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Knowledge: the good, the bad, and the ways for designer creativity

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ABSTRACT

Design is a highly nonlinear chaotic dynamic process with many possible solutions, some of which can be creative. The chaotic nonlinearity of design dynamics triggers mental stresses in designers, whose creativity happens only when their mental stresses are at an optimal level. Following a deductive approach, this paper investigates how knowledge can contribute to designer creativity by uncovering knowledge's (good and bad) roles in the design process, based on which three ways are recommended to use knowledge properly in design. The assumption is that all designs follow one governing equation, which is a recursive integration of three basic design activities: formulation, evaluation and synthesis. The difference between designs of various fields and different kinds (routine, innovative and creative) lies in the range, content, size and nature of the design space in which the design governing equation works. The design governing equation implies a nonlinear chaotic design dynamics, whose solutions are sensitive to its initial conditions and can be routine, innovative or creative. The design governing equation is solved and reformulated by the designer's creativity capability. Therefore, design researchers, practitioners and educators should cohesively look at both designer's knowledge/experience and the designer's creative thinking process.

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knowledge; designer creativity; design dynamics; creativity; mental stress

The role of a designer's knowledge in the design process has long been an important research topic, which has been used as one of the determinants to distinguish novice and expert designers (Ahmed, Wallace, and Blessing 2003; Cross 2004; Ho 2001; Ozkan and Dogan 2013; Wu et al. 2019). Some believe that a designer's knowledge is the core of a creative design process (Christensen and Ball 2016; Kunrath, Cash, and Kleinsmann 2020; Li et al. 2007). Without knowledge, it would be impossible to create anything that could meet the design requirements. Knowledge plays a good role for designers to deeply and differently understand design problems (Grauberger et al. 2022; Lee et al. 2021). Some believe that a good design process and methodology are the foundation of creative design (Liu et al. 2011; Thoring and Müller 2011). Some others believe that both design methodology and design knowledge are important to creative design (Jiao et al. 2022; Su, Akgunduz, and Zeng 2022). The variety of understandings and perspectives has many implications

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for design computing (Lee et al. 2021), design practices (Buker et al. 2022; Lindwall et al. 2022; Madhusudanan, Gurumoorthy, and Chakrabarti 2019), design management (Du and Jiao 2022; Shafqat, Oehmen, and Welo 2022), and design education (Borgianni et al. 2022; Prabhu et al. 2022).

The present paper aims to provide a theoretical, deductive and perspective analysis of the role of knowledge in design by answering the following four research questions:

- **Q1:** What is design creativity?
- **Q2:** What is designer creativity?
- **Q3:** What is the role of knowledge in design/designer creativity?
- **Q4:** When and how to use knowledge in design?

The rest of the present paper is organised as follows: Section 1 answers Q1 by employing a mathematical theory of design. Section 2 answers Q2 and Q3 by analyzing the dual roles (the good and the bad) of knowledge in design by using a TASKS framework. Section 3 answers Q4 by providing three ways enabling designers to effectively and efficiently use knowledge in creative design. Finally, section 4 summarises the paper and briefly discusses implications of the perspectives offered in the paper. To facilitate the reading of the present paper, we have made the headings and subheadings self-explainable showing the logic of the arguments made in the paper.

Design creativity: knowledge drives a design process to creative designs

Design creativity generally refers to the situation that the created product is creative. Three standard criteria of design creativity are originality (or novelty), effectiveness (or utility and usefulness) (Sternberg and Lubart 1999), and surprise (Boden 2004; Runco and Jaeger 2012; Simonton 2012). Furthermore, Simonton (2012) proposed a quantitative three-criterion equation to describe design creativity in terms of novelty, utility, and surprise.

Different designs fundamentally follow the same mechanism

As Herbert Simon described, design is an action aimed at changing existing situations into preferred ones (Simon 1981). We are all designers since the intelligent activity that produces an engineering product is fundamentally no different from the one that prescribes interventions for a patient, the one that proposes a healthcare act for a country, the one that creates a plan for career success, or the one that arranges a vacation for a family. Design is the core of all professional and everyday thinking dealing with various situations (Norman 2013; Simon 1981). The situation is where a design product is to work.

Zeng defined the situation as a part of the environment in which the product is expected to function (Zeng 2002, 2015). Therefore, the design process can be viewed as an environment-changing process, as illustrated in Figure 1, where the product comes from the environment, serves the environment and evolves the environment.

The environment evolution can be represented in Eq. (1), where $\oplus$, the structure operation defined in (Zeng 2002), represents the union of an object and the relation to the object itself. When a new product (S_i) is created into its environment (E_i), the structure of the original environment ($\oplus E_i$) will be changed into a new structure ($\oplus E_i + 1$), which has

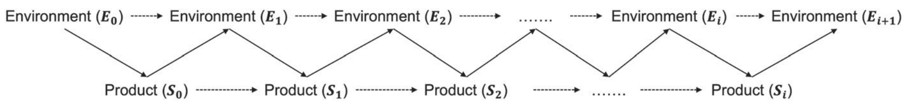

Figure 1. Design: environment changing process.

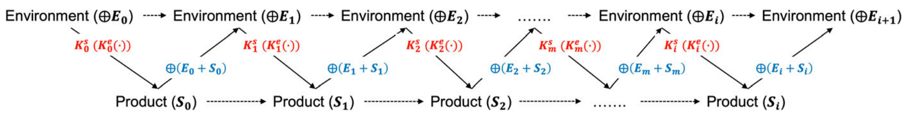

Figure 2. Design: evolution from $\boldsymbol{E_i}$ to $\boldsymbol{E_{i+1}}$.

four components: the structure of the original environment ($\oplus E_i$), the structure of the new product ($\oplus S_i$), and the mutual interactions between the original environment and the new product ($E_i \otimes S_i$ and $S_i \otimes E_i$). The environment structure of the initial state ($\oplus \boldsymbol{E_i}$) includes the description of the design solution at the design stage i, the design requirements for the design stage (i+1), the related design knowledge, and other relevant design information (Zeng 2004). It was shown that environment structure embodies everything appearing in design activities, including design requirements, knowledge, and solutions (Zeng 2004)..

