Chapter 4

Artefacts of EM, PD and SD

Chapter 3 highlighted the importance of artefacts in determining the nature of EM, PD and SD. Further investigation of the nature of these artefacts requires an understanding of what makes them essentially different. This investigation demands a framework for identifying and contrasting the properties of artefacts.

This chapter compares the artefacts of EM, PD and SD to identify how they are essentially different. A framework is provided by a set of creative properties, characterized in the theory of creative cognition [FWS92], and their complementary analytical counterparts. The results of examining the artefacts of the lift project with respect to each of the properties are given. The characterization of artefacts is extended to construals for representing novel phenomena [Goo90] and engineering drawings [Fer92].

4.1 Definition

Established definitions of the term artefact provide an appropriate place to start defining what is meant by the term artefact as used in this thesis. The Webster dictionary [web13] provides two entries for the word artefact (or artifact):

> **1.** a usually simple object (as a tool or ornament) showing human workmanship or modification. **2.** a product of artificial character due to extraneous (as human) agency.

It is clear from these definitions that an artefact is something made by humans as opposed to naturally occurring. These definitions are of limited use because (1) is too specific and (2) is too general. A definition is needed that gives a better characterization of what an artefact is. Simon provides just such a definition by characterizing an artefact in terms of form (inner-environment), context (outer-environment) and purpose (the terms form and context are used by Alexander in a similar characterization [Ale67]):

> **A.** an artifact can be thought of as a meeting point - an "interface" in today's terms - between an "inner" environment, the substance and organization of the artifact itself, and an "outer" environment, the surroundings in which it operates. If the inner environment is appropriate to the outer environment, or vice versa, the artifact will serve its intended purpose [Sim81].

According to (A) an artefact is characterized, not so much by a physical object, but by an abstract boundary that divides the world into form and context. For example, the essential qualities of a cup, its purpose, to hold liquid, and its shape, approximately cylindrical, form an abstract characterization of the artefact. Since the abstract interface cannot exist in the world, it must be represented in the mind or by an artefact constructed for the purpose of representing knowledge. Norman [Nor91] defines a cognitive artefact:

> **B.** an artificial device designed to maintain, display, or operate upon information in order to serve a representational function.

The artefacts defined in (B), which include books, drawings and computers, are commonly used to empower the cognitive processes of the human brain during the construction of artefacts. However, contemporary research of cognitive artefacts has typically explored their use in what is essentially non-creative contexts [FWS92]. Research on cognitive artefacts has tended to focus on how they support the mental processes of analysis, rather than creativity, when they are used to represent familiar artefacts. Since cognitive artefacts have mostly been studied with respect to the construction of familiar products, such as road systems [Per95], they have arguably become associated with analysis.

In this thesis, the word artefact is used to mean the artefacts constructed during EM [BC95], PD and SD in the lift project:

- the LSD specification, visualization and animation of EM;
- the sketches of PD;
- the structure, behaviour and process models of SD.

Although the established meanings of the term artefact apply to these artefacts the definition of cognitive artefacts is perhaps the closest. However, because of its association with analysis, the term cognitive artefact perhaps best defines the artefacts of SD in the lift project. Since the artefacts of EM and PD were found to support creative cognition [FWS92] the artefacts in this thesis are simply referred to as "artefacts" without qualifying them as cognitive.

4.2 Need for artefacts and how they help cognition

Artefacts, such as those used during EM, PD and SD in the lift project, are needed to extend the limited information storage and processing capability of the human brain so that people, such as modellers, designers and software developers, can be more creative and analytical. The limitations of the human brain are well known in this respect:

- In the information processing model of the human brain memory is divided into short-term and long-term stores [HF75]. All new information is processed by short-term store before it becomes embedded in long-term store. The capacity and duration of short-term store is severely limited:
  - the duration of visual short-term store limited to a fraction of a second, even though the capacity is practically unlimited [Gre70, Gre94];
  - the capacity of verbal short-term memory limited to approximately seven units of information [Mil56] and its duration limited to approximately twenty seconds [HF75].

These limitations constrain the processing capability of short-term store and therefore reduce the flow of information into long-term store.

- Cognitive scientists [JL83, JL88, GS83] believe that people make predictions about the world by forming mental models: internal structures that represent the external reality in at least approximate ways [HT95]. Norman [Nor91] observes that mental models have their limitations:

  - mental models are incomplete;
  - people's abilities to "run" their models is severely limited;
  - mental models have a limited duration before parts of them are forgotten;
  - similar mental models become confused;
  - mental models are kept simple so as not to exceed the limited capacity.

  These limitations place constraints on what can be apprehended.

The artefacts of the lift project mirrored the short-term stores and mental models in the heads of the modellers, designers and software developers. In this way, the artefacts empowered the mental processes of analysis and creativity. Whether an artefact improved on analysis or creativity appeared to depend on the nature of the artefact.

4.3 Characterization of artefacts

In this section, the EM, PD and SD artefacts of the lift project are characterized in terms of the creative and analytical properties listed in Table 4.1.

The following definitions of creative properties are based on those given in [FWS92] (a review of this book is given in Appendix D) that describes them as being some of the most important for supporting creative cognition:

- **Novelty** is probably the most important. Although a familiar structure might be interpreted in creative ways the possibilities for creative discovery should be much greater if the structure is relatively uncommon to start with.

Creative	Analytical
Novelty	Familiarity
Ambiguity	Unambiguity
Implicit meaningfulness	Explicit meaning
Emergence	Completeness
Incongruity	Consistency and Congruity
Divergence	Convergence

Table 4.1: Creative and analytical properties

- **Ambiguity** should afford greater opportunities for creative exploration and interpretation. For this reason one might want to avoid imposing narrow interpretations onto the structures when they are being formed.

