

# Chapter 2

## Design Creativity Research

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**Abstract** We take *design as a plan* by which some undesired reality is envisaged to be changed into some desired reality. It is the plan for creation of an intervention, e.g., a product or a service, with which to bring about this change. *Designing*, or design process whereby the *plan is conceived and embodied*, starts with the perception of the need for a design. Products and the processes of their creation have undergone considerable changes over the last decades. Products have become more complex, and stronger customer awareness and stricter legislation resulted in shorter product life cycles and tighter requirements. Products have to be technically as well as commercially successful. In order to be able to cope with these changes and remain competitive, new approaches to improve effectiveness and efficiency of the product development processes are needed. The overall aim of design research is to support practice by developing knowledge, methods and tools that can improve the chances of producing a successful product. In this chapter, we provide an overview of the broad issues that are investigated in design research, introduce DRM - a design research methodology developed for systematic exploration of these issues, and provide an overview of research at IdeasLab, Indian Institute of Science (IISc) in the areas of design creativity. The following questions are addressed: What is creativity? How can it be measured? What are the major influences on creativity? How does exploration of design spaces relate to creativity? How well do designers currently explore design spaces? How can creativity be supported?

### 2.1 Design, Design Research and Its Methodology

We take *design as a plan* by which some undesired reality is envisaged to be changed into some desired reality. It is the plan for creation of an intervention, e.g., a product or a service, with which to bring about this change. *Designing*, or design process

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whereby the *plan is conceived and embodied*, starts with the perception of the need for a design. Products and the processes of their creation have undergone considerable changes over the last decades. Products have become more complex using new technological developments and integrating knowledge of various disciplines. Increasing competition, stronger customer awareness and stricter legislation resulted in shorter product life cycles and tighter requirements. Products have to be technically as well as commercially successful. As a consequence of product changes, the product development process has changed. Complexity, quality pressure and time pressure have increased. New approaches to improve effectiveness and efficiency of the product development processes are needed to be able to cope with these changes and remain competitive.

The overall aim of design research is to support practice by developing knowledge, methods and tools that can improve the chances of producing a successful product (Blessing et al. 1992, 1995, 1998; Blessing and Chakrabarti 2002, 2008). This aim raises questions such as

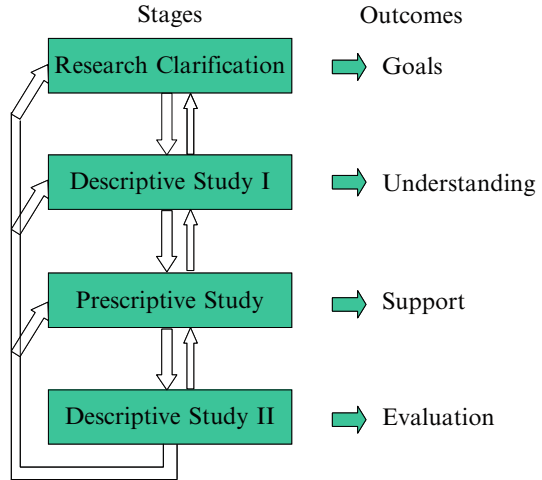
- What do we mean by a successful product?
- How is a successful product created?
- How do we improve the chances of being successful?

The first question leads to issues such as what criteria to be used to judge success, that is, what measures will determine whether our research has been successful. The second question leads to issues such as what the influences on success are, how these influences interact and how to assess them. Investigating these issues would increase our understanding of design which is needed to improve the design process. The third question gives rise to issues related to the translation of this understanding into design methods and tools and to the validation of these methods. Validation is needed to determine whether the application of these methods indeed leads to more successful products as determined by the criteria.

A pure product-focused research effort cannot resolve these issues. That this has been recognised is shown by the increasing number of studies of the way in which a design process actually takes place – to increase understanding on this process – both as a cognitive and a social process and in the organisation. Traditionally this is not the type of research conducted within engineering and it is not possible to transfer research methods directly from other disciplines – a new approach is required. To address these issues in an integrated and systematic way, a research methodology specific to studying and improving design as a phenomenon is needed.

Two characteristics of design research require the development of a specific research methodology. First, the selection of research areas is not straightforward due to the numerous influences and interconnectivity between them. Design involves, among others, people, products, tools and organisations. Each of these is the focus of a particular discipline with its own research methodology and methods, such as social science, engineering science, computer science and management science. Design research is therefore bound to be multidisciplinary. An additional complication is the uniqueness of every design project. This particularly affects repeatability in scientific research. The second characteristic of design research is that it not only

**Fig. 2.1** DRM stages, links and outcomes



aims at understanding the phenomenon of design, but also at using this understanding in order to change the way design is carried out. The latter requires more than a theory of *what is*; it also requires a theory of *what would be desirable* and how the existing situation could be changed into the desired. Because this cannot be predicted, design research involves design and creation of methods and tools and their validation. Methods from a variety of disciplines are needed.

Figure 2.1 introduces DRM (Design Research Methodology) – arguably the most widely used methodology for design research. A simple example is used to clarify its main stages.

### 2.1.1 *Research Clarification: Identifying Goals*

The first stage is to clarify the aims and objectives of the research, with the resulting identification of the criteria for success of the research. For instance, in an example research a reduction in time-to-market may be identified as a criterion for success. This provides the focus for the next step and is the measure against which a design method or tool developed in the research would be judged.

### 2.1.2 *Descriptive Study I: Understanding Current Situation*

In this stage, observational studies are undertaken to understand what factors currently influence the criteria for success, and how. In the example case, a descriptive study involving observation and analysis may show that insufficient problem definition relates to high percentages of time spent on modifications, which is assumed

to increase time-to-market. This description provides the understanding of the various factors that influence, directly or indirectly, the main criterion, in this case time-to-market.

### ***2.1.3 Prescriptive Study: Developing Support***

In this stage, understanding of the current situation from the last step is used to develop a support (methods, guidelines, tools, etc.) that would influence some of the factors to improve their influence on the success criteria. For instance, in the example case, based on the outcome of the descriptive study and introducing assumptions and experience about an improved situation, a tool is developed to encourage and support problem definition. Developing methods and tools is a design process in itself.

