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DESIGN COGNITION DIFFERENCES WHEN USING STRUCTURED AND UNSTRUCTURED CONCEPT GENERATION CREATIVITY TECHNIQUES

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Abstract: This paper presents the results of measuring and comparing design cognition while using two different creativity techniques for concept generation in collaborative engineering design settings. Twenty-two senior mechanical engineering students were formed into teams of two. Each team was given the same two design tasks, respectively using an unstructured concept generation technique (brainstorming) and a structured technique (TRIZ). A protocol analysis was carried out where the designing activities were audio-visually recorded and analysed using the FBS ontologically-based coding scheme. Preliminary results indicate that the students' design cognition differed when designing with different concept generation creativity techniques. The inter-technique differences were mainly noticeable in the early stages of designing. Specifically, designers tend to focus more on the problem-related aspects of designing, i.e., design goals and requirements, when using this structured technique. Alternatively, when using this unstructured technique, designers focus more on the solution-related aspects of designing, i.e., a solution's structure and behavior.

Keywords: *creativity techniques, design cognition, FBS ontology, protocol analysis*

1. Introduction

The creativity of engineering product design is primarily determined in the conceptual design activity, in which design concepts are generated and fundamental characteristics of design outcomes are mainly defined (French, 1999; Keinonen, 2006). Due to the importance of conceptual design, numerous concept generation techniques have been developed to stimulate creativity in engineering design (Cross, 2008; Smith, 1998). These creativity techniques fall into two broad categories, unstructured/intuitive techniques and structured/logical techniques (Shah, Kulkarni, & Vargas-Hernandez, 2000). Unstructured techniques aim to increase the flow of intuitive ideas and facilitate divergent thinking. Brainstorming is a well-known unstructured intuitive technique. It is a group creativity technique developed and popularized by Alex Osborn (1963). The essential principle underlying this technique is to remove mental blocks and increase the chance of producing creative ideas by suspending judgment and criticism during the idea generation process. The main objective of brainstorming is to produce as many ideas as possible. The solution space produced as a result of the generation of ideas can be further expanded by amalgamating and refining the ideas while judgment is still deferred.

In contrast to unstructured techniques, structured concept generation techniques provide a defined direction for the concept generation process, e.g., applying a systematic approach to analyse functional requirements and generate solutions based on engineering principles and/or catalogued solutions from past experience (Moon, Ha, & Yang, 2011). TRIZ is a well-developed structured creativity technique. TRIZ, which is the acronym in Russian for the theory of inventive problem solving, was developed by Genrich Altshuller (1997, 1999). It is based on critical analyses of historical inventions, from which a set of fundamental principles was derived aiming to discover and eliminate technical and physical contradictions in the solution (Silverstein, DeCarlo, & Slocum, 2007; Terninko, Zusman, & Zlotin, 1998).

Brainstorming and TRIZ have both been widely applied in industry. The research reported in this paper focuses on the effects of brainstorming and TRIZ on design cognition when given tasks of similar levels of complexity. If a significant difference is identified, future studies will further investigate the relationship between the cognitive difference identified here and the creativity of design outcomes.

Compared with brainstorming, TRIZ prescribes an "abstraction" procedure of defining the contradiction (Silverstein et al, 2007), which requires designers to formulate their generic question in terms of requirement, function and expected behaviours. This study thus hypothesizes that designers using the TRIZ concept generation creativity technique have a relatively higher focus on understanding the problem than when using the brainstorming technique.

Design theories usually assume that there is "a regularity in designing that transcends any individual or situation" (Pourmohamadi & Gero, 2011). In particular, the designing process generally commences with an articulation of design problems before moving to the generation and evaluation of solutions. Therefore, the second hypothesis for this study is that designer's focus on the problem decreases along with the progress of designing, independent of which particular concept generation creativity technique is used.

2. Research Design

Twenty-two mechanical engineering students participated in this study voluntarily. They were formed into teams of two. Each team was given the same two design tasks, to which they respectively applied brainstorming and TRIZ techniques. During the experimental sessions, the students were asked to collaborate with their team members to generate a design solution that meets the given design requirements within 45 minutes. All the design activities (including conversations and gestures) were audio and video recorded for later analysis.

