

Fostering a Symbiotic Handheld Environment

Although researchers have already begun building the infrastructure to make a symbiotic environment of handheld systems and related devices possible, business needs will drive this technology's real growth.

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A short walk through the Akihabara Electrical Town in Tokyo (www.akiba.or.jp) reveals the latest trends in handheld devices, including their tremendous variety. Such devices range from high-end PDAs to miniature cell phones, MP3 players, digital cameras, GPS navigators, and devices that integrate all these capabilities into a single portable unit. Handheld devices, especially when endowed with a programmable computing engine and connectivity, let people work or entertain themselves while on the move. Their key advantages thus include portability, sole ownership, and privacy.

However, handhelds face important limitations. They must be small and light enough for users to carry them. Size restrictions place a limit on their display and number of buttons or dials. Voice-based interfaces cannot always solve these problems because handheld use often occurs in public places. Further, from now through the near future, using powerful handhelds will be restricted by their relatively short battery life.

Given these limitations, we can reasonably ask whether handhelds will become more common in the midterm future. For example, the widespread deployment of WiFi networks leads people to favor always-connected laptops over intermittently connected handhelds. It seems that connectivity, better I/O capabilities, and CPU power offset the larger

size of these laptops. At the spectrum's other end, wearable computers or even body-implanted computers could displace handhelds if these alternatives become easily available and safe.

To predict the future of handhelds, we borrow some ideas and models from biology and look at our current computational environment as a jungle where multiple device types compete for market survival. As in nature, the fittest devices rapidly increase their presence and succeed. In this jungle, success is measured by how useful humans perceive a device to be.

In nature, organisms pursue many different survival strategies, but we will explore only one survival mechanism that biological organisms use: *symbiosis*. Initially defined by Anton de Bary in 1879, symbiosis describes a mutually beneficial relationship between dissimilar organisms.¹ Normally, we can distinguish three types of symbiotic relationships:

- *mutualism*, in which all organisms benefit from their relationship to each other;
- *commensalism*, in which one organism benefits with minimal cost or benefit to the others; and
- *parasitism*, in which the benefits that one organism achieves come at a cost to all others.

Common usage applies the term to just commensalism, even though researchers understand symbiosis to refer to the entire continuum.

A New Generation of Display Devices

Researchers are at work creating a new generation of display devices in labs worldwide. One major trend involves displays that connect to wearable computers. Although many wearables rely on goggles or similar head-mounted displays, recent research has explored less intrusive display systems such as wristwatch computers. A typical example, IBM's Linux watch, combines a complete computer system with a programmable display. Bluetooth-enabled, the wristwatch can connect to other machines in the environment.

Several prototypes use tiny, low-power, vector-based laser displays to let handhelds project images on surfaces. For example, VKB (www.vkb.co.il) produces a small device that connects to commercial handhelds and projects a virtual keyboard on everyday surfaces. The system incorporates an infrared detection system to determine when a user has touched the projected keys, effectively empowering a handheld with a full-size keyboard.

The appearance of prototype steerable projectors provides another interesting development. With these projection devices, users can command a projected image to move to different sur-

faces. In response to such a command, the projector manipulates a pan-and-tilt mirror or gimbal system to move the projected image. For example, in IBM's Everywhere Displays steerable projector,¹ a pan-and-tilt camera and a gesture-recognition system can create interactive displays on virtually any surface.

Finally, researchers have made several breakthroughs toward the production of flexible display systems based on organic electronics.² The advantages of such displays over traditional LCD technology include low power consumption, screen flexibility, and thinness, which make this technology a primary candidate for embedding display capabilities in the surfaces of everyday objects such as tables, cabinets, and walls.

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Developers of handhelds have already explored symbiosis to overcome some limitations. The commensal relationship between PDAs and larger desktop or laptop computers offers a classic example. The desktop's full-size keyboard and larger display simplify the management of data and applications on the linked PDA. The synchronization process between the two devices simply and safely backs up the PDA's data. In addition to other advantages, such as ease of use and application availability, symbiosis with personal computers gave PDAs a clear competitive advantage over simpler electronic address books, rapidly pushing these rivals toward extinction.