### ***2.1.4 Descriptive Study II: Evaluating Support***

In this stage the support developed is applied and a descriptive study is executed to validate the support. In the example case, this included two tests. The first test is whether problem definition is supported. The second test is whether less time was spent on modifications, and whether this, in turn reduced the time-to-market. There might be reasons as to why the second test fails, such as side-effects of the method.

Note that design research embraces both traditional, analytical research, and interventional, synthetic research. While its Descriptive Study stages involve understanding a given situation (with or without the support) as the primary motive, and therefore are primarily analytical in nature as in research in the natural sciences, its Prescriptive Study stage involves a synthesis activity, developing interventions to change the current situation. Unlike in the natural sciences, understanding a situation in design research is not per se the goal, but only a means to change the situation for better.

## **2.2 Objectives of This Paper**

The rest of this chapter provides an overview of research at IdeasLab, Indian Institute of Science in the areas of design creativity. The following questions are explored:

- What is creativity? How can it be measured (Section 2.3)?
- What are the major influences on creativity (Section 2.4)?
- How does exploration of design spaces relate to creativity (Section 2.5)?
- How well do designers currently explore design spaces (Section 2.6)?
- How can creativity be supported (Section 2.7)?

## 2.3 Definition and Measures for Creativity

Creativity is essential in design. Definitions of creativity, however, are multiple and varied, and factors influencing creativity myriad and various. Moreover, the definition, the influences and their measures are not linked in a systematic way. Consequently, metrics for estimating creative potential of agents or methods are few and only as sound as the theories on which they are based. In this section, we explore what should be the:

- ‘Common’ definition of creativity
- ‘Common’ measures for assessing creativity

Unless stated otherwise, all references are cited from [Davis \(1999\)](#).

### 2.3.1 *What Is Meant by Creativity?*

There have been multiple attempts at qualifying and quantifying the main characteristics of a creative idea. Many see novelty as the sole essential characteristic of a creative idea, e.g., to Newell, Shaw and Simon, “creativity appears simply to be a special class of psychological activity characterized by novelty.” For Rhodes, “Creativity . . . is a noun naming the phenomenon in which a person communicates a new concept.”

On the contrary, many others, like Davis, argue that an idea must have novelty as well as some sense of “appropriateness, value or social worth” for it to be considered creative. Perkins states that a “creative person by definition . . ., more or less regularly produces outcomes in one or more fields that appear both original and appropriate.” Hennessey and Amabile argue that “to be considered creative, a product or response must be novel . . . as well as appropriate.” In earlier papers, we defined ([Chakrabarti 1998](#); [Chakrabarti and Khadilkar 2003](#)) creative outcomes as “new as well as interesting”. However, these multitude of definitions of creativity leaves one wonder whether it is possible to arrive at an encompassing definition of creativity in a systematic way, rather than assuming allegiance to any particular definition. After all, for a research community that works on creativity to build on each other’s work, such a ‘common’ definition and related ‘operationalisable’ measures are essential to have. This led us to undertake a more rigorous approach to understand what is meant by creativity, with the eventual aim of arriving at a ‘common definition’ and related measures. In the rest of this section, a summary of this work is given. For details, see ([Sarkar 2007](#); [Sarkar and Chakrabarti 2007a, 2008a](#)).

### 2.3.2 *A ‘Common’ Definition*

Development of a ‘common’ definition requires that the research community is able to agree on what is meant by a ‘common’ definition, and is able to operationalise this

meaning into a definition. In our view, a ‘common’ definition must embody what is common across existing definitions. Therefore, we collected a comprehensive list of creativity definitions (see [Ideaslab 2007](#) for the list) from literature. Two possible meanings for ‘common’ definition were proposed. The first utilizes in the ‘common’ definition those concepts that are most frequently used across the current definitions, since the definition should reflect the views of the *majority* of the researchers in the domain. The second, alternative meaning is based on the possibility that the above – majority based – definition may not capture the rich, underlying *relationships* among the concepts used in the various definitions, and may not provide a ‘common’ definition that represents all the definitions. In this analysis, the features of the definitions are analyzed to identify the *relationships* between them and integrate the feature into hierarchies of *related features*. The overarching, high level features from the hierarchies that represent all the other features within the hierarchies are then integrated into a ‘common’ definition of creativity, thereby representing also those definitions that use these lower level features. The list of creativity definitions was analyzed using each of these approaches. The first approach is called *Majority Analysis*, and the second *Relationship Analysis*. The results from these two analyses were compared with each other in order to develop the proposed ‘common’ definition.

Using Majority Analysis, the ‘common’ definition of creativity was found to be the following: ‘*Creativity occurs through a process by which an agent uses its ability to generate ideas, products or solutions that are novel and valuable*’ (Definition 1).

Based on Relationship analysis, the proposed ‘common’ definition is: ‘*Creativity is an ability or process using which an agent generates ‘something’ that is ‘novel’ and ‘valuable’*. This ‘something’ can be a ‘problem’, ‘solution’, ‘work’, ‘product’, ‘statement’, ‘discovery’, ‘thought’, ‘idea’ or ‘judgment’ (i.e., evaluation). For design, ‘something’ is taken as ‘problem’, ‘solution’, ‘product’, ‘idea’ or ‘evaluation’ (Definition 2).

The difference between the two definitions lies in the meaning of ‘something’. In Majority Analysis, ‘something’ means ideas, solutions and products, while in Relationship Analysis it has a wider variety of meanings – in particular problems and evaluations. Since problem finding and evaluation are essential subtasks in any creative activity, we argue that, ‘generation of ideas, solutions or products’ already encompasses these subtasks and their outcomes. The definition of creativity from Relational Analysis is hence simplified as: ‘*Creativity in design occurs through a process by which an agent uses its ability to generate ideas, products or solutions that are novel and valuable*’. This is the same as Definition 1, from Majority Analysis, and is taken here as the general definition of creativity.

