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Research Article

A Mathematical Framework for Interpreting Playing Environments as Media for Information Flow

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This paper proposes a novel strategy of designing play equipments. The strategy introduces two loose constraints as a guideline for designers. The first constraint is "describing unit of play action chain" $\langle O, S, V\rangle$ based on Barthes' semiology, and the second is the infomorphism between designer, play equipment, and players based on channel theory. We provide detailed explanation of the strategy through an example of a designing process of playing environment where the players usage of the play equipment cannot be foreseen.

1. Introduction

When playing computer games, users sometimes tend to add their own original rules to make games more exciting; thus the games (or more generally speaking the play equipment) do not have a unique "right way" to be played but have the potential to be played in various ways. This potential is usually interpreted as a problem to be avoided in the field of conventional system design because it may lead to unexpected danger. In the field of designing play equipment, however, the potential is an important element for producing entertainment.

It is needless to say that designers of conventional systems, to, often assume users' various ways of using a system and handle them one by one. In designing play equipment in which the events caused by the equipment are prepared by the designers (e.g., computer games), a variety of decision branches are considered an essential element for making the play equipment "entertaining"; the knowledge regarding adequate size of the decision branches and how to create them is organized as gamenics [1].

On the other hand, users of such play equipment are not always satisfied with the given decision branches, and sometimes create a new and unpredicted way of playing. In this paper, we focus on this point and target outdoor play equipment that is often seen at playgrounds as equipment for which it is difficult to assume players' intentions.

We expect to gain broad knowledge that also covers "event-foreseeable play equipment" through analysis of such play equipment, for example, factors that cause entertainment or guiding principles of how to design "enjoyable-to-use tools". Unlike gamenics, this knowledge is not organized at present and is a challenging task to tackle.

It is impossible to design these types of targets by combining rigidly pre-constructed building blocks; "correspondence between playing actions and pleasure" and "correspondence between play equipment's characteristics and pleasure" are both context-dependent. Furthermore, we must not assume that the context can be fully clarified because we aim to construct a framework that can tolerate unpredictable ways of playing. This paper therefore first focuses on "correspondence between playing actions and pleasure" in Section 2 and proposes "describing units of the play action chain"; this unit introduces play equipment's components and its characteristics as a context that (not fully but to some extent) regulates the correspondence. This unit functions as a first "loose" constraint. Though play actions and pleasure cannot be uniquely correlated, allowing spontaneous description of the correspondence will lead to a denial of any systematic operation. The adoption of

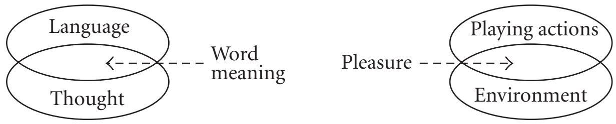

Figure 1: A unit of linguistic thought and playing action.

the new unit is namely an adoption of an intermediate (loose) level of constraint; we fix only the description format and vary the implication of the description itself, case by case. Next in Section 3, by using the format introduced in Section 2, we adopt a new strategy for designing targets whose influence cannot be foreseen. The main idea of the strategy is to individually describe the part that can be locally decided and describe what cannot be locally decided as a correspondence between local description. That is to say, give a correspondence between the 3 factors: assumption of the designer, assumption about the user, and an event that can be generally assumed to happen in a physical environment. Here, we give a second loose constraint. Though bijection, the most rigid correspondence, is too powerful, allowing spontaneous correspondence is meaningless. On loosening the powerful bijection constraint, we can adopt various strategies such as surjection and injection, but in this paper we adopt "infomorphism." Infomorphism is essentially a projection that is consolidated to formulate qualitative information flow, and formation of an infomorphism is assumed as formation of information flow.

