

Personal Information Ecosystems: Design Concerns for Net-Enabled Devices

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Abstract

Today, with the proliferation of affordable computing, people use multiple devices to fulfill their information needs. Designers approach each device platform individually, without accounting for the other devices that users may also use. In many cases, the software applications on all the user's devices are designed to be functional replicates of each other, often with an emphasis on keeping their form and function consistent with the same application on other device platforms. In this paper, we present the idea of a personal information ecosystem, an analogy to biological ecosystems, which allows us to discuss the inter-relationships among users' devices. Using the examples of now-ubiquitous web-enabled devices, we discuss how considering the user's ecosystem of devices as a holistic design target gives designers and researchers a language to describe and discuss the design of applications that span multiple devices.

1. Introduction

The last few years have seen a massive proliferation of a variety of computing devices spread across a broad spectrum of computing and communications capabilities and form factors. Each class of these devices has features and affordances that makes it unique from the others. Users do not use a single device in isolation, but use multiple devices in concert with one another to accomplish their everyday computing tasks. Weiser's vision [18] of embedding invisible computation into the environment is becoming a technological reality.

In this paper, we present a conceptual framework for a *personal information ecosystem* (PIE). This framework borrows terminology from biological ecosystems to allow us to study the collection of devices being used together to satisfy the user's needs. The collection of devices is considered

an ecosystem. Each device is characterized as an organism; the pairing of devices is characterized by a particular type of relationship analogous to relationships in biological ecosystems. We also introduce the concept of 'equilibrium' based on the information flow that exists in a personal collection of devices.

The paper is organized as follows. In section 1.1, we present the state-of-the-art in the use of multiple devices drawing from a survey we conducted. In section 2, we discuss problems that exist in the domain of multiple net-enabled devices. In section 3, we introduce the terminology of personal information ecosystems. We conclude with implications for the design and research of future net-enabled devices.

1.1. Devices and Activities of Users

In order to understand the collective use of multiple net-enabled devices, we conducted a survey among knowledge workers (N=220) in August 2007 [17]. The survey highlighted the fact that today's knowledge workers use multiple devices and information services simultaneously or in conjunction with one another. In this section, we discuss a few findings from the survey that help motivate the goals of this paper.

The current trend in multiple device use is towards mobility and away from stationary platforms such as desktop computers. About 96% of the participants used at least one laptop computer compared to just over 71% who used at least one desktop computer [17]. Laptop computers are so popular, that more people reported using them over cell phones. Those who used multi-function devices (such as Personal Digital Assistants (PDAs), Blackberries or iPhones) used them extensively for Personal Information Management (PIM) tasks such as email, calendaring and instant message (IM), and also for news and (limited) Web browsing. A few participants reported that the presence of these handhelds had changed their personal infor-

mation practices to an extent where they were able to leave their laptop computers at home when they did not expect to work on complex documents (e.g. when away on vacation).

In addition to the preference for mobility, we observed that many workers have opted to use a single computer, often their laptop, instead of moving files back and forth between their office and their off-site locations [17]. To minimize the disruption of their workflow, users seem to simply opt to carry their office with them by keeping all of their data in a single device (laptop) and taking it with them.

Several users reported that they used devices together as a group. Figure 1 shows the most common device groups. 52 users (almost 24%) reported that laptops and cell phones were used together as a group. The use of devices together is leading to a convergence in the user's personal information needs towards fewer, yet more capable devices. For example, PDAs without an integrated cell phone are less used for almost all activities when compared to cell phones and integrated PDA-phones. It appears that less-capable devices like PDAs are slowly disappearing from general use.

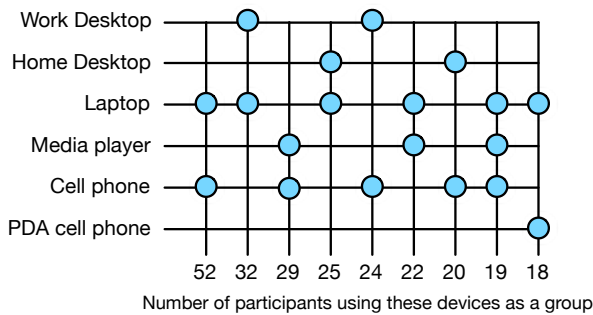


Figure 1. Devices used in groups.