As some researchers have already observed,²⁻⁴ symbiosis will be a key component for handhelds' survival, which can only be achieved by their everyday use in future computing environments. In parallel with improving these devices' core technologies, developers should explore ways to help overcome handhelds' limitations by establishing relationships with other computational services and devices present in the environment. Examples of this approach include the Parasitic Computing Enabler³ and the Personal Server.⁴

The Pebbles project³ shows how a handheld could work together with a PC by using it as a private display, scratch pad, and remote control. The IBM Meta Pad splits a PC into two components, an I/O device and a core that includes a processor, memory, and disk. This core can be attached to either a small portable display for mobility or to a regular monitor for a better user experience.

The WebSplitter project⁵ separates XML streams into parts that go either to the handheld or to other devices. Several projects in pervasive computing—

such as Aura, CyberForaging, Gaia, iCrafter, Oxygen, Portolano, and Trust Context Spaces—have looked at some of the issues that arise while attempting to use a collection of devices.

Overall, the symbiotic approach may require rethinking and redesigning applications and developing new algorithms, systems, and protocols that will enable these symbiotic relations. For example, the PDA-computer symbiosis only became possible when researchers developed technology for fast synchronization.

To simplify our analysis, we focus on symbiotic relationships between handhelds and other computational devices that help improve the display and other input-output limitations. We argue that advances in technology will not significantly mitigate handhelds' limitations because human perceptual and motor systems—not the underlying technology—are the real limiting factors.

THE ECOSYSTEM OF DISPLAYS

Symbiosis is only possible when the ecosystem has enough diversity to enable new, advantageous relationships among organisms. For displays, sufficient diversity already appears to be present. In today's ecosystem, displays include CRT monitors, laptops, PDAs, telephones, projectors, televisions, wristwatches, clocks, navigation systems, and even baby monitors. We include these devices in our analysis along with other display types being developed and tested in laboratories across the world, as the "A New Generation of Display Devices" sidebar describes.

We believe that no particular display device will dominate because the human visual perceptual sys-

Table 1. Current and maximum possible display resolution according to human limitations.

Display type	User distance in inches	Typical width in inches	Typical width in pixels	Typical resolution in DPI	Maximum resolution* in DPI	Maximum width in pixels
Cell phone panel	10	1	100	100	350	350
PDA display	12	2	300	150	291	582
Laptop display	16	10	1,200	120	218	2,180
Desktop monitor	20	15	2,000	133	175	2,625
Laser printer hardcopy	12	7	2,100	300	291	2,037
Television set	100	25 **	694 **	28	35	805
Meeting room screen	230	80	1,200	15	15	1,200
Movie screen	500	720	5,000 ***	7	7	5,040

* Maximum resolution is computed using 20/20 human visual acuity, which is one minute of arc.
 ** For television sets, resolution is computed in the vertical considering the NTSC limit of 520 lines.
 *** Considering standard 35-mm film stock with 4,000-dpi grain.

tem imposes strong constraints on these devices. For example, human visual acuity imposes an upper bound on display resolution. Given that even people with perfect vision cannot resolve details smaller than one minute of visual-arc angle, increasing display resolution beyond that point does not contribute significantly to improvements in the amount of information shown. Table 1 shows that the display resolution of several common devices already approaches the limits of human visual acuity. We derived the table's cells based on typical display widths, the distance at which they are normally used, and human limitations on visual acuity. We note a similar trend with other attributes, such as brightness and color.

Besides human perceptual constraints, different kinds of displays also have limitations related to group and social norms. For example, using a projection screen in a meeting room is inappropriate for displaying personal information. Similarly, it is virtually impossible for more than two people to work with a single PDA display. Figure 1 captures some of these limitations and shows how they affect different display devices. It provides a comparison among devices either commercially available or in development, according to six different dimensions:

- maximum width, according to the preceding analysis;
- portability, the ease of carrying the device around or installing it in an environment;
- ubiquity, the ease of finding a display in an environment;
- saliency, the display's ability to attract the user's attention in the context of the user's environment;
- privacy, the display's capacity to hide and share information according to the users' intent; and
- simultaneity, how well multiple users can access the display.

