An Integrating Framework for Mixed Systems

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Abstract Technological advances in hardware manufacturing led to an extended range of possibilities for designing physical-digital objects involved in a mixed system. Mixed systems can take various forms and include augmented reality, augmented virtuality, and tangible systems. In this very dynamic context, it is difficult to compare existing mixed systems and to systematically explore the design space. Addressing this design problem, this chapter presents a unified point of view on mixed systems by focusing on mixed objects involved in interaction, i.e. hybrid physical-digital objects straddling physical and digital worlds. Our integrating framework is made of two complementary facets of a mixed object: we define intrinsic characteristics of an object as well as extrinsic characteristics of an object by considering its role in the interaction. Such characteristics of an object are useful for comparing existing mixed systems at a fine-grain level. The taxonomic power of these characteristics is discussed in the context of existing mixed systems from the literature. Their generative power is illustrated by considering a system, Roam, which we designed and developed.

Keywords Mixed Systems, Mixed Object, Interaction Model, Characterization Space, Taxonomy.

1 Introduction

The growing interest for mixed interactive systems is due to the dual need of users to both benefit from computers and stay in contact with the physical world. Mixed systems can take various forms and include augmented reality, augmented virtuality, and tangible systems. Although mixed systems are becoming more prevalent, we still do not have a clear understanding of this interaction paradigm. In particular, we lack capitalization of our experience, comprehension of problems when explaining the choice of a design to other designers. In addition, we are not able to explore the design space in a systematic way, and as a result quite often find a better solution after the development is finished. Even though several conceptual results exist for understanding and designing such systems, they do not address the entire design and remain local, and are not related to each other. As a consequence, it is difficult to compare existing mixed reality systems and explore new designs.

Rather than present yet another taxonomy that would not improve the clarity of this domain, we capitalize on existing research in our framework:

- We encapsulate related works in order to provide a coherent, integrating and unifying framework.
- We identify overlaps between existing studies, so that we can contribute to a better comprehension of the domain.
- We refine existing taxonomies as well as identify new characteristics and uncover areas to be explored in the design space.

The basis of our integrating framework is that we take the viewpoint of the objects involved in interaction with mixed systems, namely mixed objects, i.e. hybrid physical-digital objects straddling physical and digital worlds. Our framework is therefore made of characteristics of mixed objects. The characteristics are useful for analysis and comparison of existing systems as well as for design: indeed the characteristics allow generation of ideas and choice of design alternatives. Since these characteristics are also used for design, we organized them according to two points of view of a mixed object that make sense for design: intrinsic and extrinsic characteristics. These two sets of characteristics enable designers to study the reusability of their design for different application contexts. Indeed intrinsic characteristics of a mixed object are not modified from one context to another, whereas extrinsic characteristics are modified.

In this chapter, we first recall our definition of a mixed object [8][9] and then present the corresponding intrinsic characterization space of a mixed object while demonstrating its taxonomic power. We then focus on interaction with mixed objects [8]: we present the resulting extrinsic characterization space of a mixed object and study its taxonomic power. The taxonomic power of our intrinsic and extrinsic characteristic framework is studied in the light of several existing mixed systems that we present in the following section. Finally, in the last section, we show how our characteristic framework is useful for the design, in the context of a new mixed system that we designed and developed.

2 Illustrative Examples

For demonstrating the taxonomic power of our framework, we rely on existing mixed systems. We purposely chose mixed systems that seemed similar at first glance. Indeed, the selected mixed systems support interaction with objects on a horizontal surface. These systems are from the literature (i.e., not designed using our framework) and are therefore unbiased examples for evaluating the taxonomic power of our framework.

NavRNA [2] is a system for interacting with RNA molecules. As shown in Fig. 1 (left), biologists are gathered around a table equipped with a camera and a projector. The camera captures the positions of the blue tokens that the users hold and move in order to explore (i.e. move, turn, resize) the 2D view of RNA.

Fig. 1. NavRNA (left), the MIT Great Dome Phicon in the Tangible Geospace (center), the reacTable (right).

Phicon [22] stands for Physical Icons. In the Tangible Geospace [22] (Fig. 1, center), the phicon is a tool shaped as the MIT Great Dome. Users hold and move it on the table, where a map of the campus is projected. In this way, the location of the Phicon on the table always corresponds to the location of the Dome on the map.

The reacTable [16] (Fig. 1, right) is used as a music synthesizer, where mixed cubes and tokens represent the synthesizer modules. Users can directly touch the surface with several fingers in order to interact. They can also hold and move, change the relative distance, orientation and relation of the objects on the table in order to control the synthesizer. When studying reactTable, we only consider the interaction with the objects. The table is augmented by a camera, which tracks the nature, location and orientation of the objects and by a projector for displaying animation corresponding to the state of the objects onto the surface.

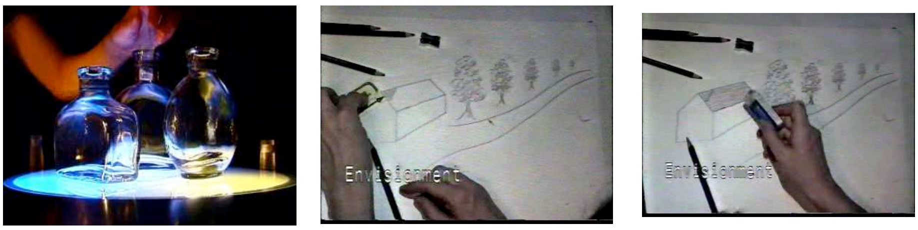


Fig. 2. The music bottles (left), filling a drawing (a roof with tiles) with the Digital Desk (center) and erasing a part of the drawing with the Digital Desk (right).