2. Analysis of Perception-Action Chain Structure

In a playing environment, pleasures prompt new playing actions that in turn generate new pleasures. These perceptions of pleasures and playing actions are coupled dynamically. In other words, the playing environment involves many "perception-action chains" in terms of ecological psychology [2]. Vygotsky advocated in his psychological studies that the primitive unit of linguistic thought is not a single word or a syllable but "word meaning," which has both properties of language and thought [3]. These properties are coupled dynamically, and variations of these properties generate new "word meanings." Interpreting this notion of linguistic thought to playing environment, a unit of playing actions should have both properties of actions and environment, and should be able to describe relations between play equipment and players in order to grasp the generations of pleasures in the playing environment as shown in Figure 1. Furthermore, variations of playing actions or environment perceptions generating new pleasures correspond with the characteristic of the unit of linguistic thought. We describe analysis of the perception-action chain for outdoor play equipment in the next section, using one of four types of pleasure actions: "imitative action," "resting action," "vertiginous action," "challenging action," which are observed in using outdoor play equipment [4].

Table 1

Actions	Therblig
Climbing	Transport empty → grasp → transport loaded → use
Swinging	Transport empty → grasp → transport loaded → use

2.1. Perception-Action Chain Analysis Using Therblig

To describe processes of generation of pleasures from playing actions, we separate playing action using the "therblig" as a unit that is beyond an analyst's subjectivity. Therblig analysis [5] is the notation evolved from the observation of human manual operation and is made up of 17 types of basic motions called "therbligs." For example, describing two different actions "climbing" and "swinging" observed on the rope of outdoor play equipment using therbligs is performed as shown in Table 1.

This analysis gives the same result. This means that using the therblig cannot derive various pleasures from different playing actions.

Therblig has much less basic motions for analysis for playing actions, so we cannot describe all of the playing actions using therblig. Additionally, therblig does not have properties of environment perception. Generally each playing action does not correspond to a unique "pleasure," so we cannot derive pleasures generated in the relations between play equipment and playing environment even though we can assign one of the therbligs to each action. Furthermore, this method cannot allow us to describe generation of new pleasures from linked actions. Thus, the therblig, which is one of the reductionism units, is not suited for analysis of playing action. The "PTS" has more basic motions [6], but it is not suited for them in the same way.

2.2. A New Unit $\langle O, S, V \rangle$ Based on Barthes' Semiology

As noted in Section 2, reductionism units such as the therblig or PTS are not suited for analysis of playing action. Additionally, a unit of playing actions should have both properties of actions and environment and represents the "pleasure of a combination of actions" that is not just a integration of its constituent actions. In this section, we propose a new unit of playing action based on Barthes' semiology, "the fashion system," which has a syntax structure that is suited for representing linked playing actions.

The fashion system

Barthes proposed "a unit for describing fashion [7]," which is defined as an association of three elements: object (O), support (S), and variant (V) as follows:

S: the garment's technical existence. Support of signification (e.g., the collar),

V: the garment's signifying existence. The point of the matrix from which signification emerges (e.g., open/closed),

O: the material element of the garment. Object of the signification. (e.g., the cardigan).

For example, analysis of "a sporty cardigan" is as follows:

$$S(\text{collar}) + V(\text{open}) + O(\text{cardigan}) \equiv \textbf{sporty}. \quad (1)$$

A new unit $\langle O, S, V \rangle$

We propose "a unit of playing-actions $\langle O, S, V \rangle$" based on the fashion system in Barthes' semiology [7] as follows:

S: a technical factor that determines a position of a part of play equipment (e.g., dropped down vertically),

V: a playing action that is carried out in a part of play equipment (e.g., climbing),

O: a device to be a part of play equipment (e.g., a rope).

For example, describing two different actions "climbing" and "swinging" observed on the rope of outdoor play equipment is as follows, using one of four types of pleasure actions: "imitative action", "resting action", "vertiginous action", "challenging action", which are observed in using outdoor play equipment [4]:

$$\begin{aligned} &S_1(\text{dropped down vertically}) + V_1(\text{climbing}) + O_1(\text{rope}) \\ &\quad \equiv \text{pleasure of } \textbf{Challenging Action}, \\ &S_1(\text{dropped down vertically}) + V_2(\text{swinging}) + O_1(\text{rope}) \\ &\quad \equiv \text{pleasure of } \textbf{Vertiginous Action}. \end{aligned} \quad (2)$$

These units correspond to various pleasures. In particular, we can represent new actions and new pleasures involved in the same device. The substance of pleasures depends on choices of V (actions) in the same parts; also choices of V depend on S and O. Players recognize V and S as characteristic of O. These operations correspond to that of variant V in "the fashion system," in that V has the right of determination of fashion mode and becomes characteristic of O with S.

