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Reflective practice, artificial intelligence, and engineering design: Common trends and interrelationships

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Abstract

Some historical and current trends in reflective practice (RP), artificial intelligence (AI), and engineering design (ED) are presented and compared. Human artistry, context, and connectionist approaches to knowledge are the common threads highlighted. ED is considered to be a type of RP and AI a part of RP. This is supported by an analysis of the transformation processes involved in each. AI and systems are presented as approaches for the formalization of RP at the technical and conceptual levels, respectively. Interconnectedness in a hierarchical fashion and purposeful process loops are defined as the key ingredients of a systems approach. AI techniques that could support a range of ED categories (case-based reasoning, decomposition, and transformation) are identified, as are the wider RP approaches that subsume those categories. The ED, AI, and RP categories are identified as spanning from routine to creative, connectionist to cognitivist, and intuitive to deliberate, respectively.

Keywords: Artificial Intelligence; Engineering Design; Reflective Practice; Systems; Technical Rationality

1. INTRODUCTION

Reflective practice (RP), artificial intelligence (AI), and engineering design (ED) have become topical and issue-laden areas of study in recent times. This paper will give brief historical descriptions of developments in these fields and identify parallels and relationships among them. It will argue that RP, despite its human element, can be formalized, albeit loosely, through "soft" systems approaches. While admitting that the computational and algorithmic details of AI techniques appear to make it part of the paradigm of technical rationality (TR), the paper will also argue that AI is a part of RP, too, because of its goals and the "behavior" that emerges from its techniques. Finally, we suggest ways in which AI and RP could be utilized in ED and identify three ED process models and the corresponding AI and RP approaches.

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2. RP APPROACH

The term RP is taken from Donald Schon's ground-breaking book, *The Reflective Practitioner* (Schon, 1983). In the book, he asks why professionals often seem to know more than they can articulate. This question, of course, was asked many centuries ago in Plato's "Meno" (Sharples, 1980) in a slightly different form:

> And how are you going to search for this [i.e., excellence], Socrates, when you don't have the faintest idea what it is? Which of the things that you don't know will you suppose that it is, when you are searching for it? And even if you do come across it, how are you going to know that this is the thing you didn't know?

The question was addressed by Polanyi (1958, 1967), who suggested that the solution to the dilemma of the Meno was the idea of tacit knowledge, which we acquire when we "interiorize" our tools of exploration.

Schon (1983) describes the mental processes of the professional as thinking in action and, when those processes

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are more deliberate, as reflection in action. The important thing is however that there is a vital engagement with the actual situation at hand. Blockley (1992) has developed these ideas into the concept of a RP loop, consisting of world–perception–reflection–action–world. The key element here is reflection, which can be carried out at a deep or shallow level, depending on whether the action is carefully thought out or instinctive, respectively. The circular interaction with the world, which involves receiving feedback from performed action, is also important.

Although professionals (and, indeed, all humans) have been engaged in RP from time immemorial, its particular relevance today arises from its contrast with TR. Schon (1983) describes TR as a product of the European enlightenment in general and positivist philosophy in particular. The result of the pervading influence of positivism in the seats of higher learning was to consider mainly quantifiable knowledge as admissible. The result of this was that academe became removed from reality, which did not always lend itself to neat theoretical formulations; at the same time, successful practitioners who interacted with the real world were associated with mystique (as opposed to knowledge).

The model of TR was enormously successful in advancing scientific knowledge over the last 300 years. At a different level, it also helped to solve management problems through operations research (OR) over the past 50 years. However, limits to mathematics and physics have arisen in the form of Gödel's theorems, Heisenberg's uncertainty principle, and chaos theory. Furthermore, Kuhn's description of scientific progress (Kuhn, 1970) has revealed the extent to which it is dependent on social context.

The TR approach to management has also been critiqued since the 1970s; for example, Rosenhead (1989*a*) describes a shift from an old to a new paradigm. These old and new paradigms map onto Schon's TR and RP, respectively. Table 1 shows some contrasting features of these paradigms. Because TR ignores all aspects of a problem that cannot be cast into a theoretical formulation, it is characterized by "selective inattention." On the other hand, the hallmark of RP is "reflective interaction," which is insightful consideration of the entire problem solving scenario (Dias & Blockley, 1995).

The first set of features in Table 1 relates to the problem itself, which is assumed to be well defined under TR but accepted as a "mess" under RP (Schon, 1983). This causes the TR approach to be one of tactical problem solving as opposed to the strategic problem identification of RP. Again, the TR approach tends to be more concerned about the elegance of theory, leading it to be reductionist in nature, whereas the RP approach concentrates on relevance to the context, seeking to support all the real world complexity, including uncertainty and incomplete knowledge. Rosenhead (1989*a*) also makes the very interesting distinction between mathematical and graphical approaches to problems; this will be commented on later in this paper. Finally, the real world is seen by RP as a set of processes that display hierarchical emergence, whereas in TR it is seen as a set of events on the same level. In fact, AI itself can be seen as part of either RP or TR, depending on whether one recognizes emergence.