- **Implicit meaningfulness** is a general perceived sense of "meaning" in the structure. This sense of meaning is related to interpretation. Artefacts often seem to have a hidden underlying meaning to them which encourages further exploration and search.

- **Emergence** refers to the extent to which unexpected features and relations appear in the structure. These features and relations are not anticipated in advance and become apparent only after the structure is completely formed.

- **Incongruity** refers to the conflict or contrast among elements in a structure. This often encourages further exploration to uncover deeper meanings and relations in order to reconcile the conflict and reduce the psychological tension it creates.

- **Divergence** is related to ambiguity but refers more specifically to the capacity for finding multiple uses or meanings in the same structure. Something could be relatively unambiguous in terms of its underlying structure but still afford a variety of interpretations: "A hammer, for example, is a relatively unambiguous form but can be used in a variety of different ways - as a tool, a paperweight, a weapon and so on" [FWS92].

The following definitions of analytical properties were devised by the author as counterparts for the creative properties defined above. The properties of unambiguity, consistency and completeness are familiar in logic and mathematics to do with formal specifications [Win90, Sai96, Hal90, BH95, San88], convergence is based on the notion of convergent thinking [FWS92], explicit meaning is based on semantics, and familiarity is intended to be thought of as the opposite of novelty:

- In this thesis **familiarity** is the analytical counterpart of novelty. Familiarity is probably the most important analytical property because it implies there exists knowledge about the structure on which to base analysis.

- In this thesis **unambiguity** is the analytical counterpart of ambiguity. In the formal sense, a structure has the property of unambiguity if and only if it has only one meaning [Win90]. In this thesis, a structure is unambiguous when it provides little opportunity for creative exploration of its meaning.

- In this thesis **explicit meaning** is the analytical counterpart of implicit meaningfulness. In this thesis a structure has an explicit meaning when there is a general agreement about the meaning of the structure. This agreed meaning is typically represented as a statement in a commonly understood language, such as a natural language description or a C++ program. In such cases the meaning depends less on individuals and particular situations and more on symbols and conventions for representation.

- In this thesis **completeness** is the analytical counterpart of emergence. In the formal sense, a structure has the property of completeness if and only if inconsistencies in the structure can be detected by methods that are defined independently of the notion of truth [Hod77]. Most methods of analysis are defined independently of the notion of truth whereas creative exploration deals with truth. Formally, a structure is complete when all inconsistencies can be detected by analysis. Less formally, a structure is complete when searches fail to reveal any emergent features.

- In this thesis **consistency** and **congruity** are the analytical counterparts of incongruity. In the formal sense, a structure has the property of consistency if and only if it is not possible to derive any contradictions from it [Win90]. In this thesis consistency is treated as the formal case of congruity. Congruity refers more generally to the sense of harmony among elements in a structure.

- In this thesis **convergence** is the analytical counterpart of divergence. In this thesis convergence is a property of a structure that promotes convergent thinking: "In *convergent thinking*, one goes from an initial problem state through a series of prescribed operations in order to converge upon a single correct solution. Convergent thinking is ideal for well-defined problems for which there is only one allowable conclusion" [FWS92]. In this thesis convergence is associated with a methodical process arriving at one of possibly a number of satisfactory solutions.

What follows is a characterization of EM, PD and SD artefacts of the lift project in terms of the creative and analytical properties defined above.

For convenience, the illustrative examples that go with this chapter have been organized into an appendix at the end of this chapter.

4.3.1 Novelty and familiarity

The SUL and MUL were found easier to represent than the Hydrolift. The SUL and MUL were familiar to the modellers, designer and software developers in the lift project. The modellers were able to represent the structure and function of the SUL and MUL in visualizations and animations without first constructing an LSD specification. The designers were able to produce detailed sketches of the SUL and MUL components. The structure and function of the SUL and MUL were described in requirements statements, as shown in Example 4.1.

Little use was made of an LSD specification in constructing the SUL and MUL visualizations and animations. The SUL and MUL were modelled in the lift project by writing DoNaLD and ADM scripts directly. The modellers were already familiar with the way the lift system looked and functioned from their viewpoints as users so were able to turn these ideas directly into visualizations and animations, as shown in Example 4.2. The SUL and MUL LSD specifications were written after the construction of visualizations and animations had already commenced.

The approach taken by modellers changed when representing the Hydrolift, with more emphasis being placed on the construction of the LSD specification. The modellers used the LSD specification during the early stages of modelling to represent their first tentative interpretations of the Hydrolift, as shown in Example 4.3. The LSD specification was used by modellers to share their early interpretations of the subject with one another. It was subsequently used as the basis for constructing a visualization and animation.

Stating the requirements for the novel Hydrolift was found to be more difficult than stating the requirements for the familiar SUL and MUL. The problem was describing the subject in sufficient detail, for the software developer to construct structure, behaviour and process models, with no other reference than the vague idea of what a Hydrolift was. The requirements for the Hydrolift were stated by describing detailed EM and PD artefacts that represented the structure and function of the subject in terms of geometrical shapes and prescribed behaviours.

4.3.2 Ambiguity and unambiguity

There always seemed to be multiple interpretations of the subject when it came to stating the requirements in the lift project, as shown in Example 4.4. This suggests that the SUL, MUL and Hydrolift were ambiguous with respect to natural language. It was found difficult to decide between alternative statements indicating that there was no clear correspondence between the elements in the statement of requirements and the elements in the subject it described. It is this lack of correspondence between the domain of natural language and the domain of lift systems that made the statement of requirements in the lift project ambiguous.