2.1. Participants

The participants were recruited from the first semester of a senior capstone design course at a large land grant university. As seniors, the students' prior design education was a cornerstone experience in a first-year engineering course and a sophomore-level course that focused on exposing students to engineering design and design methods at an early stage of their professional development. In the capstone sequence, student teams work with a faculty mentor on a year-long design project. The students' primary goal for this first semester is to scope their given design problem, generate several potential solutions, and select an alternative to embody during the second semester. It is in this initial semester that the students received instruction on different concept generation techniques that are explored in this study

2.2. Design Experiments

The brainstorming technique was taught in a lecture the week before the related experiment. It covered the fundamental principles that contribute to intuitive concept generation, e.g., delaying judgement, production for quantity rather than quality of ideas, welcoming strange or unusual ideas, and inter-connection and cross-pollination on basis of the generated ideas.

The TRIZ session was organized two weeks later. The TRIZ lecture focused on the concept of contradiction and the TRIZ procedure. A hardcopy of the 40 inventive principles and contradiction matrix was provided during the lecture and design experiment.

The complexities of the two design tasks were set at the same level, as judged by design educators and expert designers.

3. Ontologically-based Protocol Analysis

The video record of design activities were analysed by protocol analysis using an ontologically-based protocol segmentation and coding method (Gero, 2010; Pourmohamadi & Gero, 2011).

3.1. The Function-Behavior-Structure Ontology

The FBS ontology (Gero, 1990; Gero & Kannengiesser, 2004) models designing in terms of three classes of ontological variables: function, behavior, and structure plus an external requirement and a design description, Figure 1. The *function* (F) of a designed object is defined as its teleology; the *behavior* (B) of that object is either derived (Bs) or expected (Be) from the structure, where *structure* (S) represents the components of an object and their relationships. These classes are augmented by *requirements* (R) that come from outside the designer and *description* (D) that is the document of any aspect of designing.

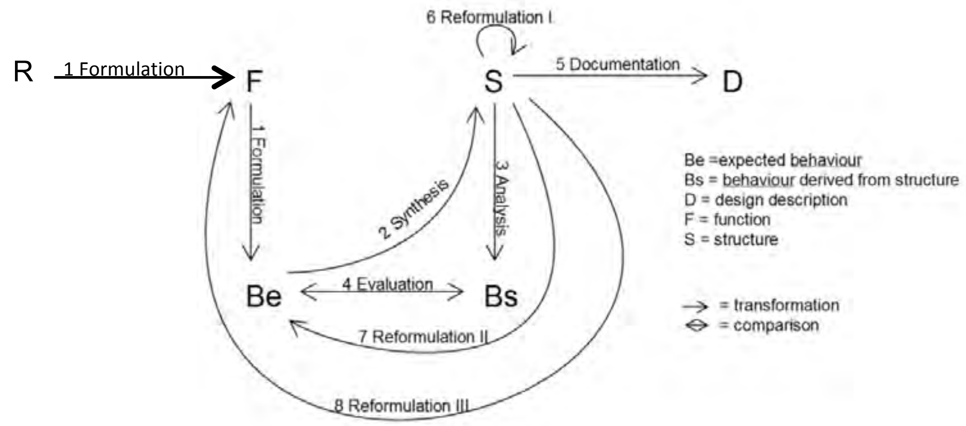

Figure 1. The FBS ontology (after Gero & Kannengiesser, 2004)

In this ontological view, the goal of designing is to transform a set of requirements and functions into a set of design descriptions. The transformation of one design issue into another is a design process. As a consequence of this ontology, there are 8 design processes that are numbered in Figure 1.

3.2. Integration of the FBS-based Coding Scheme with Problem-Solution Division

The analyses reported in this paper use an integration of the FBS ontologically-based coding scheme with a Problem-Solution (P-S) division (authors, 2012). The designing process is often viewed as constant interactions between two notional design "spaces" of the problem and the solution (Dorst & Cross, 2001; Maher & Tang, 2003). This paper uses the P-S division to reclassify design issues and syntactic design processes into two categories, as presented in Table 1. The FBS-based coding scheme does not specify description issues with the P-S division. Description issues and the process of "documentation" are thus excluded in the analysis using the P-S division.

