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Physical Interaction and Multi-Aspect Representation for Information Intensive Environments

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Abstract

Embedded technology and networking allow for the integration of physical objects with information infrastructure and augmentation of the physical environment with information and computing functions. The concept of intelligent artifacts associated with robots will be restructured to many different forms of intelligent and interactive artifacts and environments that range from simple objects with a tagging chip to complex physical systems with local intelligence and actuators connected to a large-scale information infrastructure. This opens a new problem space of interactive systems design: how to control remotely connected objects, how to interact with intelligent environments, and how to combine physical and media entities. This paper explores the issues of interactivity in physical space and media space, models of physical interaction, system architecture and the design methodology from the viewpoint of human-centered system design.

1 Introduction

Some products such as office equipment and home appliances are built with microprocessors for complex monitoring, control and user interface functions. Some of them have communication functions that allow connections with other systems through networks and telephone lines, yet they operate independently within their own functional boundaries without interacting with other items in the environment. When many physical objects obtain computational and networking functions and are integrated into a coherent mechanism of an information infrastructure, the physical world will become intensively interconnected and expands its possibility in developing new functionality and quality of human experience [1].

The development of information technologies enabled to create a conceptual space composed of abstract and virtual information entities. On the other hand, because of the symbolic nature of the media entities detached from the physical world, it is difficult to access, understand and use them as live knowledge in action. In this paper, the term "media space" is used to represent the space composed of information entities since these entities and relations between them are represented in some form of information media. The space composed of physical entities that can be experienced through our perception and physical interaction is called "physical space". With embedded technology and networking technology, the two spaces once separated can be bridged to create an environment that can sustain coherent relations between physical objects, media entities, human experience and knowledge in our activities. A product of this kind is positioned across the physical space and the media space, and holds characteristics both as a physical entity and a media entity at the same time. Although the intention of bridging physical space and media space is to eliminate unnecessary cognitive load on users to access information functions in our activities, the dual nature of the product could claim more complex cognitive work of users to understand many different aspects and unfamiliar properties unless it offers an appropriate interface.

We see an object from different viewpoints in different situations. Different people also have different viewpoints depending on the nature of concerns developed as they engage in the

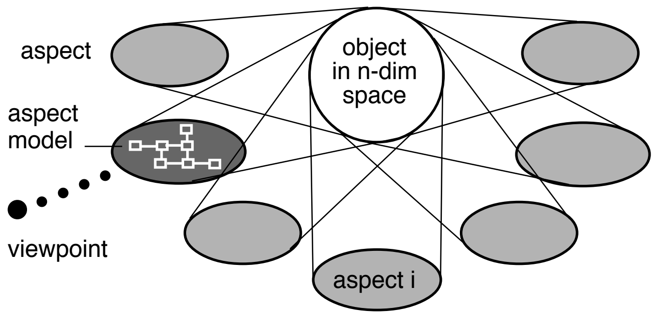


Figure 1 Multi-aspect model of an object in n-dimensional space

object. Through our experience with the object we develop multiple mental models to describe it as schematically shown in Figure 1. In the development of a system, we also need to use multiple models to describe different aspects of the system such as information flow, mechanical structure, electronic schematics that are necessary to design and implement the system [2]. Aspect models used in system development need to have explicit representation methods for clear communication and disciplinary functions such as design and analysis. Some aspect models are introduced to understand and describe users' views and interactive behavior and reflecting users' needs in design. Because of the complexity and the unprecedented nature of human interaction created by the integration of the media space and the physical space, it became critical to incorporate users' viewpoints in the design process to produce consistent qualities that accommodate users' needs from cognitive, social, cultural contexts as well as functional needs.