Although essentially ambiguous with respect to general interpretation, the statement of requirements was found to be unambiguous with respect to the specific interpretation of structure and function. Analysis of a statement of requirements resulted in few alternative structure, behaviour and process models, as shown in Example 4.5. This was probably due to the direct correspondence between the elements in the statement of requirements and the elements in the SD models. For example, nouns and verbs in the statement of requirements corresponded to classes and actions in the structure model.

Few ways were found of describing the SUL, MUL and Hydrolift in an LSD specification suggesting that the subjects of the lift project were essentially unambiguous with respect to LSD, as shown in Example 4.6. Few significant changes were made during the construction of visualizations and animations indicating a direct correspondence between the LSD specification, in terms of observables and agents, and the subject as perceived by the modeller. It is this correspondence between the domain of LSD and the domain of lift systems that made the LSD specifications in the lift project unambiguous.

It was found that the artefacts of EM and PD afforded reinterpretation similar to that of the subject. The artefacts preserved the essential ambiguity of the subject through mimicry. This allowed the artefacts created by modellers and designers at one stage of the lift project to be creatively reinterpreted later in the lift project in place of the subject, as shown in Example 4.7. For example, the artefacts constructed to represent the MUL were reinterpreted in the construction of the artefacts to represent the Hydrolift.

4.3.3 Implicit meaningfulness and explicit meaning

The meaning of the structure, behaviour and process models was found to be essentially independent of the subject. The meaning of each model was defined explicitly in terms of the other models and the statement of requirements, as shown in Example 4.8:

- the meaning of the process model was defined in terms of the statement of requirements and the behavioural model;
- the meaning of the behavioural model was defined in terms of the statement of requirements and the structure model;
- the structural model was defined explicitly in terms of the statement of requirements.

The dependency between the statement of requirements and the subject was not passed on to the models through transformation. The nouns and verbs, that give the statement of requirements its meaning, were treated as symbols in the construction of the structure, behaviour and process models: the verbs and nouns from the statement of requirements were listed then the positioning of the verbs and nouns in the statement of requirements was analyzed.

The analysis of the statement of requirements was found to be simple in comparison to formulating it in the first place. Stating the requirements meant repeated interpretation of the SUL, MUL and Hydrolift until a consistent description of the structure and function of the subject was achieved. EM and PD artefacts were found to help in this process of interpreting the subject in terms of nouns, verbs, phrases and sentences. It was found easier to construct and describe EM and PD artefacts, with the same sense of meaningfulness as the subject, than it was to write a statement of requirements based on the subject alone.

The EM and PD artefacts were found to have the same sense of implicit meaningfulness as the subject they represented, as shown in Example 4.9. This meaningfulness was given by the direct correspondence between artefact and subject. The obvious similarities between sketches, visualizations and animations meant that their meaningfulness to modellers and designers in the lift project was not surprising. The meaningfulness of the LSD specification was more surprising because it was neither visual nor interactive like the subject. The direct correspondence between the LSD specification and the subject as perceived by the modeller seemed to give it a similar depth of meaning as the visualization and animation.

4.3.4 Emergence and completeness

The EM artefacts in the lift project were found to have the property of emergence, as shown in Example 4.10. Modellers in the lift project would think they had finished an artefact only to find emergent features indicating incompleteness. Features emerged during exploration that were not intentionally included within the artefacts by the modellers. Construction of EM artefacts can be thought of in two phases:

1. representing the obvious features of the subject in the LSD specification, visualization and animation;

2. exploring the LSD specification, visualization and animation to discover emergent features and searching for the features in the subject.

The LSD specification was found to be least helpful in discovering emergent features because it represented elements of the subject that were obvious to the modellers including observables and agents. The visualizations and animations, however, represented structural and functional features of the subject that were not obvious at the start of modelling and only emerged in the subject after repeated generation and exploration of artefacts. Emergent features discovered by modellers in visualizations and animations were subsequently incorporated into the LSD specifications.

The statement of requirements was found to be complete in the sense of Hodges [Hod77] discussed above. It was complete with respect to the structure, behavioural and process models, as shown in Example 4.11. Essentially, the structure of the statement of requirements contained the information necessary to construct the structure, behaviour and process models without having to explore the meaning of its contents. All inconsistencies in the models could be found by examining the structure of the statement of requirements without having to consider the truth of the statement. This meant that the SD statement of requirements and structure, behaviour and process models were complete.

4.3.5 Incongruity and congruity

The concept of the Hydrolift was chosen for its incongruity. Based on the familiar notion of a conventional lift system, the SUL and MUL contained few conflicting elements. The Hydrolift combined the incongruous elements of water and conventional lift systems.

The designer began by constructing an incongruous sketch of the Hydrolift then continued by resolving the conflicts between elements within the sketch, as shown in Example 4.12. The designer first sketched the MUL with water filling the shaft. The resulting artefact preserved the same sense of incongruity as the imagined subject by juxtaposing representations of a conventional lift system and water. The rest of the design of the Hydrolift involved adding components representations, including a pump and sonar, to resolve the conflicts.

A similar approach was taken by modellers in the lift project. Instead of adding a representation of water, the modellers added definitions of agents associated with water, including a pump and sonar, to the MUL LSD specification. The resulting specification preserved the same sense of incongruity as the imagined subject. The rest of the modelling involved the reinterpretation of MUL observables and reassigning of definitions and protocols to new pump and sonar agent definitions, as shown in Example 4.13.