We also found that activities performed across devices involved multiple configurations and use of the individual devices. For example, some devices were used together: users tethered their laptop to their cell phone to share the cell phone's network connection, without having to forfeit the richer form factor of the laptop. In other situations, one device was used exclusively for an activity: music was moved off the laptop onto the media player because the media player always was at hand in addition to the laptop. The particular pairings were unique to the type of devices in the group.

A common thread under all these findings is the lack of terminology or conceptual framework that allows researchers and designers to discuss the complexities of use of such devices. The prevailing design practice is that all devices are intended to be functional replicas of each other. Our survey findings clearly indicate that is not the case. A

goal of this paper is to provide a conceptual framework and terminology that can be used to discuss these multi-device work environments.

2. Interaction with Current Generation of Net-Enabled Devices

Much of today's hardware that runs mobile applications evolved from that of the traditional desktop computers. This trend towards miniaturization of components on the hardware side has roughly followed Moore's law. An unfortunate consequence on the software side has been a similar trend to create shrunken versions of desktop computer interfaces. While hardware miniaturization is a physical reality, the same strategy does not apply to the development of mobile user interfaces. In this section, we explore some of the problems we find in the current generation of net-enabled devices and discuss how the lack of a conceptual framework makes it difficult to properly discuss and characterize the concerns raised.

2.1. Mobile Apps as Clones of Desktop Apps

Today's dominant design trend is to think of mobile applications as clones of desktop versions that can run on resource-constrained platforms. Often, maintaining consistency of look and feel across disparate platforms has sometimes been a focus of mobile design. For example, Microsoft Windows Mobile (for mobile devices) is a scaled-down version of desktop versions of Microsoft Windows, with a similar *start* button and user interface widgets. Similarly, calendar, address book, and email programs have been ported from the desktop platform to PDAs with only superficial changes to the user interface. Most of these applications provide a duplication of functionality across devices because of what appears to be the designer's implicit assumption that a user would want to perform the same tasks on all devices.

2.2. Devices Isolated from Each Other

Each device is often treated in isolation from other devices, both at the systems level and the user interaction level. For example, a user can set an alarm on their desktop calendar software, and through synchronization, this alarm is often duplicated onto a number of devices (e.g. laptop computer, PDAs, cellphones, and iPods). Since none of these devices is aware of the presence of others, the inevitable outcome is the (almost) simultaneous ringing of all alarms at the appointed hour. Even more frustrating is that the user has to, at times, turn off each of the alarms individually. This demonstrates a lack of understanding on the de-

signer's part of the relationships among devices and a lack of consideration for the context in which they may be used.

2.3. The Need for Explicit Synchronization

The approach of replicating similar functionality across platforms demands an explicit provision for each device to be able to synchronize data with another. The need for such explicit synchronization mechanisms highlights the fact that these devices were designed as disparate islands of information that need to be bridged together to be used effectively. The synchronization software and an explicit synchronization procedure is a requirement for a new device to be integrated into a user's work environment. Synchronization was reported by our survey participants as the most frequent problem they encountered when using multiple devices [17].

Since users' information is not automatically available on the appropriate devices, there is an extra burden required of them to engage in *planful opportunism* [13]. It also taxes them with extra efforts in keeping track of which files they need to copy and knowing which of their many platforms has the latest versions of their personal information, all of which is cognitively demanding.

Most of these devices are net-enabled, yet most of the time they still require an explicit data synchronization event. And often, all the devices assume a single master device exists in the group of user devices (often the desktop or laptop computer). Devices and applications are moving towards having data in the cloud, but we are not quite there yet.

2.4. Poor Support for Users' Workflows

It is common today to find users moving their work back and forth between different computers (e.g. home and office). The need to transfer task information between various platforms burdens users with synchronization or workarounds like USB key drives, remote desktop software, e-mail files, or network file storage. The burden has taken a toll; many users are giving up the movement of data between devices and simply using a laptop for all of their computing needs.