$$\oplus \boldsymbol{E_{i+1}} = \oplus(\boldsymbol{E_i} + \boldsymbol{S_i}) \tag{1}$$

A design process indeed governs the environment-changing shown in Figure 1. Formulation, synthesis and evaluation are three primary phases in the design process (Jones 1963). First, design formulation aims to collect and formulate the design problem, which corresponds to the structuring of the environment $\oplus \boldsymbol{E_i}$ in Eq. (1). Secondly, design evaluation, corresponding to $\boldsymbol{K_i^e}(\oplus \boldsymbol{E_i})$ in Eq. (2), is the process to identify the gap of the existing product descriptions with the design requirements formulated in design analysis. In most cases, design evaluation would take causal knowledge to assess the product performance (Kim and Kim 2011). Finally, design synthesis is a process that generates new product descriptions according to the identified gap from design evaluation. Zeng and Cheng (1991) integrate the three operations into the recursive logic of design, based on which Zeng and Gu (1999b) developed a mathematical theory to formally represent the recursive formulation, evaluation and synthesis processes. Zeng (2004) further formalised the process into the recursive evolution of the environment structure, which is called the design governing equation (Zeng and Yao 2009; Zeng 2002; Zeng 2004), as shown in Eq. (2).

$$\oplus \boldsymbol{E_{i+1}} = \boldsymbol{K_i^s}(\boldsymbol{K_i^e}(\oplus \boldsymbol{E_i})) \tag{2}$$

where a design problem is formulated by analyzing the current design state (environment $\oplus \boldsymbol{E_i}$) through $\boldsymbol{K_i^e}(\oplus \boldsymbol{E_i})$ using the evaluation operation $\boldsymbol{K_i^e}$. Then a new design state (i+1) (environment $\oplus \boldsymbol{E_{i+1}}$) results from the application of the synthesis operation $\boldsymbol{K_i^s}$ to the formulated design problem $\boldsymbol{K_i^e}(\oplus \boldsymbol{E_i})$. Combining Eq. (1) and (2) with Figure 1, we can get an updated design process, as shown in Figure 2.

In the design governing equation Eq. (2), the design requirements and solutions define a design space through the structure operation $\oplus$, which will be stretched by the synthesis operation and shrunk by the evaluation operation, as shown in Figure 3. The final design

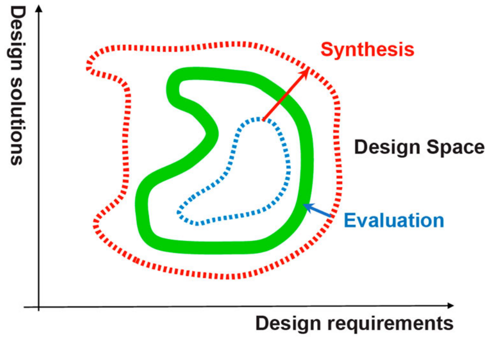

Figure 3. Design space under synthesis and evaluation.

solutions are the result of balancing the stretching and shrinking operations. Design is such an ill-defined problem where designers will continuously define and redefine the design problem/requirements, constraints, and context (Simon 1973).

The fundamental design mechanism is a recursive, nonlinear, and chaotic dynamics

It was proposed that the design governing equation, Eq. (2), implies recursive nonlinear chaotic dynamics (Zeng 1992, 2001), under which a slight difference in initial conditions could lead to chaotic fluctuations during the time course with the synthesis and evaluation as stretching and folding operations. The same observation was made by Richards (1996, 2001, 2021) in that creativity follows a nonlinear dynamics (chaotic), demonstrating the Butterfly Effect. Chaos does not mean randomness or disorder; indeed, chaotic dynamics is a well-established scientific discipline.

The design mechanism is recursive in the following two aspects:

(1) Design problem, solutions, and knowledge evolve simultaneously and recursively during the design process. This recursion was mathematically and logically identified as the recursive logic of design (Zeng and Cheng 1991). As a confirmation, Roozenburg associated the recursive logic of design with Charles Pierce's innovative abduction (Roozenburg 1993). Furthermore, Dixon and French further studied this phenomenon in the context of Deweyan logic (Dixon and French 2020). At a different level, Maher, Poon, and Boulanger (1996) and Dorst and Cross (2001) claim that the design problem space and design solution space follow co-evolution during the design process. The co-evolution process is driven by a reaction to a surprise (change in environment) (Dorst and Cross 2001). The same can be found in Campell's evolutionary theory (Campbell 1965) and Simonton's evolutionary model (Simonton 1999).
(2) Evaluation knowledge, synthesis knowledge and structure operation recursively interact in the design process. This recursive interaction between the three design subprocesses was formulated and formalised in (Zeng and Jing 1996) and (Zeng and Gu, 1999a).

Eq. (2) is not a linear equation in that the superimposition rule fails the equation. As a result, multiple design solutions exist, and different initial conditions could lead to different solutions. Furthermore, this nonlinear dynamic design process becomes chaotic since the recursive dependence among evaluation knowledge, synthesis knowledge and structuring operation implies the stretching and folding operations necessary for chaos to emerge in nonlinear design dynamics. Therefore, the design governing equation Eq. (2) defines recursive, nonlinear and chaotic dynamics for the design process.

With a similar line of understanding, some scholars have noted the importance of recursion in the sub-phases of creativity (Lubart 2001; Zeng, Proctor, and Salvendy 2011). In describing the design (Gero and Kannengiesser 2004) highlighted that an 'agent's view of the world changes depending on what the agent does'. In describing the creative process, Corazza (2019) stressed that continued exploration is a primary force driving the creative process, while bidirectional dynamic interaction with the environment influences the recursion underlying the creative process in terms of dynamic assessment and the emergence of unpredictable new functionalities. Lubart (Lubart 2001) indicated that initial ideas might interact with the developing work in a dynamic and evolving creative process. Lubart also raised several critical questions for future research on creativity, such as 'to what extent is the creative processes recursive?'; 'how exactly is this recursion organized?'; 'what provokes recursion?'; and 'what metacognitive functions control the choice of certain subprocesses and their recursive application?'