Table 1. *Differences between old (TR) and new (RP) paradigms in management science*

Old Paradigm (TR)	New Paradigm (RP)
Problems	Messes
Problem solving	Problem identification
Tactical	Strategic
Practitioner free	Practitioner dependent
Elegance	Relevance
Theoretical	Contextual
Reductionist	Complex
Mathematical	Graphical
Flat	Hierarchical
Events	Processes
Recommendation	Implementation
People—passive objects	People—active subjects
Consensus assumed	Conflict clarified
Individual decision making	Bottom up planning
Task	Responsibility
Solving	Learning

The second set of features (Table 1) relates to implementation, which the TR approach largely ignores. As a result, people are treated as passive objects and it is assumed that there is consensus regarding the assumptions in modeling. On the other hand, RP is acutely aware of implementation, resulting in people being treated as active subjects who participate in making changes; any conflict between parties regarding assumptions made during modeling is clarified. The assignment is treated as a responsibility in RP, as opposed to a mere task. Finally, the idea of learning (by both the social entity in which the change is made and the agents of change) is central to the RP approach (Checkland & Scholes, 1990; Senge, 1992), whereas the TR approach is only interested in a problem being solved by the agent of change.

Rosenhead also edited a collection of some RP approaches to management (Rosenhead, 1989*b*). These support most of the RP features in Table 1 and reflect an alternative paradigm to that embodied in OR techniques. Flood (1999) also reviewed some RP approaches espoused by various researchers, emphasizing the importance of learning.

One of the reasons why practice is held in low academic esteem compared to theory is its lack of a rigorous and coherent formalization. Practice is often seen as a collection of particular activities, which lack a generalized framework. It is generalization that creates formalism and results in the emergence of a discipline. Such generalization can be made at the level of concepts and/or techniques.

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In the engineering and management disciplines, among others, theory (or TR) is formalized at the level of techniques by the language of mathematics. At the conceptual level, TR is formalized by what constitutes the scientific method. An increasing number of disciplines are seeking academic respectability by adopting elements of the scientific method (e.g., reductionism, objectivity, etc.) and by attempting quantification.

On the other hand, since the middle of the last century or even before, there have been various attempts to define a systems language that would serve as a metadiscipline to other disciplines (von Bertalanffy, 1950). Systems then could be the answer to the problem of finding a formalization for RP at a conceptual level. The term systems has been used to describe a variety of approaches, but the following can be identified as the core concepts of a systems world view.

1. Interconnectedness in hierarchical fashion (Simon, 1996). This hierarchy also displays emergent properties at each higher level (Polanyi, 1958, 1967), so that a member of the hierarchy can be said to be both a whole and a part (i.e., a "holon"; Koestler, 1967); this means that each whole is greater in significance than merely the sum of its parts. Cross-hierarchical linkages can also be accommodated in such hierarchies (Koestler, 1967).
2. Purposeful process loops, including the ideas of interaction with the environment and feedback and participation of the change agent in the process, leading to learning (Checkland & Scholes, 1990; Blockley, 1992; Senge, 1992).

We therefore have two graphical images that can be built on to develop a language of systems (i.e., an inverted tree and a loop). Senge (1992), for example, describes a series of management situations by graphical constructs that have been built up out of just three simple primitives (a balancing loop, a reinforcing loop, and a delay loop).

It must be emphasized that RP, because of its human element, can only be formalized in a loose manner. We could use the term soft systems (Checkland & Scholes, 1990) to describe the formalization that is proposed. Checkland and Scholes (1990) also contrast their type of systems with hard systems of the OR type. In the latter, the world is treated as being *systemic* (i.e., having reasonably definable interacting components and an interface with its environment) and the modeling as *systematic* (i.e., using well-defined algorithmic procedures). In a soft systems approach the world is treated as *chaotic* and the modeling is treated as systemic. Here there are no established procedures, only guidelines and frameworks. The CATWOE [customers, actors, transformation process, weltanschauung (worldview), owners, and environmental constraints] method (Checkland & Scholes, 1990) is an example of a soft systems approach.

Table 2. *Contrasts of RP and TR approaches*

Approach	RP	TR
Characteristic	Reflective interaction	Selective inattention
Basis	Practice	Theory
Formalization		
Concept level	Systems methods	Scientific methods
Technical level	AI (knowledge processing)	Mathematics

AI can also be considered as a generalizing language or tool for RP, because the same AI techniques (such as expert systems and neural networks) can be used in a range of professional practices. The goals or outcomes of AI (as shown below) are concerned with human intelligence, experience, and even artistry, which is what RP is also about. Therefore, AI is a very appropriate language for RP. However, there is a TR aspect to AI as well, and this tension will also be explored below. It would appear that RP can be formalized at two levels. On the conceptual level, we can use a systems approach; on the technical level, we can use AI techniques. The differences between the RP and TR approaches are summarized in Table 2. Reich (1994) presented similar differences between "practicism" and "scientism" (which map onto RP and TR, respectively).