An example of people adapting their workflow is when they use alternate strategies to try to keep the work products of an interaction available to themselves. Jones, Bruce and Dumais [7] found that people often emailed the URLs of the websites they visited or the 'favorites' list to themselves when they have the need to access it from a different location. This approach is often preferred over bookmarking at the browser level since most bookmarks are tied to each individual browser. Many solutions have emerged to compensate for this problem, from commercial services like Google Bookmark Sync to social bookmarking services like

Del.icio.us. Some of these solutions are available only for the most basic of user's activities (e.g., email, bookmarks, photos).

2.5. Increases in Information Fragmentation

Information fragmentation is the condition of having a user's data tied to different formats, distributed across multiple locations, manipulated by different applications, and residing in a generally disconnected manner [4, 3]. In current PIM systems, information formats determine storage locations, means of access, addressing of individual pieces of information, and facilities to store or search the collections.

The use of multiple net-enabled devices complicates the information fragmentation problem. Now information is scattered over devices in addition to the existing fragmentation.

2.6. Support for Offline Usage

The use of net-enabled devices often occurs in situations when there is no network connectivity. Each device design must anticipate this situation and allow the user to continue doing work while offline. Browsing offline has received some attention in the research literature [1, 8]. The problem with current devices is that they are designed for use under optimal connectivity. Rarely there is a consideration of what can be done while offline.

3. Personal Information Ecosystems

We argue that most of the problems presented in the previous section can be begun to be addressed with the development of appropriate terminology, conceptual framework, and principles with which to study them. In this section, we define the collection of user devices as an ecosystem and draw parallels with biological systems as a way to understand the devices that participate in the ecosystem, the relationships among them, and the type of user activities that the ecosystem supports.

A biological ecosystem consists of organisms, the environment in which they reside, the interactions that these organisms have among themselves and with their environment, and the natural balance that must be maintained to keep the ecosystem in equilibrium.

3.1. The Idea of Personal Information Ecosystems

A 'personal information ecosystem' can be defined as 'a system of devices and applications that are present in the information environment of a user, that interact closely and richly with one another, to help the user achieve the goal of

fulfilling his/her information needs.' The following sections discuss the parallels between the two ecosystems in detail.

In order to illustrate our idea of an ecosystem, consider the example of the popular iPod + iTunes¹ multi-device ecosystem. The iTunes application supports media management, creation and editing of playlists, media playback, access to the iTunes Music Store, importing music from CDs, and other tasks through a desktop-sized multi-pane user interface. The iPod has its own media-browsing interface on a small screen that can be operated using a touch-sensitive scroll-wheel and a few buttons. More recent iPods (Shuffle, Touch) have different interface styles than the original iPod. The iPod and iTunes were designed to be used together, so much so that the iPod cannot be used effectively without iTunes. These two devices complement each others' functionality, interact and depend upon each other, and collectively fulfill the user's goal of listening to music or watching videos at the desk or when mobile.

Comparisons between technological and biological entities have been drawn in the past. For example, Nardi and O'Day [11] defined an information ecology as "*a system of people, practices, values, and technologies in a particular local environment*". Their approach takes a more social view of the information ecology; ours focuses on the user's multiple devices and how the interaction among them influences the user's information management practices.

Another work that has paired up biological systems with information systems is information foraging theory by Pirolli and Card [14]. In their theory, they stipulate that human information gathering behavior is similar to behavior that animals follow when they are looking for food. The theory has been validated in a series of studies over the years. This theory explains human-behavior and not the relationship of the devices used by the humans in their information foraging. Furthermore, the theory's predictive power when it comes to using multiple devices has not been corroborated [9].

3.2. Devices as Organisms

In a biological ecosystem, there are two types of components: *biotic* (living organisms), and *abiotic* (environmental factors), both of which are equally important to the survival and development of the ecosystem as a whole [16]. Similarly, every device in a device ecosystem is an organism. The malfunctioning of any one or more devices has the potential to cause the functional collapse of the entire ecosystem, just as harm to any species in a well-balanced natural ecosystem may ultimately lead to disastrous consequences for the ecosystem as a whole. Certain devices can be replaced by other devices (as can organisms), and this would

¹<http://www.apple.com/ipod/>

not necessarily affect the delicate equilibrium, if the replacing device can fill the just-vacated niche effectively.

