COVER FEATURE

Designing Urban Pervasive Systems

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A conceptual framework for designing and analyzing pervasive systems describes three aspects of these systems in the urban environment—architectural space, interaction space, and information sphere—and a spectrum of information "publicness."

Building pervasive systems requires new ways of thinking about the design and use of computing systems and how they interweave with the built environment. Urban areas offer the greatest opportunities and the strongest demands for pervasive systems, yet urban design hasn't featured significantly in pervasive systems research. We have no fundamental theory, knowledge base, principled methods, or tools for designing and building pervasive systems as integral elements of the urban landscape.

A systematic approach to designing the urban environment as an integrated system of architecture and pervasive technologies requires drawing on knowledge, theory, and methods from the disciplines of architecture and computer science. Key to this interdisciplinary integration is the concept of space, by which we mean not only physical location or volume but also the social protocols, conventions, and values attached to a particular space.[1,2]

Our previous research has revealed how, through its structuring of space, urban design plays a critical role in the construction of society and social behaviors.[3] Our space syntax research analyzes cities as systems of space created by the physical artifacts of architecture and urban design to understand how a city's spatial structure is related to its function. This research uses space syntax to investigate pedestrian and vehicular movement, land use, social and economic performance, crime, and many other functional aspects. We've also used space syntax as a design tool—for example, in the Broadgate development around London's Liverpool Street station.

In designing pervasive systems as an integrated facet of urban design, we're interested in designing not only the architectural space in which people move, behave, and interact but also the interaction spaces[2] for information and services they discover and use and that support their movements, behaviors, and interactions in combination with architectural space.

Bringing these systems into the public realm of the city raises questions of public—and private—access to the information and services and appropriate interfaces that support such forms of access.

Previous research focused largely on developing technical solutions for enforcing the privacy of data held within the system and securing interactions between devices. But this doesn't adequately address issues of trust in the security and privacy of interactions between people and information and services, although more recent work has begun to address these challenges.[4]

The foundation of our approach to the design of pervasive systems is a conceptual framework relating degrees of publicness to three aspects of pervasive systems: the interaction spaces that the artifacts create, the architectural spaces in which they are situated, and the information they access or exchange. The result is a 3 × 3 matrix, illustrated in Figure 1. We use the conceptual framework that this matrix provides to analyze and evaluate existing systems and to identify implications for the design of new pervasive systems.

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A SPECTRUM OF PUBLICNESS

Privacy and publicness issues have generated a range of theories and approaches. Leysia Palen and Paul Dourish note that "as a dynamic process, privacy is understood to be under continuous negotiation and management, with the boundary that distinguishes privacy and publicity refined according to circumstance."[5] Therefore, as we noted in previous work, "any essentialist public/private dichotomy is oversimplistic."[2] Similarly, Saul Greenberg, Michael Boyle, and Jason Laberge suggested that the terms "public" and "private" don't represent watertight categories but merely indicate extremes in a spectrum.[6] However, they also described the difficulties of designing systems that reflect the flexibility of real-life public/private distinctions. In integrating pervasive systems design and urban design, we aim for an approach that we can operationalize into concrete and practical design tools that take into account the built environment's features, constraints, and opportunities. Accordingly, our framework provides a deliberately simpler approach than more theoretical treatments of privacy.