The approach taken by modellers and designers in describing the Hydrolift could not be used in SD. The MUL statement of requirements and models could not be meaningfully juxtaposed with representations of water and Hydrolift components. An important property of the SD artefacts was consistency which is related to completeness discussed earlier and defined at the beginning of this chapter. The artefacts had to be descriptions of the Hydrolift after all the inconsistencies about structure and function had been resolved. This was achieved in the lift project by interpreting the congruous EM and PD Hydrolift artefacts once they had been constructed.

4.3.6 Divergence and convergence

SD artefacts encouraged convergence towards the goal of an operational model of the subject. The SD process typically began with a statement of requirements. This was transformed into a structure model that was then transformed into the behavioural model that was finally transformed into the process model by following the SD method of analysis. Each transformation brought the software developer closer to their goal of an operational model of the subject. By following the method of analysis in the lift project the software developers were guaranteed to converge upon their goal of an operational model of the subject.

The artefacts of EM encouraged convergence towards as well as divergence from the goal of an animated model of the subject. The modeller generally took convergent steps whenever possible in the lift project by adding ADM entities to circumscribe the behaviour of visualizations. However, the modellers also explored artefacts to discover alternative behaviours in the LSD specifications and visualizations that were subsequently evaluated against the subject. By taking convergent and divergent steps the modeller was able to achieve his goal of an animation by side-stepping obstacles that he encountered on the way, such as limitations in the tools and insufficient knowledge about the subject.

Pugh recommends the method of "controlled convergence" for conceptual design based on the use of decision matrices described in Chapter 2: "[controlled convergence] allows alternate convergent (analytic) and divergent (synthetic) thinking to occur, since as the reasoning proceeds and a reduction in the number of concepts comes about for rational reasons, new concepts are generated. It is alternately a generative (creative) and a selection process." [Pug91, Pug96]. This design activity parallels convergence and divergence in EM.

4.4 Further characterizations of artefacts

In this section the construal [Goo90] and design drawings, in the sense of Ferguson [Fer92, Fer77], are characterized in the same way as the artefacts of the lift project.

4.4.1 Construals

In [Goo90] Gooding explores how scientists share their experiences of a novel phenomenon in the absence of an existing framework for interpretation:

> I argue that when negotiating agreement about what they are seeing (as distinct from personal experience) observers exchange tentative constructs or *construals* of their personal experience ... Construals are a means of interpreting unfamiliar experience and communicating one's trial interpretations. Construals are practical, situational and often concrete. They belong to the pre-verbal context of ostensive practices ... my purpose is to draw attention to the neglect of something important in the history of science and probably to learning generally, namely, how observers bring unruly experience into the domain of public discourse ... This book is about how such experience moves from an observer's private world into the domain of discourse and argument [Goo90].

So, the purpose of a construal is to provide a means of interpreting novel experience and communicating trial interpretations. Gooding [Goo90] describes a variety of construal types that were used by Faraday in his experiments to understand electromagnetic phenomena:

- Sketches that "conveyed, through an image, aspects of experience that had been (or was being) made sense of," in particular, Faraday is famous for his representation of the magnetic field around conductors in the form of concentric circular directed arrows.

- Apparatus - a wooden dowel with an arrow drawn on it, wires and magnets - that was manipulated by Faraday in order to model the dynamic aspects of his experience.

- Words were used by Faraday to describe construals when the communication of experience over space and time was necessary, however, the description was not used in place of the construal only as an approximation to it.

Gooding [Goo90] also describes in some detail the typical context for construals. The context must consist of at least one observer for the construal to fulfill its purpose. In addition, the context consists of the means of generating construals and the influences that determine its eventual form: "Discovery takes place in a context replete with resources and motivations, images, models, assumptions, percepts, values, instruments, techniques, goals, allies, rivals, enemies, and so on" [Goo90].

The emphasis on purpose over form, and the variety of possible forms and contexts, suggests that a construal can be appropriately thought of as an artefact in the sense of Simon [Sim81]. With this in mind it should be possible to identify creative and analytical properties of construals. Certainly in [Goo90] Gooding provides some evidence for the emergence of creative properties:

- The argument that construals provide nonverbal "reference points" for language suggests the creative property of implicit meaningfulness, also that it becomes "easy to see" phenomena in terms of construals and they pave the way for the "self-evidence" of experience.

- Stating that "correspondences" between words and what they denote "emerges" as an instance of construing indicates the creative property of emergence.
- Saying construals "may be compatible with several theories or with none" indicates a variety of creative properties including inconsistency.

It is the presence of these properties that support creative exploration of the subject that determines the success of a construal: "The outcome of exploration with a construal will decide whether it is developed, held as an unexplored possibility, or abandoned ... the few that pass into the interpretative vocabulary of science do so in virtue of their heuristic, communicative and instrumental value."

In addition, Gooding [Goo90] provides some evidence of the analytical properties that emerge in experience with respect to a highly developed construal:

- The following suggests the analytical property of explicit meaning emerging as the result of generating a construal:

  > Some construals survive and become interpretations whose reference is gradually stabilized in terms of established observational practices. As interpretations they engage theoretical assumptions and problems ... the agency that produced it disappears [Goo90].

- Arguing that "interpretations are more literary and more theory-oriented versions of construals" suggests that construals converge upon, yet do not quite become, unambiguous, consistent and complete representations of phenomena.

So, as the development of a construal progresses more and more analytical properties emerge in the experience of the phenomena by the observer.

4.4.2 Design drawings

In [Fer92] Ferguson gives an account of how the creation of drawings help designers clarify their ideas for products and communicate their ideas to others:

> In order to produce a new machine, structure, or other technological artefact, two separate but closely related processes are generally required.