Though the nonlinear design dynamics appears to be a structured, deterministic, and causal model of design, it accommodates flexibility, uncertainty, unpredictability, and chaos through its sensitivity to initial conditions. Furthermore, the definition of the initial design condition is subjective. Therefore, the nonlinear recursive design process can be naturally viewed as an evolving creative process, and it can be derived that.

(1) Routine, innovative and creative designs follow the same design governing mechanism; and
(2) Designer creativity is the condition leading to routine, innovative and creative designs.

Design creativity crosses routine, innovative and creative design spaces

Creative design is unpredictable; sometimes, it even seems impossible – yet they happen (Boden 2004). Different designers could produce different design solutions for the same design problem, and the same designer could produce different design solutions at different times for the same design problem. Creativity may happen even if one does not mean to conduct a creative design, whereas creative design just may not come out no matter how hard one tries. Thus, a natural question is: does a designer produce routine, innovative and creative designs following one governing mechanism, as shown in Eq. (2)?

According to Gero's classification (Gero 1990), a design is routine if it proceeds within a design space of known and ordinary designs; it is innovative if it proceeds within a well-defined state space of potential designs, but produces different designs; and it is creative if new variables and structures are introduced into the design space of potential designs. A good design solution is a result of recursively selecting methods based on related good knowledge. Knowledge is a resource for designers to produce design solutions from design problems. Design can be seen as a knowledge-based problem-solving activity (Chandrasekaran 1990), in which knowledge recursively links to their problem and sub-problem

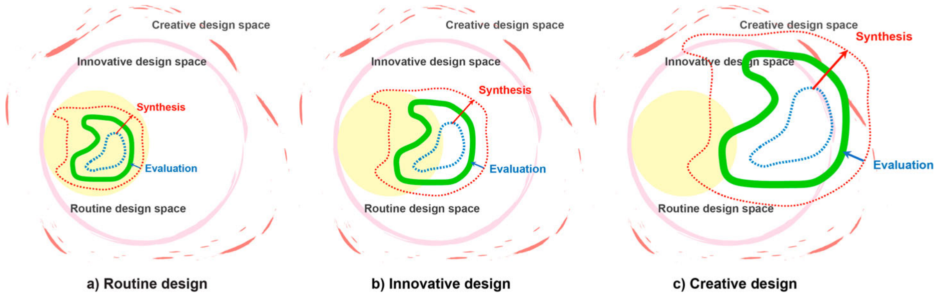

Figure 4. Design creativity: (a) routine design – synthesis and evaluation operators act only on the routine design space; (b) innovative design – synthesis and evaluation operators act on both the routine and innovative design spaces; (c) creative design – synthesis and evaluation operators act on the routine, innovative, and creative design spaces.

(Chandrasekaran et al. 1992). As such, Figure 4 defines different types of design, according to which design spaces are described where the design governing equation Eq. (2) would apply. Obviously, the knowledge and experience of the designer determines the boundaries of design spaces.

Designer creativity: knowledge-related designer capability is fundamental to creative designs

Designer creativity is the ability to come up with ideas or artifacts that are new, surprising and valuable (Boden 2004). Given a design problem, a designer will identify the relevant knowledge to generate tentative design solutions, improving the designer's understanding of the design problem. This improved understanding might lead to a reformulation of the original design problem. Reformulating the problem will lead the designer to identify new knowledge and change previously generated solutions, leading to another design problem reformulation.

Designer creativity means that the designer is creative, which is the process of design creativity. Designer creativity can be divided into static states related to how the designer's capability influences creativity and dynamic processes related to achieving creativity (Corazza 2016; Zeng and Gu 1999a). The dynamic creative process requires the available flexibility for designers to switch freely among information and idea evaluation, idea generation, and idea evolution (Corazza, Agnoli, and Mastria 2022; Jia and Zeng 2021).

It is possible that a designer is not creative but the product is and a designer is creative but the product is not. The Four C model is commonly used to describe individual creativity (Kaufman and Beghetto 2009): mini-c (relevant to the genesis of creative expression), little-c (relevant to non-professional readily creative recognition), pro-c (relevant to professional creative recognition), and big-c (relevant to eminent creativity). Some researchers argued that different factors of capability influence designer creativity, such as intelligence (Gardner 2011; Torrance 1969), knowledge, thinking style (ex. divergent and convergent thinking) (Guilford 1967), personality (Csikszentmihalyi 2014; Feist 1998; Lebuda et al. 2021; Stein 1953) and motivation (Amabile 1983; Sternberg and Lubart 1991). Torrance (1969) argued that creativity requires a certain level of intelligence. Gardner (2011) also proposed different types of intelligence and argued that creativity is multiple as intelligence is. Sternberg

(2021) argued that intelligence is adaptive, interacting with a person, task, and situation. Tromp and Sternberg (2022) applied Person x Task x Situation interaction framework to explain creativity. Guilford (1950, 1967) proposed a special thinking style, divergent thinking (divergent product), to describe creativity. He argued that it is essential for creativity to the interplay between divergent and convergent production. Recently, exploring the relationship between divergent thinking and ideation has been very often found in creativity studies (Lee and Ostwald 2022; Mastria et al. 2021). Amabile (1983) proposed a componential model that assumes three components influencing creativity: domain-relevant skills, creativity-relevant processes and intrinsic task motivation. Sternberg & Lubart (Sternberg and Lubart 1991) proposed an investment theory where an economist's vision of creativity includes six elements to form creativity: intelligence, knowledge, thinking style, personality, motivation, and circumstances.