3. HISTORY OF AI

The historical sketch of AI that follows draws primarily on Gardner (1985), McCorduck (1979), and Newell (1983), who approached the historical development of AI as a series of issues. The intellectual issues concerning the background to AI can probably be traced back to the Greek philosophers, for example, Plato's distinction between the ideal (a mental construct) and the real (a material manifestation). However, Descartes (17th century) is a more realistic starting point, because he established the concept of mind–body dualism (Newell, 1983). It is now possible to think of the mind as a separate entity to be imitated or modeled. The medium in which AI is implemented is computer hardware.

There is wide consensus that the emergence of AI itself can be dated to the mid-1950s. The Dartmouth Conference in 1956 is considered a significant event (McCorduck, 1979; Gardner, 1985), which featured key participants such as McCarthy, Minsky, Newell, and Simon. According to Newell (1983), the relevant issue was the birth of symbol processing as opposed to purely numerical processing (or number crunching) that had been prevalent up to then. Furthermore, the parallel with human intelligence was made at the more abstract level of information processing rather than at the physical level of brain cells (McCorduck, 1979).

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In the early years of AI, the main goal was to mimic human intelligence in general systems, which was epitomized by the logic theorist of Newell and Simon. However, in the early 1970s, there were moves from general to expert systems, which capture and store large amounts of knowledge regarding specific domains; examples are Feigenbaum's DENDRAL in the domain of organic chemistry and Winograd's SHRDLU in the domain of a world of blocks (Gardner, 1985). Engineering has also been a rich domain for expert system development, because of the importance of heuristics (e.g., rules of thumb) and judgment in the field.

Since the 1980s there has been a concentration on declarative (as distinct from procedural) approaches to knowledge representation and parallel (as distinct from serial) approaches to knowledge processing (Newell, 1983). This has resulted in the emergence of a connectionist (as distinct from cognitivist) view of knowledge. However, cognitive and connectionist approaches to knowledge are both part of today's AI enterprise (Minsky, 1991).

The cognitive approach is epitomized by expert systems (Hayes-Roth et al., 1983). Here the knowledge is made explicit by eliciting it from an expert, generally in the form of production rules (i.e., if–then relationships). Uncertainty can also be built into the system. Once the knowledge base is thus prepared, facts concerning a new problem situation will trigger certain rules and result in a diagnosis or decision. The triggering or firing of rules is governed by what is called the inference engine of the expert system. One of the important aspects of expert systems is that the rationale for arriving at the end result is made available to the user.

On the other hand, the connectionist approach does not force the expert to codify knowledge in the form of rules. All it requires is that the expert codify his or her experience in the form of case histories. The computer then discovers patterns of which even the expert may have been unaware; this is called the training phase. It can also predict the action that will be taken by the expert if given the parameters that define a new problem situation. In this approach, the knowledge is implicit and no explanations are given to the user (Coyne, 1990). An artificial neural network probably best epitomizes this approach.

Of greater significance in recent years (again since the 1980s) has been a fresh critique of the AI enterprise, stemming in part from the philosophy of Heidegger (1997), who argued that everyday experience is more primordial than mental representations of individual entities. Therefore, it is argued that symbolic representations are inadequate for capturing or modeling reality because they cannot handle context in a genuine way (Winograd & Flores, 1986; Dreyfus, 1991).

At the same time, many researchers (especially in process modeling) see computers as machines for supporting humans as opposed to replacing them, especially in management tasks (Platt, 1996; Blockley, 1999). The computer is viewed as a tool for conversation and transaction (Winograd & Flores, 1986). This shift is partly based on new attitudes toward language, which is now viewed as a transactional tool (Austin, 1975) as opposed to a purely representational one (Chomsky, 1957). There has been a considerable amount of cross fertilization of ideas between linguistics and AI. Process modeling (which is also treated, albeit loosely, as part of the AI paradigm) is therefore more an integrating medium than an AI tool, and it espouses much more human interaction. In fact, process support has been called "augmented intelligence" by workers in computer supported collaborative work (Monarch et al., 1997). Suchman (2001) also endorses such interaction on the grounds that humanness itself is defined more by a relational nature than an autonomous one.

Let us now consider the nature of AI. Is it part of the RP or TR paradigm? Reich (1994) has pointed out that both scientism (TR) and practicism (RP) are worldview models that have guided AI research, but he does appear to favor practicism. Coyne (1995) argues that the design of information technology (albeit a broader entity than AI) has to be embedded in a practical context; he also says that metaphor more than method does and should drive such design. The historical trends described in this paper also reflect a move from TR to RP approaches (e.g., from AI as tools to AI as environments).

Another way of deciding where AI belongs is to consider its goal, which in most cases is the solving of practical problems, which are often based on practical experience or heuristics. This places AI within a paradigm of practice. We could even say that it is part of the RP paradigm if we see that the reflection of experts is embedded in the heuristics that are captured during knowledge elicitation.