Note that the feature social ‘value’ in this definition can be more specific in the context of engineering, where it becomes utility value – or ‘usefulness’. Thus in the context of engineering design, the definition of creativity can be further specified as: ‘*Creativity is a process by which an agent uses its ability to generate ideas, solutions or products that are novel and useful*’ (Definition 4). We call this the definition for design creativity.

Together these two definitions (Definition 1 or 3 for creativity in general and Definition 4 for design creativity) provide an inclusive framework for creativity.

They also provide a justification for the various measures proposed by earlier authors for creativity, and how directly these relate to creativity, allowing most existing definitions to be subsumed and represented by the above two definitions, and at a greater degree of directness.

### 2.3.3 ‘Common’ Measures

In order to operationalise the above common definition of engineering design creativity, we must be able to assess its two core components: ‘novelty’ and ‘usefulness’. For this, the following information is needed:

- Candidate measures for novelty, usefulness and creativity, where creativity is a function of novelty and usefulness. Many measures are available in literature, but how they are related to one another is missing.
- Some way of independently assessing novelty, usefulness and creativity against which potential measures can be evaluated. This is also missing.

An ideal means for independent evaluation would be to use the collective knowledge of experienced designers from the domains to which the newly generated products belong. In a design house, creativity of new solutions is typically judged by experienced designers to decide whether to develop these solutions into products. In patent offices novelty and usefulness of products are judged by experts from related areas. We argue, like Amabile (1996) who suggest the use of experts to identify what is ‘creative’, that for any measure of novelty, usefulness or creativity to be valid, the results should reflect the collective notion of experienced designers. We use this as the benchmark for evaluating the potential measures.

#### 2.3.3.1 Novelty

‘New’ is something that is recently created. ‘Novel’ is one that is socially new. ‘Novelty’ encompasses both new and original (Cambridge 2007). We need a direct measure of novelty. Developing a measure involves developing both a scale and a process of measurement. For detection of novelty of a new product, its characteristics need to be compared with those of other products aimed at fulfilling similar need (the process). The difference in these characteristics would indicate how novel the new product is. If no other product satisfied a similar need before, the new product should be considered to have the highest novelty (the maximum value in the scale). If the product is not different from previously known products, its novelty should be zero (the minimum value in the scale). Thus, to assess novelty of a product, one should know the time line of similar inventions and the characteristics of similar products. It must also be possible to determine the degree of novelty (resolutions in the scale). Existing literature on measuring novelty (Redelinghuys 2000;

Saunders 2002; Shah and Vargas-Hernandez 2003; Chakrabarti and Khadilkar 2003; Lopez-Mesa and Vidal 2006) deals mainly with identification of whether a product is novel or not. Patent offices often employ experts to determine ‘novelty’, ‘usefulness’ and other aspects of patent proposals. But, little work exists in identifying the degree of novelty in products.

Two major elements are missing in these current methods: history of ideas is not taken into account, and the scale without mention of its maximum possible value is potentially incomplete. Also, while all methods use some Function-Behaviour-Structure model (FBS) (Chandrasekaran 1994; Qian and Gero 1996; Goel 1997) of the artefact for determining novelty, we argue that FBS models alone are not sufficiently detailed to enable adequate assessment of degree of novelty. We use FBS as well as SAPPhIRE model (Chakrabarti et al. 2005) to achieve this.

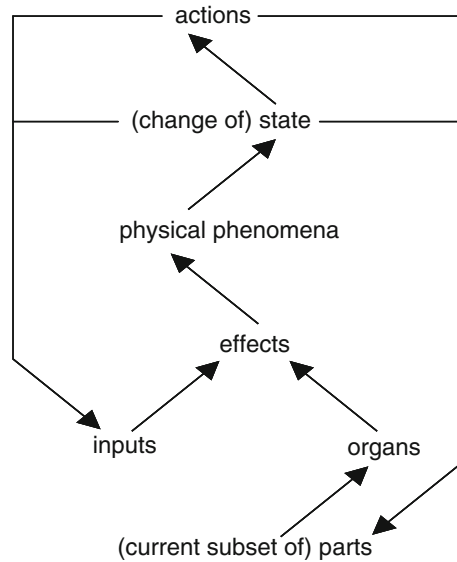
### 2.3.3.2 Proposed Novelty Measure and Validation

To determine novelty of a new product with respect to available products, comparison of these products is carried out by comparing their features. FBS models are suitable for this. Since novel products are new and original, if the functions of a new product are different from those of available products, it must have the highest degree of novelty (we call this very highly novel). If the structure of the product is the same as that of any other product, it cannot be considered novel. If it is neither, the product has some novelty. To determine the degree of its novelty, a detailed model of causality – the SAPPhIRE (standing for State-Action-Part-Phenomenon-Input-organ-Effect) model (Chakrabarti et al. 2005) is used, see Fig. 2.2. It has seven constructs. *Action* is an abstract description or high level interpretation of a change of state, a changed state, or creation of an input. *State* refers to the attributes and their values that define the properties of a given system at a given instant of time during its operation. *Physical phenomena* are a set of potential changes associated with a given physical effect for a given organ and inputs. *Physical effects* are the laws of nature governing change. *Organs* are the structural contexts needed for activation of a physical effect. *Inputs* are energy, information or material requirements for a physical effect to be activated. *Parts* are the physical components and interfaces constituting the system and its environment of interaction. Parts are needed for creating organs, which with inputs activate physical effects, which are needed for creating physical phenomena and state change. State changes are interpreted as actions or inputs, and create or activate parts. *Activation*, *creation* and *interpretation* are the relationships between the constructs.