Considering that the recursive nature of the design process leads to unpredictability and uncertainties and that the novelty of creative design would challenge the designer's comfort zone, mental stress is an inevitable outcome during the creative design process. Inspired by Yerkes and Dodson (1908), which indicated that people would perform the best under moderate amounts of stress, Zeng and his students proposed that people would be most creative when they are subject to an optimal level of mental stress (Nguyen and Zeng 2012; Zhu, Yao, and Zeng 2008). Instead of assuming an inversed U-shaped-curve relation between performance and stress, Nguyen and Zeng defined an inversed U-shaped-curve relation between mental stress and mental effort (Nguyen and Zeng 2014). Nguyen and Zeng also defined how mental stress is related to perceived workload, knowledge, skill, and affect (Nguyen and Zeng 2012, 2017b, 2017a).

Designer mental stress: designer creativity comes from the designer's optimal mental stress

Based on Nguyen & Zeng's work on mental stress and mental effort, Yang et al. (2021) proposed TASKS Framework (**T** for Task, **A** for Affect, **S** for Skills, **K** for Knowledge, and **S** for mental Stress-effort relation), which is a theoretical framework to identify implementation facilitators and barriers for human behaviour in implementing a task. The underlying reason for a person's behaviour is their perceived tasks, knowledge, skill, and affect (Nguyen and Zeng 2012). The creativity behaviour is adaptive to their perceived task. The level of mental stress, in turn, affects the designer's creative performance. As for the same question, a designer's knowledge and skills cannot change in a short period. Therefore, a designer's mental effort decides the designer's level of creativity. Low – and high-level mental stresses produce low-level mental efforts, whereas medium-level mental stress results in optimal mental efforts, which may lead to creativity, as shown in Figure 5 (Nguyen and Zeng 2012).

Importantly, Nguyen and Zeng (2012, 2017b) also formulated the cause–effect relationship of mental stress and perceived task workload, knowledge, skill, and affect, as shown in Eq. (3)**.** The perceived task workload is an external load exerted on an individual and can be associated with the complexity of the task. Both knowledge and skills form human cognitive ability and rationality. Depending on the mental capacity, the perceived task workload, which is the workload perceived by an individual, can be higher or smaller than the actual workload. The perceived task workload will then determine the mental stress. Knowledge originates in human cognition and can aid people in making proper decisions (Rowley

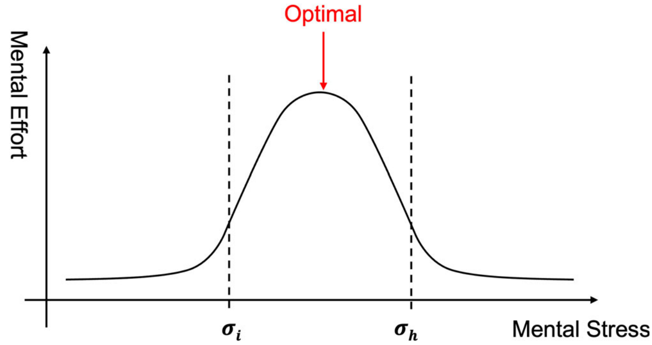

Figure 5. Relationship between mental stress and mental effort (Nguyen and Zeng 2012; Yang et al. 2021).

2007). Better knowledge could help a better decision about actions (Davenport and Prusak 1998), which can be influenced by different types of knowledge such as experience, judgement, thumb rules, and values and beliefs. Skills can be categorised into cognitive, affective and psychomotor (Bloom 1956), for which logic is critical. Affect refers to any experience of feeling or emotion, ranging from suffering to elation, such as fixation and uncertainty. Affect, which falls between 0 and 1, could determine how much of a designer's knowledge and skills can be activated and harnessed to complete a given design task. Gero also pointed to the interpreted world that is very similar to mental capability and the expected world as perceived task workload (Gero and Kannengiesser 2004).

$$\boldsymbol{Mental\ stress} = \frac{Task\ workload}{Mental\ capability} = \frac{Perceived\ task\ workload}{(Knowledge + Skills) \times Affect}, \ A \in (0,1) \tag{3}$$

TASKS framework identifies barriers and facilitators to human behaviours. In the TASKS framework, barriers and facilitators build on the gap between the ideal TASKS components and the implementer's actual mental capability (ASK). Yang et al. (2021) categorised implementation barriers/facilitators into four types: knowledge, logic, emotion, and resource. The good knowledge for designers is the facilitator, whereas the bad is the barrier. In the following session, we will discuss when the designer's knowledge could lead to good (facilitator) and bad (barrier) mental stress.

The good: proper designer knowledge maintains the designer's mental stress to the right level to trigger the creativity

Designer creativity happens when designers' mental stress is optimal, which means the combination of perceived task workload, knowledge, skills, and affect are optimal. The designer's knowledge and skills can be assumed to be constant during a short design process; thus, the designer's perceived task workload will be mainly influenced by the affect. The perceived task workload in a good affect (close to 1) reflects the actual one more than that in a bad affect (close to 0).

If a designer has the perfect knowledge for a given design problem, then the design solution will be available simultaneously (Yoshikawa 1981). However, because of the limitation in human understanding of the world, designer knowledge is never perfect and always goes with the designer's perception (Zeng 2002). As a result, the design problem becomes open-ended and ill-defined, and the design process becomes recursive, nonlinear and chaotic. Furthermore, the uncertainty can appear in different ways: (1) the design requirements may be unclear, incomplete, or conflicting; (2) the environment and its possible interactions with the product may be unknown due to the lack of knowledge; and (3) the lack of design thinking and capability to deal with the first two situations. Nevertheless, the uncertainty arising from a design task is the condition for a designer to demonstrate creativity (Nguyen and Zeng 2012), and uncertainty makes creativity possible (Beghetto 2021; Runco 2022).

Under an uncertain situation, designers must employ their creative capabilities to find and apply proper knowledge to their design problems. Too much uncertainty could make it difficult for a designer to find the proper knowledge to understand and solve the design problem, which could bring the designer into the over-stress zone and thus defy the designer's effort to perform. Equipped with proper knowledge, certain degrees of uncertainty mean more possibilities that fall under the designer's capability zone. The unknown can be exciting and motivating, prompting designers to experiment with and develop new ideas. Without any uncertainty, there is likely no emotion and stress to drive designers to experiment with and try new things. Both the knowledge and affect factors will regulate the designer's mental stress, according to Eq. (3). The knowledge-related skills introduced in Section 3 will help designers identify and acquire the necessary and proper knowledge for creative designs.