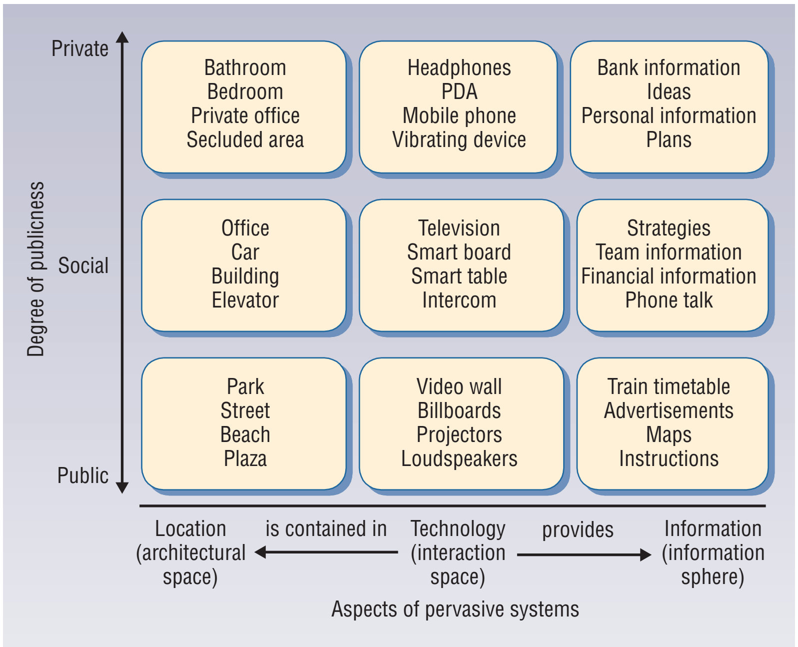

Figure 1. Publicness spectrum. The vertical axis represents the degree of publicness, while the horizontal axis describes three main features of pervasive systems and the relationship between them.

Michael Boyle and Saul Greenberg argued that "technocentric bottom-up approaches do not readily yield insight into how to diagnose privacy problems and predict when they will occur, or provide an intellectual foundation from which to generate new kinds of solutions."[7] Our framework provides just such an intellectual foundation, offering a top-down approach to urban pervasive systems design that yields such insights and, when used as a design tool, reveals many of the situations in which privacy problems might occur.

Rather than propose another theory of privacy, we draw on a fusion of two theories of information privacy that have been developed independently of pervasive systems research:

- *Control theory* maintains that you have privacy if and only if you have control over information about yourself.[8] Researchers argue that this theory's strength lies in the recognition that individuals with privacy can grant, as well as deny, others access to private information.
- *Restricted access theory* describes privacy in terms of limiting access to information about yourself in certain contexts.[9] Its strength is that it recognizes the need for zones that protect privacy.

Typically, researchers have used control theory to manage and justify privacy, while they've used restricted access theory to understand the concept of privacy. James Moor's control/restricted access theory provides an interesting mix of each theory's strengths.[10] However, his work remains highly philosophical. Here we draw directly on the two original theories.

One axis of our framework is a spectrum that describes degrees of publicness. One extreme of this spectrum, marked *private*, denotes that one person is in control or has access. It indicates that social, economic, physical, or other barrier types deny others access. It also denotes that the person in charge may choose to grant others access.

The opposite end of the spectrum, marked *public*, denotes open access. "Public" implies that no single person is in charge of or controls access. The term also denotes that there are minimal or no barriers that could deny access.

The spectrum's middle region, marked *social*, is best described as being neither private nor public. No single person is in charge or has absolute authority, yet access is less open than in the case of public. "Social," therefore, denotes that a group of people has access and that this group can manipulate numerous barriers—social, physical, economic, and so on—to prevent others from obtaining access.

The boundaries between public, social, and private control are neither precise nor fixed, but rather are fuzzy and mobile. Spaces, information, and services fluctuate along the publicness spectrum due to factors such as people's presence or absence, the built environment's changing characteristics (such as a public tennis court being locked at night), the technologies being used, and the information or services being accessed. Therefore,

we don't try to categorize instances of "pure" public, social, or private spaces or information. For example, a room in a house can, in different circumstances, represent a social space or a private space.

So how do we identify a particular situation or system feature with a particular region of the publicness spectrum, and how can we conceptualize what causes that situation or feature to shift along the spectrum?

Building on the control and restricted access theories, we use the concept of barriers to differentiate our spectrum's private, social, and public regions. Technological or spatial features in the environment can introduce barriers. Barriers constrain access and thereby shift the degree of publicness along the spectrum that forms the vertical axis in Figure 1.