2.2.1. Binding of Units

In "the fashion system", multiple units link together and generate a new unit and describe fashion mode as follows:

$$\begin{array}{ccccc} \langle\text{white} & & \text{braid and white} & & \text{buttons}\rangle \\ \langle S_1 V_1 & O_1\rangle & & \langle S_2 V_2 & O_2\rangle \\ & \langle S_0 & V_0 & S_0'\rangle & \\ & & \mathbf{S}. & & \end{array} \quad (3)$$

S_0 represents $\langle O_1, S_1, V_1 \rangle$. Similarly, S_0' represents $\langle O_2, S_2, V_2 \rangle$. Each meaning of units is transmitted to the final unit. We can apply this representation to the playing action as follows:

$$\begin{array}{ccc} \text{dropped down vertical climbing rope} & & \\ \langle S_1 & V_1 O_1\rangle & \\ \text{drop the rope down} & & \text{swinging bar} \\ \mathbf{S_2} & & V_2 O_2. \end{array} \quad (4)$$

$\langle O_1, S_1, V_1 \rangle$, which is represented by S_2, generates "challenging action" pleasure. S_2 makes a new unit with O_2 and V_2 and generates a new pleasure of "vertiginous action." This means that we can grasp the new pleasure on a larger scale when playing actions that are linked together, which is not described in the method using therbligs. We can adopt this method in analyzing the playing action in connected multiple parts of play equipment.

3. Information Channels in Playing Environment

We discussed the syntax structure of units of playing actions. In a playing environment, there are information flows involving generation processes of new playing actions that are observed on play equipment based on players' interpretations. We propose a mathematical framework for qualitative information flows of designing processes of the playing environment.

In the conventional way of designing play equipment, a designer recollects some devices (e.g., ladder) associated with a specific action (e.g., climb) and integrates the device as a part of play equipment. But in such a case, we cannot capture the emergence of new actions in the playing environment. We cannot adopt the strategy of deriving an action correlated to a combination of devices by consolidating actions correlated to its constituent devices. In this chapter, we interpret that individual descriptions of the part are not devices but a correspondence between three factors: assumption of the designer about "character of play equipment and pleasures," assumption of the user about "character of play equipment and actions afforded from," and equipment and actions that can be generally assumed to happen in a physical environment. Then, we adopt a strategy that can be locally decided on and describe what cannot be locally decided on as a correspondence between local descriptions.

Bijection, the most rigid correspondence, is too powerful, and allowing spontaneous correspondence is meaningless. On loosening the powerful bijection constraint, we can adopt various strategies such as surjection and injection, but in this paper we adopt "infomorphism" in channel theory [8, 9]. Infomorphism is essentially a projection that is consolidated to formulate qualitative information flow, and formation of an infomorphism is assumed as formation of information flow. So, we interpret the playing environment as a new medium that mediates play equipment and players, by focusing on interactions between artifacts and users, and define a model for representing designers—play equipment—players as information channels based on channel theory [8, 9]. Channel theory is the qualitative theory of information advocated by Barwise and Seligman.

Channel theory defines a classification (D) such as $\langle \text{typ}(D), \text{tok}(D), \vDash_D \rangle$. Given a set of tokens: tok(D) and a set of types: typ(D), $a \vDash_D \alpha$ means that the type of $a(\in \text{tok}(D))$ is $\alpha(\in \text{typ}(D))$. A unit of playing action $\langle O, S, V \rangle$ has both properties of action $\langle V \rangle$ and environment $\langle O, S \rangle$. It is appropriate to separate both properties to typ and tok in the classification of Channel theory. The separation of both properties can be done in an intensional or extensional way. In this paper, we adopt an extensional separation, in which recitation of properties of environments defines properties of actions that are attributes of playing environments. For playing environment, we define three classifications as follows.

Classification of designers assumption: D_{ds}

tok(D_{ds}): a set of "pleasures T_i".

typ(D_{ds}): a set of "features of playing environment E_i."

$T_i \vDash_{D_{\text{ds}}} E_i$: Pleasure T_i is observed in environment E_i.

Classification of equipment: D_{pl}

tok(D_{pl}): a set of "playing actions V_i."

typ(D_{pl}): a set of "parts of play equipment O_i."

