided by how many numbers are

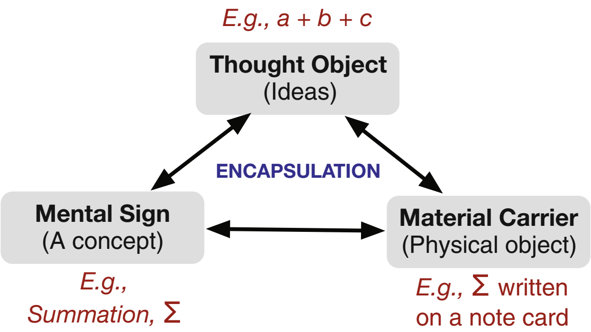

Fig. 17.2 Use of signs for thinking

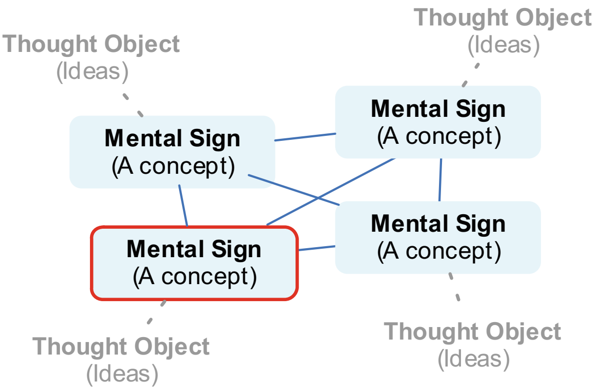

Fig. 17.3 Embeddedness of a sign in a system of signs

in the set) or external forms (e.g., the sound of the word *Average*). Vygotsky talks of a stick between a child's legs becoming his horse, a block representing an idea [16]. Externally instantiated signs have been referred to as 'material carriers' of thought [22]. One can think of them as essentially 'physical, tangible signs.' Any perceivable object (spatial location, gestures, objects or even sounds) in the environment can opportunistically and temporally be appropriated for use as material carriers to assist thinking thus bringing spatial ability and perception into play. In theory thus, the material carrier can be anything that may or may not resemble the mental object.

17.4.2 Higher-Level Thinking

According to Vygotsky [17], the formation of concepts, and thus the creation of meaning and true understanding, is achieved only when a sign is embedded within a 'system of signs,' as illustrated in Fig. 17.3. He gives the following example: "The relationship of the word "flower" to the object is completely different for the child who does not yet know the words rose, violet, or lily than it is for the child who does."

Similar mediated models of cognition has been advanced by others as well apart from Vygotsky. The theory of distributed cognition, first proposed by Edward Hutchins [23], based on his study of airline cockpits, holds that we 'offload' cognition (thinking) onto tools, artifacts, people and processes. The theory of situated cognition, from the work of Lave and Wenger [24] in situated learning and apprenticeships, maintains that people act and learn in context, reinforcing he inextricate link between thinking and the contexts in which it occurs. Last but not least, activity theory [25] from Leont'ev and Engestrom has as its basic premise that any activity is goal-directed and mediated through the use of tools or artifacts.

17.5 Augmenting the Intellect

Using the theoretical framework of the sign mediation theory, we propose that at least three key processes need to be supported to allow higher-level thinking to occur. Augmenting human's thinking capabilities may work through the facilitation of the:

- **Creation of material carriers:** Binding a thought object to a physical object;
- **(Re-) Access to signs:** Uptaking the signs through the material carriers to avoid memory overtaxation;
- **Manipulation of signs through their material carriers:** Manipulation means higher level processes such as association, extension, pattern recognition, inferencing, abstraction.

In the paper world, we have developed a range of material innovations, processes, and procedures that can support each of these three processes in various ways persistently across time: A notecard allows one to quickly and easily create a recognizable material carrier for a particular concept. The notecard, or physical proxy of the sign, can then be picked up whenever, carried around, and referenced at one's convenience; and across space: A series of notecards representing distinct signs can be manipulated (turned upside down, sideways, etc.), laid out spatially to facilitate manipulation of signs to which they are associated. Information on note cards can cross-reference other repositories of personal information (e.g., referencing notebooks and journal entries) and knowledge encoded in broader society. The concept of 'archival publications' book indices, and the entire domain of 'library studies' were designed around the primacy of paper as the chief extender of human intelligence beyond a single episode of thought, a single person, a single community, a single society, a single generation, and a single epoch.