Control theory maintains that individuals should be able to grant or deny access to information. With pervasive systems, technology-induced barriers—the obvious example being electronic access controls—can achieve this control.

The relationship between people, space, and barriers is crucial to identifying the degree of publicness.

Restricted access theory maintains the need for privacy zones. In pervasive systems, the built environment's spatial characteristics and the barriers they introduce generate these zones. For example, individuals inside a room with a closed door can participate in a seminar while the walls and door serve as barriers denying access to those who are outside.

Space-induced barriers can be physical, economic, social, or any other type that prohibits people from obtaining access. Economic barriers include having to buy a ticket to watch a film or needing a computer to surf the Web, while social barriers include norms and protocols restricting entry and access.

The relationship between people, space, and barriers is crucial to identifying the degree of publicness. A space containing only one person is private, regardless of the prevailing barriers. At a given time of day, an individual could find privacy in the town square. On the other hand, the presence of more than one person in a space, coupled with strong barriers, creates a social space, and the presence of many people coupled with weak or no barriers creates a public space.

Reducing the infinite degrees of publicness to three regions is of course simplistic, but we treat these three labels as fluidly bounded regions of the spectrum rather than as three distinct and fixed categories.

KEY ASPECTS OF PERVASIVE SYSTEMS

Orthogonal to the spectrum describing publicness, we plot three aspects of a pervasive system: architectural space, interaction space, and information sphere.

Architectural spaces are the spaces in which people and technologies exist and interact. Within an architectural space, multiple technologies can be present. These technologies create interaction spaces.[2] In turn, these interaction spaces provide access to information and services, making them available to people within the architectural spaces.

Architectural spaces

Architecture is fundamentally about the design and use of space. Applying our publicness spectrum to architectural space yields three classes of architectural spaces: private, social, and public. Once again, we emphasize that a specific architectural space can fluctuate along the publicness spectrum, depending on the presence of people and barriers. As people come and go and as barriers are manipulated, a space's degree of publicness changes.

In a private architectural space, only one person is present. Here, barriers ensure a degree of privacy. One individual typically controls such spaces at a given time. Architectural spaces such as bedrooms, bathrooms, and private offices promote a sense of security and privacy. A bedroom's walls act as barriers, creating a private architectural space by allowing someone to be alone in the room.

Social norms can also act as barriers, reinforcing the view that bedrooms are places of refuge and privacy. By letting other people into the bedroom, the owner can shift that space along the publicness spectrum, turning the room into a social space. In doing so, the owner has removed or redefined some of the barriers.

Social architectural spaces are neither private (because they contain more than one person) nor public (because they restrict access through physical, social, economic, or other barriers). The main distinction between social and public architectural spaces is the barriers' manipulability. In social architectural spaces, a specific person or persons control the barriers. These barriers can be manipulated to grant or deny access to others. For example, a nightclub owner can use barriers such as ticket sales or bouncers to control access to the nightclub.

Public architectural spaces have weak barriers that individuals within the space can't directly manipulate. A public architectural space includes people who use its open access. A town square is an exemplar public architectural space, carrying with it norms and expectations concerning people's activities and behaviors in that space. The identification of a particular space with a region of our publicness spectrum is not immutable. Imposing or changing barriers—for example, by the police refusing access to some or all—can shift a normally public town square along our publicness spectrum.

Interaction spaces

Whereas architects design physical space, human-computer interaction (HCI) researchers and practitioners design *interaction* space.

An interaction space is the volume within which a device or artifact effectively supports a human activity. Designers define interaction spaces within which people can individually or collaboratively perform activities that technological and other artifacts support and enable.

Artifacts that only one person can use create private interaction spaces. For example, headphones typically create a private auditory interaction space, even if the person wearing them is in a public space. A PDA screen lends itself to creating a private visual interaction space.