The bad: improper knowledge leads to design fixation inhabiting designer creativity

Another phenomenon is design fixation, which is seen as an obstacle to design creativity (Jansson and Smith 1991). Design fixation is defined as 'blind adherence to a set of ideas or concepts limiting the output of conceptual design' (Jansson and Smith 1991). One of the distinctive features of fixation is that designers do not know when they are fixated by misleading or poor information (Linsey et al. 2010). Kannengiesser and Gero (2019), combing Kahneman's dual system (Kahneman 2011) with FBS (Gero 1990), pointed out two types of design fixation in the design process: (1) system 1: generating an initial idea or concept, and (2) system 2: elaborating the initial structure. Youmans and Arciszewski (2014) also proposed a similar fixation level: unconscious adherence, conscious blocking, and intentional resistance, where conscious blocking and intentional resistance belong to system 2.

It is worth noting that both novice and expert designers are prone to prematurely committing to design solutions (Linsey et al. 2010; Viswanathan, Tomko, and Linsey 2016). When designers encounter open-ended design problems, they retrieve potential solution concepts from their existing memory and knowledge base (Jansson and Smith 1991). Therefore, Christensen & Schunn (Christensen and Schunn 2007) argue that one of the triggers of fixation is the connection of distant domains. The designer has easier-to-retrieve concepts within closely related domains than domains distant from each other. In addition, the designer's personality types and lacking awareness of technological advances also cause fixation (Moreno et al. 2016).

In explaining design fixation following a formal causal reasoning, Nguyen & Zeng (2017a) formalised the structure of design fixation, including potential solutions and designer

Way 1: Formulating a design problem differently

$$\oplus E_{i+1} = K_i^s\left(K_i^e(\oplus E_i)\right) = \boxed{K_i^s}\left(K_i^e\left(\boxed{\oplus\left(\bigcup_{j=1}^{n_e} E_{ij}\right)}\right)\right) = K_i^s\left(K_i^e\left(\bigcup_{j=1}^{n_e}(\oplus E_{ij}) \cup \bigcup_{j_1=1}^{n_e}\bigcup_{\substack{j_2=1\\ j_2\neq j_1}}^{n_e} \boxed{\left(E_{ij_1}\otimes E_{ij_2}\right)}\right)\right)$$

Way 3: Extending synthesis design knowledge

Way 2: Changing the strategy of environment decomposition

Figure 6. Three ways in the design governing equation (n_e: the number of environment components. E_{ij}: is an environment component in the same design state (E_i))

preferences. Fixation was defined as the condition wherein designers use an inappropriate existing design idea to solve a design problem due to their strong attachment to the idea. In the design solution space, there are various design solutions. If an expected (or actual) design solution fits the designer's preference, design fixation will be more likely to happen. Corresponding to fixation in systems 1 and 2, fixation in system 1 means the designers' strong emotional attachment to their experience and efforts. This leads to failure to transfer knowledge appropriately or limit the design solution space. Fixation in system 2 means the lack of the right knowledge-related skills (including thinking styles, thinking strategy and reasoning). In the mental stress equation shown in Eq. (3), designers' different knowledge and skills influence the designer's affect, which is the designer's preference in design fixation structure. When designers lack the proper knowledge and skills, the potential solutions are also influenced by different preferences. Those knowledge-related skills introduced in Section 3 will help designers overcome fixations.

The ways: knowledge-related skills enable designers to use knowledge properly to achieve creative designs

Applying knowledge to designer creativity aims to avoid the bad and enhance the good role of knowledge. Designer creativity may happen when they use proper knowledge to solve design problems, leading to optimal mental effort successfully. In the design science domain, there are two streams to arrive at this destination: (1) realising creativity and (2) overcoming fixation. Most design methodologies are for the first stream to solve design problems creatively. Also, some researchers focus on the second stream in terms of finding more implementation methods based on fixation's trigger stimuli (Dong and Sarkar 2011; Moreno et al. 2016; Viswanathan, Tomko, and Linsey 2016; Youmans and Arciszewski 2014) and avoid factors of fixation through teamwork (Crilly 2015). This paper focuses on the first stream to realise designer creativity based on the design governing equation, as shown in Eq. (2).

Based on the design governing equation, three possible ways may lead to different design states, which can be creative designs, as shown in Figure 6. The three ways are (1) formulating a design problem differently, (2) extending synthesis design knowledge, and (3) changing the strategy of environment decomposition. The connection between related activities and ways is shown in Table 1. More details are shown in the following subsections.

Table 1. The connections between related activities and three ways ($\boldsymbol{C_i}$: a conflict at the $\boldsymbol{E_i}$; $\boldsymbol{S_i}$: the new product)

Ways	Required Knowledge	Related Activities
Formulating a design problem differently (Different E_i)	Evaluation knowledge	*Different* $\oplus\left(\cup_{j=1}^{n_e} E_{ij}\right) \rightarrow$ *different* $E_i \rightarrow$ *different* $K_i^e \rightarrow$ *different* C_i
Changing the strategy of environment decomposition (Different E_i)	Evaluation knowledge	*Different* $C_i = (E_{ij_1} \otimes E_{ij_2}) \rightarrow$ *different* K_i^s
Extending synthesis design knowledge (Different E_{i+1})	Synthesis knowledge	*Different* $K_i^s \rightarrow$ *different* $S_i \rightarrow$ *different* E_{i+1}

Way 1: formulating a design problem differently

When Formulating a design problem differently is in the original design state or during the design process. The initial difference in problem formulation will be amplified in the design process because each design stage will redefine the problem. It is common sense that changing the perspective of seeing a problem may lead to a creative solution.