Introduction of media space increases the potential for extending the modality of interaction with the multi-media technologies and abundant computing resources. Contrary to the potential advantages, graphical modes of interaction become dominant because of economic reasons, convenience of implementation, and reluctance of exploring possibilities of non-visual modes of interaction at the cost of the quality of interactive experiences of users. In bridging physical space and media space, mapping between controlled variables and interface mechanisms becomes critical design issues because of the complexity and the possible indirect relations between the user and the objects to be controlled. Users' mental models of a complex system could take many different forms depending on how they are situated and what kinds of experience they had with the objects. Some examples are causal models, function models, procedural models, object relation models, and state models. In this paper, first, the nature of interactive systems with physical and media spaces will be examined, then the framework of system architecture and representation of the system will be discussed to incorporate social and cultural factors as well as its technological potential.

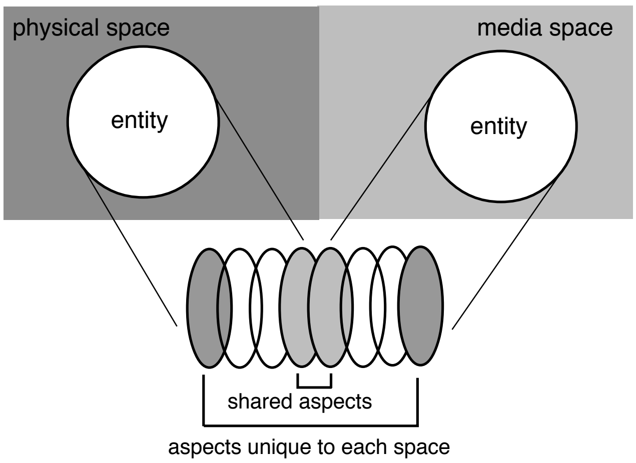


Figure 2 Common aspects shared by physical and media entities

2 Physical Space and Media Space

The human interface represents various aspects of the system to frame user experience. It provides system images that induce formation of user's mental models of the system. Different mental models represent different characteristics or aspects of the system that reflect users' concern and intention. Some models represent physical nature of systems and therefore are intrinsic to physical systems. Some aspects effectively represent natures of media entities and therefore are intrinsic to entities in the media space. Some are commonly shared by both physical and media entities as indicated by shaded ellipses in the middle in Figure 2. Some models have corresponding models in the other space, and some only maintains local relations within the same space. In an effort of understanding and interacting with the system, the user switches his viewpoints to effectively capture the information necessary for performing the currently engaged activity [3]. Users' attention is sometimes directed to physical aspects and sometimes to media aspects. The user also attempts to identify corresponding relations between aspects from each space to develop coherent relations among mental models of physical and media aspects of the system. Although the user usually knows which aspects belongs to which space, intensive engagements with particular aspects sometimes blur the boundary between physical and media spaces. This effect might cause illusion and erroneous recognition of the reality that could lead to serious consequences such as accidents. On the other hand, attempts to match different aspects and switching between different viewpoints could be used to create interesting perceptual and intellectual experiences of the user. In the development of systems composed of both physical and media entities, the multi-aspect model representation provides a conceptual framework for human-centered design methodologies to incorporate users' views in the system design.

In this paper, nature of interactive systems with physical and media entities will be examined, then frameworks of system architecture and representation methods to enhance qualities of user interaction will be discussed.

3 Information Intensive Environment

Desktops are often disorganized, and walls are covered with notes, copies and tack papers. But a mess for outsiders is not necessarily true for the primary users. Users put meanings on objects in the space and spatial relations also develop meanings such as sequences and conditions of activities that the objects are related to. Some items are moved, discarded, or replaced, and new items are constantly brought in and the environment is constantly modified to satisfy users' needs that change as the nature of their activities change. Objects and their spatial organization form contexts for user activities.

The format and carrier of information are changed as the information develops. For example, ideas exchanged in conversation are transformed to scribbles, lists and diagrams on note pads, then copied and distributed to colleagues or posted on tack boards, and extended further to a short memorandum typed in a computer. Some information items are stored redundantly in different forms at different locations for easy access and readiness for different purposes.
Conventional solutions of knowledge management or information systems only provide accesses through an electronic display whether it is stationary or portable. Usually Graphical User Interface is the only interaction mode available for such systems. The field of knowledge intensive work is not limited to a screen. Activities for such work are diverse in styles, dynamic, spatially distributed and highly context dependent. Physical objects and relations between them therefor perform significant roles of composing contexts of an information intensive workspace.