The actual AI techniques (or means) themselves may indeed be computational and algorithmic (thus putting AI in the TR camp, too). Here again, however, if we look at the overall emergent performance of such techniques, they do indeed mimic various aspects of reflection. Consider an artificial neural network, which, on the one hand, is one of the most algorithmic of AI techniques. On the other hand however, it can be argued that a trained backpropagation network behaves similarly to a human "gut reaction" in arriving at a decision based on current inputs (Dias & Weerasinghe, 1996), a Hopfield network recalls a learned pattern even though presented with a slightly corrupted version of it (the way humans recognize things ranging from faces to situations), and a Kohonen network is able to associate a complex pattern with a unique identifier (in the way we give names to complex entities). We could then say that such networks and indeed other AI techniques possess emergent RP characteristics, at least in some partial way (Aleksander & Morton, 1990).

It should be noted in passing that unless one holds a strong view of AI, which states that computers can eventually mimic and replace humans, it is probably more accurate to use the term knowledge processing to describe what we mean by AI; however, we use the better known term AI in this paper.

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4. ED APPROACH

ED is a discipline in search of itself, because of the variety of approaches adopted toward it. As Table 3 indicates, ED encompasses both product and process aspects (Dias & Blockley, 1994); in other words, it is concerned with materials (product) and management (process). However, three distinct approaches can be identified. In addition to the TR and RP approaches, there is also a historical craft-based approach to engineering.

The craft-based understanding of products was empirical in nature. The fabrication of a product was undertaken in the light of the performance of a previous one. The processes involved were traditionally handed down from one generation to the next. This system was satisfactory for engineering practice that was neither significantly innovative nor mass production oriented.

In his influential lectures on "Sciences of the Artificial," Herbert Simon (1996) attempts to set out a new curriculum for university engineering schools. These schools had been forced away from craft-based approaches by the dominant positivist philosophy toward a scientific approach. Simon did not want to reverse the move from a craft-based to a scientific approach, because the latter enabled artifacts to be understood in terms of fundamental material properties and laws of mechanics. Rather, he argued that engineering schools should introduce intellectually rigorous sciences of the artificial (or sciences of design) in addition to the natural sciences, which properly belong in faculties of science. He proposed theories of search as the sciences of the artificial. More specifically, he suggested the introduction of optimizing (or, more generally, "satisficing") techniques into the engineering curriculum. A close look at Simon's proposals indicates that they primarily constitute a horizontal move in Table 3, which is from product to process aspects; his paradigm remains largely that of TR.

Some of the differences between TR and RP with respect to ED have been dealt with by Blockley (1992) and Dias and Blockley (1995). Blockley (1992) highlighted the differences between scientific and engineering knowledge, presenting the latter as a more holistic approach that embodies an open world outlook. In general, an engineering approach is concerned with purposeful activity, whereas a scientific one concentrates on properties of isolated entities. For example, an engineer would be interested in what an artifact such as a hammer could be used to perform; whereas a scientist may seek to describe it in terms of its "intrinsic" properties, such as weight, size, and shape. In Heidegger's terms (1997), the engineering approach would be ontologically more primordial and hence richer in descriptive power. This is a very definite move away from positivism, which has its intellectual roots in Platonic thought, where the so-called essential properties of entities were considered to be more fundamental. In many cases however, the engineering (RP) and scientific (TR) approaches can complement each other, as shown by Dias and Blockley (1995).

Product and process modeling are now increasingly used in ED. Both types of modeling are more semantic than numerical, and hence richer in nature; numerical procedures can be implemented within the semantic modeling. Semantic modeling consists of first defining entities and their attributes and then defining the relationships between those entities, including communication and feedback. It is therefore more of an RP approach than is purely mathematical modeling. Product modeling has to do with modeling artifacts (Dias, 1993), whereas process modeling is concerned with modeling the actual design process. One practical goal of process modeling is the construction of software systems that will guide the design process by allowing designers to interact with each other and with the incrementally developing product model (Platt, 1996; Blockley, 1999). There is much scope for integrating product and process models for design (Dias & Blockley, 1994). Maher et al. (2000) explored the concept of a "virtual place" for facilitating cooperation between designers, in contrast to a "virtual desktop," which is more an integration of design tools.

The above trends in product modeling constitute an engineering or RP approach to design, whereas those in process modeling constitute an interactive (RP again) approach to design. This interaction (or "shared conversation") between designers is the basis of design (Bucciarelli, 1994). Promoting and supporting such discourse (Monarch et al., 1997) represents a vertical move from satisficing (TR) to reflection (RP) in the design process; it is also consonant with the ideas of Schon (1987), who is clearly not satisfied with Simon's essentially horizontal move (from scientific to satisficing in Table 3).