For detection of degree of novelty in products that are not ‘very highly novel’, state change and input constitute the next level of novelty (‘high’ novelty), physical phenomena and physical effect the following level (‘medium’ novelty), and organs and parts constitute the lowest level (‘low’ novelty) at which a product can be different from other products. Based on these, a method for novelty detection has been developed which employs FBS model first, and SAPPhIRE model thereafter to assess the degree of novelty of a product. The method was evaluated in terms of the



**Fig. 2.2** The SAPPhIRE model of causality



degree to which its output (the degree of novelty of products as determined using the method) matched (it did with an average Spearman's rank correlation of 0.93, see (Sarkar and Chakrabarti 2007a, 2008a)) with the output of experienced designers (the degree of novelty of the same sets of products as perceived by these designers).

### 2.3.3.3 Usefulness

We argue that it is the actual use of a product that validates its usefulness. Thus, the usefulness of a product should be measured, whenever possible, by its actual use, and when this is not possible, value of its potential use should be used. Products could then be compared by assessing their degree of their usefulness – the second criterion for judging creativity.

Patent offices employ experts to determine both novelty and usefulness to ascertain validity and patentability of applications, but do not use explicit measures for these. Usability is the closest measure for usefulness available in literature. It denotes the ease with which people can employ a particular tool or other artefact in order to achieve a particular goal (Nielsen 1994; Green and Jordan 2002; Graham 2003). Various norms exist for its assessment such as ISO and SIS. The methods for evaluation of designs or products (Roozenburg and Eekels 1995) are the closest available for assessing usefulness of products. However, none of these are direct measures for usefulness. We therefore propose a new method for measuring usefulness, based on the following arguments:

- Usefulness should be measured in terms the degree of usage a product has in the society.

- The scale is provided by a combination of several elements to assess the degree of usage: the importance of the product's function, its number of users, and how long they use it for or benefit from it. Together these would give a measure of how extensive the usefulness of the product is to the society.
- Though usefulness should be ideally judged by taking feedback from a statistically representative collection of users of the product, this is best approximated by the collective opinion of experienced designers who are trained to understand users well. Hence, collective opinion of experienced designers is used as benchmark for corroborating results.

### 2.3.3.4 Proposed Usefulness Measure and Validation

As to how important the use of a product is depends on its impact on its users' lives. Some products are indispensable, and should have a higher value for their usefulness. We identified five *levels of importance* of products: extremely important (e.g., life saving drugs), very highly important (e.g., compulsory daily activities), highly important (e.g., shelter), medium importance (e.g., machines for daily needs), low importance (e.g., Entertainment systems). All other parameters being equal, the products that are used by a larger number of people – the *rate of its popularity* – should be considered more useful to the society. Finally, products that are used more *frequently* and have longer *duration* of benefit should be considered more useful to the society. Assuming that their 'level of importance' and 'rate of popularity' are the same, the 'rate of their usage' increases their usefulness. Together these parameters provide a measure for usefulness:

$$U = L (F D) R \quad (2.1)$$

U stands for usefulness; L stands for level of importance; F for frequency of usage (how often people use it); D for duration of benefit per usage; R for rate of popularity of use (how many people use it). Ranking of various product-sets using the proposed measure has been found to have consistently high correlation (Spearman's rank correlation average of 0.86) with that using experienced designers' collective opinion, showing that the proposed method captures well the designers' intuitive notion of usefulness.

### 2.3.3.5 Proposed Creativity Measure and Validation

With 'novelty' and 'usefulness' of products as the *only* two direct influences on creativity (as in the common definition), a measure for creativity must express creativity as a function of these two. For a list of creativity measures, see [Sarkar \(2007\)](#). We propose the relationship to be a product of the two influences, since absence of either should lead to perception of no creativity in the outcome (C: creativity, N: novelty, and U: usefulness):

$$C = N \times U \quad (2.2)$$

To assess the degree of creativity of products in a given set, the steps are to:

1. Assess novelty of each product (using method in Section 2.3.3.2) on the qualitative scale: ‘Very high novelty’, ‘High novelty’, ‘Medium novelty’ or ‘Low novelty’.
2. Convert these qualitative values into quantitative values: Very high novelty = 4 points, High novelty = 3 points, Medium novelty = 2 points and Low novelty = 1 point.
3. Assess the usefulness of each product using the method described in Section 2.3.3.4.
4. Convert these qualitative values into relative grading using the following scale: if there are five products that are ranked 1–5, give them 1/5, 2/5, 3/5, 4/5, 5/5 points respectively.
5. Calculate creativity of each product as a product of its degree of novelty and usefulness using Eq. 2.2.

Once again, creativity ranks obtained using experienced designers’ collective opinions are compared with those using the proposed method. The results (Spearman’s rank correlation average of 0.85) show consistently high rank correlation between these, corroborating the proposed method. Further analysis shows no correlation between usefulness and novelty, indicating their independence, thus further corroborating our results.

## 2.4 Major Influences on Creativity

A wide variety of factors are cited in literature as influencing creativity. Rhodes (1961, see Davis 1999) group over fifty definitions of creativity into four Ps: product, people, process and press, the product factors being influenced by the factors of the other three Ps. Various factors related to each of these Ps have been identified, e.g., strong motivation (people), incubation (process), or relaxed work environment (press).

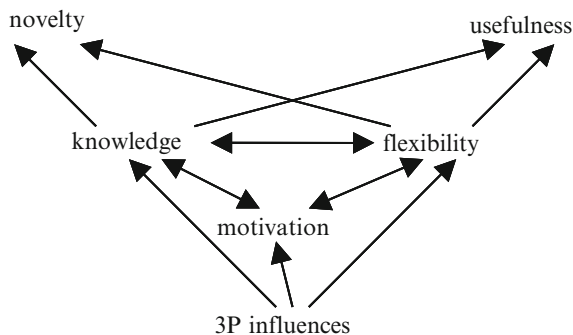
Several authors describe creativity as a special kind of information or knowledge processing (e.g., McKim 1980), and argue that information or knowledge must be a prime ingredient for creativity. For instance, Gluck (1985) sees as essential the “. . . possession of tremendous amount of raw information . . .”, as does Read (1955; cited in Davis 1999, p. 44) who describes this as “scraps of knowledge” in describing creative people who “. . . juggle scraps of knowledge until they fall into new and more useful patterns.” Note the act of juggling in this description – one proposed to be described here with the generic name of ‘flexibility’. Also note the mention of “new” and “valuable” patterns – the two aspects of creative outcomes. Various authors have also stressed the importance of flexibly processing knowledge. McKim (1980) speaks of flexibility in “levels, vehicles and operations”, and argues that seamless use of and transfer between these are important in creative thinking. Gluck (1985)

