

INFUSED DESIGN: A BRIEF INTRODUCTION

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Abstract

The paper introduces an approach for establishing effective collaboration between designers from different engineering fields in devising their designs. In the approach, the design problem representation is brought up to a mathematical meta-level, which is common to all engineering disciplines. The reasoning about the problem is then done by using mathematical terminology and tools that, due to the generality of the meta-level, are the same for all engineers, disregarding their background. This gives engineers an opportunity to infuse their work with knowledge and methods shared by specialists from other engineering fields.

The suggested meta-level consists of general discrete mathematical models, called Combinatorial Representations (CR). Specific mathematical basis for the combinatorial representations chosen in this paper is graph theory although other representations are possible. Through the CR, the design problems are elevated to the meta-level and then new types of cooperation and employing of knowledge from different fields becomes available, and is termed *infused design*. The knowledge of one domain can easily cross boundaries and is provably relevant to any problem in another domain to which it can be transformed.

The paper shows two types of cooperation made possible by infused design, and demonstrates one briefly on the cooperation between electrical and mechanical engineers at analysis tasks, and the other through collaboration between civil and mechanical engineers for solving a design problem. The paper concludes with a discussion on the design types that can be handled with this approach and their costs and benefits.

Keywords: collaboration, concurrent engineering, creativity, combinatorial representations, graph theory, knowledge sharing, knowledge infusion, product quality, design process

1 Introduction

There are many ways to design products. Some products are simple enough or very ordinary that a single designer can design them. Others are more complex, thus requiring solution by a group of designers; even though, the part of each is quite familiar and straightforward. However, new product development (and there are in the order of tens of thousands such products a year in the United States alone), are complex, unfamiliar, and as statistics shows, they tend to fail [4].

Even in successful product development projects, there are often situations where non-trivial problems arise that defy simple, familiar solutions. These situations can be considered as a local, lapse of knowledge or a knowledge gap. Present practice deals with such gaps by

outsourcing product design, exercising creativity methods (e.g., brainstorming [7], TRIZ [1]), or even negotiating the requirements with customers.

Beside these obvious opportunities for exercising creative thinking, there are other situations that engineer's face where they lack knowledge of solution methods or solutions even if they are not necessarily creative. In collaborative product design, expertise of one team member can augment or compensate for the lack of knowledge of others.

In this paper, we present infused design: an expansion to present collaborative practices in the nature of communication between participants. In infused design, design teams facing problems could infuse into their problem knowledge or solution methods from diverse disciplines in a systematic manner. This infusion is guaranteed to work in the present problem. Infused design, therefore, is a new way to approach the solution of hard problems that can be added to the arsenal of design methods. In relation to collaborative product design, we not only support “transcending boundaries while retaining the technical expertise afforded by specialization” [3] (p. 89); but also improve technical expertise by fusing interdisciplinary expertise into one amalgam. Consequently, we address the call that “research should focus on the creation, maintenance, and extension of links between the various participants” [3].

In this paper, we present a general perspective of Infused Design and demonstrate one embodiment that rests on combinatorial representations [12]. With this foundation, terminology, solution methods, and solutions can cross disciplinary boundaries and are guaranteed to address the original problem. In some cases, design is made possible, and in others, its quality is improved due to fusing knowledge and methods from other disciplines. Moreover, such benefits may also shorten the development processes. We also show how some other ideas in design research fit into infused design thus providing them with insight about future extensions. We conclude with answering a list of questions that arise naturally when encountering Infused Design.

2 Foundation of “Infused design”

Infused design deals with transferring terminology, solution methods, or solutions between different disciplines or problem contexts. Shown schematically in Figure 1, infused design has two conditions:

1. First, it requires the ability to reason from a disciplinary level (a) to more abstract representation (c) by ascending through intermediate levels (b) or directly. At the top level – the meta-level – representations of problems can be transformed into other representations by using properties of combinatorial representations (CR). These representations can subsequently serve as a starting point for descending to another disciplinary level where knowledge can be found, retrieved, and reused in the original discipline.
2. Second, infused design requires that the representation transformations be done in a way that guarantees the applicability of the knowledge embedded at each representation along a transformation path to any of the other representations visited.