The music bottles (Fig. 2, left) are objects that are part of a music player system. Each bottle contains a musical part. When a music bottle [15] is put on the table and opened, the corresponding music part is played. In addition, rear projected light corresponding to pitch and volume is displayed underneath the bottle on the table.
The Digital Desk [25] is one of the first mixed systems and was partially developed. We consider the seminal drawing scenario (Fig. 2, center and right). The user draws a

house with a regular pen on a regular sheet of paper on a table equipped with a camera and a projector. In Fig. 2 (center), the user starts drawing tiles on the roof, and then decides to use a “fill” paper button by pointing it towards the roof. She then presses the paper button, which is sensed by the camera. Then the roof is filled with tiles displayed by the projector. The resulting drawing is mixed, with physical parts, made by a pen, and a projected digital part. In Fig. 2 (right), the user erases projected tiles with a regular eraser thanks to the camera.

Fig. 3. The actuated workbench (left and center) and PICO used with constraints (right).

The Actuated Workbench [19] is a table that embeds magnets. On this table, the user or the system can manipulate pucks. The manipulation of a puck can be indirect by using a trackball (Fig. 3, left) or direct by holding the puck (Fig. 3, center).

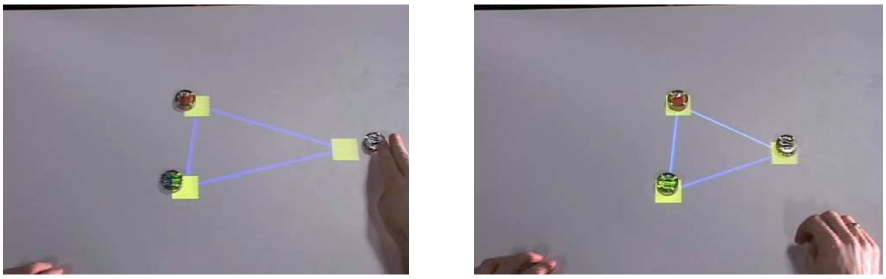


Fig. 4. The PICO system tries to have an equilateral triangle: as the user moves one puck, the system change its position in order to form an equilateral triangle.

PICO [20] stands for “Physical Intervention in Computational Optimization”. The system [20] is similar to the actuated workbench, with a table embedding magnets and augmented by a camera and a projector above. The system computes the ideal positions of the pucks on the table and the magnets automatically move them towards these positions (Fig. 4). Furthermore the user can add physical constraints: For example in Fig. 3 (right), the puck cannot access the entire surface of the table.

3 Integrating Framework for Describing and Classifying Mixed Systems

Focusing on mixed objects involved a mixed system, our integrating framework is made of intrinsic and extrinsic characteristics of a mixed object. We first present the modeling of a mixed object and the induced intrinsic characteristic framework. We then put the mixed objects into interaction context and we expose the modeling of interaction with mixed objects. From this modeling of mixed interaction, we finally describe the extrinsic characteristic framework.

3.1 Modeling of a Mixed Object

Mixed objects are hybrid objects with a physical part, like a physical object, in addition to a digital part like a digital object. For describing mixed objects, we consider its physical and digital parts as well as the link between them. On the one hand, the user interacts with the physical part, because users belong to the physical world. On the other hand, the system can interact with the digital part of the object. Physical/digital properties are properties like shape, color, weight, etc. for physical properties and a digital image, a boolean value, etc. for digital properties.

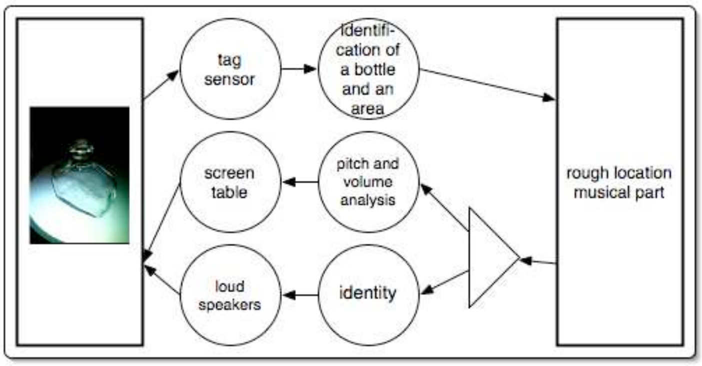


Fig. 5. Our description of the music bottle.

We describe the link between these properties with linking modalities and draw the definition of a linking modality from that of an interaction modality [24]: Given that *d* is a physical device that acquires or delivers information, and *l* is an interaction language that defines a set of well-formed expressions that convey meaning, an interaction modality is a pair *(d,l)*, such as *(camera, computer vision)*. The two levels of abstraction *(device, language)* constitute the basis of the definition of a linking modality. But in contrast to high-level interaction modalities used by the user to interact with mixed environments, the low-level modalities that define the link between physical and digital properties of an object are called linking modalities. Fig.