describes as essential in creativity the “ability to combine, order or connect” information. In C-K Theory (Hatchuel et al. 2004), the authors distinguish two different kinds of creative ideas: those that are dominated by knowledge requirement, and those that operate within existing knowledge but require imagination for conception. We interpret the first category as primarily requiring new *knowledge* while the second primarily requiring flexibility in thinking. In TRIZ (Terninko et al. 1998), children are described as capable of connecting all ideas to each other, while common adults connect only few – that too in the existing ways. In the light of flexibility and knowledge requirement for creativity, the act of children can be interpreted as having great flexibility in thinking with little knowledge of the constraints among them, while adults having far less flexibility with far more knowledge. In the four stage model of the creative process (see Wallas 1926, cited in Davis 1999, p. 44), the first stage – *preparation* is interpreted here as accumulation of knowledge – the “scraps” as described by Read. The second stage – *incubation* is one of transferring the task to the subconscious – a sign of flexibility (McKim 1980). The third stage – *illumination* – is when these two come together to create the idea. Note that ‘mental blocks’ (Adams 1993) are blocks against using knowledge in a flexible way.

We propose *knowledge, flexibility* and *motivation* (i.e., encompassing all motivational factors and indicators such as challenge, energy-level, single-mindedness and aggression) as the three factors essential for creative thinking, see Fig. 2.3. McKim has spoken of similar factors “for productive thinking” – information, flexibility and challenge. Perkins (1988, cited in Davis 1999, p. 45) describes creative people as “motivated”, have creative “patterns of deployment” or “personal manoeuvres of thought” (both of which are interpreted here as flexibility) and have “raw ability in a discipline” (seen here as knowledge). Echoing somewhat similar notions, Torrance (1979; cited in Fox and Fox 2000, p. 15) argued that “prime factors” on creativity of people are their “abilities, skills and motivation”.

The specific ideas proposed here in this regard are the following:

- Motivation, knowledge and flexibility are the broad, major factors influencing creativity.



**Fig. 2.3** Influences on creativity

- The factors are not independent of each other. Knowledge influences motivation, motivation may lead to acquiring of new knowledge; flexibility leads to development of new knowledge that may lead to more flexibility; motivation to utilise knowledge in a flexible way may lead to further flexibility leading to more motivation, etc. This idea of interdependence of factors is inspired by Lewis' model (1981) of influences on intelligence in children. Lewis sees intelligence as the ability to see and solve problems – at a broad level not very different from designing. In his model, motivation, self-image and attitude are all linked to a child's problem-handling skills, and vice-versa.
- Among these factors knowledge and flexibility directly affect the outcome of a creative problem solving process, while motivation assumes an indirect influence. Other factors, from the categories of people, process and press influence one of these factors, which in turn influence the novelty, purposefulness and resource-effectiveness of the product.

## 2.5 Effect of Search and Exploration on Creativity

The work reported in this section is primarily based on the work reported in [Sarkar and Chakrabarti \(2007b\)](#) and [Srinivasan and Chakrabarti \(2008\)](#). Design is seen by many as a phenomenon of exploration ([de Silva Garza and Maher 1996](#)) and search. Some see exploration or search as similar to idea finding since both are divergent processes, where many ideas need to be considered before selecting the best ([Roozenburg and Eekels 1995](#)). Exploration is an important part of design creativity ([Gero and Kazakov 1996](#)) since creative design is generation and exploration of new search spaces ([Stal and George 1996](#)). Exploration also improves a designer's problem understanding ([de Silva Garza and Maher 1996](#)). Thus, exploration and search are important influences on design creativity. We take 'Exploration' as a process by the space within which to search is determined. 'Search' is a process of finding improved designs in a given design space ([Sarkar and Chakrabarti 2007b](#)).

In order to understand how search and exploration takes place in design and how these influence creativity, we carried out and studied a series of design experiments, where various groups of designers solved various design problems in a laboratory setting ([Sarkar and Chakrabarti 2007b](#)). All utterances in the design experiments were video taped, transcribed and categorized into three phases: (i) problem understanding, (ii) idea generation and (iii) evaluation and selection. Each utterance was then classified into search or exploration. It was found that the number of utterances of the type 'exploration' was negligible (less than 1% in all protocols – see discussion later). Next, it was found that searches in the idea generation phase can be further classified into other sub-categories. We call these 'unknown search', 'global search', 'local search' and 'detail search'. These kinds of search are present not only in solution generation, but also in problem understanding and solution evaluation stages.

An ‘unknown’ or ‘global search’ represent search in a *global design space* that is less specific than that of the local and detailed spaces. A ‘design space’ consists of a set of ideas (which can be problems, solutions or evaluating criteria) that are similar to each other in some respect. Depending upon the relationship and level of abstraction used, a design space can overlap with, or subsume other design spaces. In a *global design space*, a solution is different from other solutions in terms of ‘state change’, ‘input’ ‘Physical Effect’, ‘Physical Phenomenon’, ‘Organ’ and ‘Parts’. A local search space is within a global search space; the ideas are different in the ‘Physical Effect’, ‘Physical Phenomenon’ ‘Organ’ and ‘Parts’ used. Solutions in *detail search* are different only in the ‘Organs’ and ‘Parts’.

The designers typically search first unknown or global, then local and ultimately detailed spaces, leading to the solutions becoming increasingly more detailed. While global, local and detailed search spaces are previously visited by designers while solving other similar problems, unknown spaces are not. Search at the higher level in the hierarchy (such as ‘unknown’ and ‘global’) include searches that are in the lower level of hierarchy (e.g., ‘local’ or ‘detailed’). Each of these searches is either on finding potential problems, solutions or evaluation criteria. For instance, a ‘global problem search’ might contain many ‘local problem searches’ and ‘detailed problem searches’, leading to identification of several potential problems at various levels of detail. There can be many problem-, solution- and evaluation-searches possible for a given problem; their existence is established when the designers are found to identify a problem or generate a solution or evaluation criterion that belongs to a specific design space.