For example, Figure 1 shows that users can easily carry a typical PDA and use it virtually everywhere. However, PDAs can only display a relatively small number of pixels and have limited ability to attract the user's attention by purely visual means. While appropriate for applications that require privacy, PDAs are inconvenient for multiuser situations.

The position of displays along the different dimensions includes some assumptions about typical usage and is not meant to be precise. Figure 1 shows that no single existing or anticipated device is better than its competitors across all dimensions. Notice also that most device limitations will not change significantly with technological advances. Bearing that in mind, symbiotic relationships between handhelds and environmental displays offer a promising approach to overcoming these constraints.

Figure 1 also provides a means for exploring possible paths for symbiotic handheld relationships in specific applications. For example, if an application requires more resolution than is available on handhelds, it should try to establish a symbiotic relationship with projectors or monitors in the environment. However, if the application also requires ubiquity, portable or steerable projectors offer better candidates for the symbiosis. Similarly, if a handheld needs to attract the user's attention using only visual means, it could look for a big screen in the environment or check whether the user is wearing some sort of eye-mounted display.

A WORLD OF SYMBIOTIC DISPLAYS

The following futuristic scenario offers the opportunity to explore symbiotic relationships among handhelds. This scenario chronicles one day in the life of Tara, a final-year undergraduate student majoring in architecture. Tara owns a handheld that can communicate seamlessly with other displays in her environment and use them to display information when needed. Tara's handheld can leverage the