> In the first, engineering designers convert the visions in their minds to drawings and specifications. In so doing, they solve an ill-defined problem that has no single 'right' answer but has many better or worse solutions. Engineers learn a great deal during the process of design as they strive to clarify the visions in their minds and seek ways to bring indistinct elements into focus. When the designers think they understand the problem, they make tentative layouts and drawings, analyze their tentative designs for adequacy of performance, strength, and safety, and then complete a set of drawings and specifications. Those who will make or build the machine, structure or system can learn exactly what they are expected to produce. Until their task is complete and the project has been turned over to the user, those drawings and specifications will be the formal instructions that guide their work [Fer92].

So, drawings and specifications represent the final products of a conversion process from the idea in the mind of the designer to physical realizations of it. Ferguson [Fer92] identifies three forms of sketches that help the designer in this process:

- "The first is the *thinking sketch.* Leonardo's [da Vinci] notebooks contain dozens of such sketches, and a host of later engineers have used sketches to focus and guide nonverbal thinking."
- "The next is the *prescriptive sketch* which is sometimes scaled and which is made by an engineer to direct a drafter in making a finished drawing."
- "The third kind of sketch, produced constantly in exchanges between technical people, is the *talking sketch.*"

Each type of sketch is used in a different context: the thinking sketch is private to a designer, the prescriptive sketch is public and the talking sketch is between a group of designers. The talking sketch is unusual because it is neither private nor public: "Such sketches make it easier to explain a technical point, because all parties in a discussion share a common graphical setting for the idea being debated" [Fer92].

It has already been previously argued in this chapter that design sketches are artefacts and that creative and analytical properties emerge in the design during the creation of a sketch. There is evidence in [Fer92] to support this argument. There is evidence for creative properties:

- Saying that "some of the choices will have been wrong" suggests the creative property of incompleteness in the design process.
- "Making wrong choices is the same kind of game as making the right choices; there is often no *a priori* reason to do one thing rather than another, particularly when neither has been done before" suggests the creative properties of ambiguity and novelty.
- The statement that "various members of a design group can be expected to have divergent views of the most desirable ways to accomplish the design they are working on" indicates the creative property of divergence.
- "The precise outcome of the [design] process cannot be deduced from its initial goal" suggests the creative properties of ambiguity, inconsistency and incompleteness.

In addition, there is evidence in [Fer92] for analytical properties with respect to prescriptive sketches and finished drawings:

- "Engineering drawings are expressed in a graphic language, the grammar and syntax of which are learned through use; it also has idioms that only initiates will recognize" suggests the analytical property of explicit meaning in finished drawings.
- Saying that "because the drawings are neatly made and produced on large sheets of paper, they exude an air of great authority and definitive completeness" indicates the analytical property of completeness.
- Stating that drawings are "precise" suggests the analytical properties of unambiguity, consistency and completeness.

So, as the design process progresses more and more analytical properties emerge in the ideas of the designers for the new product.

4.5 Summary

In this chapter the artefacts of EM, PD and SD were compared. It was found that the SD artefacts in the lift project had the properties of

- familiarity,
- unambiguity,
- explicit meaningfulness,
- completeness,
- consistency, and
- convergence

The artefacts of EM and PD were found to have the properties of

- novelty,
- ambiguity,
- implicit meaningfulness,
- emergence,
- incongruity, and
- divergence

and yet still have some of the properties of the SD artefacts. This suggests that the artefacts of SD are essentially analytical in nature whereas the artefacts of EM and PD support creativity as well as analysis.

Finally, this chapter extends the characterization of artefacts to construals [Goo90] and design drawings, in the sense of Ferguson [Fer92, Fer77]. The characterization uncovers similarities between construals, sketches and EM artefacts.

Appendix: Illustrative examples for Section 4.3

Example 4.1. Familiarity in stating requirements. The statement of requirements for the SUL

> On each landing there is a button and in the car there is a button for each floor. The user makes a request for the car to come to his landing by pressing a button. The shaft mechanism moves the car to his landing and opens the door. The user enters the car and presses a button. The shaft mechanism moves the car to the landing he requested and opens the door. The user exits the car. For safety the door is opened and closed by the brake ensuring that the door is only open whilst the brake is on.

shows a familiarity with the details of the individual components and how they function and interact with one another.

Example 4.2. Familiarity in EM. The SUL visualization shown in Appendix C and the ADM shaft entity

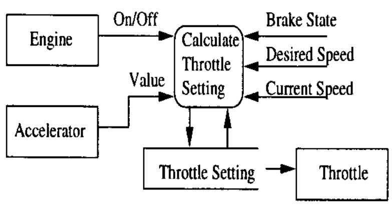
```
entity shaft() {
definition
  direction is (floor < destination) ?  UP :
               (floor > destination) ?  DOWN : NIL
action
  brake == OFF -> floor = floor + direction,
  brake == ON && direction != NIL -> brake = OFF
}
```

show a familiarity with the structure and function of the SUL:

- the shaft consists of five floors;
- if the break is on and the lift car has a destination then the next action is to release the break.

Both the visualization and ADM script represent decisions about the shape and function of the shaft that are not represented in the LSD description.

In the VCCS and digital watch projects [BBY92, BC95] the function and structure of the subjects were familiar to the modellers. The object-oriented definition of the VCCS [Boo86, Deu88, Deu89] and Statechart definition of the digital watch [Har88] showed a familiarity with both devices. The EM projects involved implementing the formal models directly in definitive languages without much use of LSD. There are clearly parallels between part of the data flow diagram for the VCCS [Boo86]



and the outline for the throttle manager agent

```
agent throttle_manager {
state
  throttleStts throttlePos
oracle
  measSpeed cruiseSpeed cruiseStts engineStts accelStts
handle
  throttleStts
}
```

suggesting that the familiar functional detail of the VCCS given in [Boo86] was represented directly in LSD and subsequently in EDEN.