5 shows the two types of linking modalities (i.e., input/output linking modalities) in the example of the music bottle. An input linking modality allows the system to compute the presence and placement of the bottle on the table. The musical part is made perceivable by the user, through two combined output linking modalities. For the composition of the linking modalities we reuse the CARE (Complementarity, Assignment, Redundancy and Equivalence [24]) properties: in the music bottle example, the composition of the two different output linking modalities corresponds to a case of a partial redundancy.

3.2 Mixed Object: Intrinsic Characterization

Based on the modeling of a mixed object, our intrinsic characteristic framework applies to a mixed object without considering its context of use in a particular interactive mixed system. We consider related studies and show how our characterization scheme unifies such approaches. Existing characteristics including affordance [18], expected and sensed actions [4], characteristics of devices [6] [17] and languages [5] [24], bounce-back physical properties [10], and some aspects of composition of physical properties [13][11]) fit in our modeling of a mixed object. More interestingly, this modeling leads us to identify new characteristics, such as generated physical properties, acquired and materialized digital properties, bounce-back digital properties and some aspects of composition of physical properties. This clearly states our contribution: we provide a unifying framework that organizes various existing characteristics into a single unifying framework and we further identify new characteristics.

Based on our modeling of a mixed object, we present our integrating framework by starting with the characteristics of the linking modalities. We then consider the characteristics that apply to the physical and digital properties.

3.2.1 Characteristics of the Linking Modalities (Devices and Languages)

As our approach capitalizes on existing studies, we reuse the results from multimodal interaction studies for characterizing the two levels of abstraction of a linking modality. Taxonomies of devices [6][17] are applied to characterize input and output linking devices. Frameworks described in [5][24] can also be applied for the linking languages: a language can be static or dynamic, linguistic or not, analogue or not (similarity with the real world or not), arbitrary or not (need to be learned or not), deformed or not (like “how r u?” as opposed to “how are you?”), local or global (only a subset of the information is conveyed or all the information). Our framework also allows study of the relationship between devices and languages [12]. For example, is the precision of the device lost through the language? Finally, we also capitalize on research on multimodality to characterize composition of modalities with the CARE properties (Complementarity, Assignation, Redundancy, Equivalence) [24]. For example we can immediately make the difference between the eraser in the Digital Desk (Fig. 2, right) and the music bottle (Fig. 2, left): the latter has a multimodal output link, whereas the first one does not.

Focusing on the relationships between input and output linking modalities of a mixed object, our model generalizes the temporal relationships identified in [14]. Indeed we refine the temporal coupling characterization from tightly/loosely coupled [14] to five possibilities: linking modalities can be asynchronous, in sequence, concomitant, coincident, or in parallel [24]. Moreover spatial coupling of input and output linking modalities has been studied as Continuity in [11], Embodiment in [13], or as Physical & Virtual Layers in [14]. As for temporal relationships, we extend these existing frameworks by considering five spatial relationships [24]: the input and output space of a mixed object can be either separate, adjacent, intersecting, overlaid, or collocated.

3.2.2 Characteristics of the Physical Properties

We use four intrinsic characteristics for physical properties, namely affordance of, bounce-back, sensed/generated, and aspects of composition of physical properties.

3.2.2.1 Affordance and Expected Changes

Affordance [18] is defined as the aspect of an object that suggests how the object should be used. A flat object can be translated on a table. Expected/non-expected actions [4] are also those we expect the user to do with an interface. Considering the physical properties, these characteristics allow us to identify a simple difference between the examples of Section 2: if we consider the symmetry of rotation of the objects, we have on the one hand objects like the tokens in NavRNA, the pucks in the actuated workbench and PICO, that are invariant when rotated. On the other hand we find the Dome Phicon, the cubes of the reacTable, the music bottles, and the objects used in the Digital Desk that are not symmetrical. Based on this absence of symmetry, we expect the user to rotate the objects of the second category more often.

3.2.2.2 Bounce-back physical properties

A bounce-back button, introduced in [10], is a button that rebounds, like a spring or a rubber band, and goes back to its initial position. Some objects have this physical property, like a simple light switch. Within our model, a physical property can be bounce-back, like the physical location in PICO: Even if the user puts it in a particular position, it tries to go back to its ideal position.

3.2.2.3 Sensed/Generated physical properties

Sensed actions [4] are those that can be captured by the system. Sensed actions and sensed physical properties are related: a sensor does not sense an action but some physical properties from which the system can identify actions. In our framework, sensed physical properties are properties that are captured by any input linking modality. We draw on our capitalization of sensed actions into our description of mixed objects in order to also characterize generated physical properties (those that are made physical by any output linking modality). We characterize physical properties with two orthogonal sensed/generated axes as schematized in Fig. 6. The sensed/generated characteristics of physical properties correspond to the "Input&Output" axis described in [14] ("what properties can be sensed and displayed back to the user (or system)?").

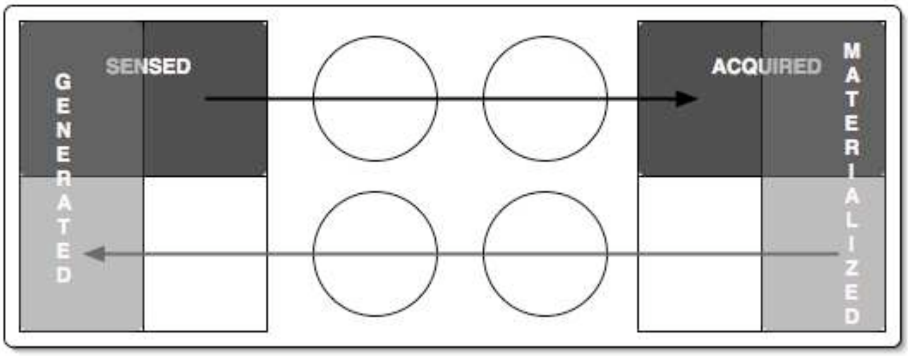


Fig. 6. Characterization of the sensed/generated physical and acquired/materialized digital properties of a mixed object.