While advancements of computation and connectivity are challenging the hegemony of paper as the chief augmenter of human thought, the promissory note of their potential remains mostly unclaimed. Unlike paper, the interface between digital technology and human thinking and learning has not had centuries of combined evolution across communities. With our model of augmentation, we seek to contribute to understanding of how tablets and touch interaction may be key elements in human intellectual augmentation.

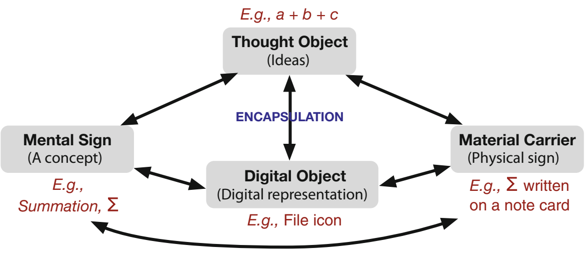

Fig. 17.4 Sign mediation with digital technologies

17.6 Digital Technology in Single Devices

With digital technologies, mental signs can be manifested not only through physical objects or material carriers, but also in the form of digital, non-tangible objects (see Fig. 17.4). Digital technologies have near infinite ability to encode and represent information, and modern display/output technologies can manifest information in multiple ways (e.g., as an icon, a text blurb, a graph, a diagram). In the language of *Sign Mediation Theory*, digital objects can describe the concept encoded by the sign. Digital objects come with both benefits and costs. Murray's four affordances of the computer illustrates well some of the benefits that the digital medium provides, for e.g., searchable databases enabling quick re-access to particular signs. The digital information object can instantaneously be linked to an existing system of concepts, e.g. clicking on a term opens up its Wikipedia page describing the history and related terms, double-clicking on a filename opens up a PDF document with an explanation of a term or a picture illustrating the concept, thus making the acquisition of the significance of the sign much easier. Furthermore, the digital object can be designed to look like anything that would support easier access to the attached thought object. The malleability of the digital world is relatively unbounded as compared to the physical world.

The design of digital interfaces has unfortunately throughout its history, for the most part, failed to fully harness that flexibility we just described. During the first forays of interface design for instance, the desktop metaphor [26] was conceived as a model to design easy-to-use interfaces. The general space for document placement is called the 'desktop' modeled after the office desktop. Icons of folders look like the paper document folder. In the "Myth of the paperless office," Sellen and Harper [27] suggest that instead of trying to mimic or reproduce exactly the affordances of paper for the design of technologies, paper should be used only as an analytical resource or inspiration.

The tremendous flexibility of individual computational devices may, ironically, be one of the hindrances to the realization of its promise for augmenting human thinking and learning. Because a single device can serve multiple purposes, it resembles a 'Swiss-army-knife' in supporting human intellectual activity. This one-size-fits-all thinking can be as limiting as a do-it-yourselfer who thinks that a single Swiss-army-knife can be his entire carpenter's toolbox. In educational technologies such thinking is evidenced in the app-oriented model where tablets and laptops are imbued with different capabilities by the simple launching of a different app.

This single device conceit does not exist in the physical paper world where devices, by design and by necessity, have different capabilities and are based on different paradigms. To give an example, while two pairs of scissors may be designed differently, they both satisfy the basic function of cutting.

17.7 Augmenting the Intellect with Technology Ecologies

Two key dimensions that the paper world has learned to handle well over its long process of design evolution are space and time. To deal with space limitations, we have created various forms of accessories ranging in size and portability from index cards to notebooks to large whiteboards. To deal with time limitations, we have bookmarks, indices, cross-references, and libraries that allow one to pause and come back to a book that one is reading or to access information at different times. Moreover paper has the advantage of being inherently persistent across time. A paper placed on a desk will remain there unless moved. This persistence over time is a natural, and necessary property of things in the physical world [28] that resonates with our sense of the world.