Table 3 also shows the differences in the types of graphics associated with the various ED approaches. The craft-based tradition of ED is very technical and focused, in the sense of concentrating on working drawings such as reinforcement details and assembly drawings. A more conceptual type of drawing that has emerged with the computer age is that of the flowchart and the network. These also tend to capture only those aspects of the problem that are solvable by theoretical procedures; hence, they could be described as characteristic of the TR paradigm. The "rich pictures" of the RP paradigm could depict hierarchical structure, interaction, and feedback (Checkland & Scholes, 1990; Dias & Blockley, 1995). The diagram is a qualitative representation of the problem, so all aspects of it can be represented; not merely those that are amenable to theoretical

Table 3. *Different approaches to engineering design*

	Product	Process	Graphics
Craft based	Empirical	Traditional	Working drawings
TR	Scientific	"Satisficing"	Flowcharts
RP	Engineering	Interactive	Rich pictures

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formulation or quantification. It is also the most "subjective" and practitioner dependent; this means that the experience of the practitioner can be reflected in the rich picture.

5. RP, AI, AND ED

5.1. Common threads

We can now identify some common threads that link RP, AI, and ED. One is the historical influence of positivism, which probably has its intellectual roots in ancient Greek philosophy; however, its stronger unbroken tradition dates back to Descartes and the European Enlightenment. Positivism gave rise to the TR views of professional practice (the opposite of RP) in general (characterized by OR techniques), and ED in particular (characterized by scientific approaches to product and satisficing approaches to process aspects). Positivism, in the form of mind–body dualism, was also responsible for creating the notion that the mind could be modeled independently, that is, that AI was possible. Furthermore, the same mind–body dualism encouraged the idea that knowledge could be acquired from, and applied to, an external world by a detached agent. Rosenhead's (1989*a*) old paradigm (Table 1) springs directly from this idea, as does the satisficing approach to ED process (Table 2).

The other thread is an opposite one to positivism. We have already seen how the AI enterprise has been critiqued based on Heidegger's view of the primacy of experience over representation. This critique has been extended to the symbol manipulation approach (i.e., a TR approach) to ED as well (Mitchell, 1990), particularly by Coyne and Snodgrass (1993). These issues have also been considered by Dias and Blockley (1994, 1995), again in the context of ED and RP.

The most recent trends in RP, AI, and ED thus support the ideas of human artistry and interaction. Human artistry is acknowledged in the very term RP, and the new paradigm is characterized as being practitioner dependent (Table 1). The trends in process modeling (in AI and in the process aspect of ED) for supporting human involvement are also an acknowledgment of this artistry. However, we could say that TR and RP continue to be both conflicting and complementary paradigms in ED and AI. Dias and Blockley (1995) have shown that RP can be a context for, precondition to, and constraint on TR.

Context is now accorded an important place. Here Heidegger (1997) is relevant through his idea of "being-in-the-world" to describe human existence: in other words, a relatedness to context. The RP approach is one that interacts with the world (i.e., one's context) and seeks to understand and change it. In Schon's (1983) view, action in the world itself is a source of knowledge. In AI, the shift from early general systems to later expert systems constitutes an appreciation of the need for contextual (or domain specific) knowledge. In ED, Blockley's (1992) advocacy of a holistic engineering approach as distinct from a scientific one (Table 2) is also a statement regarding the importance of context. Engineers are intimately involved in a variety of differing contexts, in contrast to scientists, who try to abstract generalizations and separate them from their contexts.

The final thread that links current views of RP, AI, and ED is the connectionist theme. The idea of connectionism relates primarily to artificial neural network type approaches in AI, involving declarative programming, message passing, and massively parallel processing. Part of the impetus for this type of approach is that it is structurally analogous to neurons in the brain while functionally mimicking brain functions such as pattern recognition. The RP approach to reality (including its approach to ED) can also be described as connectionist in that it appreciates the interrelationships between entities, some of which are the practitioners themselves. Connectionism also carries with it the connotation of emergence. Thus, pattern recognition behavior can emerge from AI techniques that are merely algorithmic, and innovation can emerge from shared conversations in ED. Hierarchical emergence is also a key concept in both RP and in soft systems approaches that seek to formalize it (Table 1).

5.2. Relationship to each other

Apart from the commonality described above, we can also explore the way in which RP, AI, and ED relate to each other. The analogy proposed for this relationship is depicted graphically in Figure 1; it can be called a "hot dog" analogy. This shows AI as a part of RP; that is, RP could involve the use of AI, but RP is a wider and more comprehensive activity than AI. On the other hand, ED is a type of RP; that is, it is a particular kind of RP. The length of the hot dog represents the variety of RP that can be found in all professions. ED, being a particular type of professional practice, is represented by, perhaps, one "bite" of the hot dog. The fact that the AI "sausage" extends along the entire length of the RP hot dog conveys the idea that virtually all types of professional practice (e.g. even the legal profession) can be served by AI, because the knowledge in most professions is amenable to logical and symbolic processing (although it may not be quantifiable via mathematics). The place of TR

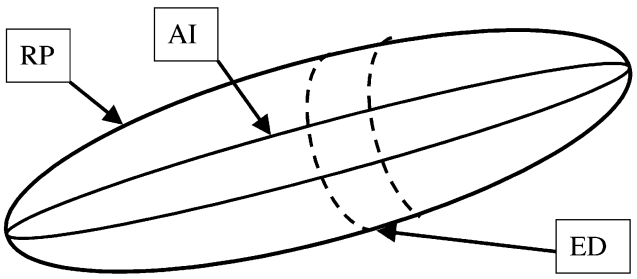


Fig. 1. The relationship between RP, AI, and ED ("hot dog" analogy).