If we consider the physical location of the mixed objects presented in Section 2, we obtain the classification presented in Table 1. All these objects share this physical property: they all have a physical location. For almost all these objects, their location is sensed, but it is also generated for two types of objects: those in PICO and Actuated Workbench. Studying the location of the objects in lights of our framework leads us to three main classes of mixed systems.

Table 1. Studying the physical location of mixed objects in light of our framework.

Physical Location	**Generated**	**Non Generated**
Sensed	PICO Actuated Workbench (in computer vision mode)	NAVRNA Tangible Geospace reacTable Music Bottle Digital Desk
Non Sensed	Actuated Workbench (in mouse mode)	

Table 2. Studying the color of mixed objects in light of our framework.

Color	**Generated**	**Non Generated**
Sensed		NAVRNA reacTable
Non Sensed	Music Bottle PICO Actuated Workbench (in computer vision mode)	Tangible Geospace Actuated Workbench (in mouse mode)

Towards a more detailed classification, we consider another physical property: the color. In examples like NavRNA or reacTable, the color is sensed by the camera and is used by the language of the input linking modality to compute the location of the object. In the case of the reacTable the modality tracks markers, so their color cannot be changed at all, or can be changed in a very limited way. Similarly for NavRNA, the color cannot be changed. In examples like the Music Bottles, PICO and Actuated Workbench, the color is not sensed: the system senses the infrared light emitted by the objects for the later, and an electromagnetic resonator tag is used for the Music Bottles. Contrastingly, color is generated for these three systems. Finally for the case of the Tangible Geospace, the color is neither generated nor sensed - infrared is used instead. Note that we do not consider the Digital Desk example for this physical property since this part of the system was not developed. By considering the color property, we then obtained three classes of systems as shown in Table 2.

3.2.2.4 Aspects of the composition of physical properties

Based on the spatial and temporal composition of linking modalities, we can characterize at the physical level the coupling between sensed and generated physical properties. More interestingly, we can also consider the spatial and temporal compositions of those sensed/generated physical properties with the non-sensed/non-generated physical properties. This relation has five possibilities: properties can be asynchronous, in sequence, concomitant, coincident, or in parallel (temporal aspects) or either separate, adjacent, intersecting, overlaid, or collocated (spatial aspects) [24]. For example the generated display of the reacTable cube is adjacent to the non-generated part of the object (Fig. 1, right), whereas in the actuated workbench in computer vision mode (Fig. 3, center), the generated display is collocated with the non-generated part of the object.

3.2.3 Characteristics of the Digital Properties

We use two intrinsic characteristics for digital properties, namely acquired/materialized and bounce-back digital properties.

3.2.3.1 Acquired/Materialized digital properties

By considering the digital properties symmetrically to the sensed/generated physical properties, we characterize digital properties with two orthogonal acquired/materialized axes as schematized in Fig. 6. A digital property can be acquired and/or materialized by any input/output linking modality. This set of characteristics is independent of the types of linking modalities.

We consider the example of the digital property corresponding to the location. For most of our examples, this property is a pair of coordinates (x, y). The music bottle is the only object that does not need such a precise location. The system only needs to know the area (one of the three defined parts of the table). If we consider in Table 3 the Actuated workbench in mouse mode (Fig. 3, left), in this case the digital location is not acquired: it is updated indirectly through a tool, and therefore the object has no input linking modality acquiring this digital location. The other examples in Table 3 show that the digital location of the mixed object is acquired. Yet, for example like the Actuated Workbench in computer vision mode, the reacTable and PICO, the digital location is materialized through a projection on the table. In contrast to the others, the system does not provide observability of the state of the object: the acquired digital location is not materialized. Through this example, we are then able to more finely classify the examples of Section 2: for example the difference between the NavRNA and reacTable tokens is based on the affordance of the physical properties and whether the digital location is materialized or not.

Table 3. Studying the digital location in light of our framework.

Digital Location	**Materialized**	**Non Materialized**
Acquired	Actuated Workbench (in computer vision mode) reacTable PICO	NAVRNA Tangible Geospace Music Bottle Digital Desk
Non Acquired	Actuated Workbench (in mouse mode)	

3.2.3.2 Bounce-back digital properties

We generalize the bounce-back characteristic to the case of digital properties. Digital properties can also behave like a spring and when modified, go back to their initial value after a specified time. For example, we previously explained that the physical location of the mixed objects in PICO was a bounce-back physical property. This can be explained by the fact that the physical position of the pucks is generated from the digital location. The digital location corresponds to the stability value and is therefore a bounce-back digital property. This implies that the corresponding generated physical property is also characterized as a bounce-back physical property.

As a conclusion, Table 4 summaries the intrinsic characteristics of a mixed object. By characterizing a mixed object, we have shown that our framework generalizes and refines several existing frameworks and identifies overlaps between them. We therefore showed that our description of a mixed object provides a unifying framework for capitalizing existing studies. We also showed that it enables us to identify new characteristics. We demonstrated that these new characteristics of a mixed object are useful elements to finely classify existing systems.