Lively and effective interaction for knowledge-intensive work environment requires the following qualities:
1) Redundancy of information: Easy access to information sources and functions is critical for enhancing productivity in knowledge-intensive work. Redundancy of information and function allocation over space, time, and presentation modes needs to be strategically planned to accommodate variations of contexts, situations and intentions of activities.
2) Robustness of interaction sensitivity: If high degree of precision in the pattern of interactive actions is always required, it becomes distracting in the context of user activities. Patterns of human actions are not very precise unless they are necessary and enhanced by some means. The system therefor should be robust enough to accept the variation of interactive actions by users and environmental conditions.
3) Flexibility of knowledge representation modes: Different modes of activities require different modes of knowledge representation.
4) Appropriate use of active physical interface: Active interface that makes physical actions can be applied to extend the modality of interaction with objects and environment.

In order to achieve these qualities of interactive environment for knowledge-intensive work, possible models of interactive system configurations are examined, and potential development of system architecture is discussed in the following sections.

4 Models of Interactive Systems

Physical interface links human intentions and actions with objects, environments and media space. Combinations of physical interface and objects with media space produce a variety of interactive systems and interaction methods. In order to understand the frame of possible configurations of interactive systems with physical interface, the following categorization of interaction models is discussed and each model is explained with some examples.

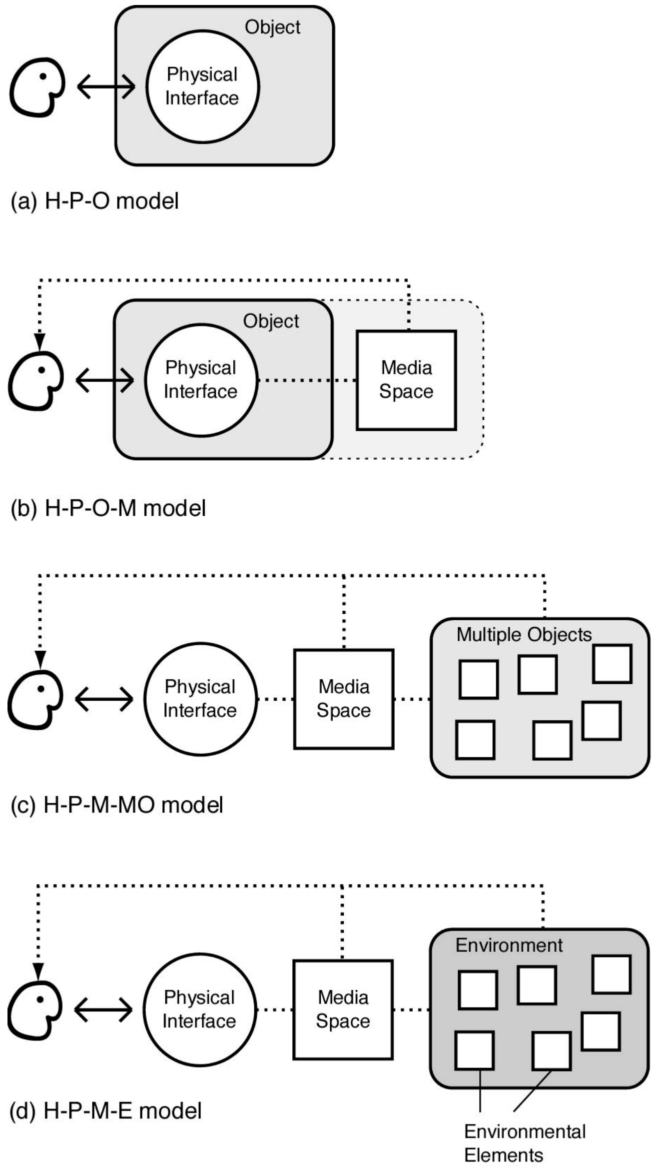
H-P-O Model
This is the most basic model representing the relation between a user (H) and a physical object (O) such as a tool, stationary, home appliance and machine. In this type of objects, physical interface (P) is usually incorporated in the object itself as shown in diagram (a) in Figure 3. We have developed and accumulated our knowledge and skill for this kind of interaction through the historical development of artifacts and personal experiences. The mapping between control actions and resulting effects is usually easy to understand and predictable. But even in a very simple case of push button control interface often used as a default solution, combinations of small number of button operations and resulting state changes produce a large number of mapping patterns. Phenomenological approaches in physical interaction addresses this type of issues fundamental to the design of physical objects [4]. Understanding the nature of this mapping problem will become even more important when media space is incorporated