In a PIE, biotic organisms are devices used by the user to accomplish their daily information needs. Abiotic components are environmental factors used to accomplish these needs. These are normally services provided by other devices or entities in the environment. For example, web-based services are considered abiotic. They are needed to carry out the daily information needs but are not devices owned or operated by the user.

3.3. Information Flow Among Components

In a natural ecosystem, energy flows from one component to another: chlorophyllous plants synthesize energy from sunlight and other raw materials, while other biological entities receive their share from plants, directly or indirectly, forming the food chain. In a device ecosystem, information can be considered the equivalent of energy. Some devices are producers of information: they capture or create information from the user (via input peripherals) or the environment (via sensors or external information sources such as the Web). It is then passed on to other devices. Certain other devices perform the role of consuming or disseminating information to satisfy the user's needs, via output devices or by exporting it to entities outside the ecosystem. Thus, there is a chain of devices that each transform information from source to destination, possibly modifying it in the process.

3.4. Variety and Diversity

One of the key characteristics of a biological ecosystem is the diversity of species found within. Similarly, a personal information ecosystem can contain a rich assortment of devices, differing in many ways (e.g. form factor, connectivity). The diversity of components in a personal information ecosystem is with respect to the capabilities of the devices to transform and transmit information. For example, large environmental displays can show status information (e.g. temperature, news), but afford minimal (if any) interaction. Some other devices such as an Apple iPod Shuffle have limited functionality and only work when paired with other devices (e.g. a computer with iTunes). This diversity of devices is analogous to the Ubiquitous Computing vision of Mark Weiser [18] where he described tabs, pads, and boards as different-sized devices that provide ubiquity.

3.5. Interdependencies

Various species in a natural ecosystem depend on one another for various reasons: the flow of energy (or, analogously, information) among them is a key motivator. In biological systems, some of these relationships exhibit unique

characteristics and are thus given special names, such as symbiosis, parasitism, and commensalism. We draw parallels between them and personal information ecosystems here.

3.5.1 Symbiosis

Symbiosis is defined as a relationship between two kinds of organisms in which one obtains food or similar benefits from the other, while the latter benefits from this partnership in some other way. Similarly, two or more devices may offer complementary functionality, and depend upon each other to perform their task well. Each brings to the table a unique feature that is not found in the other, which is the *raison d'être* behind symbiosis.

In our survey, we found that users tethered their laptop computers to their cell phones in order to provide network connectivity to the laptop. This is an example of a symbiotic relationship. Using both devices symbiotically increases the benefits of each device. The iPod + iTunes is another typical example of this interdependency. Because of the iPod, iTunes gains music playing while being away from your computer, and the iPod gains an easy to use software for managing music on the desktop or laptop computer.

3.5.2 Commensalism

Commensalism is defined as a relationship between two kinds of organisms in which one obtains food or other benefits from the other, but neither damaging nor benefiting the latter [6]. For example, in the biological world, certain species of organisms benefit by receiving shelter while living inside trees without adversely impacting the trees. Likewise, a device may provide, or broadcast, information that other devices use. For example, calendaring programs such as Google Calendar (an abiotic component in a PIE) can publish a user's schedule for use by external entities. Also, RSS feeds are routinely generated by web applications to disseminate information. In general, content syndication is an example of commensalism.

Another example is found in the Harmony series of remote controls from Logitech². These remotes are sophisticated universal remotes that provide very advanced functionality to users. However, programming the remotes is a complex task that is done in a browser using a desktop or laptop computer. The remote is an organism that benefits from the computer for its operation. The computer is simply used for the purpose of configuring the remote, and there is no harm or benefit for the computer. As a matter of fact, the computer does not even factor in the use of remote to control a TV, stereo, etc.