Table 4. Summary of intrinsic characteristics (our new characteristics are underlined).

Level	Characteristic	Possible Values
Physical properties	Affordance, expectations	
	Sensed	Yes/No
	<u>Generated</u>	Yes/No
	Bounce-back	Yes/No
	<u>Compositions</u>	Five schemas for the spatial aspects as well as for the temporal aspects
Link	Multimodality	- Direction: in/out, - Number: integer, - CARE characterization
	Precision of device	
	…	
	Dynamicity of language	Yes/No
	…	
Digital Properties	<u>Acquired</u>	Yes/No
	<u>Materialized</u>	Yes/No
	<u>Bounce Back</u>	Yes/No

3.3 Modeling Mixed Interaction: Putting Mixed Objects Into Interaction Context

A mixed interaction involves a mixed object. An object is either a tool used by the user to perform her/his task or the object that is the focus of the task. To model mixed interaction, we enrich the instrumental interaction model [3] with the notion of *interaction* modality *(d, l)* [24]. We study the two types of mixed objects, namely *mixed tool* and *mixed task object*, involved in the interaction in light of a definition of an interaction modality [24] as the coupling of a physical device *d* with an interaction language *l*:

- *A mixed tool* is a device of a given modality. In Fig. 7 (in gray) the mixed tool is a device *d* coupled with an *interaction* language *l* that will translate the action into an elementary task.
- *A mixed task object* is manipulated by the user by means of an interaction modality.

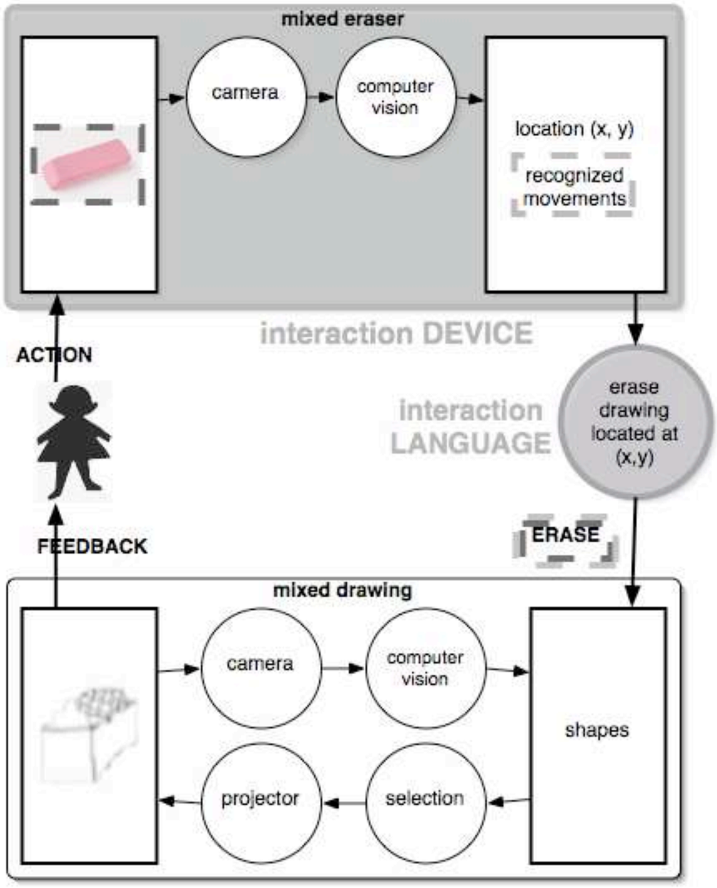


Fig. 7. Interaction between the user, the mixed tool in gray (eraser) and the mixed task object (drawing) in the Digital Desk, and assessment of the noun (dotted dark gray) and verb (dotted light gray) metaphors.

For example, in Fig. 7 we consider the example of the Digital Desk of Fig. 2 (left). The user is handling and moving the eraser – the mixed tool. This action on the physical properties of the object is sensed by the input linking modality *(camera, computer vision)* in order to update the digital properties <location> and <recognized movements>. The changes of the digital properties of the mixed tool are interpreted by the interaction language into an elementary task: (x,y) location is translated into "erase drawing located at (x, y) on the table". This elementary task is applied to the task object and the digital properties of the mixed drawing are consequently modified. The mixed drawing shows its internal digital changes by updating its display through its output linking modality – the feedback.

3.4 Mixed object: Extrinsic Characterization

Extrinsic characterization concerns the aspects of a mixed object specific to its use in a particular application. We first consider the object as a whole in the interaction and show how we can characterize its role. We then focus on the part of a mixed object that serves as an interface to its outside environment: the physical and digital properties. As for the intrinsic characterization framework, we show how related studies fit in our description of a mixed interaction. We capitalize on existing characteristics (roles [12][3], metaphors [13], physical constraints [21][23], desired actions for an application [4]) in our characterization framework. Moreover, our description leads us to identify new characteristics, such as a new dimension for metaphors, output physical ports and input digital ports.

3.4.1 Characteristics of the Roles

As identified in the ASUR (Adapter, System, User, Real object) design notation for mixed systems [12] and in the instrumental interaction model [3], an object can play two roles in interaction: it is either a tool used by the user to perform her/his task or the object that is the focus of the task (i.e., task object). In our examples of Section 2, this enables us to distinguish two categories of objects. On the one hand, the tokens in NavRNA and the Dome Phicon are tools. On the other hand the music bottle is the object of the task.