Digital technologies, on the other hand, are typically manifested only within the confines of a screen, irrespective of the size of the display, and persist only for a particular session of working with the document. Even when documents are not 'closed' after each session, they switch out of interaction focus and typically become obscured by other application windows. They disappear as the device is switched off or put to sleep. We argue that this ephemerality of digital presentation (as opposed to for e.g., the persistence of paper) can compromise the suitability of their use as *material carriers* to support thinking. A technology ecology, if properly designed, may expand tremendously the opportunities of the manifestation of digital objects within the constraints of space and time to support the creation, access and manipulation of signs.

17.7.1 Scenario of Learning/Thinking with Signs and Things

We shall use a real-life scenario description how students may think and learn using multiple technologies to illustrate our idea of the relationship between signs, material carriers, and learning (see the Sign Mediation Theory described earlier). A student, Tom, is given an assignment to produce a group report on the influence of ancient Japan on modern Japan. He works in a team of three students over a period of two weeks. On the first day of the assignment, Tom's team holds a group meeting to discuss about possible ideas for the direction of the report. In the meeting room, they brainstorm keywords related to the topic and write them on a whiteboard. They distribute the list of keywords among the team members for further research. At the end of the meeting, Tom quickly jots down his allocated keywords on a small notepad, and the group decides to go for lunch together. Over lunch, Tom casually discusses with his teammates and something that his teammate mentions advances his thinking about the assignment topic. He takes out his notepad and scans the list of keywords that he jotted down. He adds a related point next to one of the keywords. At home he does an Internet search for material relevant to his assigned keywords on his notepad. He browses through a few papers and saves them in a temporary folder on his laptop. When the group meets a few days later to review the material that they have gathered. Tom brings along his laptop and plugs it to the large screen display in the meeting room. He goes through each paper that he found with the team so that they can decide as a group which ones are relevant for the direction that they want to take for their project. He moves the relevant ones to a project folder and deletes the non-relevant ones.

This scenario describes some key tasks of part of the workflow of the creation of a group report. Tom uses a combination of the paper and the digital technology to satisfy his needs in this workflow. Figure 17.5 traces examples of signs that are created during our sample episode and re-accessed across key processes of the sensemaking workflow of Pirolli and Card [15] mentioned earlier. Space/location, time, and form in which the creation and access of signs occurs are shown in between square brackets. As can be seen, signs across space and time can vary greatly. The variance in the place and time of creation and access of signs requires the use of different devices and forms that are also noted in Fig. 17.5. One can further imagine Tom's notepad being replaced by the smartphone or the tablet for notetaking to make his experience more techno-centric.

17.7.2 Mapping to Principles of Ecology

We can now map aspects of our example and analysis into the three principles of a technology ecology discussed earlier. First, a technology ecology seeks to address the entire workflow of a task. The key stages of the sensemaking workflow in the context of the production of a report in our scenario clearly shows how integrating across workflow processes would support a student's understanding of the material transforms from surface-level relationships (e.g., facts that come from an author, things that happen close to each other in time) into more meaningful concepts [19]. This process is similar to that of 'incremental formalism' where systems of concept relationships take shape over time through interaction [29]. The workflow can further be mapped to the levels of Blooms' taxonomy of learning (see Fig. 17.5), which specifies the different depths of thinking and types of skills desired in education.

Second, a technology ecology integrates all devices within an environment. By necessity, the user presently makes use of many ad-hoc ways to integrate information across devices and across the different processes of the workflow (e.g., typing in keywords taken down in the notepad during the meeting into the laptop at home).

