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A Formalism for Coupled Design/Learning Activities

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Abstract

This paper presents a formalism to represent the inextricable link that exists between design and learning. It provides an approach to study and analyse the complex relationships that may exist between design and learning. It suggests that design and learning are linked at the knowledge level (epistemic link), in a temporal manner and in a purposeful manner through the design and learning goals.

1 Introduction

That design is inextricably linked with learning has been posited by several researchers in Machine Learning in Design (MLinD). Persidis and Duffy [1] succinctly state the relationship between design and learning: '*Design as a problem solving activity is inextricably linked with learning*.'

Chabot and Brown [2] state that "There should be no argument about the fact that designers learn while designing." While this fact may be accepted in the MLinD research community, to-date there is a lack of knowledge as to the nature and manner in which this inextricable link exists between design and learning. The purpose of this paper is to propose a formalism that represents the inextricable link between design and learning and evaluate the proposed formalism using several design activities and the related learning activities. It is envisaged that the proposed formalism could lead to a better insight into the coupled design/learning activities. This, in turn can contribute towards the building of an Intelligent Design Assistant (IDA) that "adapts to the knowledge requirements of the designer, carries out learning when requested, presents automatically generated knowledge, continually maintains (i.e. updates and evolves) its knowledge source, provide explanations about learned knowledge and provide suggestions, which may help guide the designer when exploring a design domain or solving a particular design problem" [3]. A clear understanding of the coupled activities expressed formally can thus ensure in an integrated and structured manner how design and learning functionalities can be incorporated into design support systems or an IDA.

Learning and designing can be described at different levels of abstraction. Thus in Section 2, it is necessary to show that the activities of learning and design can be described at the knowledge level. In Section 3, a design activity is defined formally to show that associated with each design activity is the knowledge change that results from the activity. Section 4 describes briefly the five basic elements of a learning activity that was first presented in Sim and Duffy [4]. Having characterised what the basic elements of a design activity and learning activity are the aim of Section 5 is to present a formalism to show the nature and manner in which design and learning activities can be coupled together. The discussion in Section 6 shows how the formalism proposed complements the dimensions proposed by Reich [5].

2 Knowledge level as the basis for the formalism

Systems (both natural and artificial) of any reasonable degree of complexity can be designed or explained at any number of different description levels [Simon [6], Newell [7], Alberts [8], DasGupta [9]). In fact, multiple description levels constitute a general (indeed, defining) characteristic of all complex systems. Recognising that complex systems can be described by functionally autonomous levels and yet organised hierarchically, DasGupta [9] extends the notion of description levels to the cognitive system - the mind-brain complex. For the cognitive systems, these widely accepted levels are:

- The knowledge level - wherein, cognition is described or explained in terms of goals, actions, knowledge and intended rational behaviour.
- The symbol level - in which cognitive processes are described or explained in terms of symbols (and symbol structures), memory (in which symbols are held), operations (on symbols), and interpretations (of the operations).
- The biological level - wherein cognition is described or explained in terms of biological structures or structures that are abstractions of biological systems (e.g. neural systems).

The knowledge level is based on Newell's Knowledge Level Hypothesis which states that:

> "*There exists a distinct computer system level lying immediately above the symbol level, which is characterised by knowledge as the medium and the principle of rationality as the law of behaviour*."

Dietterich [10] has shown that learning can be described at the knowledge and symbol level while Kocabas [11] has extended the description to include the device level[1]. DasGupta develops his computational theory of scientific creativity by showing that knowledge on concepts of micro-programming described at the knowledge level led Wilkes [12, 13] to the creative invention of micro-programming. The development of micro-programming led to an entirely new form or architecture known as the *controller unit*, a component in the computer responsible for activating its internal operations as it executes a program. It is therefore reasonable to hypothesise that both design activities and learning activities being cognitive activities can be described and

[1] In device-level learning, the methods and outcomes of learning can only be described in reference to a particular device e.g. connectionist system, neural networks.

operationalised at the knowledge level. Thus it can said that both design and learning activities are linked at the epistemic level (i.e. at the knowledge level).

3 Defining elements of Generic Design Activity

A cognitive system at the knowledge level can be referred to as an agent [9]. The main entities with which an agent is concerned with are goals, actions and knowledge (which include facts, beliefs, rules, laws, theories, and values).

The principle of rationality, the law of behaviour at the Knowledge Level, says that actions are selected to attain the agent's goals.

The identification and classification of design activities have been argued to be based on their contribution towards an increase in the knowledge of the design or the associated process [14]. Here in this paper a *design activity* is defined as an action or cognitive process taken by a design agent to achieve a knowledge increment in the state of the design and/or its associated design process in order to achieve some design goal.