3.4.2 Characteristics of the Physical Properties

We use three extrinsic characteristics for physical properties, namely noun metaphor of, ports of and aspects of composition of the physical properties of mixed objects.

3.4.2.1 Noun Metaphor

In [13], the noun metaphor is defined as “an <X> in the system is like an <X> in the real world”. To assess the noun metaphor based on the modeling of mixed interaction, we study how the physical properties reflect the task performed with the mixed object. For example in Fig. 7 (dotted dark gray), the physical properties of the eraser reflect the task: erasing. The Dome Phicon belongs to the same category, as opposed to the tokens of NavRNA, the cubes of the reacTable and the pucks of PICO.

Instead of considering only the metaphor with the "real" natural world, we consider a continuum from this real-world metaphor to digital practice based metaphors, putting thus on equal footing physical and digital worlds. For example, in the Digital Desk [25], the user interacts with a mixed tool made of paper that looks like a digital button in GUI.

Moreover, we also consider the command and its parameters as two different metaphors. For example for the case of the Dome Phicon, the physical properties reflect the parameter of the task "*move* the location of the *dome* of the map to (x,y)". In contrast the digital properties of the eraser reflect the command itself.

3.4.2.2 Ports

Physical input ports are related to the affordance of the object. Affordance [18] is defined by the physical properties that the user can act on. Some of these actions might be impossible because of external constraints, as defined in [21][23][20]: the corresponding physical ports are closed (i.e., not fully open). As explained in [20]:

- On the one hand, some physical input ports can be closed in order to guarantee data that can be processed by the input linking modality. This can be done to overcome some technological limitations: For example in most of our examples, the position of an object on a table is constrained so that it does not get out of range of the camera.
- On the other hand the user can close some physical input ports explicitly in the interaction process, as in [20] when the user puts an object filled with sand on a mixed puck in order to prevent it from moving.

We extend this characterization of physical ports by also considering the output physical ports. Output ports define properties exported by a mixed object. For example, if we consider the generated physical property corresponding to the display projected onto the table of the systems of Section 2, the output ports can be partially closed according to the kinds of projection (from the top, from behind). Indeed with a projection from the top, as in the Digital Desk, the actuated workbench and PICO, the users' hands or head may hide some parts of the projection. In contrast, with a rear-projection, as for the reacTable and the music bottle, the output ports are always open.

3.4.2.3 Aspects of the composition of mixed objects

As part of the intrinsic characterization framework of a mixed object, we described the spatial and temporal coupling of a mixed object by focusing on the relationships between its physical properties. Symmetrically, at the extrinsic level, we also study the spatial and temporal relationships between properties of different mixed objects. For example we can study the spatial relationships between the physical properties of the mixed drawing and the mixed eraser in the Digital Desk and compare it with the relationships between the physical properties of the NavRNA tokens and the projected

RNA molecule, or with the relationships between the Dome Phicon and the map. All pairs of objects are adjacent, in contrast to the reacTable cubes: Indeed the cubes and the synthesized sound are spatially overlaid – Where we can perceive the cubes, we can perceive the sound, but the reverse is not always true –.

3.4.3 Characteristics of the Digital Properties

We use two extrinsic characteristics for digital properties, namely verb metaphor of and ports of the digital properties of a mixed object.

3.4.3.1 Verb Metaphor

In [13], the verb metaphor is represented by the phrase "<X>-ing the object in the system, is like <X>-ing in the real world". To assess the verb metaphor, we study if the acquired digital properties reflect the task performed with the mixed object. For example in Fig. 7 (dotted light gray), the acquired digital property <recognized movements> of the mixed eraser reflects the task. Note that in this particular example, there is both a noun and a verb metaphor, but we can consider them independently. For example the eraser in the Digital Desk could be used without the verb metaphor, by putting the eraser on the drawing in order to erase the designated area, without moving it like an eraser. The mixed cork of a music bottle belongs to the same category.

3.4.3.2 Ports

Output digital ports define digital properties exported by a mixed object towards an interaction language. For example in Fig. 7, the mixed eraser exports the location of the eraser (x,y), that is then transformed by the interaction language to obtain the final task. The output digital port corresponds to the notion of "desired actions" in [4].

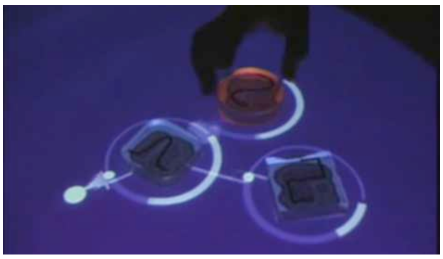


Fig. 8. A token of the reacTable with a digital property controlled by another circular tool.

We further identify input digital ports. Indeed the application context can modify and/or prevent possible values of a digital property through the interaction language.

The input digital port is then open or closed. For example, the blue tokens in NavRNA and the Dome Phicon in the Tangible Geospace have no input digital port, whereas the cubes in the reacTable do: the system can modify digital properties of some cubes, by adding an extra circular tool on the table that controls one of its digital property. Fig. 8 shows this case with a sinusoidal Low Frequency Oscillator controlling a band pass sound filter.

As a conclusion, by characterizing extrinsically a mixed object based on our modeling of mixed interaction, we have shown that our framework encompasses and extends existing frameworks. Table 5 summaries our extrinsic characteristic framework.