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is not shown in this figure for the sake of clarity. In some ways TR is an alternative paradigm to RP, but both AI and ED have RP and TR components. This paper itself could have been titled "*Professional* Practice, Artificial Intelligence, and Engineering Design," with all three entities considered as having both TR and RP elements. However, the intention is to focus on RP because it can be seen as encompassing TR (Dias & Blockley, 1995) and because the current trends in professional practice, AI, and ED constitute a move away from TR to RP.

The previously described "part of" and "type of" relationships of AI and ED to RP can be further explored by performing an analysis of the transformation processes involved in each. We follow the CATWOE analysis proposed by Checkland and Scholes (1990). The analysis is shown in Table 4. It must be emphasized that the following discussion does not demonstrate the full potential of a CATWOE analysis, which is best used to study the ramifications of a proposed change in a given context (Checkland & Scholes, 1990). Nevertheless, it does give us some insights about RP, AI and ED. In addition, it is also an example of a soft systems RP approach, especially because it helps to identify stakeholders, focus on context, and clarify interactions between various elements (Dias, 2000).

The AI transformation, which relies on a set of techniques or tools (or even an integrating environment), can be performed even by a knowledge engineer, because knowledge of the application domain itself is not paramount. It may be performed at the request of a professional in a given domain who uses AI as part of his or her RP. ED is a type of RP, where the professional is called a designer. The professional's customers are the public, which for ED specializes to a client.

The transformation process is very specific for AI, but less clear for RP and ED. The weltanschauung (worldview) that gives meaning to the transformation can be described as one of reflective interaction for RP, which for ED consists largely of achieving a balance among safety, elegance, and economy. The worldview of AI is the capturing, structuring, and, above all, processing of knowledge.

The owners of the process are those who have the power to stop it. Apart from the customers, these include the "affected public" for RP and ED, because these activities are set in a social context; they can adversely affect segments of the public, who would have the right of protest. Finally, the constraints on AI are merely the state of the technology, whereas regulations and codes (a special set of regulations), which again reflect a sociolegal context, constrain RP and ED, respectively.

The key feature of the above analysis is that the ED elements can be seen as a type of the corresponding RP elements. For example, codes are a type of regulation, and a designer is a type of professional. No such type of relationship exists between the RP and AI elements. Rather, the AI elements are components or parts of the wider RP ones. Thus, knowledge processing is a part of reflective interaction; and although a knowledge engineer cannot be seen as part of a professional, the responsibilities of the former are subsumed within those of the latter. All this indicates that the CATWOE analysis supports the hot dog analogy of Figure 1.

6. USE OF AI AND RP IN ED

We come now to the practical implications of the relationships among RP, AI, and ED, which is how AI and RP can be used to enhance ED.

The use of AI in ED was surveyed by Stomph-Blessing (1991). Although her approach and categorization are considerably different from what follows, there are a number of important conclusions that should be highlighted. She concluded that it was the later as opposed to earlier phases of ED that are most supported by AI. Earlier phases were supported only at low levels of complexity, if at all, and in a parametric, as opposed to creative fashion. This led her to say that the way forward was in supporting human interaction rather than total automation. The process modeling and design environment initiatives of the 1990s have, in fact, reflected this goal.

The same position is taken in this paper. AI is viewed as a part of RP and hence ED (see Fig. 1). Therefore, it should be available in the form of tools (or environments) for designers to use in the course of their wider design activity. At the same time, designers should cultivate the principles of

Table 4. *CATWOE analysis of RP, AI, and ED*

	RP	AI	ED
Customers	Public	Professional	Client
Actors	Professional	Knowledge engineer	Designer
Transformation process	*From* deficiency *to* improvement	*From* problem *to* solution	*From* brief *to* design
Weltanschauung (worldview)	Reflective interaction	Knowledge processing	Balancing safety, elegance, and economy
Owners	Public, affected public	Professional	Client, affected public
Environmental constraints	Regulations	Technology	Codes

CATWOE stands for customers, actors, transformation process, weltanschauung, owners, and environmental constraints.

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RP so that their activity can be governed by a holistic approach.

The categorization of ED is shown in the first column of Table 5. The three main categories correspond to Maher's (1990) categorization of ED processes into case-based reasoning, decomposition, and transformation. These categories have fairly wide acceptance among researchers, although slightly different labels may be used. Dym (1994), for example, calls them case-based reasoning, decomposition, and generate-and-test. Coyne (1995) labels them as typology, analysis–synthesis–evaluation, and generative. Table 5 also highlights some special cases of each category. The second column suggests AI techniques that could be used to support the corresponding ED categories, and the third column sets the ED processes in wider RP approaches. These RP approaches are all taken from Schon (1983), who distilled them from a range of RP situations as diverse as architecture, psychotherapy, engineering, science, town planning, and management.