²<http://www.logitech.com/>

3.5.3 Parasitism

Parasitism represents a partnership in which one kind of organism obtains food or other benefit from another, and harms the host organism in the process. Many users download email to their machines from servers that support the POP3 protocol. When the protocol was designed, it was not envisioned that a single user would ever want to download their email to more than one machine. Many email clients that implement the protocol are designed to delete email from the server once downloaded. Once this happens, any other devices that then try to access email do not get the messages that were already downloaded elsewhere. Thus, one device can act as a parasite and prevent several others from accessing information that they should have received.

3.6. Environment

In a biological ecosystem, various abiotic factors (physical as well as chemical) such as water, temperature, sunlight, etc. influence the organisms that live within it. They provide the infrastructure upon which life depends and thrives. Likewise, in a personal information ecosystem, factors such as the available power sources, network connectivity (either wired or wireless), cables and wiring, web services, etc. help sustain the devices within. Similar to how fluctuations in the environment of an ecosystem affect its equilibrium, the changes in the support infrastructure of a personal information ecosystem can have far-reaching consequences for the devices within it.

For example, cell phones depend upon an existing environment that supports cell phone service coverage with the right protocol at the right frequencies in order to be able to communicate. If additional support is available from the network, cell phones might be able to activate advanced features such as multimedia messaging, visual voicemail, and location triangulation.

In some respects, organisms that depend on a critical environmental resource migrate towards a location where that resource is in abundance. Thus, we also see the adaptation of parts of a device ecosystem towards environments that can better sustain the system. For example, datacenters are often established near sources of cheap power and Internet backbone peering points. In another common example, users are attracted towards coffee shops that provide free wireless Internet connectivity.

3.7. Processes

The dynamism in a natural ecosystem comes from the various processes that occur naturally and continually in all organisms. Some of them are *internal* to an organism, some are *between* two organisms, while some others are between

the organisms and the environment. In an analogous fashion, continual internal processing and inter-device communication occurs in the devices in an ecosystem. A typical process in PIE is the movement of data from device to device, such as synchronization events.

3.8. Equilibrium

Relationships in ecosystems are fairly complex and finely balanced. Over a period of time, these relationships stabilize and become self-sustaining. Such an ecosystem is said to be in equilibrium. A healthy ecology is not static, even when it is in equilibrium [11]. Subtle changes in the composition of an ecosystem or variations in the abiotic or biotic factors necessitate a response by the ecosystem as a whole to maintain equilibrium.

Due to the complex interdependencies in an ecosystem, changes in one part can lead to wide-ranging effects in other parts of the ecosystem. The organisms in an ecosystem adapt in response to such changes and strive to achieve equilibrium in the long run. However, at times, the introduction of certain species into an otherwise-balanced ecosystem, or the removal of certain critical species (either *foundation species*³ or *keystone species*⁴) [6] may impact the ecosystem adversely and cause it to lose its equilibrium.

We define a personal information ecosystem to be in equilibrium when the user's information needs are met effectively and the information flow and interdependencies remain stable over a period of time.

Organisms (devices or services) may be added to or removed from the ecosystem at any time. Sometimes, the addition of an organism leads to gradual evolution of the information flow. For example, replacing a desktop computer with another one of higher processing power, but running the same applications on the same data as before, represents a low-impact change to the ecosystem since it does not affect the flow of information in any significant manner. In other cases, the introduction of a new device type may completely disrupt the equilibrium. For example, the introduction of a PDA into an ecosystem may cause significant changes to the information flow and management practices of the user.

4. Implications for Design and Research

We argue that considering multiple net-enabled devices as a personal information ecosystem changes the way these

³An abundant species that is (one of) the primary producer(s) in an ecosystem, and also exerts a great deal of influence on the ecosystem as a whole.

⁴A species that may not be abundant, but is critical to the survival of the ecosystem as a whole.

devices are designed and opens up opportunities for research. The parallels we drew between biological ecosystems and personal information ecosystems offer us a new way to think and talk about the design space for multi-device interaction. Designers should think about the equilibrium of the user's information ecosystem when designing new devices. Researchers should explore how to measure the equilibrium in a PIE and identify the impacts of the introduction of new devices into the ecosystem.