Consequently, although the conditions are stated in a way that permits different forms depending on the nature of the aforementioned operations (i.e., ascending through the levels,

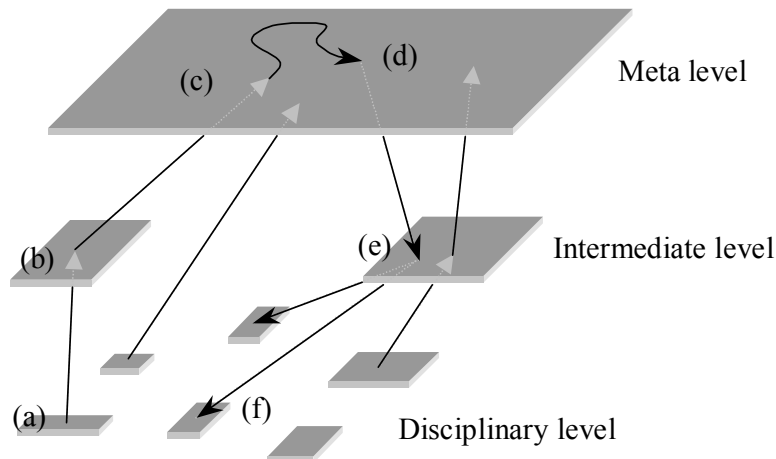


Figure 1: Level traversal in Infused Design

transforming at the meta-level, and descending through the levels), they pretty much exclude heuristic, intuitive methods since they would probably not be able to satisfy the second condition. In contrast, if the approach rests on solid mathematical foundations such as formal representations at the meta-level and transformations on these representations, that preserve intrinsic properties, we obtain the maximal benefit from infused design. In this way, infused design allows the exchange of focused, high quality, critical knowledge between project participants. Maximal benefit arises from continuous sharing of design knowledge from different disciplines and across projects.

In our research, we developed infused design on the foundation of *multidisciplinary combinatorial approach (MCA)*; an approach that allows for exchanging disciplinary knowledge across disciplines. Presently, it is seen as the facilitator of infused design by providing the mechanisms for exchanging detailed knowledge across disciplines. The idea behind MCA begins with developing general discrete mathematical representations, called Combinatorial Representations (CR). Then, each combinatorial representation is thoroughly investigated for its embedded properties and relations with other CR. Afterwards, the CR are used to represent diverse engineering problems. The mathematical foundation of the CR mainly comprises three branches of discrete mathematics: graph theory, matroid theory, and discrete linear programming, while the examples in this paper exclusively employ the graph representations just for the sake of simplicity.

Infused design is a new way of designing. We describe it through a sequence of several activities (see Figure 2): problem formulation, problem modeling and representation, problem solving, and product analysis. This description is more abstract than specifying the process by design phases such as: need identification, conceptual design, and detailed design (e.g., [5] [8]). This sequence may vary and may iterate in many ways, yet, the essence of using infused design is invariant of the precise process configuration or activity naming.

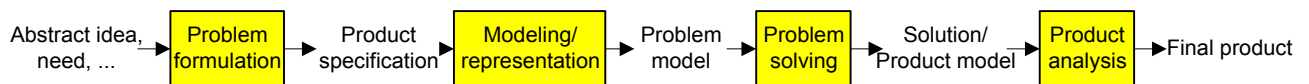


Figure 2: Design process

This approach has already been applied to different engineering fields, leading to significant results including: deriving new relations between known engineering methods [15]; developing general analysis methods for engineering systems [17]; and revealing new relations between different engineering fields [12]. This section introduces the cooperation

opportunities made possible by MCA in the context of design activities. We focus on two general types: “Cooperation through Common Combinatorial Representation (CCCR)” and “Cooperation based on the Relations between the Combinatorial Representations (CRCR).” The former cooperation is demonstrated in this paper through cooperation between electrical and mechanical engineers for analysis and the latter through cooperation between mechanical and civil engineers for design.