6.1. Case-based reasoning

Case-based reasoning is a process whereby design solutions are sought on the basis of previous cases. This is a very natural approach to design, because it uses the prior experience of designers. The AI version of this process is called the same name. Maher and Gomez de Silva Garza (1996) applied it to structural design. The RP attitude that corresponds to case-based reasoning is thinking from exemplars. This suggests the importance of careful documentation of a professional's own past cases and curiosity regarding the cases of fellow professionals. The use of case histories in ED teaching could also be useful.

Pattern recognition is a more intuitive aspect of case-based reasoning (i.e., the emphasis is more on recognition than on reasoning). This suggests the sort of situation where a combination of features in a design brief could trigger a complete (or near complete) solution, which is based, of course, on a previous solution. The AI version of this is the use of artificial neural networks for recognizing patterns, for example, floor plans (Coyne et al., 1990). A more interactive approach was used by Stone et al. (1989) for learning from structural failures. Pattern recognition is an aspect of knowing in action (RP), through which the engagement with a concrete situation can sometimes make everything "fall into place," seemingly with very little effort.

6.2. Decomposition

Top down decomposition is a very logical way of proceeding with design. It consists of breaking down the functional requirements of the artifact to be designed into those required for less complex subsystems and elements. As the decomposition proceeds, decisions are taken regarding alternative solutions to be used at lower levels. Top down decomposition is based on the RP concept that artifacts and systems are hierarchically structured (Simon, 1996) with each member of the hierarchy acting as a whole and a part, that is, as a holon (Koestler, 1967). The AI paradigm that best encapsulates top down decomposition is product modeling; this has been used very fruitfully in ED (Bjork, 1989; Dias & Blockley, 1994; Dias, 1996).

One aspect of top down decomposition is selection and development. At each level in the hierarchy, alternative solutions at lower levels have to be considered and then selected. Once selected, they have to be developed (i.e., designed in detail). Of course, this detailed design may depend on the selection of components at still lower levels. This process of design is called a multilevel selection development process model by Sause et al. (1992). In AI this process can be supported fairly well by prototypes (Gero, 1990). A prototype is a partially instantiated object, the term object being used in the context of object oriented programming (Stefik & Bobrow, 1986). The partial instantiation allows one object to be selected over another. The development consists of completely instantiating the selected object. This process is described in detail by Gero et al. (1988) and Dias and Blockley (1994). The selection and development processes in ED are a reflection of a wider RP practice of keeping options open until a commitment to a particular course of action has to be made.

6.3. Transformation

Transformation is the process of applying a rule to an entity that results in it being transformed to a new entity. It can be

Table 5. *Parallels between RP, AI, and ED*

ED	AI	RP
Case-based reasoning	Case-based reasoning	Thinking from exemplars
Pattern recognition	Artificial neural networks	Knowing in action
Top down decomposition	Product models	Hierarchical structuring
Selection and development	Prototypes	Keeping options open
Transformation	Rule-based systems	Reflection in action
Analogical reasoning	Grammars and genes	Generative metaphor

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considered a generative process, in that it generates new design solutions that are built up from primitives. It is also therefore a bottom up approach, and it can be contrasted with top down decomposition. The solutions that are generated have to be evaluated with respect to their suitability for fulfilling the design requirements. The rules governing these transformations may be based on past experience or creative analogies.

Some AI implementations of transformation have been based on analogies with Chomskian linguistics. Chomsky (1957) was interested in the generative capability of language based on syntactic rules. The AI implementations have used shape grammars (Gips & Stiny, 1980) that build up artifacts based on simple shapes and transformation rules (Baker & Fenves, 1990; Mitchell, 1990). The genetic analogy has also been studied in design research, such as in the definition of generic units (Dias & Blockley, 1994) and the application of the genetic algorithm (Gero et al., 1994; Rosenman, 1997). Experience and judgment have been used by AI to generate heuristic rules for expert systems. In general however, they have been used in top down decomposition (Maher & Fenves, 1985) as opposed to bottom up generation.

The wider RP approach corresponding to analogical reasoning is the use of generative metaphor. In fact, metaphor is fundamental to creativity (Snodgrass & Coyne, 1992; Qian & Gero, 1995). The RP approach corresponding to experience-based rules is the process of reflection in action. This is how knowledge in action gets formalized into heuristics in the mind of the reflective practitioner.

6.4. Range of RP, AI, and ED

In our discussion above we discussed a range of RP, AI, and ED approaches, which can be represented as in Figure 2. As we proceed from case-based reasoning to transformation, ED becomes less routine and more creative. If we think of the corresponding AI techniques for supporting ED (see Table 5), we move from more connectionist (artificial neural networks) to more cognitivist (expert systems) approaches (Minski, 1991). Finally, the wider RP approaches corresponding to ED (see Table 5) will range from the intuitive (knowing in action) to the deliberate (reflection in action).