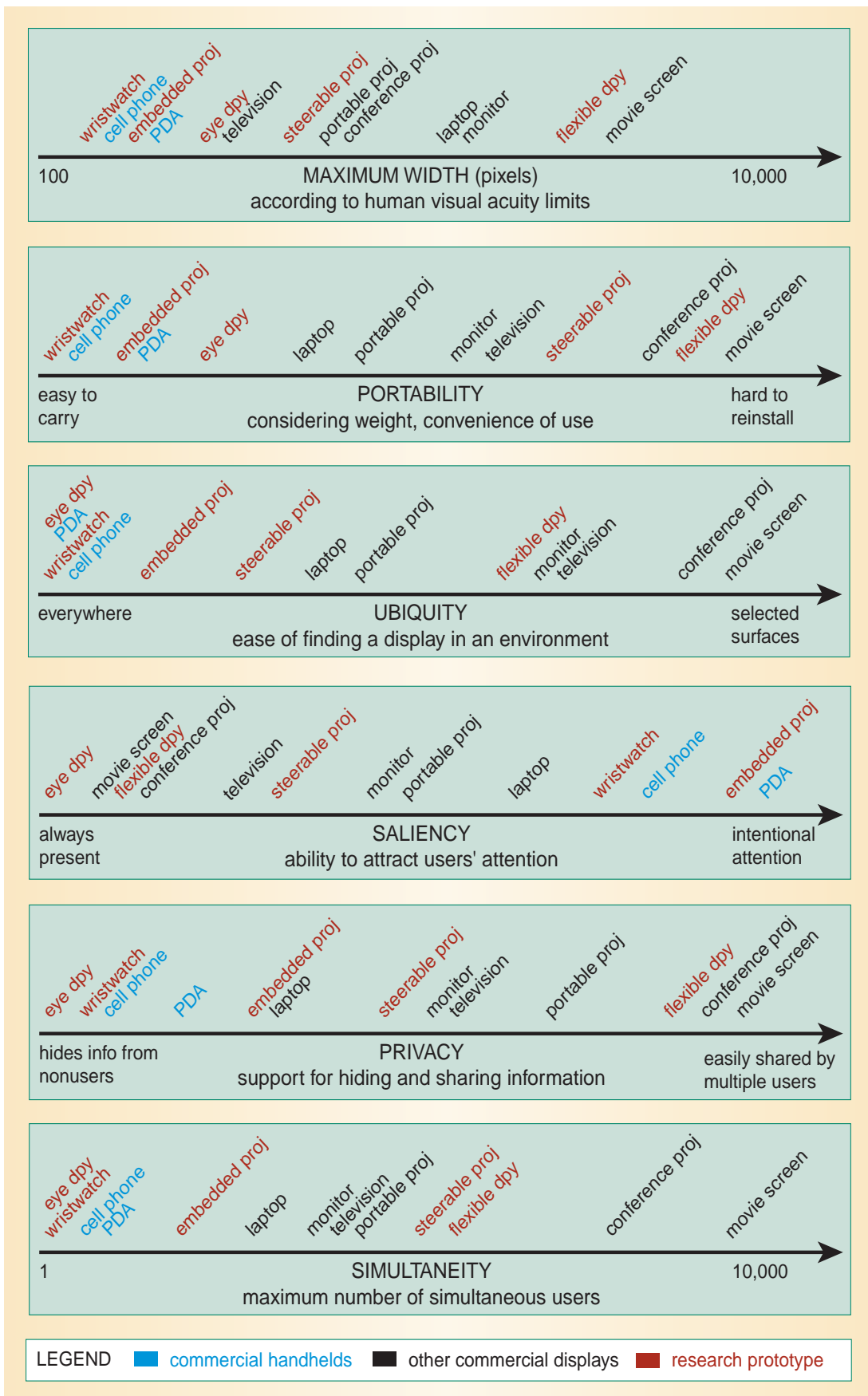


Figure 1. Display device characteristics. This comparison of six intrinsic display characteristics illustrates how they affect different devices.

A handheld's blurring mechanism can help preserve privacy when multiple viewers need to share an overview of a document.

display ecosystem around her to overcome its limitations.

Tara's day starts with the alarm buzzing at 10:20 a.m. Tara has instructed her handheld to communicate with her alarm clock—which has a ceiling-projection device embedded in it—to display the time and a summary of her day's classes on the ceiling above her bed. Seeing that the always-late Professor Gray teaches her first class, she presses the snooze button.

This simple example shows how a handheld can use another display device to facilitate the user's access to information. In this situation, the handheld display's small size is inconvenient for showing information to a semiconscious person or to one who needs glasses to read. Besides, handhelds have small saliency, as Figure 1 shows, so users usually must find them and pick them up to access their display—not an easy task for a person just waking up. By using the ceiling projector, the handheld overcomes both limitations.

On the bus ride to her classes, Tara uses her handheld to check her landscape design assignment, due the next day. She fixes a grammatical error. Later, to verify the design, she prints a copy on the printer at the back of the classroom. When Professor Gray arrives 15 minutes late, Tara has already identified many of the design's problems and made several comments on the printed hard copy.

This symbiotic scenario is already available in many environments. Easy to carry and access everywhere, a handheld device is a convenient tool for doing small corrections. However, handhelds lack pixel width, so a printer offers a good symbiotic solution to compensate for resolution constraints. In fact, printed paper is such a powerful medium that most computer users rely on it as a symbiotic enhancement to their desktop PCs.

During the lecture, the professor uses his tablet PC to write on top of his prepared material. The tablet PC also downloads copies of the pages shown on the classroom screen to the students' handheld computers. Tara then raises a question that relates to material covered in last Monday's class. To clarify her question, she commands her handheld to project the relevant page onto the classroom projector.

In this case, both the tablet PC and the handheld use the projector display to provide an application

with improved simultaneity. Some models of Internet-enabled projectors already support protocols that upload images to the projector's memory.

After class, Tara decides to send a message from her handheld to her landscape project partners. Planning to meet with them and discuss the project during lunch, she walks up to a large electronic display of the campus map and asks her handheld to locate her project partners. Her handheld transmits their coordinates to the map, which then displays the location of all the students without identifying them. Since most of her partners reside on the north side, Tara decides that Café Moe's is the best place to meet. She emails a request that everybody join her there around 1 p.m.

Large images are particularly hard to display on a handheld. Here, Tara uses a public display to overcome this limitation. However, large public displays tend to provide little privacy, which can be compensated for by hiding identities. The context of Tara's query lets her read the marks on the display and recognize her partners' locations.

Tara arrives first at Café Moe's. She asks for a table for four with a high-resolution organic display. As she waits for her partners to show up, Tara receives a long e-mail message from her boyfriend. She commands her handheld to show it on the table. To avoid the curious eyes of people around her, the message displayed on the table blurs names, times, places, and the more intimate passages, as detected by her privacy software. The contents of the blurred lines appear on the handheld, where Tara can read it up close. After reading the message, she smiles and removes it from the tabletop display.