This shift is not just based on our change of focus from single device study to personal information ecosystem; design practices in general evolve over time. McCullough [10] [p.152] discusses how “*technology-centered interface design becomes human-centered interaction design.*” In that change, emphasis shifts from one type of activity to another, thus giving rise to new optimization and performance concerns. In the domain discussed here, we have gone from usability evaluations on a single device “to whole-systems engineering for configurations we can live with, master, and tune” [10].

In the following subsections, we present a number of issues to be considered when designing and/or researching multi-device interactions in a personal information ecosystem.

4.1. Think Globally, Design Locally

When designing for an ecosystem of devices, it is necessary to consider all platforms together. We believe that this will require forfeiting interface-level consistency between two or more platforms in favor of supporting information flow among organisms. In recognizing the variety and diversity of devices in an ecosystem, designers can tailor the information flow among them in a way that best satisfies the needs of the user. This normally involves the use of standard information representations and open services that all other organisms in a PIE can use. Understanding interdependencies such as symbiosis, commensalism, and parasitism can lead to the local design of a particular device that will make a good citizen in an existing PIE.

From a research point of view, the impact of introducing new devices into an existing personal information ecosystem is not well understood. We have observed users' adaptations to new devices, but the extent of the change on the equilibrium in their PIE is still unclear. In particular, what kind of impact does the introduction of different types of devices (e.g. parasites) have on the equilibrium of a PIE? Can we measure the equilibrium, as defined above?

4.2. If Consistency is the Answer, What Was the Question?

It is not clear what level of consistency, if any, is required across devices in a PIE for the ecosystem to be in equilibrium. Do we desire consistency at all levels (mental models, data models, or interaction level)?

One level of consistency, and the most common one found, is to have all data and functionality replicated on all devices. However, we believe that this level of consistency is misguided and does not take advantage of the context of use of each device. For example, having a desktop calendar application show the entire month as a first view with overview information for each day put on the screen simultaneously is reasonable. On a cell phone, it is more appropriate to show only today's events. In our opinion, it is clear that 100% replication of functionality should not necessarily be the goal.

One could argue for data consistency and allow functionality to fit the capabilities and factors of each platform. Would this level of consistency have a negative impact on users' mental model of the system? Will users have difficulty in adapting these mental models to a new and different platforms without difficulty? We cannot answer this question with certainty, yet recent results [12, 5] show that users can adapt their mental models to different devices without much difficulty.

Applications developed for each platform must stay consistent with design guidelines for that particular platform. Apple's design guidelines for Mac OS X applications state that the default button in a dialog box ought to be the right-most in a row of buttons, whereas Microsoft's design guidelines for Windows applications suggest that it should be the left-most. Most applications available for both platforms seem to prefer platform consistency, thus leveraging the user's familiarity with the platform, rather than with each unique application.

The music-browsing interface on the iPod is consistent with iTunes to the extent that they both use the same set of playlists, music organization and media files. It does not, however, provide the same functionality that the iTunes application provides. This does not adversely affect the user's ability to listen to music because consistency is not the overriding concern in this example; instead, complementarity of tasks is. The iPod + iTunes is an excellent example of an application domain where tasks are distributed among devices in complementary ways. Furthermore, the iPod + iTunes dual-platform interface enables seamless task migration between the two devices, since synchronizing media files is a one-way process (from iTunes to iPod) and requires almost no interaction; files are automatically synchronized upon plugging in the iPod.

The iPod Shuffle, Nano, and Touch all have very differ-

ent interfaces. The consistency among them is in the brand name and in the use of the iTunes software to manage the user's information. This is consistency at the data level and not so much at the interaction level. All the user's data is stored in iTunes and organized using the same metaphors (e.g. playlists, most played list, etc.).

4.3. Consider Each Platform's Unique Affordances and Context of Use

The variety of devices present challenges and opportunities. What should identify each device? What type of information would be appropriate to have on each device? How do we copy information to and from these devices? These are questions that are at the heart of the design of a new product, and that touch on a large number of research questions.

Consider this example, based on our survey of knowledge workers: one user kept his address book "synchronized" between his phone and laptop computer. He maintained it by hand, however, because he liked to keep phone numbers only on the cellphone and email addresses only on his laptop computer. This level of flexibility is difficult to achieve with today's synchronization solutions, as they often try to replicate the data onto all devices in the ecosystem.