3 Types of cooperations

3.1 Cooperation through Common Combinatorial Representation (CCCR)

CCCR is made possible, when designers from different fields use the same combinatorial representation to represent their engineering systems. Sharing the same combinatorial representation opens a channel for transferring knowledge, methods, and designs from one field to the other through this common representation. Furthermore, this transfer of knowledge enables to utilize the knowledge embedded in the common representation.

By means of CCCR, an engineer can introduce his¹ colleague with a method (either known or new) in the field of the latter, of which his colleague is unaware. Consider for example, an electrical and mechanical engineers working for the same organization. Suppose, the mechanical engineer is requested to analyze an indeterminate truss, an issue that he has not dealt with for a long time. Usually, he would look for help only from a mechanical engineer, but CCCR opens up additional opportunities, such as cooperating with an electrical engineer by means of Resistance Graph Representation (RGR), as depicted in Figure 3.

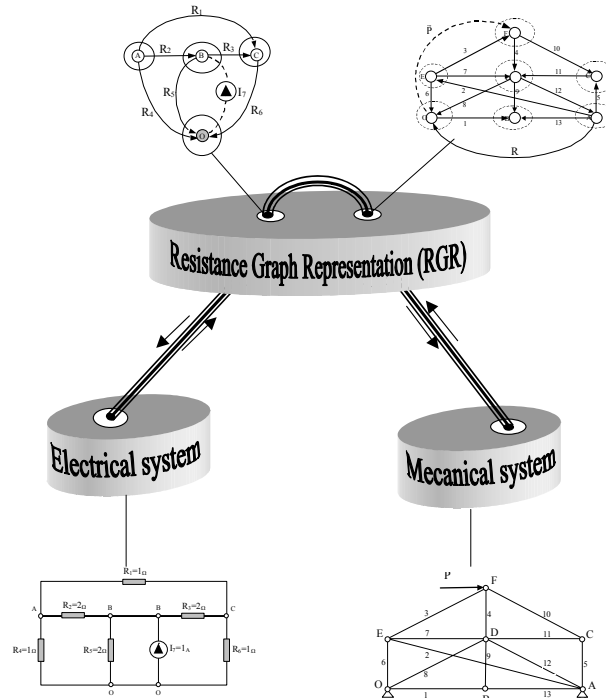


Figure 3: **Implementing CCCR for establishing new knowledge transfer channels between analysis methods for structures and electrical circuits**

¹ We use “his” or “he” for simplicity, although the text could equally mean “her” or “she.”

Such cooperation is possible since the RGR is the isomorphic representation of both electrical circuits and indeterminate trusses [12]. The electrical engineer may assist his colleague by applying the “node method” [2] from electrical circuits to the RGR [15], expanding it to a multidimensional case using the knowledge embedded in the RGR, and then concluding in a systematic manner the “displacement method” for trusses, which is a known method for solving the problem of the mechanical engineer [19]. Finally, CCCR enables an electrical and mechanical engineer to assist their colleagues by dealing with specific design tasks. This can be carried out by infusing an existing design from one field into another through the Common Combinatorial Representation.

3.2 Cooperation through Relations between Combinatorial Representations (CRCR)

One of the main activities in MCA [13] is to explore the relations between different representations. CRCR suggests sharing knowledge and methods between engineering fields that are represented by *interrelated* (and not necessarily isomorphic) combinatorial representations. One such relation is the duality between the two CR – Potential Graph Representation (PGR) and Flow Graph Representation (FGR) [12]. Since the former is used to represent mechanisms and the latter to represent trusses, infused design employs this relation to establish cooperation between structural and mechanical engineers. This issue is outlined in Figure 4 and will be employed in the design case appearing below.