$V_i \vDash_{D_{\text{pl}}} O_i$: a part of play equipment O_i enables an action V_i.

Classification of users: D_{ch}

tok(D_{ch}): a set of "playing actions of players V_i'."

typ(D_{ch}): a set of "combinations of parts and their feature $SO_i(= S_i + O_i)$."

$V_i' \vDash_{D_{\text{ch}}} SO_i$: SO_i enables an action V_i'.

In the classification of users (D_{ch}), types SO_i are defined by combining S_i in terms of units of playing actions $\langle O, S, V \rangle$ with parts of play equipment O_i of D_{pl}. S_i affects O_i in its ability to bring about some new play actions V_i.

The three classifications enable us to interpret designing play equipment as an establishment of an *infomorphism* in terms of channel theory.

3.1. Conventional Design of Play Equipment

An *infomorphism* $f : A \rightleftarrows B$ from A to B is defined as a contravariant pair of functions $f = \langle f^\wedge, f^\vee \rangle$ in channel theory. The function $f^\vee$ is a map from tok(B) to tok(A), and $f^\wedge$ is a map from typ(A) to typ(B). It satisfies the following property:

$$f^\vee(b) \vDash_A \alpha \Longleftrightarrow b \vDash_B f^\wedge(\alpha), \tag{5}$$

for each token $b \in \text{tok}(B)$ and each type $\alpha \in \text{typ}(A)$. Figure 2 shows an *infomorphism* $f : A \rightleftarrows B$ from A to B.

In the case of playing environment, the establishment of *infomorphism* from D_{ds} to D_{pl} can be seen as an accomplishment of designing play equipment in a conventional way. Namely, "a pleasure T_i in an environment $E_i(= f^\vee(O_i))$" in the mental world of a designer is implemented in the physical world as the action $V_i(= f^\wedge(T_i))$ by using equipment O_i.

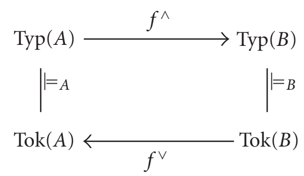

FIGURE 2: An infomorphism from classification A to B.

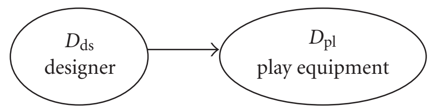

FIGURE 3: Conventional design process modeled by an infomorphism.

Figure 3 illustrates an image of establishment of an informorphism. This method describes only actions corresponding to parts of play equipment based on the designer's logic, and no actions generated by players' intentions. So, designers cannot foresee the emergence of new playing actions and pleasures.

3.2. Novel Design of Play Equipment

Channel theory defines a *channel* as a set of *infomorphisms* sharing the same codomain. In the case of a playing environment, establishment of an *information channel* between D_{ds} and D_{ch} via D_{pl} can be interpreted as an accomplishment of a novel design from the viewpoint of interpreting play environment as a medium of designers, play equipment, and children. Figure 4 illustrates an image of establishment of a channel.

3.2.1. A Concrete Example of Using Chu Map

Classification D_{ds}: first, a designer sets features of playing environments E_i and pleasures T_i in classification D_{ds} as follows. In this classification, correspondence relations of E_i and T_i are trivial, like $T_1 \vDash_{D_{\text{ds}}} E_2$, $T_2 \vDash_{D_{\text{ds}}} E_1$, $T_2 \vDash_{D_{\text{ds}}} E_4$, $T_3 \vDash_{D_{\text{ds}}} E_3$, and $T_3 \vDash_{D_{\text{ds}}} E_4$.

typ(D_{ds})

- E_1: environment that contains pleasure T_2.
- E_2: environment that contains pleasure T_1.
- E_3: environment that contains pleasure T_3.
- E_4: environment that contains pleasures T_2 and T_3.

tok(D_{ds})

- T_1: pleasure of resting action.
- T_2: pleasure of challenging action.
- T_3: pleasure of vertiginous action.

Classification D_{pl}: second, a designer sets parts of play equipment O_i and playing actions V_i in classification D_{pl} as

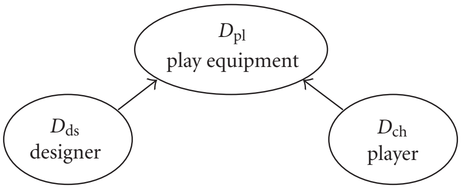

Figure 4: Novel design process modeled by a single channel.