In any given situation, the entire range of approaches may be used. In fact, in the discussion of a design critique of a student's partially completed project by an architect, Schon (1983, 1987) describes how the teacher initially draws on images and experiences not consciously reflected on or explained to the student (intuitive, connectionist, knowing in action); then keeps options open but at a point commits himself to an adequate model (hierarchical structuring, selection and development, keeping options open); and, in the process, brings his theory and discipline to bear on the subject (deliberate, cognitivist, reflection in action).

Dym (1994) suggests that the ED categories are linked to the stages of design, with decomposition being the most appropriate at the conceptual design stage, generate-and-test at the preliminary design stage, and procedural approaches at the detailed design stage. He also distinguishes between knowledge lean or ("weak") AI techniques and those that are knowledge rich (or "strong"). This distinction maps onto the connectionist/intuitive and cognitivist/deliberate difference pointed out previously. Coyne (1995) suggests that the notions of "wicked problems" (that defy typology), abduction (which is the means of generating a synthesis), and emergence (which results from the generative model) are enhancements, as well as rivals, of the three categories explored here. All of this indicates that various researchers in design are attempting to match design approaches or categories with other entities.

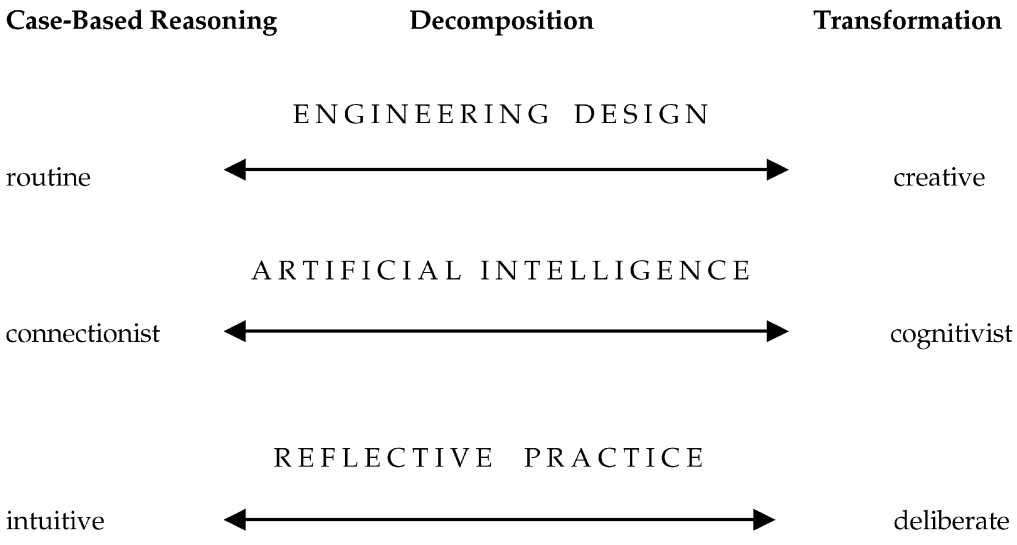


Fig. 2. The range of RP, AI, and ED.

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What has been attempted here is to match the three ED categories with AI techniques and RP approaches. We have focused on a reasonably representative and widely accepted set of ED categories and shown that different AI techniques are appropriate to different categories. However, the human element in ED makes it a type of RP. Here, too, the type of RP approach to be employed will vary according to the ED category.

7. CONCLUSIONS

1. An analysis of historical trends in RP, AI, and ED indicates some common threads. These areas have all been influenced by the TR approach, which was spawned by a positivist philosophy, as epitomized by Cartesian dualism. However, in more recent times, this TR approach and its philosophical underpinnings have been critiqued from a wide range of positions (including that of Heideggerian ontology with its emphasis on the primordiality of experience over representation). The result is that there is greater acknowledgment now of human artistry, the importance of context, and a connectionist (hence emergent) view of knowledge. Nevertheless, TR and RP continue to be conflicting and complementary paradigms in ED and AI.
2. ED is identified as a type of RP and AI as a part of RP. Further support is provided by an analysis of the transformation processes occurring in each using the CATWOE approach of Checkland and Scholes (1990).
3. AI can be seen as a formalization of RP at the technical level. Soft systems approaches have been proposed for loosely formalizing it at the conceptual level. Hierarchical structuring and purposeful process loops are considered to be the core ingredients of such a systems approach. Attempts that have already been made suggest the possibility of a graphical (as opposed to mathematical) formalization of RP using a systems approach.
4. AI techniques for supporting a wide range of ED categories—that is, case-based reasoning, decomposition, and transformation (after Maher, 1990)—have been identified, as have the wider RP approaches that subsume these categories. This range spans routine to creative categories in ED, connectionist to cognitivist techniques in AI, and intuitive to deliberate approaches in RP.

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