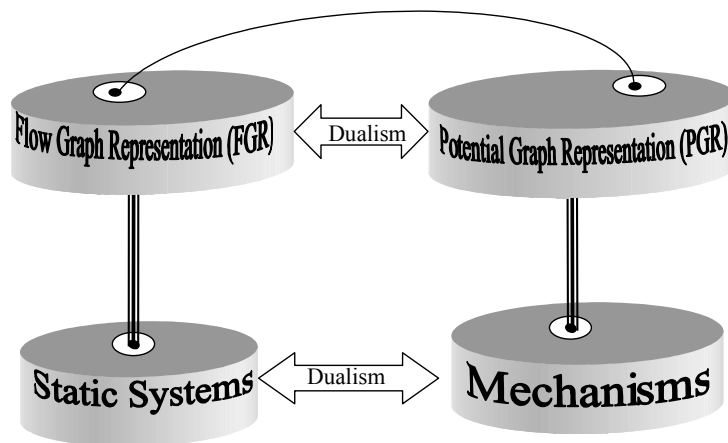


Figure 4: Derivation of the duality between static systems and mechanisms through CRCR

Design case study

Consider the following design problem: *Design a static system, such that when a small force P is applied to one of its joints, a much greater force is produced in one of its rods (rod 1).* Figure 5 schematically depicts such a structure.

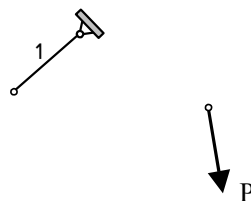


Figure 5: Design problem - designing a static system for amplifying force

We carefully reconstruct the process in this case. This is a difficult design problem that engineers find hard or even fail to solve. Nevertheless, it can be addressed with infused design as shown in Figure 6. The sequence of steps transformed an original problem into another and was able to retrieve a solution to the problem with relative ease:

(1) First, the terminology of the model is altered (flow, edge, flow source, flow laws, etc.), leading to a new model type of **flow graph models**. (2) The problem is articulated in the terminology and modeling primitives of a flow graph model: *design a system where the flow in one of the elements highly amplifies the flow in the flow source*. (3) Transform representation into the dual **potential graph representation**. The problem is translated into a new representation: *Design a system where the potential difference in one of the elements is much higher than the potential in the potential source*. (4) The mechanical engineer changes the representation to that of mechanisms. The terminology becomes: relative linear velocity, link, driving link, etc., and the model becomes the **reference** model of the **original problem model**. (5) The problem statement in this representation becomes *Find a kinematical system such that the ratio between relative velocities of its two links is large*. This is a known problem in the mechanism community. (6) Given the numerous solutions to this problem in the literature, the mechanical engineer finds the problem to be easy. The mechanical engineer outlines several solutions that he considers being valuable. He exercises his knowledge to select some or one promising solutions. (7) The selected solution is displayed. It is a *shaper mechanism* [6]. Once an existing design is retrieved, there is a question, as to its resemblance to the original problem specification. In order to adjust the existing design, step 7, the shaper mechanism is modified (8) The terminology is changed back again to the **potential graph representation** in order to map the solution through the opposite path to the original problem. (9) The adjusted solution is transformed again into the dual **flow representation**. Once the graph is constructed, its dual flow representation is constructed. (10) The final change occurs when the problem reaches its original representation through another terminology change. (11) The solution to the problem is finally obtained in the representation of a static system. Due to the original solution adjustment, the final design is guaranteed to satisfy the requirements. Once explored, this path can be easily recalled in similar future situations:

4 Discussion

Infused design is interesting since it enables establishing new types of cooperation between engineers from different disciplines. The cooperation works in a variety of engineering tasks such as analysis (shown in Section 3.1, a method from electricity was exposed as equivalent to a known method in mechanics) and design (Section 3.2). There could be other ways in which this cooperation can be valuable that we have not explored yet.