Workflow process	Bloom's Taxonomy	Creation of signs	Access to signs
Brainstorming	Knowledge, Comprehension	Keywords *[Meeting room; Day 1 morning; Oral]* Additional Keywords *[Foodcourt ; Day 1 lunch; Mental]*	Recording of keywords *[Meeting room; Day 1 morning; Whiteboard]* *[Food place; Day 1 lunch; Notepad]*
Information foraging	Knowledge, Comprehension	PDF files *[Home; Day 1 night; File icons]*	Written keywords *[Home; Day 1 night; Written in notepad]* File naming *[Home; Day 1 night; Text string on laptop]*
Drawing relations	Application, Analysis	Notes, Annotations, Comments *[Meeting room; Day 3 morning; Oral, Notepad]*	File names *[Meeting room; Day 3 morning; Text string on laptop]* PDFs *[Meeting room; Day 3 morning; Large display]* Folder structure *[Home; Day 3 night; File explorer on laptop]*
Schematizing	Application, Analysis	Mindmap, Write up	File naming
Hypothesis building	Synthesis	Report/Presentation outline	File naming
Presenting story	Synthesis	Report, Presentation	File naming

Transfer of signs

Fig. 17.5 Examples of sign creation and access throughout workflow

Within a technology ecology, devices and information flows should be designed so that the student is able to focus on the manipulation of signs (higher-level thinking) throughout without having to worry about how to move representations across the different device and application barriers. Without such support the thinking and learning process becomes as cumbersome as having to devise different ways to join pieces of cloth while trying to make a tapestry.

And third, the experience from brainstorming to story presentation is a coherent flow of engagement in higher thinking instead of spurts or fragmented episodes.

17.8 Designing Technology Ecologies

17.8.1 Fundamental Principles

The first section of this paper has presented a theoretical framework from which to understand the mechanism by which human intellect can be augmented by technology ecologies, i.e., how we can be supported to engage in higher-level thinking through technology. In this section, we draw out the implications that this important theoretical basis provides us for the design of technology ecologies. As was pointed out before, higher-level thinking such as synthesis, inference, and abstraction. occurs

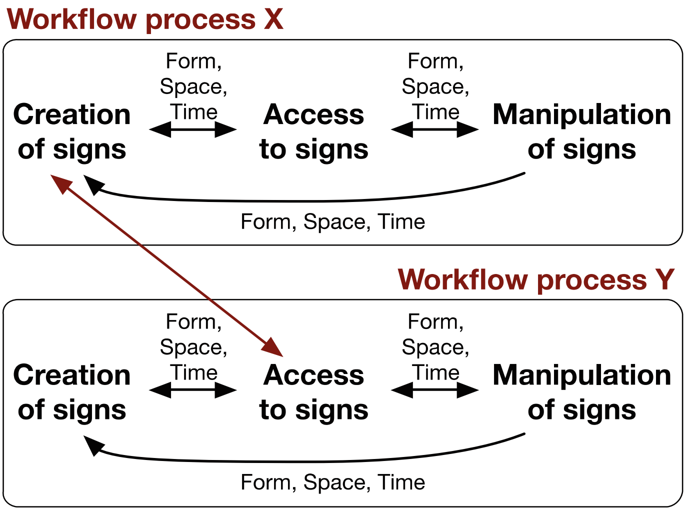

Fig. 17.6 Design framework for technology ecologies

through the manipulation of signs. We have also described previously how the presence/creation of a 'system of signs' is necessary for such manipulation of signs to take place. To do so, one must be able to hold multiple signs in mind simultaneously.

Using Fig. 17.6 that illustrates how the creation and access of signs are embedded within workflow processes, we can derive fundamental principles for the design of technology ecologies that can effectively mediate thinking:

- Each step of the thinking process, including the *creation of signs* of different forms, the storage and quick retrieval *(access) of created signs*, and the simultaneous persistence of multiple signs to enable *sign manipulation*, must be made as easy, transparent and fast as possible within itself.
- Transfer of signs from previous stages necessary for a stage to occur must be made as seamless as possible, including the conveyance of the *space* and *time* context of signs and transformation of the *form* of the sign if needed.
- Transfer of signs from other workflow processes necessary for a workflow process to complete successfully must be made as seamless as possible (this is shown as the red diagonal arrow in Fig. 17.6).