Table 1. Mapping FBS design issues & processes onto problem and solution spaces

Problem/solution Space	Design Issue	Syntactic Design Processes
Reasoning about Problem	Requirement (R) Function (F) Expected Behavior (Be)	1 Formulation 7 Reformulation II 8 Reformulation III
Reasoning about Solution	Behavior from Structure (Bs) Structure (S)	2 Synthesis 3 Analysis 4 Evaluation 6 Reformulation I

With the problem-related issues/processes and solution-related ones, this paper examines the students' design cognition from both a meta-level view (i.e., a single-value measurement) and a dynamic view (i.e., taking time into consideration).

3.2.1. Problem-Solution index as a single value

The P-S index, which helps to characterize the overall cognitive pattern of a design session, was calculated by computing the ratio of the total occurrences of the design issues/processes concerned with the problem space to the sum of those related to the solution space, as shown in Equations (1) and (2). Compared with the original measures of design issues and syntactic processes using a set of measurements, the P-S indexes with a single value can facilitate comparisons across multiple sessions and across sessions involving different technique usage in an efficient way.

$$\text{P-S index(design issue)} = \frac{\sum(\text{Problem}-\text{related issues})}{\sum(\text{Solution}-\text{related issues})} = \frac{\sum(R,F,Be)}{\sum(Bs,S)} \quad (1)$$

$$\text{P-S index(syntactic processes)} = \frac{\sum(\text{Problem}-\text{related syntactic processes})}{\sum(\text{Solution}-\text{related syntactic processes})} = \frac{\sum(1,7,8)}{\sum(2,3,4,6)} \quad (2)$$

3.2.2. Sequential P-S index as a time series

Designing is a dynamic process. A single-value P-S index for the entire session will collapse any time-based changes into a single value. This paper proposes a further measurement: the sequential P-S indexes across different sections of a design session. A fractioning technique (Gero, 2010) was used to divide the whole design session into 10 non-overlapping sections each with an equal number of design issues or syntactic processes. It then computed P-S indexes for each section, and used a sequence of temporally ordered P-S indexes to represent the cognitive progress during the designing process.

4. Results

4.1. Design Issues and Syntactic Processes

After the FBS ontologically-based protocol segmentation and coding, the video records of designing were converted into sequences of design issues and, consequently, sequences of syntactic design processes. Due the varied lengths of design sessions, the occurrences of design issues and syntactic processes were respectively normalized as the percentages of the total issues/processes in each session, Figure 2.

Compared to their experiences in using TRIZ, students using brainstorming sessions have higher percentages of structure design issues, and "analysis", "documentation" and "reformulation I" syntactic design processes. Alternatively, when using TRIZ, students' utterances were significantly more focused on the design issues of function and expected behavior, and on the syntactic design processes of "formulation" and "evaluation". These design issues and syntactic processes are then categorized using the P-S division.

4.2. Gross comparison between Brainstorming and TRIZ Sessions

Comparisons of P-S indexes between brainstorming and TRIZ sessions are presented in Figure 3 and Table 2 for the full protocol as a single activity and for each session divided into two sequential halves. These results indicate that TRIZ sessions had a significantly higher P-S index (in terms of both issue index and process index) than brainstorming sessions, for the entire design session and for the first half of the design sessions. For the second half of design sessions, though the issue index is significantly different, the inter-technique difference (mean) was reduced from -0.66 to -0.16. Paired-sample *t*-test shows that there was no statistically significant difference in terms of the syntactic process index in the second half of design sessions' protocols, $t(9)= -0.195$, $p>0.05$.