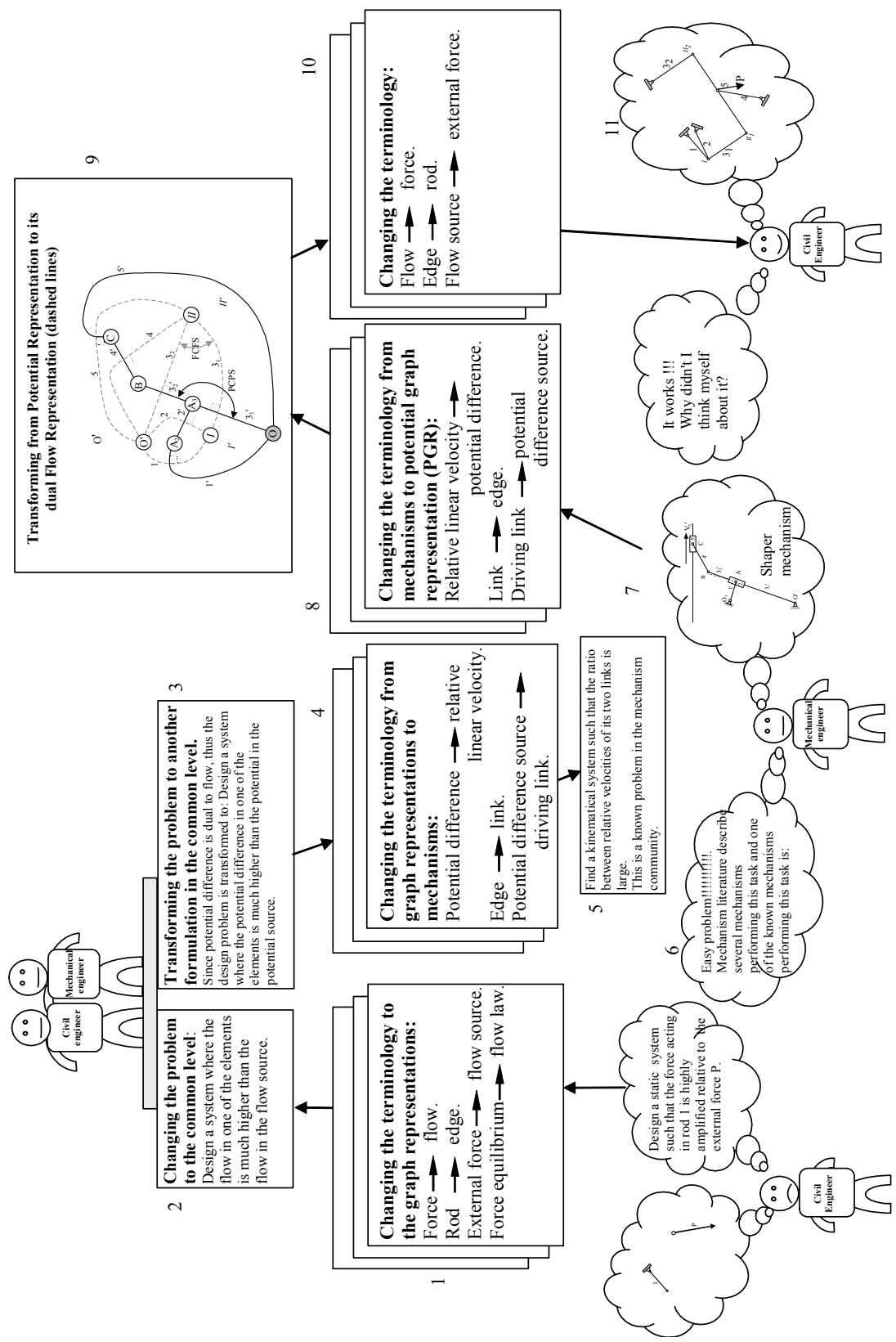


Figure 6: Process of designing a static system for amplifying force through CRCR method

Infused design can be applied to any type of design with different levels of benefit. In creative design, when new products are conceived, infused design can be most valuable. It can bring terminology, solution methods, and solutions from diverse disciplines to bear on the problem. Nevertheless, even in routine design it can be useful in bringing new perspectives into place thus preventing stagnation and initiating progress even in seemingly well-understood domains. Infused design simply presents opportunities to benefit from diverse available knowledge waiting to be tapped. The opportunity arises if the problem at hand can be modeled by a representation that satisfies the two conditions in Section 2.