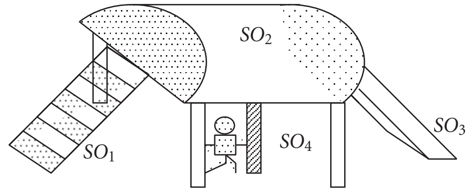

Figure 5: A slide derived from the design model using channel theory.

follows. To establish an *information channel* between D_{ds} and D_{ch} via D_{pl}, designers must set an informorphism D_{ds} to D_{pl}. In this case, a designer sets infomorphisms $f^{\wedge}(E_1) = O_1$, $f^{\wedge}(E_2) = O_2$, $f^{\wedge}(E_3) = O_3$, $f^{\wedge}(E_4) = O_4$, and $f^{\vee}(V_1) = T_2$, $f^{\vee}(V_2) = T_1$, $f^{\vee}(V_3) = T_3$.

typ(D_{pl})

- O_1: a ladder.
- O_2: a horizontal plate.
- O_3: a slope.
- O_4: a bar.

tok(D_{pl})

- V_1: climb vertically.
- V_2: walk.
- V_3: slide down.

Classification D_{ch}: finally, a designer creates units of playing actions $\langle O, S, V\rangle$, and sets SO_i, which are defined by combining S_i in terms of $\langle O, S, V\rangle$ with parts of play equipment O_i and V_i', which contain new playing actions emerged in the play environment in classification D_{ch} as follows. In this operation, designers must set S_i and V_i' to establish an information channel between D_{ds} and D_{ch} via D_{pl}. Figure 5 shows a slide derived from the design model using channel theory. Figure 6 shows an example of a channel represented by *Chu maps* [10].

typ(D_{ch})

- SO_1: a ladder that is put to SO_2 vertically.
- SO_2: a covered horizontal plate.
- SO_3: a steep slope that is put to SO_2.
- SO_4: a bar dropped down from SO_2.

tok(D_{ch})

- V_1': climb vertically.
- V_2': walk.
- V_3': slide down.
- V_4': walk into.
- V_5': walk outside.
- V_6': jump.
- V_7': scale up.

3.3. New Playing Actions Described in a Model of Information Channel

In the novel design, there are several alternatives for not only segmenting O_i but also S_i and V_i. Therefore, designers can foresee the emergence of new playing actions and pleasures.

At boundary between multiple parts

Designers have to select multiple elements when they select units at the boundary between multiple parts of play equipment. They become loose constraints that guide design processes. For example, setting S_2: "covered" generates new playing actions, V_4': "walk in," and V_5': "walk out":

(i) a playing action V_4' at the boundary between SO_1, SO_3, SO_4, and SO_2:

$$\begin{array}{c|cccc} & SO_1 & SO_2 & SO_3 & SO_4 \\ \hline V_4' & 1 & 0 & 1 & 1 \end{array}, \tag{6}$$

(ii) a playing action V_5' at the boundary between SO_2, SO_1, SO_3, and SO_4:

$$\begin{array}{c|cccc} & SO_1 & SO_2 & SO_3 & SO_4 \\ \hline V_5' & 0 & 1 & 0 & 0 \end{array}. \tag{7}$$

At one part

In the novel design of a play equipment, setting S_i makes arrangement O_i. Therefore, designers can set more playing actions in the same device, but selecting elements at one part of the play equipment depends on the designer's ability largely. For example, setting SO_1 and SO_4 generates new playing actions V_6': "jump." And setting SO_3 generates V_7': "scale up":

(i) a playing action V_6' in SO_1 and SO_4:

$$\begin{array}{c|cccc} & SO_1 & SO_2 & SO_3 & SO_4 \\ \hline V_6' & 1 & 0 & 0 & 1 \end{array}, \tag{8}$$

Typ(D_{ch}) / Tok(D_{ch}):

Tok(D_{ch})	SO_1	SO_2	SO_3	SO_4
V_1'	1	0	0	1
V_2'	0	1	0	0
V_3'	0	0	1	1
V_4'	1	0	1	1
V_5'	0	1	0	0
V_6'	1	0	0	1
V_7'	0	0	1	0