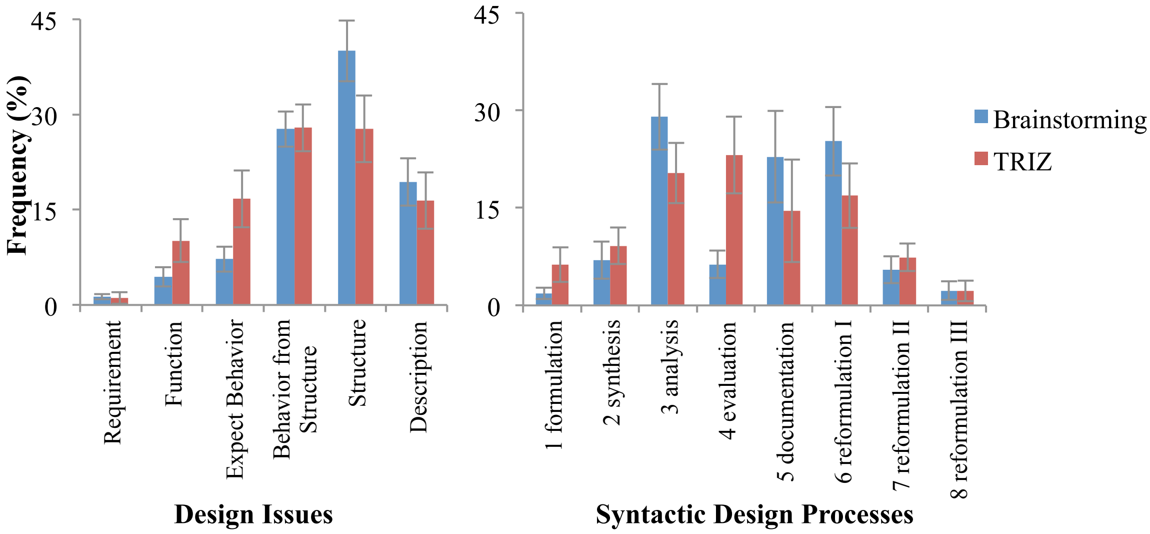

Figure 2. Frequency distribution of design issues and syntactic design processes (%)

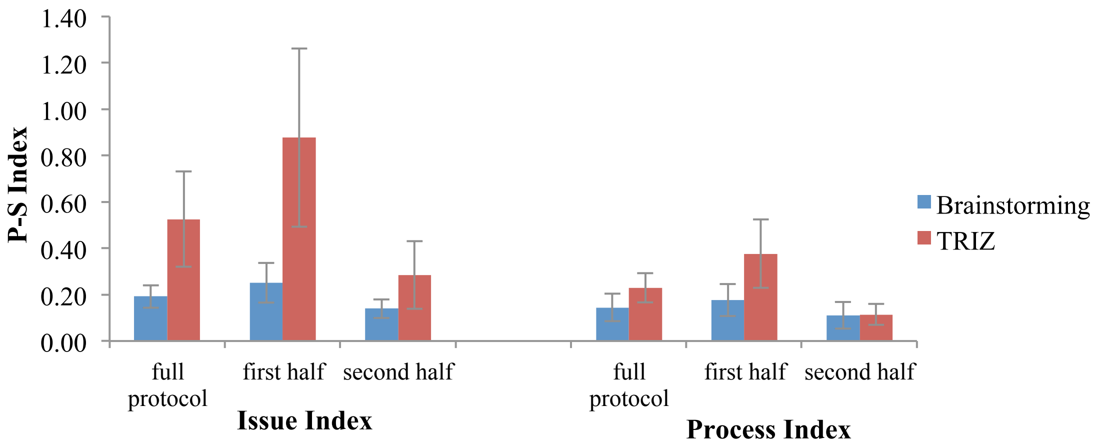

Figure 3. Comparison of P-S indexes between brainstorming and TRIZ sessions

Table 2. Comparison of P-S indexes between brainstorming and TRIZ

Fractioned protocols	Design Issue Index				Syntactic Process Index			
	Brainstorming	TRIZ	Comparison		Brainstorming	TRIZ	Comparison	
	Mean (SD)	Mean (SD)	t-score	P value	Mean (SD)	Mean (SD)	t-score	P value
Full protocol	0.192 (0.049)	0.526 (0.206)	-4.892	0.001***	0.144 (0.060)	0.230 (0.063)	-3.441	0.009**
First half	0.251 (0.085)	0.877 (0.385)	-4.704	0.002***	0.177 (0.069)	0.377 (0.147)	-4.267	0.003***
Second half	0.140 (0.040)	0.285 (0.146)	-3.252	0.012*	0.111 (0.058)	0.114 (0.045)	-0.195	0.850

* p<0.05, ** p<0.01, *** p<0.005

4.3. Dynamics of Design Cognition

The dynamics of design cognition are examined using two analytic methods. Single-value P-S indexes are compared between the first and second halves of design sessions for each concept generation techniques via paired-sample *t*-tests. The nuances of designing dynamics are then illustrated by sequential P-S indexes over time.