Groups of people interacting collaboratively with artifacts do so within a social interaction space. Tom Rodden and colleagues, for example, provide a novel arrangement of devices and applications that creates a social interaction space suited to the joint activity of a customer collaborating with a travel agent.[11]

An artifact that makes a resource freely accessible to people in a public space creates a public interaction space. For example, placing a large display in a public square, such as the big screens in New York's Times Square or London's Piccadilly Circus, creates a public interaction space. Typical artifacts used to create public interaction spaces include video walls, projectors, loudspeakers, and billboards.

Figure 2 shows different types of interaction spaces that different technologies create. In the figure, the plasma screen positioned between two people creates a social interaction space that includes both of them. The person on the right is wearing headphones, creating a private interaction space for him. The other person's PDA can create different types of interaction spaces, depending on its position and orientation. The PDA's owner can tilt the PDA toward himself, leaving the other person outside the private interaction space its small screen creates, or he can position it in such a way that it creates a social interaction space, perhaps to support collaboration.

The types of technology used (both hardware and software), their physical characteristics and affordances, and their design provide the barriers that define an interaction space's publicness. Like the architectural spaces that the physical environment defines, interaction spaces can fluctuate between private, social, and public as users manipulate these barriers. In turning the PDA to let a colleague access the information on its display, a PDA's owner is manipulating the barriers defined by the PDA's characteristics that create a private interaction space in its more usual orientation.

Interaction spaces are created within and combine with architectural spaces. Interaction spaces are also subject to the barriers present in the architectural spaces. For instance, in Figure 2, the interaction space that the plasma screen creates is bound by the physical barriers of the room in which it's placed. Additionally, interaction spaces introduce their own barriers, which are typically characteristics of the technology rather than of the architectural space. For example, users can control the volume on audio speakers, thereby manipulating the extent of the auditory interaction space that the sound from the speakers creates.

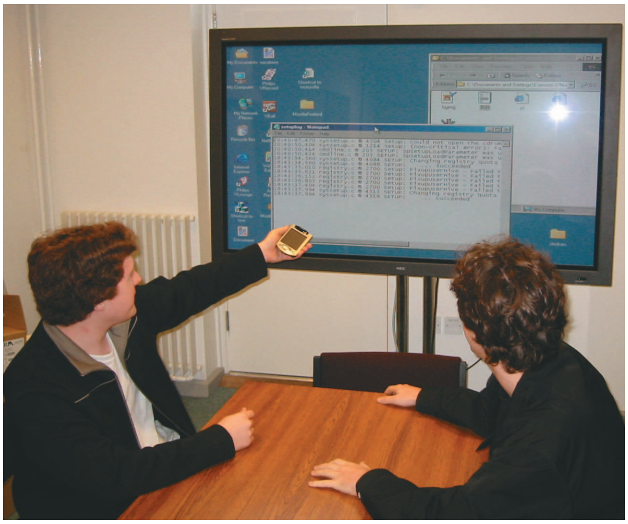

Figure 2. Interaction spaces. The plasma screen offers a social interaction space; headphones offer a private interaction space; and the PDA can offer either, depending on its orientation with respect to the users.

Information spheres

Combined with the publicness spectrum, the *information spheres* concept categorizes the specific information and associated activities or services a pervasive system offers. Typical information in the private sphere includes a bank balance or a personal diary (as opposed to a blog). The private sphere entails barriers that an individual can manipulate. This person can lift the barriers for parts of the information sphere, thus releasing information to others and shifting that information along the publicness spectrum.

Each person has access to multiple social spheres that might be both persistent or temporary. For example, sending a message to a friend or sharing a document with colleagues falls in the social sphere. Social sphere information isn't private because more than one person is involved in creating and exchanging the information. But neither is this information public, because barriers to it exist. In general, information accessible to a group of people combined with the presence of manipulable barriers belongs to a social sphere.