17.8.2 Design Affordances

The difficulty of implementing technology ecologies is that every part or whole of the framework in Fig. 17.6 can be carried out on a different device. The creation of a sign, for example, can happen on a tablet, and later re-access of the sign may be made on a laptop for workflow process X, and on a desktop computer for workflow process Y. It

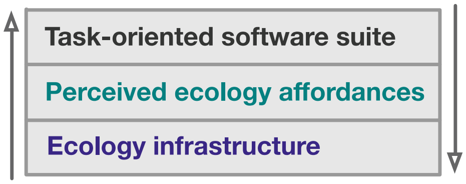

Fig. 17.7 Levels of a technology ecology

is challenging to identify design affordances that are generalizable across varying sets of technology ecologies, e.g., a set consisting of a Mac laptop, a Windows desktop, an Android smartphone *vs* a set with an iPad, a large screen TV and a laptop running Linux. It is not only a question of platforms, but also of form factors, user interfaces, applications, processor capabilities, etc. We propose that any technology ecology consists of three levels, as shown in Fig. 17.7. The bottom-most level of 'ecology infrastructure' involves the basic method by which connection is established among different devices. Much of this ecology infrastructure nowadays is set up through the Cloud. Of main interest to us is the second level of 'perceived ecology affordances,' which involves characteristics that are designed into the various device interfaces to enable the user to perceive the possibilities of interaction among the devices. The top level of 'task-oriented software suite' represents characteristics that are given to the interface of a device in the ecology at any one particular time based on the task that is being performed, e.g., when a word processing application is opened on a laptop. Generalizable affordances for technology ecologies can be made only at the second level, where the interface is not dictated by task-specific needs or by current state-of-the-art in computer network architectures.

We have conducted an exploratory study [3] collecting interview and self-reported questionnaire data of twelve students using a basic testbed technology ecology (an iPod Touch, an iPad, and a 27" iMac) to produce a knowledge discovery report on the topic of 'physical computing.' The focus of this paper is not to report on the study but we will use the findings of the study here to provide examples of design affordances for technology ecologies. Using qualitative coding methods of data analysis, the study findings uncovered five main affordances, two applicable within devices and three across devices. These are summarized in Fig. 17.8 together with associated design features:

Within device: **Iconicity and Atomization**

Iconicity specifies that the form of the digital object or physical object used to anchor the mental sign can facilitate or hinder the creation, access, and manipulation of signs. The greater the fidelity of the material carrier to the sign (i.e., how much the material carrier resembles the behavior, appearance or certain characteristic of the sign), potentially the easier the binding of the signs to the digital/physical object, and the easier the recall of the mental sign from perception reuptake of the material carrier. The use of file renaming and organization of folder structure are examples of instances when iconicity helps specific digital objects to be used as proxy for mental signs and thought objects. Thus, providing functionalities in device interfaces that facilitates the control of structure, mnemonicity, and customization may help with the handling of iconicity.

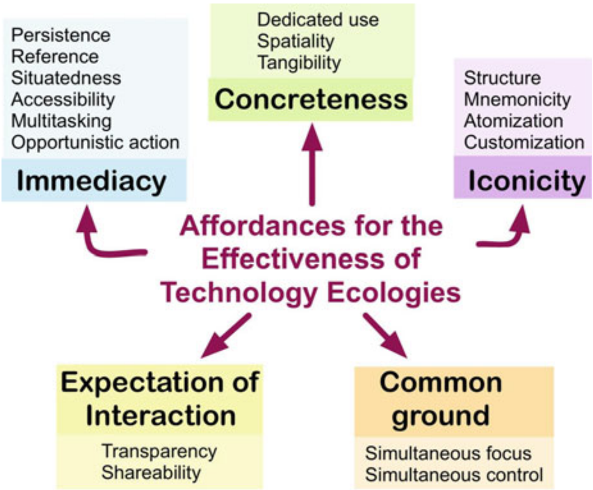

Fig. 17.8 Examples of design affordances for technology ecologies

Atomization is a related feature that supports the association of digital objects to mental signs. A mental sign is typically an atomic concept 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 'Average/mean' in our earlier example. A Wikipedia page on 'Means' would be an apropos digital object for the concept, but a whole book on mathematics would not (even if it contains a section on 'Average'). Features to support atomization may include, for instance, enabling bookmarking of individual components larger text documents at different levels of abstraction.