4.3.1. Intra-session Comparisons

A comparison of the P-S indexes between the first and second halves of design sessions are presented in Table 3. It indicates that, regardless of the concept generation technique employed and the measurements of issue/process index, the first half of the design sessions had a significantly higher P-S index than the second half of the design sessions.

Table 3. Intra-session comparison of P-S indexes

Creativity Technique	P-S Index	First half	Second half	Within-session comparison	
		Mean (SD)	Mean (SD)	t-score	P value
Brainstorming	Issue Index	0.251 (0.085)	0.140 (0.040)	4.100	0.003*
	Process Index	0.177 (0.069)	0.111 (0.058)	4.323	0.002*
TRIZ	Issue Index	0.877 (0.385)	0.285 (0.146)	6.022	0.000**
	Process Index	0.377 (0.147)	0.114 (0.045)	6.485	0.000**

* p<0.005, ** p<0.001

4.3.2. Sequential P-S Index over Time

The intra-session differences of design cognition are further explored using sequential P-S indexes that divide the entire design session into 10 successive non-overlapping sections. Design cognition here is measured by both a sequential issue index, Figure 5, and by a sequential process index, Figure 6, and showed a decreasing trend across the design sessions for both measurements. The TRIZ session had a relatively larger decreasing rate, as it started with a greater focus on the problem than the brainstorming session did.

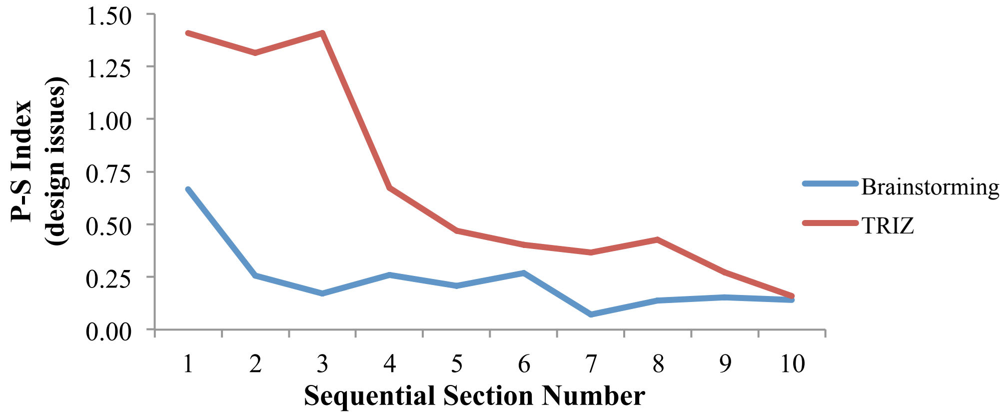

Figure 4. Sequential issue index in ten sections of design protocols

Comparing sequential P-S indexes between the brainstorming and TRIZ sessions, the inter-session differences were mainly in the early stages of designing. In the first 4 sections, the TRIZ sessions' P-S index (both in issue index and process index) was greater than twice the index value in the brainstorming session. In the last two sections of design sessions, there were no statistically differences found in terms of either issue index or process index.