While individuals have their own private spheres, and different groups have different social spheres, only one public sphere exists. Some researchers view the public sphere as a conceptual area in which members of the public can discuss issues of general concern and form opinions. Others have defined it as the space in which citizens deliberate about their common affairs and where they generate, circulate, contest, and reconstruct social meanings.[12] Public sphere information includes

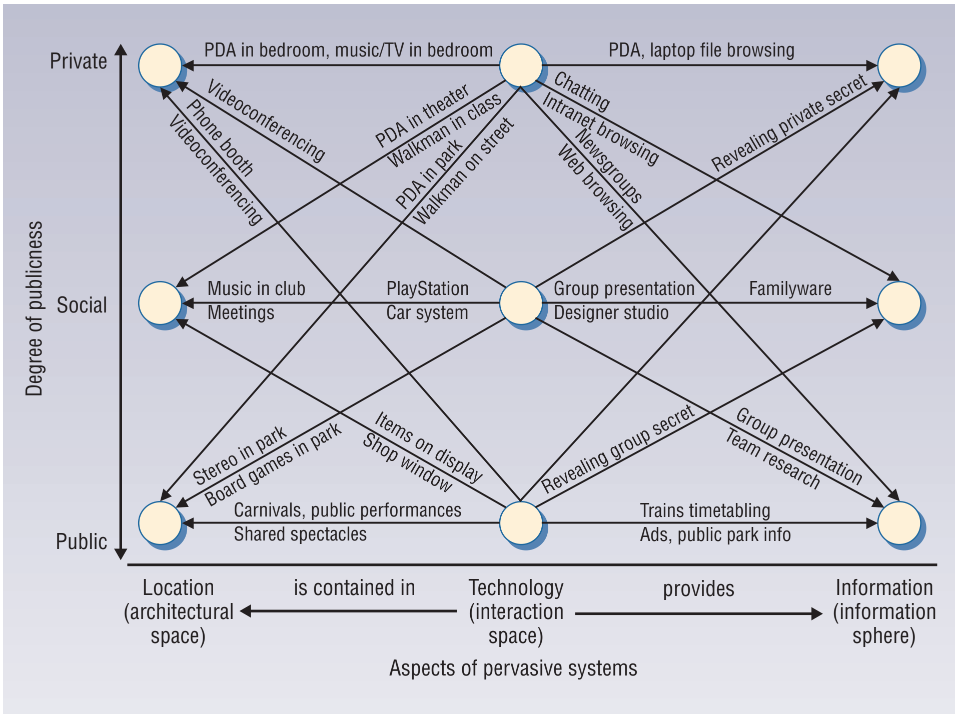

Figure 3. Matrix for mapping existing systems and situations. Nodes represent interaction or architectural spaces or information spheres. The connecting lines represent situations or systems that combine these spaces and spheres.

public transport timetables, voting schemes, and even laws and court judgments.

ANALYZING SYSTEMS AND SETTINGS

We can use our framework as an analytical tool to examine relationships between the pervasive technologies we're interested in designing, the urban spaces in which they are situated, and the information and services they deliver.

In Figure 3, the connecting lines represent situations or systems that combine an interaction space created by a pervasive technology with either an architectural space or an information sphere. In each case, the combination can be within a region of the publicness spectrum or can span more than one of these regions.

Interaction space/architectural space links

Consider a PDA as an example of a technology defining a private interaction space (top-center node of Figure 3). People can use a PDA to create a private interaction space within a public, social, or private architectural space, as the connections labeled "PDA in park," "PDA in theater," and "PDA in bedroom" exemplify.

In contrast, consider a videoconferencing system. This technology can connect an individual in a private architectural space, such as a private office, to a small group of colleagues in another office or to the public via an audiovisual link in a city street. The first instance links a social interaction space to a private architectural space—represented by the connection between the dead-center and top-left nodes in Figure 3.

The second instance uses the same technology to link a public interaction space to a private architectural space—connection between the bottom-center and top-left nodes in Figure 3. Meetings in rooms with artifacts such as a slideshow creating interaction spaces exemplify social architectural spaces hosting social interaction spaces (connection between the center-left and dead-center nodes in Figure 3). In these situations, the social architectural space is flooded with the social interaction space that the technology used to support or enable the group activity creates.