Table 5. **Summary of extrinsic characteristics (our new characteristics are underlined).**

Level	Characteristic	Possible Values
Mixed Object	Role	Tool/Task Object
Physical properties	Noun metaphor	Absence / <u>Related to a command / Related to a parameter</u> and <u>related to natural to digital world</u>
	Input ports	Open/Closed
	<u>Output ports</u>	Open/Closed
	Compositions	Five schemas for the spatial aspects as well as for the temporal aspects
Digital Properties	<u>Input Ports</u>	Open/Closed
	Output Ports	Open/Closed
	Verb metaphor	Absence / Related to command and <u>related to natural to digital world</u>

Our integrating framework is made of both intrinsic and extrinsic characteristics of a mixed object. Table 4 and 5 respectively list the identified intrinsic and extrinsic characteristics. Based on this integrating framework, we are able to classify the existing mixed systems. To conclude on the taxonomic power of our framework, Table 6 shows how the examples of Section 2 differ from each other based on the identified intrinsic and extrinsic characteristics. In this Table, we see that the framework allow us to find at least one characteristic to make a difference between systems. Finally each system belongs to a single category, even if they were chosen similar at the beginning.

4 Integrating Framework for Designing Mixed Systems: the Case of Roam

Having presented our framework and studied its taxonomic power, we now focus on the design and illustrate the generative power of our framework. We purposely choose for our design example an application that is of a radically different type than the considered existing mixed systems of the previous section. The considered mixed system that we designed and developed is Roam, a mobile recording system.

We designed and developed Roam as part of a multidisciplinary project involving a designer and computer scientists. Roam is a mobile mixed system for recording (pictures, sounds). Even if users already use camera for recording images as keepsakes, the intention during the design of Roam is to have a tool that does not distract user's attention from the world. With commonly used recording tools, like camera, people focus on the tool in order to record a souvenir. In contrast Roam is intended to stay in the background of the focus of attention and not to distract the user from the facts of interests.

Table 6. Classification of the existing systems of Section 2. In this table, for clarity purposes, we show only one difference based on a given characteristic between each system, while several characteristics can be applied to distinguish them. Our new characteristics are underlined. Differences are made by characterizing (1) sensed/generated physical location, (2) sensed/generated color, (3) materialized / non materialized digital location, (4) simple/multimodal output link, (5) affordance, (6) adjacent/collocated generated and non generated parts, (7) tool / task object role, (8) command/parameter noun metaphor, (9) digital input port and (10) physical output port (display can be hidden or not).

	NavRNA	Phicon	PICO	bottle	drawing	eraser	reacTable	Puck (vision)	Puck (trackball)
Puck (trackball)	(3)	(3)	(2)	(1)	(1)	(1)	(1)	(1)	
Puck (vision)	(3)	(1)	(1)	(10)	(1)	(1)	(6)		
reacTable	(9)	(9)	(10)	(2)	(3)	(3)			
eraser	(5)	(8)	(1)	(4)	(7)				
drawing	(7)	(7)	(1)	(4)					
bottle	(2)	(2)	(10)						
PICO	(3)	(1)							
Phicon	(2)								
NavRNA									

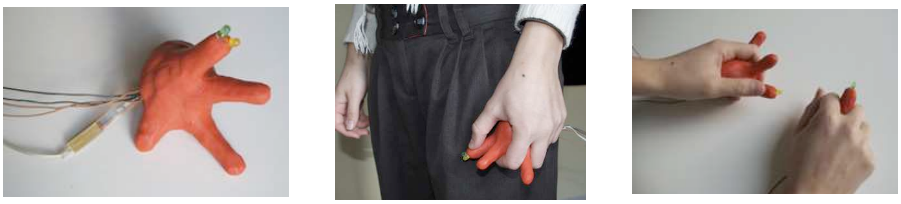
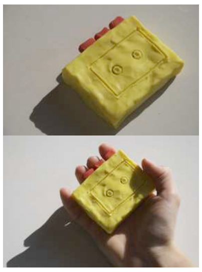


Fig. 9. Roam tool prototypes: close-up of final prototype with bend sensors and green/yellow LEDs (left), in the hand of the user (center). Another prototype of the Roam tool with separated physical properties (right).

Fig. 9 (left and center) shows the pictures of our prototype of the Roam tool for recording sound souvenirs. It fits in the hand of the user in an unobtrusive way. She can bend a part in order to start recording, and release to stop recording. A yellow LED enables her to know if she bent or released enough to start or stop recording. A green LED allows her to know if the tool is actually recording. Play-back of the record is not planned in Roam but can be done using a computer (i.e., after using Roam).

Table 7. Exploring the design of the Roam tool thanks to the noun metaphor dimensions: the task is "record the sound" in contrast to "record the image".

	"Natural" practice	↔	**Digital practice**
Command (record)	 Octopus (record as taking/eating: the octopus eats through the beak and takes things from the environment with tentacles)	 Crank handle as with old cameras (record as un-winding of a film)	 Red dot (record icon usually used in systems)
Parameter (sound)	 Ear	 Horn of the early phonographs	 Tape recorder

We focus on the design of Roam and show how our framework helps in exploring the design space by considering examples during the design process. Since we know the application context of the tool, we first focus on extrinsic design exploration of the Roam tool. We then present examples of intrinsic design exploration.