Given the above definition of design activity, the basic elements of a design activity may consist of:

- Existing design knowledge as Input knowledge, I_k.
- Design activity, D_a
- Output knowledge, O_k
- Design goal, D_g.

The basic elements of designing may be related as shown in Figure 1.

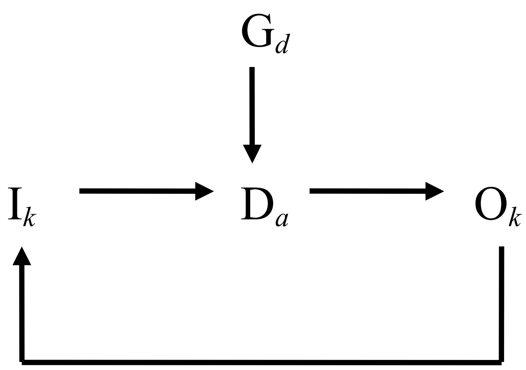

Figure 1 Elements of generic design activity

The design activity is initiated by a design goal G_d and the appropriate design knowledge I_k as inputs. The knowledge input may be the current state of the design, the resources in terms of people and knowledge (i.e. domain knowledge, heuristics, methods or techniques), tools, constraints and external requirements (e.g. regulations). The goal(s) of a design activity G_d determine the type of design activity to be performed by the design agent. The output knowledge O_k from the design activity stems from the application of appropriate input knowledge to enable the design to progress towards the design goal and hence towards the ultimate goal, the design solution.

4 The elements of learning activity

Sim and Duffy [4] present a foundation for learning in design using five key elements:

- Existing knowledge as Input knowledge, I_k.
- Knowledge transformers, K_t
- Output knowledge, O_k
- Learning goal or reason, G_l
- Learning trigger, T_l

These basic elements of learning are related as shown in Figure 2.

In this figure, the input knowledge is transformed into new output knowledge that can then feed back into the learning activity as input knowledge for yet new knowledge. This output knowledge may in itself also trigger or act as a reason or goal for a learning activity.

The Knowledge Learnt or Output Knowledge
The types of design knowledge to be learnt is dependent on the activity of the design

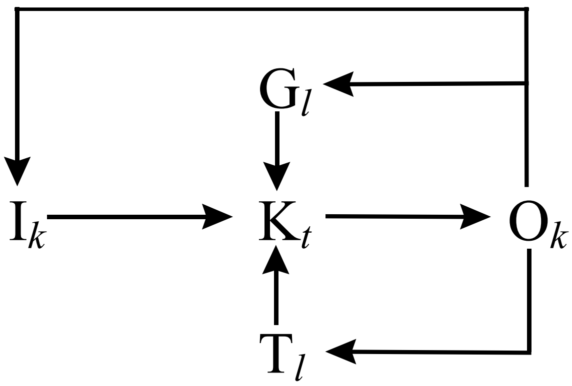

Figure 2: Elements of learning

process, the types of input knowledge, the goal of the learning process and when does learning take place. The review of MLinD systems by Sim and Duffy [4] indicates that there are numerous types of design knowledge that can be learned from past designs and from the design process itself. The discussion in Section 6 would therefore exemplify the type of knowledge that can be learnt.

The Learning Goal
The learning goal directs the learning process. The learning goal may be novelty driven, excellence driven or failure avoidance driven. The learning goal influences what parts of the existing knowledge are relevant, what knowledge is to be acquired, in what form, and how the learned knowledge is to be evaluated.

Knowledge Transformers
Sim and Duffy identify seven pairs of knowledge transformers that characterised the learning process in most MLinD systems. They are as follows:

- Group Rationalisation (or Clustering)/Decomposition (Ungroup)
- Similarity comparison/Dissimilarity comparison
- Association/Disassociation
- Derivations (Reformulation)/Randomisation
- Generalisation/Specialisation
- Abstraction/Detailing
- Explanation/Discovery

They also classify the learning triggers that activate the learning process into three main categories: in-situ, provisional and retrospective[2].

5 The interaction between learning and design activity.

The learning triggers provide the basis for three ways in which learning and design activities can be coupled. In retrospective learning, the learning activity occurs after certain type of design activities so that knowledge learnt can serve as input knowledge for future design problems. In-situ learning occurs when knowledge is learnt while designing is in progress. In provisional learning, the learning activity precedes the design activity in anticipation of the knowledge required as input into the design activity. The purpose of this Section is to show that learning and design interact in a temporal manner through temporal links and also in a purposeful manner through teleological links in the learning and design goals.

5.1 Retrospective learning or post design learning

In retrospective learning or post design learning, learning is triggered after the completion of certain design activities so that the knowledge learnt is current and most up-to-date and therefore of great utility value for future designs. Past design cases especially successful ones are good knowledge sources for retrospective learning. The knowledge learnt is stored in memory[3]. The purpose of learning in hindsight is to learn design patterns that led to the successful designs, relationships in design parameters, to understand and predict underlying trends in classes or types of designs and to extrapolate design attributes of future designs. Figure 3 shows the manner in which design and learning interact in retrospective learning.