Public spectacles such as carnivals involve public architectural spaces hosting public interaction spaces—(connection between the bottom-left and bottom-center nodes in Figure 3), whereas artifacts such as a stereo system or a board game create a social interaction space within a public architectural space—connection between the dead-center and bottom-left nodes in Figure 3.

Interaction space/information sphere links

The examples on the right-hand side of Figure 3 illustrate the links between interaction spaces and information spheres. Consider again the PDA example. With a PDA, a user can access private, social, and public sphere information through a private interaction space.

The connections originating from social interaction spaces are instances in which a group of people in the same physical space share information. The information they share might belong to the public sphere (exemplified by team research), in which case the group is accessing publicly available information. Similarly, if it is accessing a social sphere (connection between the dead-center and right-center nodes in Figure 3), the group is sharing and accessing information restricted from public access by some forms of barriers. Examples include group presentations, classroom teaching, and familyware (home-based systems, such as sticky notes on the refrigerator).

Finally, accessing a private sphere from a social interaction space (connection between the dead-center and top-right nodes in Figure 3) reveals private information. This might be intentional, such as when a team member shares some sketches created over the weekend. In other cases, however, this sharing might be unintentional and could signify a privacy breach.

Finally, public interaction spaces (bottom-center node in Figure 3) often provide information in the public sphere—for example, train timetables, park information, and advertisements (connection between the bottom-center and bottom-right nodes in Figure 3).

When public interaction spaces provide social information (connection between the bottom-center and center-right nodes of Figure 3), they reveal group information beyond the group. Similarly, when public interaction spaces provide private information (connection between the bottom-center and top-right nodes in Figure 3), they reveal private information.

In each of these instances, the revelation of information might be unintentional, indicating a privacy breach. These examples illustrate our framework's power as an analytical tool that fulfills Boyle and Greenberg's[7] desire for a top-down approach that helps to diagnose privacy problems and predict when they will occur.

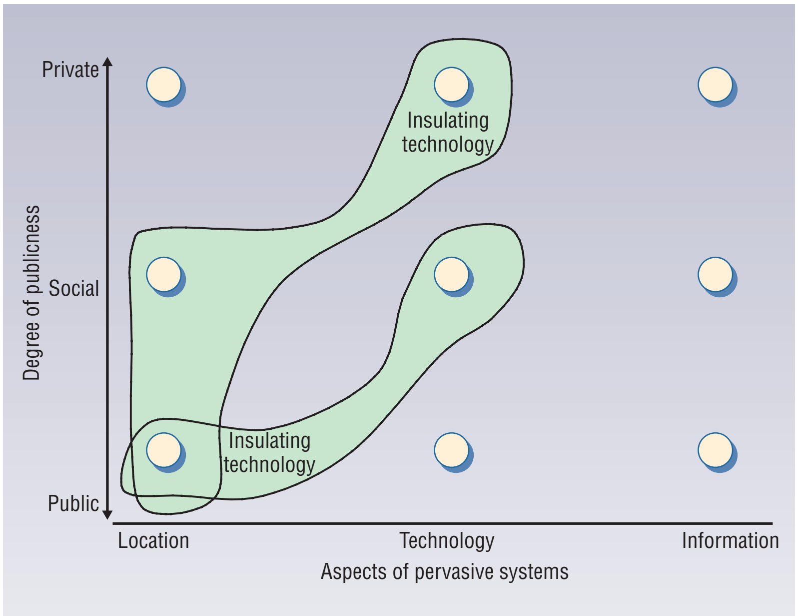

Figure 4. Insulating technology isolates individuals from their environment.

PERVASIVE SYSTEM PATTERNS

The analysis illustrated in Figure 3 helps to identify recurring patterns in the design and use of pervasive systems. These patterns can support practitioners in designing new pervasive systems. The patterns are abstractions of commonly occurring pervasive system design instances. We've identified these patterns both from our analytical use of the framework and from our empirical studies of information use and system requirements in a range of settings. Here, we provide an overview of two patterns, highlighting issues that designers must be aware of in relation to each pattern.