Analyses showed the following results:

- Each design process observed used all 12 variants of search –four types (unknown, global, local and detail) at three phases of problem solving (problem understanding, solution generation and solution evaluation).
- Higher levels of search had a strong influence on the lower levels of search, i.e., the number of unknown search influenced the number of global, local and detailed search, the number of global search influenced the number of both local and detailed search, and the number of local search influenced the number of detailed search.
- Assessment of creativity of the design groups using the creativity measures described in Section 2.3 of their final design outcome and its correlation with various searches carried out showed that the number of search at each phase variously correlate with creativity, with the highest correlation being with solution search (average correlation 0.85) and least with evaluation search (0.62), with problem search in between (0.67), see [Sarkar and Chakrabarti \(2007b\)](#) for more detail.

There is complementary evidence from the recent work of [Srinivasan and Chakrabarti \(2008\)](#) where video recordings of the design processes of various groups of designers were analysed using a model of designing called GEMS of SAPPhIRE as RS (Generation, Evaluation, Modification and Selection/Rejection of State-Action-Parts-Phenomena-Input-oRgan-Effects as Requirements-or-Solutions), and the number of ideas generated at the SAPPhIRE levels were correlated with

the novelty of the solution spaces generated. The results showed that the number of ideas generated at higher levels of abstraction had a greater positive influence on the creativity of the solution space. A major conclusion from the above results is that carrying out search in greater depth at all design problem solving phases and at all levels of abstraction, in particular at the higher abstraction levels, substantially improve the creative quality of the solutions developed.

## 2.6 How Well Do Designers Currently Explore Design Spaces?

Sarkar and Chakrabarti (2007b) found that across all design cases studied, the design process follows a general pattern (with a correlation of 0.99), irrespective of whether it is in problem understanding, solution generation or solution evaluation. Observations indicate that unknown design search are generally less in number, followed by a larger number of global search but comparatively fewer local search, followed by a huge number of detailed search. This is contrary to the expectation that the number of searches should increase consistently as it gets more detailed.

There are two potential explanations for this anomaly. One is that the trend is due to progressive divergence and convergence in the number of searches performed, a commonly known means used by designers in order to control the amount of information handled as they go from less to more detailed phases of design (Liu et al. 2003). However, this does not explain why convergence has to be at the local search level only. The second possible explanation is that, once the required design functionality is established, designers work primarily at the device level. This is evidenced by the observation that designers frequently bring to fore past designs and try to mould them to do the current task. The sparse use of local searches likely to be due to *a lack of knowledge of phenomena and physical principles*, and due to the belief that working at the device level is likely to be more pragmatic in terms of creating realistic designs faster.

Further evidence of similar kind is found by Srinivasan and Chakrabarti (2008). In their design studies, they counted the number of ideas generated at each level of the SAPPhIRE, and found that for each team of designers, while the number of ideas at the action, state change and input levels steadily higher, the effects and organ level ideas are particularly low, before the number of ideas at the part level become high again. This is consistent with the findings of Sarkar and Chakrabarti (2007b). We argue that this indicates a serious deficiency in the uniformity and consistency with which search is carried out currently. This leaves substantial scope for bridging this gap and improving the creative quality of the solution space.

## 2.7 Supporting Creativity

Based on the findings discussed in the earlier sections of this chapter, we conclude the following. Since the two major direct influences on creativity are knowledge and flexibility, since creativity is enhanced if search is carried out uniformly in at all levels of abstraction of design at all phases of design problem solving, and since this is currently not followed, support is necessary to ensure that designers' knowledge and flexibility are enhanced to carry out search uniformly.

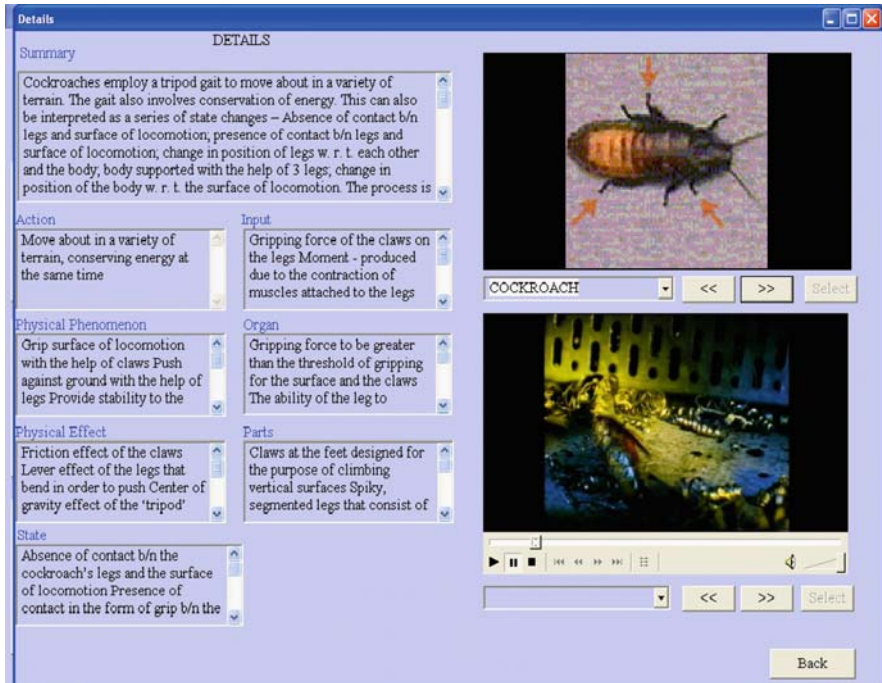
One way to support this is to provide stimuli as an inspiration for creativity. Inspiration is useful for exploration of new solution spaces (Murakami and Nakajima 1997). Literature provides evidence that presence of a stimulus can lead to generation of more ideas being during problem solving (Kletke et al. 2001), that stimulus-rich creativity techniques improve creativity (MacCrimmon and Wagner 1994), and that when stimulated with association lists people demonstrate more creative productivity than when not stimulated (Watson 1989). Both natural and artificial systems are seen as rich sources of inspiration for ideation. The importance of learning from nature is long recognized, and some attempts made (Vogel 1998; French 1998) to learn from nature for developing products. However, while artificial systems are routinely used for inspiration (e.g., in compendia, case based reasoning systems, etc.), natural systems are rarely used systematically for this purpose. Analogy is often proposed as a central approach to inspiring generation of novel ideas, and many methods and tools to support this are proposed (Gordon 1961; Bhatta et al. 1994; Qian and Gero 1996). Our objective is to support systematic use of biological and artificial systems as stimuli for aiding generation of creative designs.