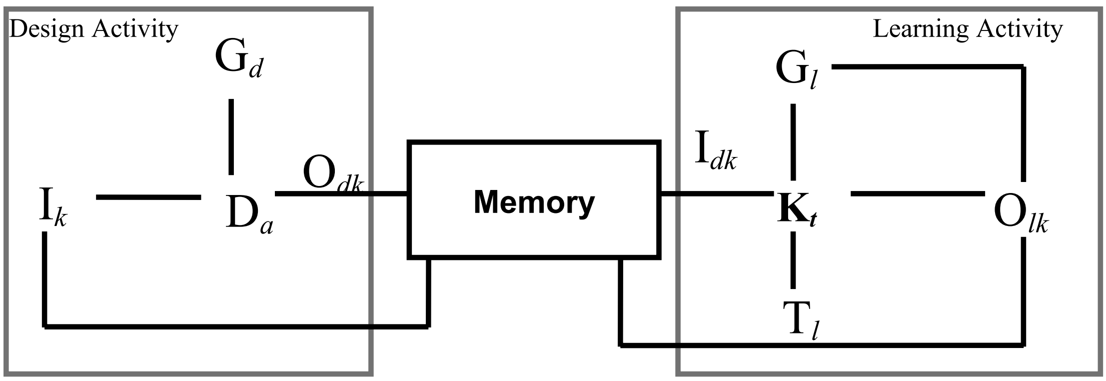

Figure 3 Retrospective Learning

The output knowledge from the design activity becomes input knowledge to the learning activity. The output knowledge of the learning activity is dependent on the goal of the learning activity. The knowledge transformer used in the learning activity is dependent on the nature of the input knowledge and the learning goal (See Sim and Duffy).

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[2] *In-situ triggers* are activated when there is a need to acquire new knowledge while the design is under focus of attention. *Provisional triggers* are activated when there is a foreseen event that is envisaged to require additional knowledge. *Retrospective triggers* are activated after an event. That is, learning is triggered by the need to learn from successful design(s)/failed design(s) and/or processes in hindsight.

[3] Space limitation does not permit discussion on the nature of memory which in this paper is taken to denote dynamic memory which is updated by the design activity or learning activity.

Retrospective learning is only effective when the output knowledge from the design process is definite and final. Therefore only knowledge output from certain design activities such as synthesis, quantitative model analysis/quantitative evaluation of final designs, optimisation can be considered for retrospective learning.

5.2 In-situ Learning

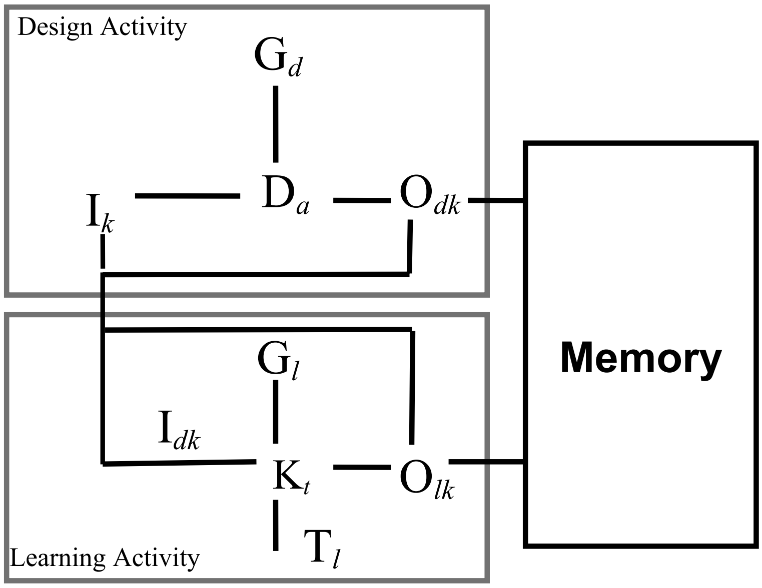

Figure 4: In-situ Learning

In in-situ learning, the design activity and the learning activity occur collaterally. That is while the design activity is in progress, the learning activity can take place. For example, while decision making is in progress to select the best design(s), learning of the arguments for or against the designs and final decision taken can be learned in-situ.