Insulating technology

The *insulating-technology* pattern describes technologies that isolate individuals from their physical environment. Private interaction spaces in social and public architectural spaces and social interaction spaces in public architectural spaces instantiate this pattern.

In Figure 4, the shaded parts of our framework, when connected, instantiate this pattern. The use of headphones, which create private interaction spaces within public spaces, is an example of this pattern. The privacy that headphones create can be desirable or undesirable, depending on the activity and context.

This pattern illustrates how introducing technology-induced barriers can achieve required effects. Specifically, because social and public architectural spaces don't provide barriers to isolate individuals from their environment, using technological barriers, such as headphones, can create private interaction spaces.

Designers must be sure that their systems use privacy and isolation mechanisms when required. This requirement provides a validation check on pervasive systems designs.

An analysis of a system design should identify patterns of insulating technologies when they're appropriate. The absence of such patterns should indicate to the designers that their system doesn't support individual or group privacy.

The unwanted presence of this pattern could also indicate a problem. In this case, the designer should be aware that the technology is isolating individuals, which could lead to undesired effects.

Of course, the people using a system are likely to identify and use a pattern when it's appropriate for their purposes. The extent to which they can instantiate the insulating technology pattern can affect their perceptions of system characteristics from usability to security.

Secrets revealed

The *secrets-revealed* pattern describes situations in which private or social information is made public. This happens when people use social or public interaction spaces to access a private sphere or use public interaction spaces to access a social sphere. When connected, the shaded parts of the matrix in Figure 5, on the next page, instantiate this pattern.

Using a public interaction space to access private-sphere or social-sphere information is likely to be inappropriate and insecure. Instances of this might include

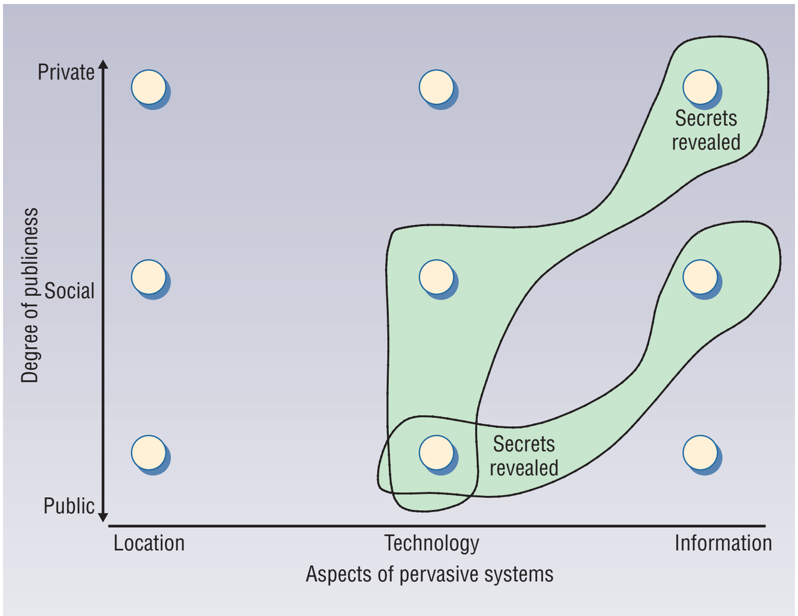

Figure 5. The secrets-revealed pattern describes situations in which people publicize private information.

showing the contents of a person's wallet on a video wall display or posting the details of a personal bank account on a public Web site.

Using social interaction spaces to access the private sphere raises similar issues. An instance of this might be accessing your e-mail (private information) on a computer in a crowded café, where other customers can see the display (social interaction space). A more insidious instance is the use of spyware to create a social interaction space for a group of people to access an individual's personal information, often without the individual's consent or even knowledge.

Designers must be aware that this pattern describes situations that can undermine information privacy or security. However, such a situation might be desirable, as in instances when an individual wants to reveal information to others.