### 2.7.1 *Idea-Inspire*

We developed a computational tool called 'Idea-Inspire' (Chakrabarti et al. 2005) for supporting designers to generate novel solutions for design problems by providing natural or artificial systems as analogically relevant stimuli to be used for inspiring ideation. It has two databases: a database of natural systems (e.g., insects, plants, etc.) exhibiting diverse movements, and a database of artificial systems (e.g., vacuum cleaners, clutches, etc.). The behaviour of these natural and artificial systems are described using the SAPPhIRE model of causality. Designers, with a problem to solve, are supported to describe their design problem using the constructs of SAPPhIRE – the software would search the databases for the entries in the databases that could analogically relevant for solving the problem.

The database of natural systems has over 300 entries from plants, animals and natural phenomena describing their motion behaviour. The motions analysed are varied in both the media in which they occur (air, water, land, desert, etc.), and the way in which they occur (leaping, jumping, walking, crawling, etc.). The description contains the function, behaviour and structure as well as a SAPPhIRE model





**Fig. 2.4** A natural system as entry in idea-inspire

based description of each system, as well as their pictorial and video data about their behaviour. An example of an entry is given in Fig. 2.4. The database of artificial systems has over 400 entries and contains similar information as in the database of natural systems plus animation of the system behaviour for many mechanisms for which video is not available. An example of an entry is given in Fig. 2.5. Associated reasoning procedures are developed to help browse and search for entries that are analogically relevant for solving a design problem.

### 2.7.2 Using Idea-Inspire

Idea-Inspire can be used in two different modes:

- When a designer has a well-defined problem to solve. In this case, the designer defines the problem using the SAPPhIRE constructs, and uses reasoning procedures of the software for automated search for solutions. In some cases, the designer may try out different versions of the problem using the constructs until satisfactory solutions are obtained.
- When a designer does not have a well defined problem to solve. In this case, the designer can browse the databases and view related entries, then get interested in

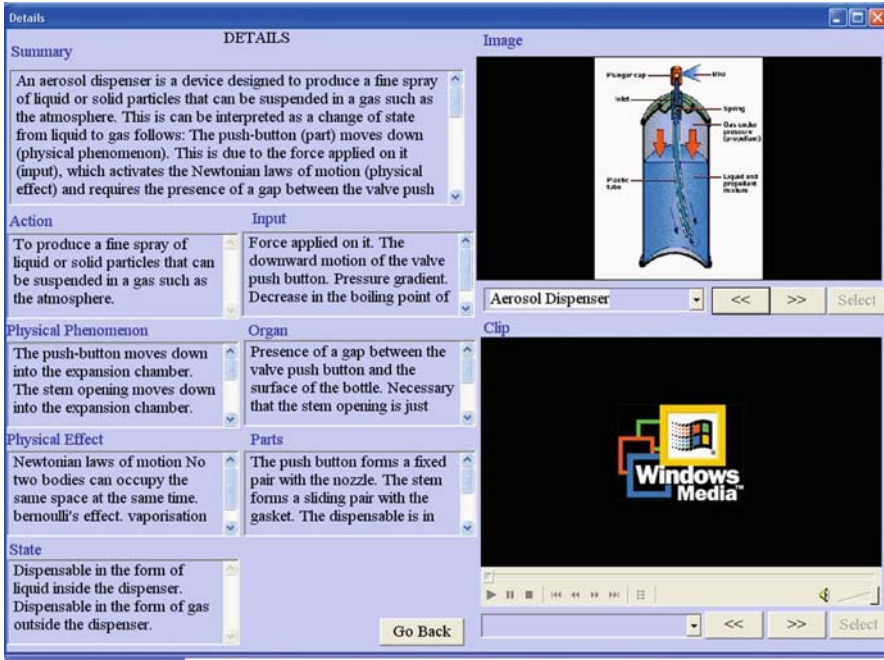


Fig. 2.5 An artificial system as entry in idea-inspire

some of these, and work on these in greater depth to solve the problem. Browsing may also help in understanding a problem better, as a designer gets exposed to a wider variety of related yet concrete solutions.

In each of these cases, the output from the software is a list of entries that match the constructs provided to the search engine as the problem. A design problem is often described using the *action* required to be fulfilled, and the search task is to retrieve all entries that have synonymous actions. An action is described using a verb-noun-adjective/adverb triplet. For instance, consider this design problem: *Design an aid that can enable people with disabled upper limbs to eat food.* A designer could describe the action required in many alternative ways- using different sets of verbs, nouns and adjectives. Some examples are

1. V = feed, N = solid, A = slow (put solid food in the mouth)
2. V = consume, N = solid, A = slow
3. V = take, N = solid, A = (nil)

Alternatively, the problem can be decomposed into sub-problems and solutions for each can be searched. Some such combinations are

4. (V = hold, N = solid, A = quick) + (V = move, N = solid, A = slow) + (V = push N = solid, A = slow) (here, the device is intended to take the food in a container, move close to the mouth, and transfer to the mouth)
5. (V = get, N = solid, A = slow) + (V = swallow, N = solid, A = slow).