5.3 Provisional Learning

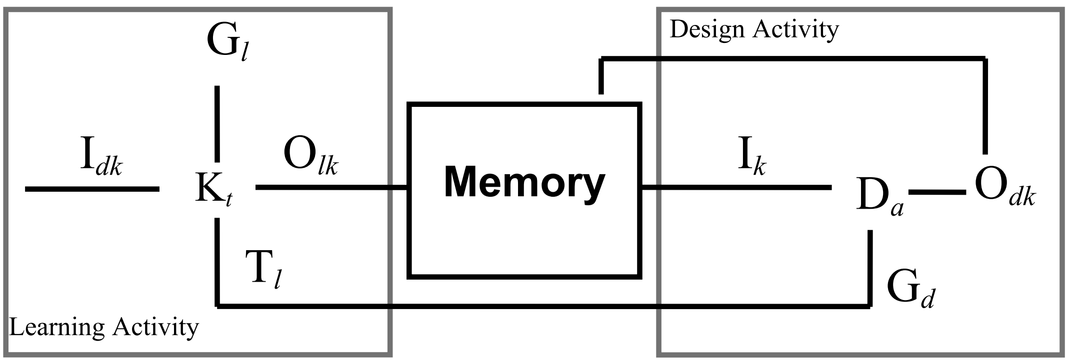

Figure 5: Provisional Learning

In provisional learning, the learning takes place in anticipation of the knowledge required for a downstream design activity. It is triggered by certain design activities. For example, the design goal of searching the design solution space would trigger provisionally the learning of heuristics that may be applied to reduce the complexity of search. The learning goal is thus directed to achieving the anticipated design goal.

5.4 Teleological Link through design and learning goals

Both design and learning are considered here as purposeful activities. Each has a specific goal to achieve. But design and learning are inextricably linked in that the learning goal is subservient to the design goal. For example, the design goal of preliminary synthesis activity is to reduce the complexity of the conceptual design space and the goal of learning from past design(s) compositional and taxonomic knowledge of design concepts will expedite the synthesis design activity. The goal of a constraining activity is to reduce the complexity of the design parameter(s) space. The goal of learning knowledge on design constraints by detecting failed constraints or anticipating crucial constraints during design is to streamline the design process.

6 Discussion

The formalism presented here provides an approach by which learning and design activities can be analysed and studied. By applying the formalism to the analysis of generic design activities and learning activities, relationships between the elements of these activities can be made explicit (See Table 1 for a sample of ananalysis). This formalism is proposed as an complementary to Reich's dimensions as it not only addresses the issues raised by Reich but suggests in a structured and integrated manner the nature of the relationships that exist in the set of dimensions (See Table 2).

Reich's dimension (RD)	Sim & Duffy's formalism
• Who is learning?	• Design agent
• Why does the learner want to learn?	• Learning is driven by design goal G_d and/or learning goal G_l.
• When does the learner learn?	• Retrospective/in-situ/provisional triggers T_{lt} and/or learning goal G_l.
• What is the learner doing?	• Certain design activity D_a
• What is learned?	• Output knowledge from learning activity O_k
• How does the learner learn?	• Knowledge transformer K_t
• What are consequences of learning?	• Acquired knowledge to achieving the design goal G_d in terms of time, cost or quality.
• What resources are needed to carry out the learning activity?	• Not addressed

Table 2: Comparison between Reich's dimension and Sim & Duffy's formalism

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Design activity D_a	Output Design Knowledge O_{dk}/I_{dk}	Design Goal G_d	Learning Goal G_l	Learning Trigger T_l	K_t	O_{lk}	MLinD System
Generating Concepts	• F → B → S Mapping	• Generate as many feasible solutions as possible.	• New concept(s)	• In-situ/ Retrospective	• Association	• New F → B → S Mapping	• NODES [15]
Optimising	• Starting points, constraints and best technique(s) used in past optimisation(s)	• Optimal design solution satisfying requirements/constraints.	• Reduce design solution search space and computational time	• Retrospective	• Group rationalisation	• Starting points, • Constraint incorporation to reduce search space. • Evaluation criteria	• Schwabacher et.al. [16]
Synthesising	• Knowledge of product configurations. • Knowledge of relationships of design properties. • Knowledge of integrating physical building blocks/chunks.	• Optimal layout/assembly of parts/subsystems into whole. • Totality in the design of product.	• Improve quality of new design(s) through flexible spatial viewpoint. • Expedite preliminary design • *Customised* design perspective(s).	• Retrospective/ • *In-situ* • Retrospective • *In-situ*	• Topological/ geometric generalisation • Topological/ geometric abstraction • Numerical association. • Generalisation of similar designs.	• New generalised knowledge of layouts • Hierarchical levels abstraction.	• SPIDA [17] • SPIDA • NODES • PERSPECT [3]
Evaluating Performance	• Design configurations satisfying given design function(s) and performance criteria.	• Compare novel concept with existing design.	• Identify performance trends for novel/innovative design.	• Retrospective	• Group Rationalisation	• Clusters of design solutions mapped to performance evaluation space.	• Murdoch & Ball [18]

Table 1: Analysis of design and learning activities using the proposed formalism.