Example 4.3. Novelty in EM. The LSD specification of the SUL shaft agent, prior to the construction of the visualization and animation

```
agent shaft() {
state
  floor destination direction
oracle
  brake
handle
  brake
derivate
  direction is (floor < destination) ?  UP :
               (floor > destination) ?  DOWN : NIL
protocol
  brake == OFF -> floor = floor + direction,
  brake == ON && direction != NIL -> brake = OFF
}
```

lacks the commitment to structure and function that comes from familiarity with the subject:

- no indication of the shape of the shaft;
- no detail of the behaviour of the shaft.

LSD was found suitable for representing aspects of the subjects that were not yet familiar to the modeller. Although the above definition appears similar to the subsequent ADM script the status and meaning of the LSD specification is very different from the ADM script as mentioned in Chapter 2.

LSD was made use of during the early stages of the classroom interaction project when the combined behaviour of pupils and teachers was unfamiliar to the modeller. It was fairly straightforward for the modeller to identify pupils as agents, but behavioural aspects were less well understood. The modeller continued by attributing states, oracles and handles to the pupil:

- the location of the pupil in the classroom (`location` state),
- the activity that the teacher is engaged in (`teacherActivity` oracle), and
- the ability for a pupil to change their mind (`memory` handle).

Descriptions of the behaviour of pupils and teachers emerged during EM as the modeller became more familiar with the behaviour of pupil and teacher interaction through the process of observation and experiment. This knowledge was subsequently represented in visualizations and animations of the classroom.

Example 4.4. Ambiguity in stating requirements. The subject of the MUL brake was found to be ambiguous with respect to stating its requirements with many ways of describing the brake emerging during the lift project. For example, statements describing the car stopping included the following

- "The shaft mechanism stops at a landing then the brake is applied".
- "The shaft mechanism begins stopping before the destination landing, allowing the car to gently decelerate, then the brake is applied".
- "The shaft mechanism moves the car towards a destination landing stopping whenever the brake is applied".

Each statement means something slightly different but all describe the same observation of the car stopping. The last statement was the one actually used in the statement of requirements for the MUL.

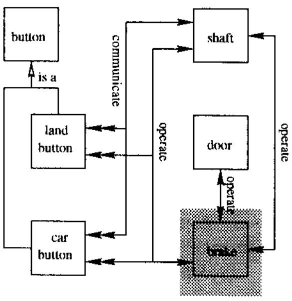
Example 4.5. Unambiguity in SD. The MUL requirement for the brake

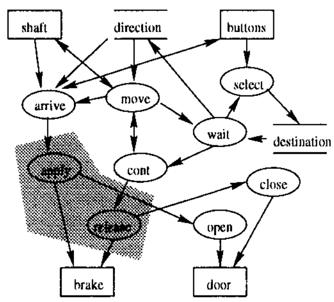
> ... The shaft mechanism moves the car towards a destination landing stopping whenever the brake is applied. The brake is applied whenever the car arrives at a landing requested by a user ... The shaft mechanism releases the brake and starts the car moving again. For safety the door is opened and closed by the brake ensuring that the door is only open whilst the brake is on.

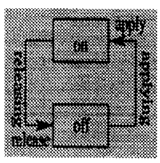
was found to be unambiguous with respect to the representation of structure, behaviour and function. By analyzing the structure of the statement, and largely ignoring the content, by treating the nouns and verbs as essentially meaningless tokens, it was found that

- the "brake" is related structurally to the "shaft", "door" and "buttons",
- the "brake" is "applied" by the "buttons" and "released" by the "shaft", and
- the "brake opens" and "closes" the "door".

This information was used to construct the model for the brake








```
apply is
        apply brake;
        generate opening.

release is
        generate closing;
        release brake
```

that explicitly shows the structural and functional relations identified in the analysis of the requirements.

Example 4.6. Unambiguity in EM. It was found in the lift project that the LSD agent definitions, such as the definition of the shaft

```
agent shaft() {
state
  floor destination direction
oracle
  brake
handle
  brake
derivate
  direction is (floor < destination) ?  UP :
               (floor > destination) ?  DOWN : NIL
protocol
  brake == OFF -> floor = floor + direction,
  brake == ON && direction != NIL -> brake = OFF
}
```

seemed to represent the subject unambiguously, with respect to the subject, with few alternative representations emerging during the project. There seemed to be a direct correspondence between the agents and observables in the LSD definitions and those perceived within the subject:

- the shaft agent corresponded to the notion of the mechanism responsible for raising and lowering the car;
- the observables corresponded to what the modeller imagined the shaft must be sensitive to or be able to act upon in order to move the car.

This suggests that the choice of agents and observables corresponded closely to peoples' perceptions of lift systems.

The LSD specification constructed during the classroom simulation project is also essentially unambiguous. There is clearly a direct correspondence between pupils and teachers and LSD agents. The meaning of observables, such as

- `name`,
- `activity`, and
- `ability`

have relatively unambiguous common-sense meanings. or teachers.