in interactive systems as described in the next model.

H-P-O-M Model
Physical objects can be interconnected with each other by either direct or indirect means. Objects may have independent computing functions embedded within their boundaries or connected to external computing functions provided as part of the infrastructure. In either case, media space (M) is formed behind or within the object in order to augment the object or establish access to information or computing functions through the object as depicted in Figure 3 (b). The prototype vacuum cleaner shown in Figure 4 operates autonomously or its spatial pattern of movements can be programmed by entering music with keypads on the top [5]. This model shows the basic structure of an independent object with some computing functions forming media space. It can be also considered as one of basic components in pervasive or ubiquitous computing environments. For example, any physical objects such as paper documents can be tagged with a RF chip [6] or a bar code to be identified and incorporated in the information infrastructure for tracking, accessing and processing. Another example is the connection of home appliances to the Internet for monitoring, control and information access functions.

H-P-M-MO Model
When we have many objects (MO) to control at the same time, some kind of media support is necessary to transmit control message to multiple units. If many objects have shared objectives to achieve, it is more effective to deal them as an integrated body rather than dealing individual units. In contrast to the previous H-P-O-M model, media space appears in front of users to represent the status of the group and interpret user control to the individual constituents of the group machine as shown in Figure 3 (c). Mapping between physical interface, collective variables representing the group of objects, and their representation in the media space becomes an interesting design problem. One example of this type of interaction is with a cluster of many miniature machines to replace one powerful larger size.

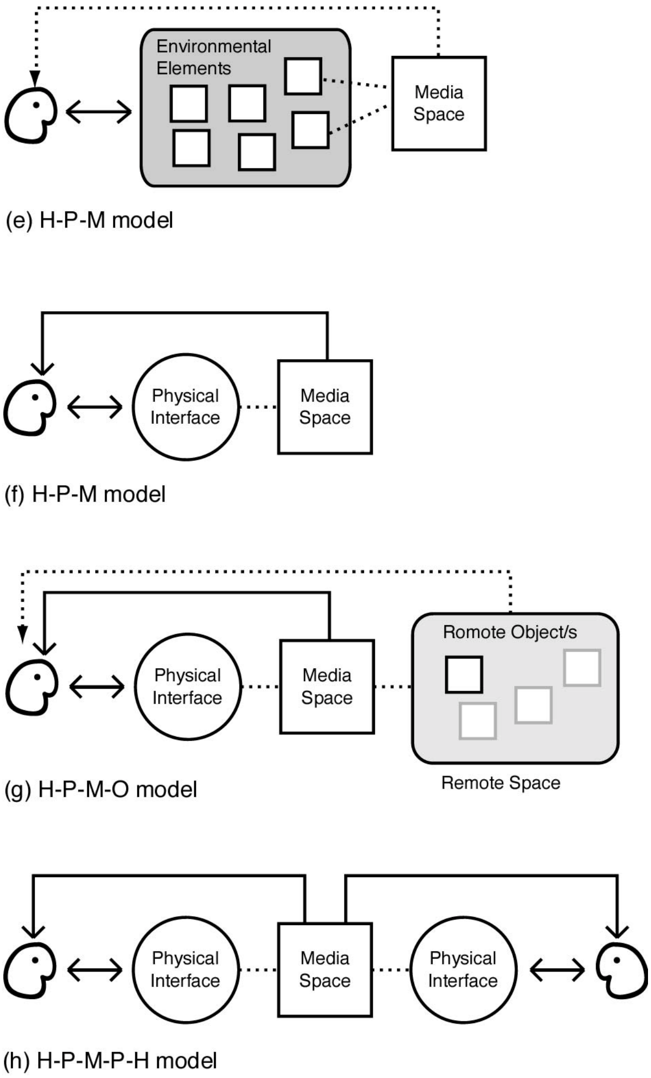
H-P-M-E Model
As discussed in the earlier sections, embedded technologies and networking enable our environment (E) become interactive and augmented. As figure 3 (d) indicates, it has a similar structure to the H-P-M-MO model in (c). Examples of elements in the environment are architectural elements, and ambient elements such as light, sound, and air. Media space provides fields for interconnection of these environmental