Consider another example: the Apple iPhone supports browsing the web with Mobile Safari, a full-fledged browser. It also supports the development of small applications that can be installed directly on the phone. So, a company like Facebook⁵, for example, is presented with a dilemma. Do they just let iPhone users browse their regular site using Mobile Safari or do they provide a version optimized for Mobile Safari/iPhone? Or, more interestingly, do they build their own client application for the iPhone platform, thus giving them access to additional functionality that is not available to web applications? Designers need to be able to consider what the choices are among these three approaches. Researchers need to identify how best to measure usability when these platforms are so different.

The environment also plays a significant role in the creation of applications and use of devices in an ecosystem. Location awareness is, for example, a significant factor in the design of applications for small devices. From our own work, we considered the following question: what would having a net-enabled handheld device do to riding the public transit bus in Blacksburg, VA? The Blacksburg Transit bus operators provide the entire bus schedule on the Web. But interpreting the schedule is complicated. It depends on routes, on the time of the day (day vs. evening routes), the time of the week (weekday vs. weekend routes) and even the time of the year (school weeks vs. academic breaks).

⁵<http://facebook.com/>

But, for a person standing at a bus station, the key information is when the bus would arrive and how long it would take to get to the intended destination.

An appropriate solution to this would be to have a small application for a device that provides quick access to this information. The application can sense the environment, determine location, find the closest bus stations, and provide those as choices. With the selected departing station, the software can then prompt for the destination. Given the time of the day, the day of the week, and the time of the year, the software determines the appropriate schedule and provides the user with the time of the next bus at that station that will take him/her to the desired destination.

4.4. Facilitate Migrating Enough Task State and Data

Synchronization of data between two devices only means that their internal state will be made as consistent as possible. Simple synchronization implies nothing about the user's interaction with those devices. From prior research [2], we know that file management is a cognitively demanding task and potentially introduces more file and information management tasks for the user to deal with. Thus, synchronization subjects users to higher cognitive load—something that designers should strive to reduce.

The current implementation of synchronization in several design scenarios is an all or nothing approach that involves full replication of data across devices, or none at all. It also requires a great deal of manual configuration and initiation. Several participants in our survey reported that they did not consider automatic synchronization reliable enough because of negative experiences on several occasions. In these cases, a deeper thought to issues such as information flow and equilibrium among devices can help in the development of a synchronization algorithm that works reliably for users, where the reliability is a measure of whether the end results match the expectations of the user.

A *task disconnect* represents the break in continuity that occurs due to the extra actions necessary when a user attempts to switch devices to accomplish a single task [15]. A task disconnect is the cost of moving work from one device to another. When a user incurs these extraneous costs, the information flow between devices interrupts the equilibrium in the ecology. We consider seamless task migration a principal attribute of an ecosystem in equilibrium. It is the designer's responsibility to support seamless task migration and other emergent usage in a user's personal information ecosystem in the products they create. To achieve seamless task migration, some or all of the data associated with a running application need to be transferred from one device to another before interaction can proceed seamlessly on the second device.

Given the vastly different capabilities of various devices,

it is not always practical to transfer the entire task data from one device to another. Shared data across platforms requires at best partial consistency. For example, synchronization software available on many cell phones copies only a few upcoming weeks at a time. The software assumes that the devices will be synchronized frequently (at least weekly) and thus saves memory in the cellphone by only having upcoming events stored. We believe that the context of interaction, the capabilities of the device, and the appropriateness of the interaction should dictate the amount and nature of task state and data that should be migrated. This, however, is difficult to decide at design time as it depends on the particular types of devices that a user has available in his/her PIE.

4.5. Design for Offline Usage

Many portable devices are designed with the best case connectivity scenario in mind: high-bandwidth uninterrupted network access. Several applications can only function when online, and are not able to degrade gracefully in the absence of connectivity, or in cases of low-bandwidth or high-latency connectivity. This points to a lack of awareness on part of the designer of the possible operating environment of the device. Just as an organism must learn to live and adapt to its environment — or face possible extinction — devices must also be able to function, perhaps at reduced levels of functionality, in the face of adverse operating conditions.