Example 4.7. Ambiguity in EM. The first two guards of the MUL LSD specification of the landing

```
agent landing(_F) {
state
  landButton
oracle
  floor direction brake
handle
  brake destination
protocol
  landButton{_F} == UP && _F == floor + 1 && brake == OFF -> brake = ON,
  landButton{_F} == DOWN && _F == floor - 1 && brake == OFF -> brake = ON,
  landButton{_F} != OFF && direction == NIL -> destination = _F,
  floor == _F -> landButton{_F} = OFF
}
```

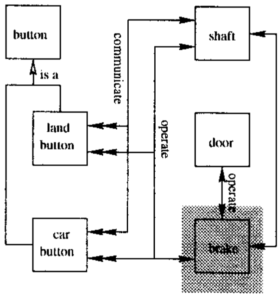
represent the observation of the car arriving at the landing. At a conceptual level there is little ambiguity as to what this observation means. However, at a more detailed level this observation may be made in many different ways. There is scope for creative exploration of the alternatives. For example, in the specification of the same two guards in the Hydrolift landing

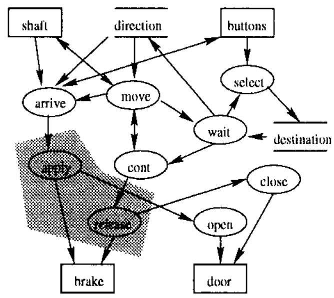
```
landButton{_F} == UP && sensed{_F - 1} == UP && brake == OFF
landButton{_F} == DOWN && sensed{_F + 1} == DOWN && brake == OFF
```

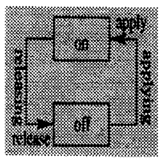
the observation is realized by a sensor that is attached to the side of the shaft and detects the direction of travel of the car.

Ambiguity in EM artefacts generally arise when the modeller cannot observe a feature of the subject. In the classroom simulation project the modeller is able to describe the observables of pupils and teachers quite unambiguously because they can be observed through experimentation. This was not so for the definition of the "decision function": "the decision function is the part most crucial to modelling the realistic behaviour of pupils because it decides what the pupil will do next depending on the situation they are currently in and the contents of their memory" [Dav96]. The definition of the decision function is more ambiguous because it represents the workings of the mind that are inherently unobservable and difficult to conceptualize therefore having many possible interpretations. The modeller implemented the decision function in ADM by adopting a traditional method of functional decomposition (p.54 [Dav96]).

Example 4.8. Explicit meaning in SD. The MUL artefacts constructed by software developers







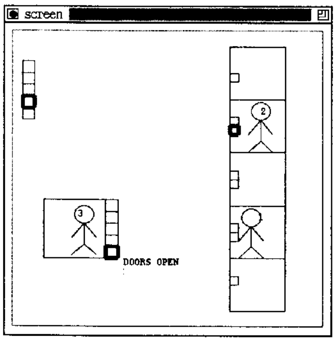

```
apply is
        apply brake;
        generate opening.

release is
        generate closing;
        release brake
```

had an explicit meaning given by the relations between parts. These relations define parts of the model in terms of the parts of other models. There are also relations between parts of models and elements of the statement of requirements:

- The nouns "brake" and "shaft" are related to the object Class representations in the structure model.
- The verb phrase "the door is opened and closed by the brake" are related to the functional association between the brake and door Object classes in the structure model.
- The verb phrase "The shaft mechanism moves the car towards a destination landing stopping whenever the brake is applied" is related to the functional association between the brake and shaft Object classes in the structure model.
- The phrase "The brake is applied whenever the car arrives at a landing requested by a user" is related to the functional association between the brake and lift button Object classes in the structure model.
- The verbs "applied" and "released" are related to the actions and transitions of the brake Object class represented in the behaviour model.

This closed set of relations between the statement of requirements and models gave them an explicit meaning.

Example 4.9. Implicit meaningfulness in EM. It was found that the MUL visualization/animation



and LSD specification

```
agent landing(_F) {
state
  landButton
oracle
  floor direction brake
handle
  brake destination
protocol
  landButton{_F} == UP && _F == floor + 1 && brake == OFF -> brake = ON,
  landButton{_F} == DOWN && _F == floor - 1 && brake == OFF -> brake = ON,
  landButton{_F} != OFF && direction == NIL -> destination = _F,
  floor == _F -> landButton{_F} = OFF
}
```

captured a similar sense of meaningfulness as the subject. This suggests a direct correspondence between the elements of the artefacts and the elements of the subject in the mind of the modeller. In the case of the landing agent

- stating behaviour of the landing in terms of cause-and-effect,
- representing the landing as an agent which senses and responds to its environment, and
- concentrating on the observable aspects of the landing

all contribute to the intuitive meaning of the LSD specification.

Example 4.10. Emergence and completeness in EM. During the early stages of constructing the MUL artefacts there seemed no reason to change the SUL LSD specification of the user. However, after experimenting with the MUL visualization and animation it emerged that for a multiple user lift there had to be an up and a down button on each landing for the user to indicate his desired direction of travel. These features only emerged in the subject after the issue of request scheduling had to be addressed in the animation and ADM script. The protocol for pressing the button in the SUL

```
TRUE -> landButton{floor{_U}} = ON
```

was changed to

```
TRUE -> landButton{floor{_U}} = UP,
TRUE -> landButton{floor{_U}} = DOWN
```

to include this emergent detail. It was realized that the change did not alter the essential meaning of the specification - the landing button being up or down still meant that it is was on - only the level of detail at which it represented the subject. This suggests an essential completeness about the LSD specification with respect to the subject.