Fugure 3 Moddels of physically interactive systems

Figure 4 MusiCleaner: a mobile mini vacuume cleaner controled bu music input

Figure 5 An exibit system with physical interface divices



Fugure 6 Moddels of physically interactive systems

elements and enables augmentation for effective support for human activities in the space as well as sophisticated controls of environmental elements [7].

H-E-M Model

When networking and computing functions are completely embedded within ordinary non-electronic artifacts in the environment, user interaction with the environment takes place directly with those artifacts without specialized interface as shown Figure 6 (e). With H-P-O-M and H-P-M-E models, this model is another case of pervasive or ubiquitous computing. This is the most basic and effective model to form physical environment for knowledge-intensive work [8].

\H-P-M Model

There are many forms and modes of accessing, entering and manipulating information provided by information systems or computing systems depending on the nature and purposes of activities and their environments. Figure 6 (f) shows a structure of this mode. The question “how can the physical and information or media worlds be mapped to each other for natural and effective interaction?” opens the new design space, and is the primary concern addressed in the area of physical computing and physical interaction design. In this model, physical objects are used to access and manipulate information entities in much more direct ways than conventional keyboard-mouse and graphical user interface. Figure 5 shows this model of interaction for exhibition and learning that allows direct manipulation of information entities in the media space mapped to the physical interface objects on the back lit table [9].

H-P-M-RO Model

In order to interact remotely located objects (RO), media space can function as an intermediate or virtual field of user-object interaction as shown in Figure 6 (g). Some form of representation of objects, part of objects, variables to be controlled or a combination of them are represented in the space. User representation could be also designated in the space to depict the nature of interaction, relations to other elements and its situation for better user understanding and control. Computer-supported control of remote objects such as surgical manipulators and robotic devices are typical examples of this model. A museum robot developed at Tsukuba University can be controlled of its browsing movements in the real museum space by Internet users [10]. In such case, interactions between the robot and people in the same space raise social and cultural issues to explore.

H-P-M-P-H Model
This is a model of computer-mediated human to human communication. The media space set between remotely located users attempt to provide fields and facilities for better interaction. The same model could be applied to the situation where users are in the same site but interacting through communication devices to add some functionality supported by media technology. Multiple player electronic games are examples of this model. Particularly in communication and collaboration applications, the main reason of introducing physical objects as interface devices is to provide shared physical experience for the enhancement of communication quality to remotely located users. Figure 7 shows a conceptual structure of an internet-based collaborative learning system for children as an alternative to the conventional keyboard and mouse style interface inadequate for implementing non-verbal communication. The system uses puppet-driven interface to implement the concept of shared reality and re-configurable interface that enhances the quality of interaction. In this example, the media space functions as fields and facilities for interactive collaboration between users. Graphic models of puppets in the media space represent users and are controlled by physical interface puppets at remote sites. Figure 8 shows a user station with a puppet interface device and a display stage setting. [11]