5.1 Extrinsic Design

This tool is to be used in a mobile context. We therefore need to avoid obtrusiveness. Apart from its role, some extrinsic characteristics are yet to be explored. We selected examples from the characteristics of our framework: the noun metaphor and the digital/physical ports.

We first present the example of exploring the different types of noun metaphors. A noun metaphor can be related to a command such as the eraser of the Digital Desk or to a parameter of the command such as the Dome Phicon of the Tangible Geospace. We also identify a continuum from the real-world metaphor to digital practice based metaphors. For the Roam tool, this helped us to generate six ideas, presented in Table 7. We chose the octopus because it fitted better in the hand of the user.

We now consider the input digital ports. Exploring the design space along our characterization framework, we identified the need for an output digital port – isOn. Apart from this required output port, our design space drove our attention to the possibility of having a digital input port in our tool. It inspired us to come up with the idea of a response from the task object (the record) towards this tool: the tool contains a digital property that conveys the success of the record action. If this input digital property is then materialized, this enforces the observability principle [1] as we argued in [8]. We chose to have an input digital port, named isOk.

Fig. 10. Design alternatives for output ports: sound (left), light (LEDs in center and right). Focusing on the output ports: according to the way the tool is handled by the user, the lights may be hidden or not.

We now consider the examples of exploring the physical properties of the tool and its output physical ports. The framework enabled us to explore physical properties that can be output ports. We explored alternatives and found sound and light: beeping (Fig. 10, left) and blinking (Fig. 10, center and right).

For our mobile tool, this also highlights which and how physical properties are going to be perceivable in the context of use. For example the sound of the loudspeakers can be too intrusive according to the environment: the others can hear it. Moreover, depending on how the tool is handled by the user, the physical properties generated by the LEDs can be hidden (Fig. 10, right). Thus we studied the placement of the LED as shown in Fig. 9 (left and center) and 10 (center).

Exploring the design space thanks to the dimensions identified with our framework gave rise to the design of alternatives that were not envisioned at first sight. It thus assisted us in exploring the extrinsic design space. We now present the intrinsic design of this tool.

5.2 Intrinsic Design

We first consider the example of the bounce-back characteristic for digital properties. We already identified, thanks to extrinsic design, two digital properties: an output port isOn and an input port isOk. From the intrinsic viewpoint on design, we can study if the two properties are bounce-back or not. Given that the output linking language turns the yellow LED on as long as isOn is true, if isOn is bounce-back, then the yellow LED only blinks once. If isOn is not bounce-back, then the yellow LED is on as long as isOn is true. In our design, we chose isOn not to be bounce-back. On the contrary, we chose isOk to be bounce-back: according to the output linking language, if the user wants to be sure the system is recording, she has to have a quick look at the green LED when she bends the tentacle.

We can also consider the composition of the physical properties. Thanks to our framework, we can envision multiple spatial compositions of the physical properties of the tool. They can be collocated and adjacent (Fig. 9, left and center) or separated, manipulated by the two hands (Fig. 9, right).

In this section we showed how the new characteristics we identified thanks to our framework were useful for the design of a tool. The characteristics allow generation of ideas by suggesting different types of alternatives. We chose to only illustrate the new characteristics identified with the framework, but the complete framework was used to design Roam. We studied the reusability of our intrinsic design for a different application context: Indeed the Roam tool can be used for interaction with Google Earth, which is a completely different application. However in this context, intrinsic characteristics of the tool are not modified. For example, the digital property isOn is still not bounce-back. On the contrary, some extrinsic characteristics are modified: Google Earth does not enable the property isOk to be an input digital port. These ideas show the benefits of using the framework for design.

6 Conclusion

This chapter has introduced a new way of thinking of interaction design of mixed systems in terms of mixed objects. We presented intrinsic and extrinsic characteristics of a mixed object, the object being a tool or a task object. By showing how this characteristic framework enables us to classify existing similar systems, we demonstrated the taxonomic power of our framework. We also illustrate the generative power of our framework by considering the design of a mixed system, Roam. In addition to Roam, the framework has also been used to design other mixed systems such as ORBIS [9], RAZZLE [8] or Snap2Play [7]. Moreover we are currently conducting an evaluation of our framework by considering the design of objects for exhibits in museums.

Several characteristics of our framework come from related work. Our contribution lies in the capitalization of these results into a single unifying/integrating framework and in the identification of new characteristics. However a more thorough analysis of mixed systems could lead to extensions of the framework with new intrinsic or extrinsic characteristics of mixed objects and to a better assessment of its limitations.

As on-going work, we are focusing on the design of mixed objects based on our framework. Design relies on both “thinking it through” and “working it through”. We are working on putting the conceptual framework in operation for designing by prototyping. A toolkit for building mixed objects explicitly based on the underlying concepts of the framework is under development. The toolkit covers existing development frameworks and toolkits and provides modularity, and extensibility. This toolkit will enable us to quickly develop prototypes that look like and work like the intended designed mixed object, as illustrated with the Roam system.

Acknowledgments We would like to thank the authors of the example systems for using their illustrations, Jérôme Drouin, designer, for his participation in the Roam project and George Serghiou for reviewing the paper. The work presented in the article is partly funded by the "Plan Pluri-Formation" on Multimodal Interaction (financed by four Universities in Grenoble), by the French Research Agency under contract CARE (CulturalExperience: Augmented Reality and Emotion) - www.careproject.fr and by the European Commission under contract OpenInterface (FP6-35182), www.oi-project.org.

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