Function Formulating a design problem differently will result in different initial design states. A design problem is a request to design something that meets a set of descriptions of the request (Zeng 2004). Formulating a design problem is included in the environment structure $\oplus\boldsymbol{E_i}$. The inclusion or exclusion of an environment component $\boldsymbol{E_{ij}}$ will lead to different $\oplus\boldsymbol{E_i}$. Designers may form a design problem differently by grouping different environment components into one assembly, which will lead to a change of $\oplus\boldsymbol{E_i}$. As a result, because of its nonlinearity, different initial conditions of the design problem may lead to different design solutions, some of which might be creative.

In practical applications, these initial conditions may be manifested as different designers or as the same designer designing at different times. Since novice and expert designers have pretty different experiences, they usually apply different methods to formulate the problem. As a result, they got different solutions. Even if the same designer changes a perspective, the design problem will be formulated differently. Consequently, the object $\boldsymbol{C_i}$ (Table 1) could be changed, which in turn changes the initial condition of the design process. The process could result in a significant change in design solutions. Therefore, different knowledge can formulate a design problem differently.

How Formulating design problems is realised through designers' knowledge and skills, such as information search and understanding, which is led by the following activities: (1) search and identify evaluation knowledge, (2) search, identify and redefine critical requirements, (3) generate and update primitive design solutions, and (4) evaluate, analyze and recompose partial design solutions. From a macro perspective, designers may use different methodologies during the design process, which lead to different design formulations. From a microscopic perspective, even if designers use the same methodology, different designers will use different knowledge and experience to formulate problems differently, depending on their affect and perception at the time of designing.

pt Different design methodologies naturally help designers formulate a design problem differently since different methodologies lead to different evaluation knowledge. According to how a methodology formulates a design problem, Zeng classifies design methodologies into three types (Zeng, 2021): (1) product-based, (2) product-environment interaction-based, and (3) environment-based. Product-based methodology mainly focuses on evaluation and optimizations, such as axiomatic design (Suh 1998), decision-based design (Hazelrigg 1998; Wassenaar and Chen 2003), and structural topology optimisation (Bendsøe and Kikuchi 1988; Bendsoe and Sigmund 2003). The product-environment interaction-based methodology includes function-based design and affordance-based design. Pahl and Beitz (1988) proposed a systematic approach to formulate design problems in generic systems. Pahl and Beitz combined general systems modelling with functional modelling to model artifacts in a hierarchy of subfunctions sharing flows of material, energy, and information (Pahl et al. 1996). Hubka and Eder (1988) also proposed the theory of technical systems in the same year. Umeda et al. (1990) developed a function-behaviour-state (FBS) connected them through physical phenomena. Gero & Kannengiesser (Gero 1990; Gero and Kannengiesser 2004) proposed situated function-behaviour-structure (FBS) to formulate a design problem in terms of three entities (function, behaviour and structure) situated in three worlds (external. interpreted, and expected world). Using situated FBS, Becattini et al. (Becattini et al. 2020) investigated how individually pre-conceived expectations influence the different surprise emergence. Chandrasekaran et al. and Bhatta & Goel (Bhatta and Goel 1997; Chandrasekaran, Goel, and Iwasaki 1993) proposed the structure-behaviour-function (SBF) knowledge representation for engineering systems. Stone and Wood (1999) built a functional basis for engineering design. Quality function deployment (QFD) is a methodology to ensure that customer needs are adequately transformed into engineering characteristics for a new product (Akao and Mazur 2003). The house of quality gives several perspectives on customer requirements and engineering characteristics to formulate design problems differently. Maier and Fadel (2009) proposed an affordance-based design to formulate a design problem regarding a designer – artifact – user (DAU) system. Affordance is a relation that one system (an artifact) provides to another system (a user). DAU system points to artifact-user affordance and artifact-artifact affordance. Dinar and Shah (2012) established a problem map framework to represent a design formulation strategy containing five groups of entities: requirement, function, issue, artifact, and behaviour.

In contrast, the environment-based methodology is centred on the environment to formulate problems. Human-centred design (HCD) is an approach for creative problem-solving in several fields, starting with understanding the product's human environment (Norman 2013), such as stakeholders' needs and requirements. Mike Cooley coined the term 'human-centred systems' in the context of the environment transition in the design process (Cooley 1980). Zeng (2004) proposed environment-based design (EBD) to formulate a design problem in terms of product environment, structural requirements, and performance requirements. Structural and performance requirements are related to the product environment, divided into natural, built (physical and digital artifact), economic, and social environments (Yang et al. 2020). In EBD, the question-asking tool is applied to help designers formulate problems effectively and efficiently (Wang and Zeng 2009), especially for novice designers. Dorst and Cross (2001) also proposed a process to formulate a design problem by asking a quasi-standard set of questions.

Way 2: changing the strategy of environment decomposition

When Changing the strategy of environment decomposition happens after designers have developed an in-depth understanding of the design problem and have identified existing conflicts included in the problem. Identified design conflicts can be resolved in different ways. Conflict is an insufficiency of resources for an object to produce a desired action on its environment or to accommodate the object's action on its environment (Zeng 2015). Conflict is different from the notion contradiction in TRIZ. Contradiction refers to the propositions that assert apparently incompatible or opposite things (Altshuller 1984) whereas conflict refers to the insufficiency of resources for an object. Contradiction focuses on the product behaviour while conflicts addresses the root of contractions.

Function A different strategy to decompose the environment results in different combinations of different environment components $\boldsymbol{E_{ij}}$, leading to different problem reformulations. Strategy is a plan intending to achieve a particular purpose. Changing the strategy of environment decomposition is related to how to arrange the order of conflicts to resolve. Designers might decompose the environment of the original design problem once they have developed an understanding of the relationship between environment components. Different strategies of product environment decomposition result in different structural and performance constraints. As a result, the newly decomposed environment will formulate a new design problem. Also, the design process is a nonlinear process that concerns flexibility, uncertainty, and unpredictability of the design problem. Therefore, the environment will be continuously decomposed until the design problem becomes primitive. Generally, no two designers have precisely the same design knowledge, so they will use different ways to decompose the environment. Different sequences of environment decomposition will give rise to different reformulations of the design problem when designers apply their knowledge. As a result, the final solutions may be different.