Unexpected features were seen to emerge through interaction with visualizations and animations in most EM projects:

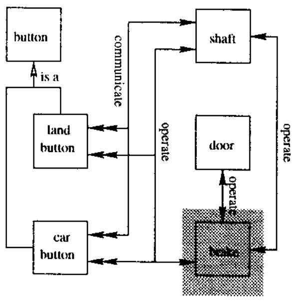
- it emerged during simulated sailing in the SBS that the model represented the boat capsizing even though this behaviour was not intentionally included by the modeller;
- the insufficient modelling of the synchronization between OXO players emerged when the computer-player played out-of-turn and won;
- it emerged during the railway simulation that the implementation of the guardsman protocol resulted in him stepping onto the track as the train was departing the station.

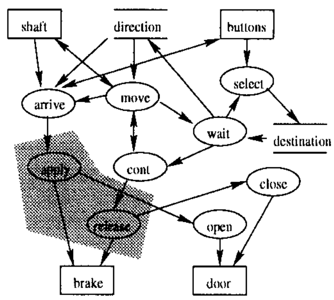
All these emergent features were identified and explored by the modellers resulting in subsequent modified models. This process resulted in a better understanding of the behavioural details of sailboats, playing OXO and railway systems.

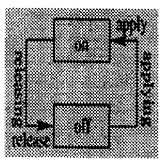
Example 4.11. Completeness in SD. The statement of requirements for the brake

> ... The shaft mechanism moves the car towards a destination landing stopping whenever the brake is applied. The brake is applied whenever the car arrives at a landing requested by a user ... The shaft mechanism releases the brake and starts the car moving again. For safety the door is opened and closed by the brake ensuring that the door is only open whilst the brake is on.

was found to be complete with respect to the MUL structure, behaviour and process models



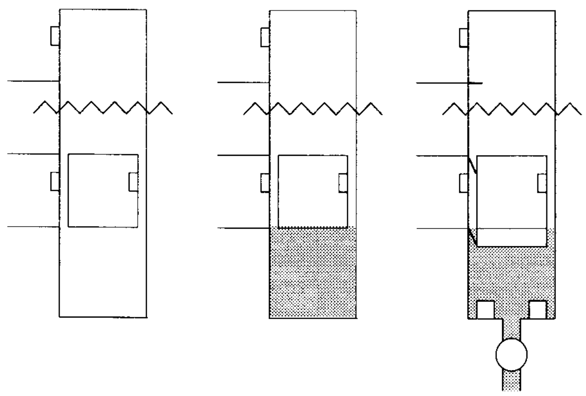





```
apply is
        apply brake;
        generate opening.

release is
        generate closing;
        release brake
```

It was found possible to check for inconsistencies in the description of structure and function in the statement, using the models, without having to think much about what the statement meant.

Example 4.12. Incongruity and congruity in PD. The following three sketches



show the three steps in designing the Hydrolift:

1. the designer retrieved their sketch for the MUL;
2. the designer added a representation of water filling the shaft resulting in the conflict between a conventional lift system and a hydraulic lift system;
3. the designer resolved the conflict between the two representations by adding more detail to the sketch in the form of appropriate components, such as a pump and sonar.

The design process was largely motivated by the designer's desire to progress from an incongruous sketch of a conventional lift system with water to a congruous sketch of a Hydrolift.

Example 4.13. Incongruity and congruity in EM. One source of conflict within an LSD specification is the lack of oracle-handle pairs. An oracle-handle pair indicates a link between agents. In the MUL the oracles and handles of the car and shaft agents are

```
floor direction brake destination
```

The modelling of the Hydrolift involved defining the pump, sonar and sensor agents with the following oracles and handles

```
pressure chan1 chan2 direction sensed
```

Each set of observables belong to a different domain. The MUL set are high-level concepts associated with use whereas the Hydrolift set are detailed concepts associated with engineering. The need to link the car, shaft, pump, sonar and sensor in the Hydrolift resulted in the creative exploration of alternative engineering interpretations of the MUL observables:

- the floor was interpreted as the pressure of the column of liquid at the base of the shaft;
- the direction was interpreted as the signal from a direction sensor;
- the destination was interpreted as a target pressure.

The changes resulting from these interpretations can be seen in comparing the MUL car and shaft agents with the pump agent in Appendix C. Such interpretations enabled the modeller to form oracle-handle pairs between agents to form a system.

The decision in the OXO project to define an umpire and board agents can be explained in terms of resolving conflicts due to observables. In the OXO model the LSD definition of the player

```
agent Player(P, O) {
state
  choice
oracle
  turn Board
handle
  Board
protocol
  turn == P && available(Board, choice) -> take(Board, choice),
  !available(Board, choice) -> make_new_choice()
}
```

is incongruous to the modeller because of the observations of oracles without corresponding handles. This conflict was resolved in the OXO project by defining an umpire and board agents.

Example 4.14. Divergence and convergence in EM. The construction of the Hydrolift artefacts in EM involved divergence from and convergence towards the goal of a detailed animation.

An example of a divergent step was the juxtaposing of the MUL LSD specification with the LSD specification of a pump, sonar and direction sensor (see Example 4.13) which resulted in the creative exploration of alternative representations of the Hydrolift without much progress towards a detailed animation.

An example of a convergent step was the commitment to the LSD specification of the pump, shown in Example 4.13, and its transformation into the ADM entity

```
entity pump() {
definition
  k = 100,
  change is (pressure < target) ? k :
            (pressure > target) ? -k : 0
action
  target == pressure + change && brake == OFF -> brake = ON,
  change == 0 -> target = chan1*k,
  pressure == target -> chan2 = target/k,
  brake == OFF -> pressure = pressure + change,
  brake == ON && change != 0 -> brake = OFF
}
```

which formed a part of the final animation. It was found that the mixture of divergence and convergence was essential to the construction of the Hydrolift artefacts.