The entries retrieved for the first and last problem alternatives are

- Case 1: List of some of the entries found by the software: Aardvark, bar-racuda, Duck, Clam Defence, and Pitcher plant, etc.
- Case 5: List of some of the entries found by the software:
- Sub-case 1: (V = hold, N = solid, A = quick) – Reciprocating lever gripper, Rack and pinion gripper, Hydraulic gripper.
- Sub-case 2: (V = move, N = solid, A = slowly) – Camel moving, Millipede, Baboon, Crab walking, Transport mechanisms, Belt drives, etc.
- Sub-case 3: (V = push N = solid, A = slowly): no entry was found for this.

Depending upon a designer's interest, various details of an entry could be explored. The problem may have to be redefined several times, using different VNA words, until satisfactory solutions are found.

### **2.7.3 Evaluation**

In order to evaluate the effectiveness of the software in inspiring creative solutions in designers, a series of interventional case studies were undertaken. In the first study (Chakrabarti et al. 2005), two designers solved individually two design problems of their choice from a pool of problems given, first without using the Idea-Inspire software and then by using the software. The idea was to see if the intervention made any substantial difference in the number and kind of solutions generated. The number of ideas that were created as a result of being triggered by some entries (that are used as an inspiration) from the software, as well as ideas that were identical to some entries (that can be used directly as a solution), were both noted down. It was found that by using the software, each designer was able to create additional solutions for each problem after they completed created solutions without using the software. On average, the number of ideas created with the software constituted about 35% of all ideas created, that too with a database having a limited number of entries (about 200).

In a subsequent evaluation, three designers solved individually one engineering design problem, first without and then with the aid of Idea-Inspire (Sarkar et al. 2008). In each problem solving session, they first generated the ideas, and then selected those which they felt were worth developing further, and developed them into solutions. It was found that, despite some individual variations, the designers on average created 165% more ideas with the aid than without, that too after they felt (at the end of their session without aid) that they exhausted the ideas they could think of for solving the design problem. The size of the database used was about 500. It is also to be noted that about 40% of all ideas were chosen by the designers as worth developing further, indicating that the ideas generated with inspiration from Idea-Inspire were not only large in number but also similar in quality to those generated by designers on their own.

The software has been delivered to the Indian Space Research Organisation (ISRO) for aiding ideation of concepts to solve space-related design problems,

and has been customised for use by IMI-Cornelius for aiding their designers both in individual and group ideation sessions. However, the work is far from over. While understanding has substantially increased over the years, it is still not well-understood what elements in the descriptions provided in the entries inspired ideation. Specific studies need to be undertaken to understand how best to support and encourage ideation for all types of search at all levels of SAPPPhIRE.

While the above are the aspects of the content of the material for stimuli, another complementary but important aspect is the form in which a stimulus is provided. We provide the information about a stimulus (an entry in the database) in textual, graphical, animation/video and audio forms. The textual material is structured using FBS and SAPPPhIRE models. How does the same information in different forms affect ideation differently?

To answer this question, a subset of Idea-Inspire entries were taken, and each entry was represented as several, alternative entries each of which was described using a different representation (textual only, graphical only, etc.). Different representations of these selected entries were placed in separate slides in a presentation form. The sequence of representations for each stimulus was randomized. Later, each slide was shown to six volunteer design engineers who solved the same, given problem, using each slide as a stimulus. The engineers were asked to capture each solution they generated in white sheets, along with the number of the slide that triggered the solution. The experiments were conducted in laboratory setting. Even though there was no strict time constraint, each slide was shown in the main experiment for about 5 min. The results (the stimuli and corresponding solutions created) provided the data required to answer the research question. It was found that in general non-verbal representations (graphical, followed by video) have a greater influence on the creative quality of the solutions generated than verbal means (Sarkar and Chakrabarti 2008b). However, each has its complementary, positive aspects. A video is inherently better in showing the dynamic aspects of the content while the verbal mode is better in terms of explaining the behaviour of a stimulus, and an image could be used for explaining its internal and the external structure. We argue that the ‘non-verbal’ representations of a stimulus should be shown first, followed by its ‘verbal’ representations, in order to draw attention first, and make all its aspects available for exploration.

## 2.8 Summary and Conclusions

The chapter strings together work from several research projects and PhD theses at IdeasLab in the last 7 years to provide an overview of the understanding and support developed in the area of design creativity. A ‘common’ definition for creativity has been developed after analysing a comprehensive list of definitions from literature. The two direct parameters for discerning creativity are found to be *novelty* and social *value*. The definition is further specified for engineering design creativity where value is taken as the utility value or *usefulness*. Both novelty and usefulness are operationalised into measures for creativity, and a relationship between these measures

and creativity is established where creativity is assessed as a *product* of the value of these two measures. All of these are validated by comparing the outcomes of ranking product sets using the measures developed with that using the collective opinion of experienced designers. Using extensive analysis of work from literature, the three major factors influencing creativity were formulated to be *knowledge, flexibility* and *motivation*.

In order to understand how search and exploration affects creativity, design processes were recorded and analysed using protocol analysis methods. Four different types of search were identified, and all were found to be present in each of the three main phases of design problem solving. Searching design spaces well at all these levels were found to have a strong impact on creativity of the solution space. Ideas were found to be generated at all levels of abstraction modelled by the SAPPPhIRE constructs, and search at all these levels, in particular at the higher levels was found to have a strong impact on creativity.

It was found that designers were consistently deficient in searching the effect and organ levels of abstraction – i.e., generate ideas in terms of the physical effects and properties of the products envisaged. This distinct gap, we felt must be bridged in order to enable a more uniform search of design spaces. Various forms of support are under development at IdeasLab; one of them – Idea-Inspire – has been described in some detail in this chapter.

For a given problem, Idea-Inspire searches its database of natural and artificial systems as entries to find relevant entries that can be used as stimulus for inspiring solutions to the problem. In the design cases studied, it consistently helped designers in ideation. The influence of both the form and content on ideation was studied. The work shows substantial potential, even though much is still to be researched.

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