How Changing the strategy of environment decomposition involves specific skills such as conflict identification and problem generalisation. Changing the environment decomposition may be led by two activities: (1) search for critical conflicts and (2) identify evaluation knowledge. This process is related to information understanding from which knowledge is acquired. From a macro perspective, different methodologies have different rules for decomposing the environment. From a microscopic perspective, even if following the same methodology, different designers will use different knowledge and experience to get a strategy to decompose the environment.

The strategy of environment decomposition includes breadth-first and depth-first. Breath-first decomposition explores each subproblem, while depth-first decomposition focuses on a specific subproblem in detail. In general, novice designers tend to use a depth-first approach to explore partial sub-solutions. At the same time, experts prefer a breadth-first strategy to develop sub-solutions in parallel, with a switch to a depth-first approach when facing unfamiliar problems (Cross 2011). That is because the depth-first strategy requires little domain knowledge, whereas the breath-first strategy needs considerable domain knowledge (Chandrasekaran et al. 1992). In EBD, the strategy is hybrid rather than depth-first and breadth-first, which is considered the best way to minimise uncertainty and induce creativity in the problem formulation process (Wang, Nguyen, and Zeng 2015).

Way 3: extending synthesis design knowledge

When Extending synthesis design knowledge happens in design solution synthesis. Based on decomposed sub-problems, different or new knowledge might lead to diverse angles to discover a creative solution.

Function Extending synthesis design knowledge will change the relation from conflicts to design concepts $\boldsymbol{S_i}$**.** The extended knowledge provides the possibility for the selection of different $\boldsymbol{K_i^e}$and $\boldsymbol{K_i^s}$, which results in the different intermediate design state $\oplus \boldsymbol{E_{i+1}}$. We can see that some new and different primitive products may be generated for a specified environment part by extending synthesis knowledge. The newly generated concepts are considered the environment components and analyzed by combining other identified environment components for generating a new round of design concepts. Therefore, extending synthesis design knowledge can help designers generate more candidate solution concepts, increasing the probability of generating a good concept. As a result, the final design solutions could be significantly different.

There are a few possibilities: first, more conflicts can be chosen at the same time to generate a design concept $\boldsymbol{S_i}$; and secondly, the same design conflict may be resolved by different design concept $\boldsymbol{S_i}$. Both cases will update the environment structure $\oplus \boldsymbol{E_{i+1}}$ differently. When design conflicts are identified by analyzing the relations between environment and product, designers will use their knowledge and experience to generate some candidate solution concepts. The number and quality of the design concepts largely depend on the designers' knowledge and experience. That is also a big difference between novice and expert designers. The generated concepts need to be evaluated to satisfy the specified product requirements. Novice designers cannot often evaluate the generated concepts using the proper criteria and finally fail to generate a good design solution. When we compare designs by a novice designer and an expert designer, we can see a big difference in the design solutions.

How Extending synthesis design knowledge through effective information acquisition, knowledge learning, and scientific discovery. Knowledge cannot be tied to one task but depends on its use (Bylander and Chandrasekaran 1987). Generating new knowledge is a reasoning task (Chandrasekaran et al. 1992). Right questions can identify new knowledge sources against relevant information and determine a degree of fit (Chandrasekaran 1986). Different information collection methods require different levels of knowledge. For example, depth-first search requires little domain knowledge, whereas hierarchical classification needs considerable domain knowledge (Chandrasekaran et al. 1992). The right level of knowledge acquisition consists of a problem definition, representation and inference strategy (Bylander and Chandrasekaran 1987).

The knowledge structure follows a hieratical pyramid called the data-information-knowledge-wisdom hierarchy (DIKW) (Ackoff 1989). The hierarchy describes knowledge coming from information as information comes from data. Knowledge can also come back to information and data, which is called de-knowledging (Davenport and Prusak 1998). Data, information, and knowledge are related to each other, which forms a recursive process. Knowledge is information with added value, experience, and context, which can provide a framework for synthesising, evaluating and incorporating new experiences and information (Davenport and Prusak 1998).

Knowledge generation transfer information to knowledge through a cognitive understanding and reasoning process (Polanyi 2012). Reasoning is the process of the mind using existing knowledge to think, understand, conclude, and form judgments logically, which generally includes the minor premise as the situation and knowledge as the major premise. There are four types of reasoning (Zeng and Cheng 1991): (1) deductive logic, (2) inductive logic, (3) abductive logic, and (4) recursive logic, in which only deductive reasoning is deterministic, and all other reasoning modes are implausible (Zeng 2002). Recursive logic combines deductive logic, inductive logic, and abductive logic. As a result, these four types of reasoning lead to four methods that can help designers extend synthesis design knowledge: knowledge derivation, extraction, generalisation, and discovery.

Knowledge derivation (deduction)

Knowledge derivation follows deductive logic to derive synthesis knowledge from one or more pieces of information and existing knowledge. Knowledge derivation starts with the assertion of a general rule to reach a logical conclusion, which aims to predict the future based on the information provided in the task description and the existing knowledge. Information is organised or structured data by some purpose and relevance. For example, following the deductive approach, Cascini et al. (Cascini, Fantoni, and Montagna 2013) proposed a framework applying Gero's Function-Behavioure-Structure (FBS) to represent a product's needs and requirements and their relationship with FBS dimensions and other papers on the same topic (Fernandes et al. 2007; Sim and Duffy 2003).

Knowledge extraction (abduction)

Knowledge extraction follows abductive logic to extract synthesis knowledge from small data, which begins with an incomplete set of observations and looks for causes from given effects by applying a set of existing knowledge. As abductive reasoning requires, knowledge extraction hangs on a particular theory in the reasoning process. Through the application of abduction to a small set of data, knowledge can be extracted by removing certain details embedded with the data. For example, Cheligeer et al. (Cheligeer et al. 2022b) proposed ROM-based (Zeng 2008) semantic networks to address knowledge graphs related to the design problem from a seed design statement. Similar efforts can be found in a few other papers (Lin, Fox, and Bilgic 1996; Rockwell et al. 2009).