5. Conclusions

In this paper, we presented the problems users face when using multiple devices. We proposed the idea of a personal information ecosystem, provided a definition, and discussed their characteristics with examples. We posit a view of personal information management that is essential for the design of future ubiquitous environments given the plethora of devices in existence today. In our research, we have encountered numerous examples of devices that, when used individually, satisfy traditional usability requirements; however, when considered as part of a personal information ecosystem, tend to disrupt the users' information flow and throw their ecosystems out of equilibrium.

Future research should study how to evaluate the equilibrium of a personal information ecosystem and to assess the short- and long-term impact of the introduction and removal of devices.

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References

- [1] G. Ananthanarayanan, S. Blagsvedt, and K. Toyama. Oweb: A framework for offline web browsing. *la-web*, 0:15–24, 2006.
- [2] D. Barreau and B. A. Nardi. Finding and reminding: file organization from the desktop. *SIGCHI Bull.*, 27(3):39–43, 1995.
- [3] O. Bergman, R. Beyth-Marom, and R. Nachmias. The project fragmentation problem in personal information management. In *CHI '06: Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 271–274, New York, NY, USA, 2006. ACM Press.
- [4] R. Boardman and M. A. Sasse. "stuff goes into the computer and doesn't come out": a cross-tool study of personal information management. In *CHI '04: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 583–590, New York, NY, USA, 2004. ACM Press.
- [5] C. Chhatpar, S. Lambros, and M. A. Pérez-Quinones. Variability of user interaction with multi-platform news feeds. Technical Report TR 04-22, Dept. of Computer Science, Virginia Tech, 2004.
- [6] E. C. Jaeger and I. H. Page. *A source-book of medical terms*. Charles C. Thomas, Springfield, Ill, 1953.
- [7] W. Jones, H. Bruce, and S. Dumais. Keeping found things found on the web. In *CIKM '01: Proceedings of the tenth international conference on Information and knowledge management*, pages 119–126, New York, NY, USA, 2001. ACM Press.
- [8] A. Joshi, S. Weerawarana, and E. N. Houstis. On disconnected browsing of distributed information. In *RIDE '97: Proceedings of the 7th International Workshop on Research Issues in Data Engineering (RIDE '97) High Performance Database Management for Large-Scale Applications*, page 101, Washington, DC, USA, 1997. IEEE Computer Society.
- [9] S. Lambros. Investigating the applicability of information foraging theory to mobile web browsing. Master's thesis, Virginia Tech, May 2005.
- [10] M. McCullough. *Digital Ground: Architecture, Pervasive Computing, and Environmental Knowing*. MIT Press, 2004.
- [11] B. Nardi and V. O'Day. *Information Ecologies: Using Technology with Heart*. MIT Press, 2000.
- [12] A. Parush. The measurement and comparison of cross-device mental models. <http://www.carleton.ca/hotlab/hottopics/Articles/OnMentalModels.html>, 2004.
- [13] M. Perry, K. O'Hara, A. Sellen, B. Brown, and R. Harper. Dealing with mobility: understanding access anytime, anywhere. *ACM Trans. Comput.-Hum. Interact.*, 8(4):323–347, 2001.
- [14] P. Pirolli and S. Card. Information foraging. *Psychological Review*, 106(4):643–675, 1999.
- [15] P. S. Pyla, M. Tungare, and M. Pérez-Quinones. Multiple user interfaces: Why consistency is not everything, and seamless task migration is key. In *Proceedings of the CHI 2006 Workshop on The Many Faces of Consistency in Cross-Platform Design.*, 2006.
- [16] A. G. Tansley. The use and abuse of vegetational concepts and terms. *Ecology*, 16(3):284–307, 1935.
- [17] M. Tungare and M. Pérez-Quinones. It's not what you have, but how you use it: Compromises in mobile device use. Technical report, ACM Computing Research Repository, 2008.
- [18] M. Weiser. The computer for the 21st century. *Scientific American*, 265(3):66–75, 1991.