This scene, pictured in Figure 2a, shows another way to increase the resolution of a handheld while keeping privacy concerns to acceptable levels. While the image on the table provides the resolution needed for the display, the blurring mechanism can preserve the most private sections. The handheld thus functions as a privacy magnifying glass. This method of preserving privacy in large displays can be used when viewers need an overview of a document whose parts are not all equally private. To interact with the table, a participant might use an overhead camera with a system capable of interpreting hand positions relative to displayed user-interface elements.

After everyone arrives and orders their food from the interactive menus on the table, they load their design drawings onto the table and revise them. When the food arrives, they move the drawings to the table's center to make space for their plates, but keep working. After lunch, the participants synchronize the latest set of drawings into their handheld devices.

Handhelds, given their size, have limited capabilities for use in collaborative situations. In this example, however, they take advantage of large displays to facilitate collaboration.

At the library, Tara works on the drawings all afternoon. There, she uses one of the available monitors to improve the drawings. At some point, she is so overwhelmed with the work's details that she asks the local steerable projector system for display space on the floor to simplify the visualization of the whole landscape map. This service will cost her \$10 an hour. Tara authorizes the charge to her campus-wide IT account.

In an extension of the current Internet café model, we believe that along with free public displays, pay-per-use displays such as the floor display shown in Figure 2b will be available that users can rent to perform specific tasks.

After many hours at the library, Tara returns home. She places her handheld in its cradle and, using a special hand gesture, tells the design landscape application to follow her around the house. As she walks, the project's images follow her, moving from one display to another.

If a user enables multiple displays to relate symbiotically in an environment, a scenario like the one we've described becomes possible through the addition of user tracking. A user-following display system has already been implemented using cameras to track user location.⁶ Other mechanisms, such as threshold-crossing detectors, could be used as well.

While she eats in the kitchen, staring at the project shown on the refrigerator display, Tara decides to call Bryan, the course teaching assistant. When she picks up the phone, an ED-projector automatically projects her phone list beside the phone. A recorded voice tells her that Bryan cannot talk right now, but is reading instant messages. A laser-projected keyboard then appears on the kitchen table, which Tara uses to type a message to Bryan.