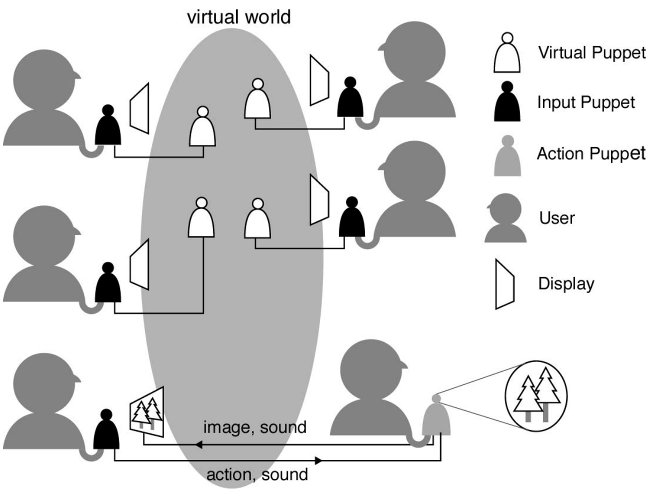


Figure 7 Shared reality concept for remote communication

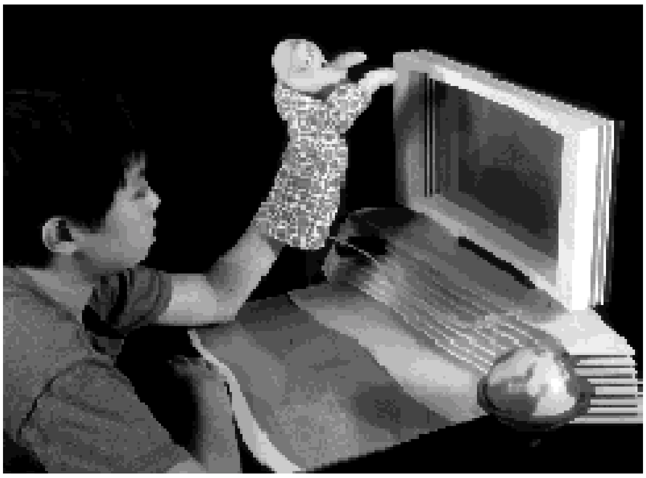


Figure 8 Puppet-driven communication interface for remote collaboration

The models of interactive systems introduced above are composed of many different types of components including ordinary physical objects, sensors, electronic hardware, firmware, software and mechanical devices. The complexity of such amalgamated systems requires clear frameworks of system architecture and methods for representing the interactive nature of user interaction and its contexts in the system development.

5 System architecture and representation

The boundary of a physical artifact is well defined by its physical separation from the environment. When it is connected to media space and other objects, some functions of media entities and other objects become accessible through the artifact. In some cases, it is difficult for the user to identify the carrier of the functions and the source of information within the overall system, and boundaries between individual entities becomes ambiguous. In the networked system, one function could reside anywhere in the system, be composed of remotely distributed functions, or simply reside in the entity that the user is facing.

The integration of individual artifacts into a larger system through media space also allows the flexibility of function allocation over the system in the development process because of seamless connectivity between parts of the system. A function originally allocated to the artifact could be re-allocated to other part of the system, duplicated or even decomposed to component functions and distributed over multiple components of the system. The implication of this nature of flexible function allocation is significant in system development.

Figure 9 schematically shows different distribution patterns of functional units over the system to compose higher level functions exemplified by 1, 2 and 3. Physical entity b can be seen as a self-contained system to perform three functions, but through the connection to media space the boundary of the entity extends to B including media entities c and d to enhance function 2 and 3. Another extension is to incorporate physical entity a to better perform function 1. System boundary D is formed to access function 3 provided by media entity f. The last boundary indicated by E is the most comprehensive one that covers all entities both in physical and media spaces.

As the system switches the function from one to another, the system boundary dynamically changes according to the predetermined pattern of function allocation over the entire networked system. In more advanced form of system architecture, allocation of functions can be dynamically determined by searching appropriate subfunctions to compose a requested function by the user. Software modules could be also transported through network from one part of the system to another for optimizing functional configuration or upgrading currently deployed modules. Internet agents are examples of autonomously moving function modules implemented in media space with some form of intelligence, mobility and autonomous behavior, which duplicate basic qualities of robots in physical space.