Consequently, the issue of representation is of utmost importance. One of the fundamental issues of infused design is to decide which type of representation is to be engaged. The main criterion for choosing such representation is whether it is isomorphic to the engineering system, namely, whether the representation reflects all the engineering properties, and thus the reasoning can be performed upon the representation instead of the engineering system. Once the representation is found to be appropriate, it can be employed in a variety of ways, both for analysis and design. Another condition for approving a new representation is that it is based on discrete mathematics. The main reason for this is that the suggested approach, although not shown the paper, is aimed to be computerized, which can be done with such representations.

Infused design rests on intricate mathematical foundation; nevertheless, it is not difficult to use. We have experience in teaching MCA - the foundation of infused design - to high school students with great success (see also [14]). Students learned the mathematical foundations, applied it in design projects, and won prizes in design contests. We certainly experienced teaching it to undergraduate mechanical engineering students. Therefore, we see no obstacle to introducing infused design into design practice from this perspective. We are certain that the benefit from infused design far outweighs the cost. Usually engineers follow their known practices in solving familiar problems. Infused design comes into play when solving complex unfamiliar problems that anyway take much longer to address if using present practices. The breakthroughs that are afforded by infused design are invaluable.

Even without infused design or the transfer of disciplinary knowledge across disciplinary boundaries, there is a wealth of information that needs to be managed for effective reuse. When new sharing opportunities such as infused design, are introduced, a new layer of possible knowledge transfer is added and needs to be managed for its effective dissemination and reuse. While we recognize immediately the important role of computational support for such knowledge management, and even though we can offer good solutions for such management (e.g., n -dim [11][18]), infused design can be done manually. Moreover, since the representations are based on discrete mathematics known as the mathematical foundation of computer science, it paves a way for computerizing the processes of infused design. In this paper, we concentrate on the fundamental concept of infused design and leave the computational support to future studies.

Infused design is reminiscent of design by analogy or even some forms of case-based design or even approaches that used graphs to represent cases (e.g., [9]). Nevertheless, they are markedly different. Infused design *guarantees* applicability of the knowledge embedded in cases to the new problem. Through infused design, elaborated solution methods can be transferred as well as any other knowledge embedded in the CR. This is definitely not the case in existing approaches that are heuristic in nature. Notwithstanding, these approaches

might augment infused design in selecting among competing representations as we indicated elsewhere [10].

5 Conclusions

Infused design is a new way of addressing multidisciplinary product development projects. It allows members of the development team to exchange knowledge in fundamentally different ways, this time through discrete representations, than is presently conceived. From the present state of sharing project documents or parameters, and common language, we expand the scope of sharing to include a pivotal exchange of knowledge consisting of disciplinary concepts, problem formulations, solution methods, and solutions. This exchange crosses and breaks disciplinary boundaries.

In the examples, we showed how the simultaneous use of multiple representations augments human thinking with previously unknown knowledge. We demonstrated an example of such knowledge transfer in the form of solution methods. Elsewhere, we also demonstrated that past experiences could be transferred into completely different disciplines and solve complex, engineering problems [16]. Such transfer in design has not been demonstrated before. Clearly, infused design expands the scope of engineering practice, opening avenues for expanding our understanding and supporting various design practices such as creative design.

We illustrated infused design in the context of two knowledge transfer principles - CCCR and CRCR; however, infused design is not limited to these principles. We are continuing to elaborate the set of principles thus expanding the scope of infused design.

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