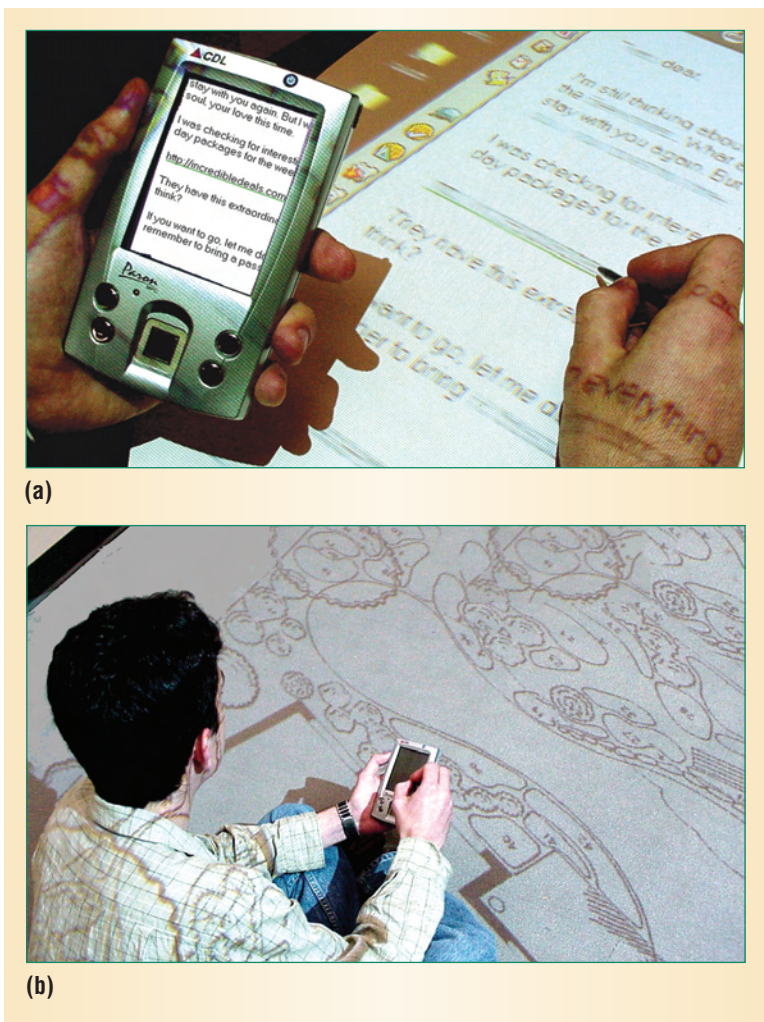


Figure 2. Two examples of symbiotic-display relationships between a handheld and an environmental display. (a) The display table blurs selected information in an e-mail message to increase privacy. The user can point to the table display and read the nonblurred detail image on the handheld's screen. (b) A user projects a large-scale map on the floor and uses his handheld to interact with it.

Another symbiotic development relies on information about user actions in the environment. In our example, the phone senses when Tara picks it up and passes this information to the handheld or other device running a helper agent. However, to be really useful, the agent must find a suitable device that can deliver information as close to the action as possible. Steerable interface projectors are good candidates to fulfill this kind of integration with the real world.

While waiting for Bryan's answer, Tara watches television. After awhile, the bottom half of the TV goes blank and shows a message from Bryan saying that tomorrow's 9 a.m. landscape design lecture has been cancelled and all assignments postponed because Professor Sanders has the flu. Relieved, Tara crawls into bed and, with a single touch of her wristwatch, turns off all displays—at least until tomorrow morning.

We must elevate displays from simple pixel-rendering engines associated with a single host processor to intelligent, first-class network elements.

This example shows how the interconnected network of devices detects the user state, communicates with a handheld or similar personal device, and chooses a display device to deliver information. To achieve this level of symbiotic relationships between computer devices, we still need many technological improvements and important changes in the way devices communicate and interoperate.

SYMBIOSIS-ENABLING TECHNOLOGIES

Let's take a closer look at the Tara scenario and see what must happen from a technological perspective to enable the seamless symbiotic relationships it illustrates. First and foremost, we must elevate displays from simple pixel-rendering engines associated with a single host processor to intelligent, first-class network elements. These displays need the ability to support a network interface, engage in a meaningful dialogue with other devices on the network, and accept and display information.

Discovery and association

When operating in an environment where intelligent displays are commonly available, handheld devices need a way to discover these displays and associate with one or more of them. Discovery and association are the first steps toward making any sort of symbiotic interaction possible.

One approach to providing this capability presents a list of available displays to users and prompts them to select one. Ideally, the infrastructure would carefully prune the list of displays to show only the relevant ones for the action contemplated. Several discovery schemes—such as UPnP, Jini, SLP, and UDDI—aim to solve the discovery problem under slightly different sets of assumptions.

We can also solve the discovery and association problem by letting users simply point⁷ to a given display. For example, if the handheld had an infrared transmitter and the displays had infrared receivers, the selection process could involve the handheld establishing the association by sending its network address to the display over the infrared channel. Other ways of achieving the same goal might involve using stereo cameras to determine user gestures. In the near term, however, it is unlikely that a single technology will emerge as a standard solution to discovery and association problems.

Authentication and payment

Once users determine which display to use, they may have to complete an authentication process

and possibly even pay for usage to access the display. In an environment such as the user's home, any device physically located within the environment could be permitted to use the displays in that environment—explicit authentication and payment steps would be unnecessary. Using a network firewall can help to ensure that home displays remain inaccessible to devices outside the home.

In the classroom setting, the instructor would normally control the class displays and decide when to yield that control. In public settings, such as a restaurant or library, more complex authentication mechanisms may be needed. At the library, Tara's handheld would probably have to present tokens that indicate her account number for usage charges. The restaurant's management might not charge patrons for using the displays, instead considering these devices a means of attracting more customers to buy their establishment's food services. Alternatively, the restaurant could sell advertising space on the display. Regardless, this scenario could require authentication schemes to ensure that only customers seated at a particular table have access to the table's display.