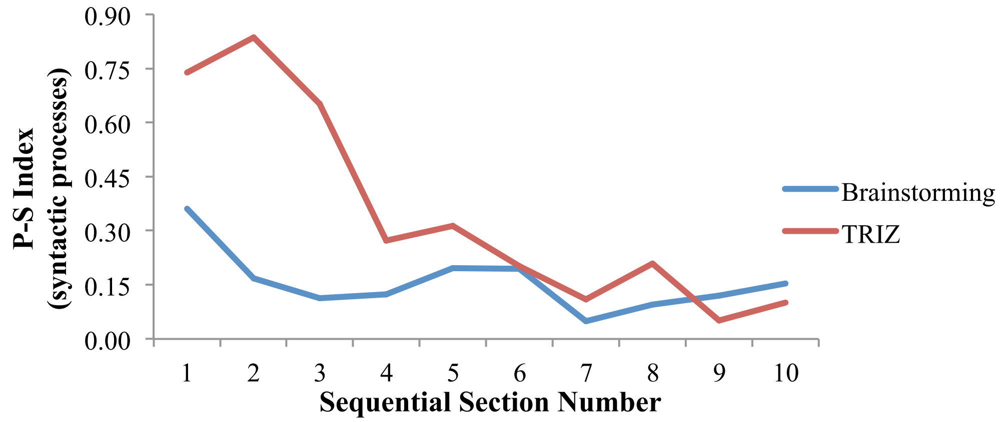

Figure 5. Sequential process index in ten sections of design protocols

5. Discussion & Conclusion

This paper examined the effects of structured/intuitive and unstructured/logical concept generation creativity techniques on design cognition in a collaborative engineering design setting. The analyses and discussions are undertaken in response to the two hypotheses presented in the Introduction.

(1) designers using the TRIZ technique have a relatively higher focus on the problem than when using brainstorming techniques, and
(2) designers commence with a relatively higher focus on the problem and this focus decreases as the design session progresses, independent of which particular creativity technique is used.

5.1. Designing with TRIZ is more Focused on Problem than Brainstorming

Results from this experiment provide evidentiary supports for the hypothesis that students generally spent more effort reasoning about the problem when using the structure concept generation technique of TRIZ than they did when using the unstructured brainstorming technique. This applied to almost the entire design session for the P-S design issue index and to the first half of the design session for the P-S design process index, Figures 5 and 6. This qualitative assessment is confirmed with paired-samples *t*-tests applied in the protocols of the entire design sessions, as well as those of the two halves of the design session. Statistical results confirm that statistically significant differences occur between the brainstorming and TRIZ sessions in terms of overall issue and process indexes characterising the entire design session.

The fractioning technique further indicated that the cognitive differences between the two creativity techniques were primarily observed in the early stages of designing, Table 2. It suggests that using brainstorming and TRIZ may mainly affect the students' design cognition during the initial problem framing and concept generation phases of designing, and that they have relatively less influence on the design cognition related to the further development of design concepts.

This cognitive difference corresponds with the manner in which the two concept generation creativity techniques are formalized. In order to use the TRIZ and its 40 inventive principles and contradiction matrix, a designer must first formulate the design problem into an abstract contradiction. This explicit, structured instruction requires a designer to engage in cognitive exercises pertaining to the requirement, function and expected behaviour of the design problem. Brainstorming, in comparison, offers no structured direction for the designer, thus the novice design tends to jump straight to activities related to solutions without fully scoping the design problem.

5.2. Focus on the Problem Decreases while Designing Progresses

The second hypothesis concerning the independence of overall design behaviour from particular concept generation creativity techniques employed, i.e., a "regularity" of designing, was qualitatively shown with the line plots of the sequential P-S indexes in Figures 5 and 6, and statistically validated by the comparison of the P-S indexes between the two halves of design sessions, Table 3. Figures 5 and 6 both demonstrate decreasing slopes against the ascending order of sequential section number. Irrespective of which particular creativity technique is used, the issue index and process index measured in the first half of design sessions' protocols were significantly larger than those in the second half of the design sessions' protocols as presented in Table 3, providing evidentiary support for the hypothesis. As both concept generation creativity techniques are oriented towards the goal of identifying a solution to the design problem, it is not surprising that a designer's cognition is more focused on structure issues towards the end of the designing process.

5.3. Conclusion and Future Research

This paper compares senior mechanical engineering students' design cognition when designing with two concept generation creativity techniques: brainstorming and TRIZ. The protocol analysis used two novel measurements on the basis of an integration of the FBS ontologically-based coding scheme with a P-S division. Preliminary results indicate that using different concept generation creativity techniques may induce different behaviours in designers, and the technique-specific differences are within an overall "regularity" of designing. Specifically, designers using the structured TRIZ technique tend to focus more on the problem-related aspects of designing than when using the unstructured technique of brainstorming.

The next step of this study aims to assess how using different concept generation techniques affects the creativity of design outcomes, as well as whether the cognitive differences are correlated to the creativity difference of design outcomes.

The findings of this paper are limited by the sample size of this study and the specifics related to the research setting. Confirmative studies with a larger sample size, as well as including other types of designers, are needed to generalize the influence of brainstorming and TRIZ on design cognition. It requires examining more concept generation creativity techniques in order to generalize the findings beyond brainstorming and TRIZ techniques to other unstructured and structured techniques.

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