In either case, designers who are aware of this possibility can choose the most appropriate design, based on the situation and activities that the system supports.

USING THE FRAMEWORK IN DESIGN

A hospital accident and emergency (A&E) department example that we analyzed for potential pervasive systems support illustrates how we can use our framework as a design tool.[13] The situation involved an instance of the secrets-revealed pattern, and a proposed design solution involves the insulating technology pattern.

The A&E department has a large waiting area, a public space that people can freely enter—typically when they have been injured. Connected to the waiting area is a reception area, a social space restricted from the public that only staff can access. A wall with a large hatch and a counter separate the waiting and reception areas.

The reception desk staff had placed a list of medical staff telephone numbers on the wall next to the counter for use in locating their colleagues. The information in the list belonged to the social sphere because the phone numbers were meant to be used only by staff and didn't belong in the public domain. However, the technology used to provide access to the information (in this case, sheets of paper) was visible to anyone on the public waiting area side of the desk, thus creating a public interaction space for this social sphere information. This created a privacy breach because telephone numbers that weren't meant to be in the public sphere were made public.

An unintended and unwanted use of this design involved members of the public causing problems by calling staff members. There were also unintended beneficial uses, such as staff in the waiting area having easy access to the phone numbers.

In producing an alternative design, we exploited our contention that the characteristics of interaction spaces are defined in part by the characteristics of the architectural spaces to which they're bound, and proposed changing the existing setting by relocating the phone lists in the reception area so that they are not visible from the waiting area. This would create a social interaction space within the reception area's social architectural space that meets the design's intended purpose by providing this social sphere information only to the staff.

Alternatively, instead of relocating the lists, we could use completely different technology. For example, we could give each staff member a personal electronic device to use for accessing the telephone numbers. This device would be portable for use anywhere in the hospital. Furthermore, we would require these devices to create a private interaction space, providing insulating technology so only the device's owner could access the information.

In this case, we would have to test that the personal electronic devices satisfied this privacy requirement. For instance, when a staff member uses the device in a public space (such as in the waiting room), the information that the device displays, as well as the interaction techniques used, must insulate the user from the environment, denying anyone else access to the information.

As a design tool, our framework doesn't deliver to pervasive systems designers the "right" design solution for every situation, if such a panacea were possible. But it does help to identify problems with existing and proposed designs so that designers can propose and explore alternative solutions. This illustrates the power of our framework as a design tool to fulfill Boyle and Greenberg's[7] desire for a top-down approach that provides an intellectual foundation from which to generate new kinds of solutions.

Appropriately matching the interaction space that a fixed device defines to its corresponding architectural space and the services it delivers is challenging. The services desired or available in that architectural space can change over time and vary for different people. In addition, the physical characteristics and social protocols associated with the space also typically change over time and at different rates.

The design challenges are even greater for a pervasive system's mobile elements. Mobile devices typically define a limited interaction space but can be carried and used to deliver diverse services within a hugely diverse range of architectural spaces, with correspondingly diverse physical and social characteristics. Testing our framework's analytical and design power across this diversity is a continuing empirical challenge.

Our space syntax research into the relationships between urban design, space, and people's behavior suggests other avenues for further development of our conceptual framework and its applications. For example, there can be privacy in anonymity, reflected in the loneliness that individuals might experience in a crowded urban environment; conversely, a nosy neighbor in a small village might manage to gather surprising amounts of private information about others. Paradoxically, one way of achieving control might be to open up access.

Another important issue is the notion of spatial configuration. In space syntax, our measures of control relate to the degree to which a space controls the access or egress of its neighbors. We find empirically that in considering networks of space, such as a city, the local and the global contexts have strong correlations. These configuration issues are likely to map on to both social networks and technologies.

The concepts that we've discussed here form part of a larger research program. Our framework addresses the issues of architectural space, interaction space, information sphere, and the relationships among them. This work, along with related analyses of urban spatial structure, forms a basis for theoretical advances, a design methodology, and tools for pervasive systems design in urban environments. ■

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