Typ(D_{ds}) / Tok(D_{ds}):

Tok(D_{ds})	E_1	E_2	E_3	E_4
T_1	0	1	0	0
T_2	1	0	0	1
T_3	0	0	1	1

Typ(D_{pl}) / Tok(D_{pl}):

E_1	E_2	E_3	E_4	O_1	O_2	O_3	O_4	Tok(D_{pl})	SO_1	SO_2	SO_3	SO_4
1	0	0	1	1	0	0	1	V_1	1	0	0	1
0	1	0	0	0	1	0	0	V_2	0	1	0	0
0	0	1	1	0	0	1	1	V_3	0	0	1	1

Figure 6: A description of a "playing structure design" by Chu maps.

(ii) a playing action V_7' in SO_3:

	SO_1	SO_2	SO_3	SO_4
V_7'	0	0	1	0

(9)

3.3.1. Constraint in Classification

Channel theory defines a constraint such as $\Gamma \vdash_A \Delta$. Given a classification A, a token $a \in \text{tok}(A)$ satisfies a sequent $\langle \Gamma, \Delta \rangle$ of typ(A) provided that if a is of every type in Γ, then it is of some type Δ. A constraint is a sequent $\langle \Gamma, \Delta \rangle$ for which, $\Gamma \vdash_A \Delta$. The following are part of constraints in classifications D_{ds}, D_{pl}, D_{ch}:

(1) constraint of D_{ds}

$$E_1 \vdash E_4, \qquad E_3 \vdash E_4, \tag{10}$$

(2) constraint of D_{pl}

$$O_1 \vdash O_4, \qquad O_3 \vdash O_4, \tag{11}$$

(3) constraint of D_{ch}

$$SO_1 \vdash SO_4. \tag{12}$$

Constraints $E_1 \vdash E_4$, $E_3 \vdash E_4$ in D_{ds} are directly translated in D_{pl}, but not in D_{ch}. This means that a designer's inference is described in D_{ds} and D_{pl}, because of D_{pl} being a step in which designers correspond parts of play equipment to playing actions, but which is not translated in D_{ch}. In other words, generating V_7' in tok(D_{ch}) disturbs establishment of $SO_3 \vdash SO_4$.

4. Discussion

In Channel theory, there are several ways of setting of *infomorphism* between same classifications. For example, we can set different *infomorphism* between 3 classifications D_{ds}, D_{pl}, D_{ch} shown in Figure 6. We can conclude that this case corresponds to players interpreting playing environments in different ways from designers' intentions, even though players seem to adopt the ways satisfying designers' intentions. We are now exploring the setting of classification in depth to describe this representation.

In this work, we discussed linked playing actions using the syntax structure of $\langle O, S, V \rangle$ binding them. Therefore, we are investigating a way of representing the linked playing actions by operation of classification in channel theory.

Furthermore, we discussed an environment where only a single play equipment and a single player exist. But a real playing environment can be seen as a medium for mediating plural equipment and players. Therefore, we are now investigating a way to develop our framework for multiactors.

5. Conclusions

We focused on a playing environment and analyzed the perception-action chains in order to argue playing environment on a theoretical ground. We showed that reductionism units such as therbligs are not suitable for analyzing perception-action chains. Then, we proposed representational units of playing actions $\langle O, S, V \rangle$, which have both properties of actions and environment.

There are high degrees of freedom for segmenting playing environments. $\langle O, S, V \rangle$ can be seen as one of the loose constraints for the segmentation. There are several alternatives for not only segmenting O_i but also selecting S_i and V_i. These constraints provide a guide for design. They are not excessively strict, therefore designers' ability can be utilized properly. But as long as designers follow the format $\langle O, S, V \rangle$, they are forced to pay attention to boundaries of $\langle O, S, V \rangle$, which enable designers to foresee the emergence of new playing actions.

Furthermore, $\langle O, S, V \rangle$ enables designers to interpret the playing environment as an *information channel* in terms of channel theory, which is also an appropriate loose constraint for designing a play environment. The establishment of an *information channel* between a designer and a player via play equipment supports in a mathematical way a good environment from the viewpoint of information flow.

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