Knowledge generalisation (induction)

Knowledge generalisation follows inductive logic to generalise synthesis knowledge from big data. Inductive logic begins with observations. Knowledge generalisation aims to develop new knowledge from available evidence or collected knowledge. The process related to converting data into information and knowledge makes data meaningful, valuable and relevant. Many methods exist to transform data into information, such as adding meaning to data, categorising data, mathematically analyzing data, correcting errors in data, and condensing data (Davenport and Prusak 1998). Numerous methods, algorithms and applications can be found in the contemporary machine learning-related literature.

In the field of design, examples of work in this category include the generalisation of product customisation knowledge through mass customisability analysis (Hou and Jiao 2020; Jiao and Tseng 2004; Zhou, Du, and Jiao 2022), emotional design (Zhou, Ji, and Jiao 2021), patent data-driven to generalisation of engineering knowledge (Jiang and Luo 2022; Siddharth et al. 2021; Song, Luo, and Wood 2018; Song and Luo 2017), and big data-based customer analytics to generalise knowledge of customer requirements (Jin et al. 2016; Liu et al. 2020; Tong et al. 2022). Cheligeer et al. (2022) summarised machine learning methods for requirements elicitation. In the health domain, Wu et al. (2022) use machine learning methods to evaluate and generalise adverse events knowledge from electronic medical record (EMR) data. Notably, Quan et al. proposed the ICD coding system as meta-level knowledge for electronic medical administrative data (Eastwood et al. 2022; Quan et al. 2005). Using ICD coding system, researchers can generalise medical knowledge from the EMR system for precision medicine, such as comorbidities (Quan et al. 2005), hypertension (Quan et al. 2009), and diabetes (Chen et al. 2010).

Knowledge discovery (recursion)

Knowledge discovery follows the recursive logic to discover knowledge from nothing/zero data. Recursive logic combines deductive logic, inductive logic, and abductive logic. Popper (Popper 2012) proposed a tetradic schema for knowledge evolution from an initial problem (P_1), tentative theory (TT), attempts at error-elimination (EE) to further problems arising out of the critical process (P_2), which also follows a recursive process. Furthermore, he proposed 'Three World' ontology categories (Popper 1978): (1) World 1: the world of physical states and processes, (2) World 2: the mental world of psychological processes and (3) World 3: the world of knowledge in its objective sense.

Knowledge discovery is the same as design problem solving, where researchers must formulate an ill-defined research question and design a research protocol. The problem formulation, research design, and research results evolve simultaneously. At the beginning of knowledge discovery, we only know the environment of the phenomenon to be investigated.

Summary and discussions

Summary

Herein, this paper presents the difference between design and designer creativity to uncover the roles of knowledge in designer creativity, based on which three ways are recommended to use the knowledge in design. First, routine, innovative, and creative designs follow the same design mechanism, and designs from different fields also follow the same design mechanism. That mechanism is the design governing equation. Second, the difference between routine, innovative and creative designs and between designs of different fields lies in the range, content, size and nature of the design space in which the design governing equation works. Finally, design creativity is caused by the initial conditions for the design governing equation, which is solved and reformulated by the designer's creativity capability.

Recursion: designer creativity for the design creativity

The design process is to change the current environment ($\oplus E_0$) into a new environment ($\oplus E_1$), where the result can be creative, as shown in Figure 7. The fundamental design mechanism is a recursive nonlinear chaotic dynamics, which follows a basic environment evolutionary process (Figure 2). Recursive nonlinear chaotic dynamics leads to design uncertainties and is subject to the designer's fixations. Based on Nguyen & Zeng's (2017)

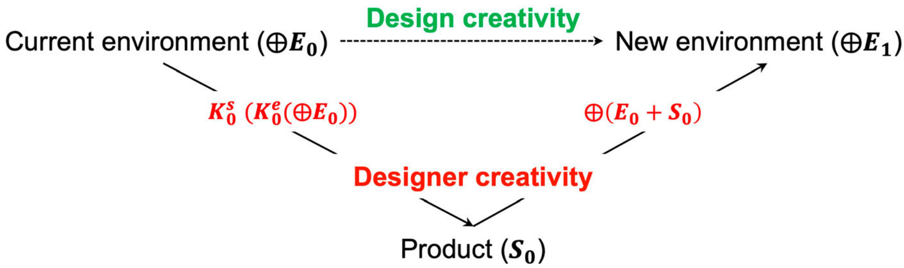

Figure 7. Designer creativity for design creativity

fixation structure, the designer's synthesis knowledge and evaluation knowledge determine the designer's preference, which determines potential design solutions. Then, the designer proposes a design solution by design evaluation and synthesis ($\boldsymbol{K}_0^s(\boldsymbol{K}_0^e(\oplus \boldsymbol{E}_0))$). The environment structure ($\oplus(\boldsymbol{E} + \boldsymbol{S})$) updates every state of the evolving design process.

Design is a problem that will simultaneously formulate the problem, find the knowledge, and generate the solutions (Zeng and Cheng 1991). Design problem formulation, design evaluation and design synthesis are three pillars of a design process. The designer's creativity capability dictates how the design process can generate creative design solutions through the recursive formulation of the design states.

Creative thinking and knowledge: if one is missing, only routine design will happen

Creative thinking and good knowledge are two essential characteristics of a creative designer. Producing creative designs is the most desired situation for a design. Unfortunately, routine design is what happens in the majority of cases. Two common scenarios occur for routine design: (1) the designer is creative without knowledge; (2) the designer has knowledge without creative thinking.

By citing the concepts in Figure 4, the first scenario describes a situation where the designer's innovative and creative design space is only a subset of the field's routine design space. The designer can be creative only in other people's routine design space. On the other hand, the designer may have rich knowledge, which could be effectively used to produce innovative designs; however, the designer may lack the creativity capabilities to recursively implement the formulation, evaluation and synthesis processes. As a result, the designer's knowledge will probably become a source of design fixations; creative solutions are most unlikely to happen.

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