More public settings will require stronger authentication and payment mechanisms. These could include postpaid schemes coupled with login accounts and prepaid schemes based on credit cards or anonymous payment mechanisms. Billing for services could use one of several techniques, such as the period of display use or amount of data sent.

Formats for data exchange

Both the display and handheld must agree on the data exchange format. In extreme cases, the handheld might send pixels to the display. This scheme consumes the most bandwidth and uses more battery power. Other commonly used data representations that operate at a higher semantic level—such as PDF, PostScript, or Flash—could be used as well. Alternatively, the data could be sent in its native document format. Clearly, using higher semantic levels offers the potential advantage of sending fewer bits. This method also supports data modification on the display.

Making these data exchanges possible requires robust, low-power wireless communication technology. The current attractive candidates include infrared, Bluetooth, and IEEE 802.11. Infrared line-of-sight technology can be useful for certain applications, but omnidirectional technologies such as Bluetooth and 802.11 might be more usable. Currently, however, the power requirements of

802.11 and even Bluetooth are too demanding for handhelds' batteries.

Newer technologies—such as ultrawideband, which promises megabytes for milliwatts, or ongoing efforts in the 802.11 and 802.15 standards bodies—hold the promise of offering low-power, short-range wireless connectivity for handhelds. Many researchers are already working to improve low-power wireless technologies, which leads us to believe a solution will be found.

Since different displays will have different ability levels, we must find a way for displays and handhelds to negotiate the data formats. Perhaps the display can send accept headers to the handheld to indicate which formats it can accept, just as browsers indicate to Web servers which data formats they can display. Displays might also support downloadable code that accompanies the data and carries instructions for displaying it. In addition, the downloaded code might know how to react to user inputs and how data should be stored and saved. Also, if the data sent to the display has been interactively modified, the updates will need to be synchronized back to the handheld using standards such as SyncML.

As the handheld moves from one symbiotic interaction to another, its applications and content must adapt to different kinds of displays and systems. Simple technologies such as X11, VNC, and RDP can deal with multiple displays and have been in use for some time. Moreover, comprehensive technologies that deal with application mobility are emerging, such as Internet Suspend-Resume⁸ and MIT's IP mobility.⁹

Data security and privacy

If the handheld's interactions occur in a trusted environment such as the user's home, special security mechanisms probably will not be required. If the handheld and display communicate over an untrusted network, however, we will need cryptographic mechanisms to secure the communication from eavesdroppers. A mechanism such as SSL with public-key infrastructure certificates can provide this security. Alternatively, when the display and handheld know each other a priori, simpler shared-secret-based schemes can provide security.

The display itself may be untrusted—the restaurant's display table in the Tara scenario, for example. Or the user may want a guarantee that the display will not retain a copy of the data. As part of display characteristics exchanged during the association step, the display could include a privacy promise similar to P3P. If this proves inadequate, the handheld

might choose to send data at a much lower semantic level, such as mere pixels. Alternatively, the handheld could send data at a higher semantic level but eliminate certain critical portions of identifying information.

As users leverage symbiosis, they run the risk of leaving behind a trail that shows where they have been and what they have done. The added benefits of symbiosis should not cost users their privacy. In particular, developers must design schemes that safeguard user location privacy. The negotiation between handhelds and displays should preferably include privacy guarantees concerning user location. Anonymity or pseudonymity techniques also can improve user privacy.

ECONOMIC MOTIVATIONS

How quickly we can deploy a widespread symbiotic ecosystem will depend on several factors, including:

- the driving forces that will motivate businesses or individuals to build shareable displays,
- the catalysts that will engender the creation of standards for symbiosis between handhelds and displays, and
- how using these devices will make or save money.

Our vision of a rich display ecosystem will likely be realized more quickly if strong business issues require the deployment of such devices. It is true that academic and government institutions have started several large infrastructural deployments—most notably the Internet. Yet the Internet did not gain its current prominence until businesses began using it to increase revenue and profits.