Within device: Concreteness
In our study we saw how the whiteboard that affords the use of space and how the iPad that runs applications using the full screen real estate aid information to become what Heidegger [28] calls a 'thing,' something tangible for the student to grasp in her thinking process. **Concreteness** is the extent to which the physical object or digital object that is appropriated to anchor a mental sign is physically manipulable or tangible like a wooden block would be as a material carrier. Concreteness aids in the (re-)access of signs by for example providing focus of attention, and in the manipulation of signs through spatiality, change of perspectives, etc. The kinds of design features that can help to instill the sense of concreteness in technological devices and digital objects may be an interesting research question for one to empirically pursue.

Across devices: Immediacy
Immediacy concerns features that allow the user to convey signs to himself across space (from one device to another) and time (at a later point in time), and to others. Digital objects must be able to be transferred and shared across devices without going through one or more indirect actions. Essentially, immediacy attempts to minimize the 'cost' of information [30]. 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 a cloud storage location and tell him where to get it before they can discuss its contents. The lack of immediacy then hinders the opportunistic use of the document as a focus of discussion or thought.

Transparent interoperability across platforms may support immediate action as do consistency of interaction techniques (consistent ways to move and manipulate digital objects across platforms is critical to support their use as material carriers of signs). In our study, participants used persistence to allow information to stay immediate: 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.

Across devices: Expectation of interaction
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. Users should be able to expect that the creation of a sign at any one particular moment or place will not impede its re-access and later use for higher-level thinking through sign manipulation at other times and places, or for later parts of the workflow. For example, one can read what has been written on a sticky note at any time anywhere. 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 technology 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 the user's expectation of interaction in our study is one instance where the students spent one entire meeting only to set up shared Dropbox [31] folders and Evernote [32] notebooks.

Across devices: Common ground
The technology should provide support for students to easily share digital objects with the potential to become *common material carriers*. A common digital object may not necessarily be the proxy for the same mental signs for two different people. This is essentially the question of inter-subjectivity [33]. 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 establish and maintain **common ground** with the 'information channel', where work is carried out.

17.9 Summary

This paper advanced that the possibilities of the augmentation of human intellect by digital technologies are limited unless we design for technologies to function in ecologies. Further, our aim was to fill the gap in our understanding of a mechanism by which technologies ecologies may then augment the human intellect. The contribution of this paper is at least three-fold: (i) we provide a theoretical framework using sign mediation theory to understand higher-level thinking; (ii) we derive principles that can guide the design of technology ecologies from the theoretical foundation; and (iii) we describe an initial set of design affordances of technology ecologies that can be translated into device features.

In a nutshell, our theoretical framework proposed that thought is encapsulated within and mediated by mental signs. We anchor signs onto external objects to help higher-level thinking, which consists of the creation of a 'system of signs.' External objects that are used to anchor signs can be either physical objects or digital objects. This framework suggests that three key processes need to be supported for higher-level thinking: the creation, access, and manipulation of signs. Integrated into a technology ecology whose aims is to integrate all devices within an environment, address all processes throughout a workflow, and engage the user in an experience of flow, technology ecologies should facilitate each of the three key processes of thinking, the transfer of signs across the three processes, and the transfer of signs across workflow processes. Examples of technology affordances are iconicity, concreteness, immediacy, expectation of interaction, and common ground.

17.10 Conclusion

The paradigms of learning and education have not developed in tandem with progress in technology, as epitomized in the tablet one-to-one programs. A major reason is that our understanding of how to design technologies that integrate well into the learning process is currently insufficient. While we are intuitively still making headway into the implementation of technologies that are necessary for the formation of technology ecologies such as cloud computing and peer-to-peer communication networks, we have yet to grasp the broader vision of how new technologies may be harnessed for deeper learning and thinking. A firm theoretical foundation and systematic derivation of design principles can go a long way to help in our quest to further augment the human intellect beyond the vision of Vannevar Bush and Doug Englebart.

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