The concept of robots is generally associated with a physical system that has its intelligence, mobility and autonomous behavior. When an object acquires computing functions, networking, and physical actions, it starts conforming to the concept of robot. Some only show intelligence, some show autonomous features, some show minimal degree of actions, and some can show all features that the concept of robot requires. Then the distinction between this concept and physically active and intelligent objects, or interfaces, becomes ambiguous. Development of new concepts in system architecture to respond to user needs, in turn, leads to re-definitions of artifacts and new interactive mechanisms.

As the system gains more flexibility and adaptability, it becomes more difficult for the user to develop consistent mental models that accommodate multiplicity of system configuration and dynamically changing system boundaries. The system image presented to the user, therefor need to not only reflect these qualities and structures but also provide interpretive mechanisms to support user interaction. Effective methods for interactions with a wide range of emerging patterns of system architecture need to be explored and experimented.

6 Conclusion

Figure 10 shows an artifact that spans across the physical space and the media space. A user of such artifacts needs to develop meta-level knowledge necessary for structuring, managing, and integrating knowledge of physical aspects and knowledge of media aspects of the artifact in order to understand it and interact with it. When a community shares a set of meta-knowledge related to daily concerns of users such as values, attitudes, and use methods of an artifact, the shared knowledge forms a foundation of a culture that attributes to the artifact. Design of artifacts therefor not only should propose functions and user experience with artifacts, but also needs to position them in relation to the existing system of users' knowl-

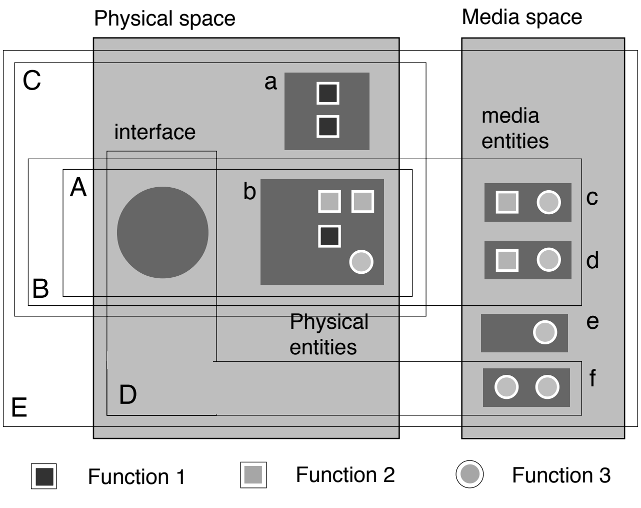


Figure 9 Multiple system booundaries formed by distributed function allocation

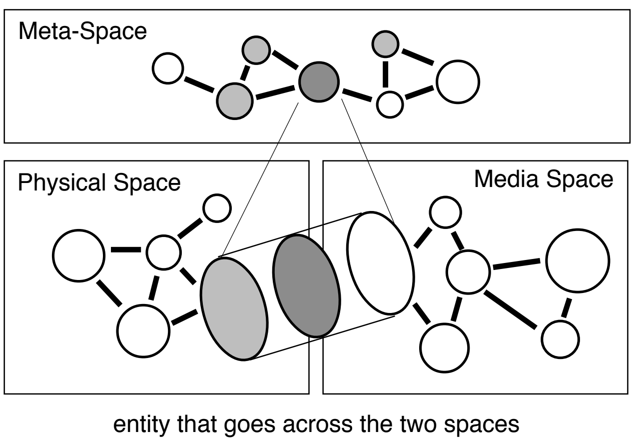


Figure 10 A dual space entity and a meta-model

edge or culture formed in the meta-space.

In order to respond to the issues addressed above and in the previous sections, new concepts of system architecture need to be defined in the space that incorporate social, cultural factors as well as technological factors. Educational issues need to be also addressed to better prepare engineers and designers in various disciplines to understand this new realm of design problems.

6 Acknowledgement

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