Established symbioses

Signs of symbiotic technological relationships already exist. For example, in the consumer products domain, VCR programming became considerably easier once VCRs started using the TV screen rather than small built-in LED displays to present programming information.

Network-attached printers offer a simple example of well-established symbiosis between computing devices and displays that benefits both an organization and the individual users it employs. Several factors motivated deployment of the printer ecosystem, which took more than 10 years. First, printers are useful devices. Second, the growth of office productivity software led to a significant increase in documents. Third,

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the development of printing standards such as PostScript enhanced compatibility among different printer models. The fourth factor was the growth of networking and the ability to attach printers directly to a network.

We are beginning to see a similar trend at work to standardize conference room projectors. Until a few years ago, compatibility issues prevented laptops from easily working with projectors. However, these issues have been largely resolved, and enterprises now find it attractive to invest in such projectors. We see the beginnings of a trend toward network-enabled projectors that elevate these devices to first-class network objects, similar to printers. The VGA cable connection between the laptop and projector is being replaced by a virtual connection. With this change, small handhelds that do not include a standard VGA connector can also use the projector's services.

Business model evolution

Widespread symbiosis between devices will evolve slowly and could take many years. In the early stages, deployments will likely occur at academic or research campuses, funded by research grants. Initially, displays will continue to remain subordinate to and associated with specific computers. The early adopters will build glue software layers to network-enable the displays and make them accessible to other devices in the ecosystem. Progressively, network enablement will reach the lower-end displays as well.

For added ease of use, businesses will initially deploy network-enabled displays in meeting rooms to replace directly attached displays. High-end hotels and preferred-customer lounges in airports could also deploy these displays to help differentiate themselves. As the technology spreads and the connections become standardized, display costs will likely decrease, enabling the restaurant with tabletop displays described in the Tara scenario. Businesses will need mechanisms to measure increases in revenue and profit from this new technology, which could increase customer traffic, make it possible to charge premiums, and create other revenue generators.

The market may support businesses that let customers use displays for a fee. For example, public libraries could someday deploy fee-based displays alongside the fee-based printers and copiers they offer now.

Once the trend toward network-attached displays begins, display device vendors will see the

new market for such displays broadening and, as it matures, they will begin developing design standards. Perhaps displays will use Web services APIs to publish their capabilities. By that time, if a few winners have been identified among short-range wireless technologies, the display vendors will likely incorporate these technologies into their displays to improve their utility.

Even after we solve the technological and business issues associated with symbiosis, establishing the social norms required for proper resource sharing may take more time. We will likely see an imitation of traditional social structures and behaviors in which users form circles of trust, use and return favors, and buy and sell things. Similarly, legal issues will begin to arise when sharing displays becomes commonplace. For example, we can easily share an Internet connection with a neighbor through an 802.11 access point but most ISP contracts make such sharing illegal. Will people use public displays to view sensitive content, even if they are alone in the environment?

Social interaction and the use of symbiotic handhelds will likely also produce new and unexpected applications for multiple displays. For example, a new genre of video games is appearing in which multiple players use cell phones to play a game that spawns multiple locations. Given the personal nature of today's handheld devices, such games have had little public visibility even when they involve thousands of players. If large public displays could be integrated into this kind of game, the content would be viewed, shared, and propagate through a wider social spectrum, possibly making it as much part of the cultural and social landscape as a Hollywood blockbuster release is now.

At the same time, giving handhelds the ability to make symbiotic display connections may increase environmental noise and clutter. Thus, we must strike a fine balance, especially concerning issues such as visual, audio, and peripheral-vision alerts. In addition, care must be taken in demanding user attention. Rapidly changing visual displays could be distracting, which would make techniques to minimize such annoyances useful.¹⁰

We see symbiosis as an important direction to not only guarantee the survival of handhelds in the marketplace, but also to effectively achieve the goal of ubiquitous access and use of information, services, and entertainment. No single device will fulfill the needs of all users and applications, so researchers have begun creating the hardware and

software infrastructure necessary to realize environments in which handhelds and other devices share not only display capabilities, but also processing power, communications bandwidth, and, ultimately, the users' attention. ■

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