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CREATIVITY THEORIES AND SCIENTIFIC DISCOVERY: A STUDY OF C-K THEORY AND INFUSED DESIGN[1]

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ABSTRACT
Creativity is central to human activity and is a powerful force in personal and organizational success. Approaches to supporting creativity are diverse and numerous. The only way to understand the diversity and utility of these methods is through their careful analysis. This paper demonstrates the benefit of conducting analyses of methods with the aid of a theory. As a first step, we use Infused Design (ID) method to generate new concepts and methods in the classic discipline of statics, in addition to its prior use in the generation of a number of creative designs. The use of the ID method in the creative scientific discovery process is modeled with C-K design theory, leading to better understanding of ID and C-K. The exercise in this paper illustrates how the synthesis of a theory, a framework and methods that support discovery and design is useful in modeling and evaluation of creativity methods. Several topics for future research are described in the discussion.

Keywords: design theory, creativity, infused design, C-K theory, scientific discovery

1. INTRODUCTION
Creativity is central to human activity and is a powerful force in personal and organizational success. As the interest in the subject never ceases to grow, new methods for enhancing creativity are constantly proposed. The only way to understand the diversity and utility of these methods is through their careful analysis.
In several interrelated studies, we initiated our efforts towards systematic analysis of creativity methods by defining a general framework that organizes the methods and illustrating the analysis by comparing specific methods within a formalization of a design theory (Shai *et al*., 2008; Reich *et al*., 2008a,b). The present study continues that thrust by showing how new concepts and theorems in engineering could be derived by using Infused Design (ID); resulting in a creative act, ID is a design method that supports the transfer of knowledge between disciplines and through this, the ability for creative design (Shai and Reich, 2004a,b; Shai *et al*., 2008). In this paper, we extend our exploration by showing how the creative act that is supported by ID is describable within C-K theory – a formal design theory that embeds creativity as a central part of its scope (Hatchuel and Weil, 2003, 2007, 2009).
Specifically, this paper shows the process of generating new entities or variables and theorems using ID in the classic field of statics. A discovery of such entities and theorems would be considered as a high level of creative thinking.[2] The process in ID engages two types of dualities: the graph theory duality and the projective geometry duality. The modeling of these processes in C-K has led to better understanding of ID and C-K. The exercise in this paper illustrates how the synthesis of a theory, a framework and methods that support discovery and design is useful in modeling and evaluation of creativity methods.

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The remainder of this paper is organized as follows. Section 2 reviews the methodology of our studies. Section 3 provides a brief overview of C-K and ID. Section 4 presents a case study in which ID was used to create new concepts in a discipline that is so traditional and accomplished, that it would seem unlikely that such a new concept could have been discovered. Section 5 is the core of the analysis, explaining the case study in C-K terminology and section 6 concludes the paper.

2. METHODOLOGY

Reich *et al*. (2008b) describe a methodology for conducting qualitative as well as theory-based studies of creativity. The first step in the analysis involves generating a classification of creativity methods and the second step, an analysis of methods with respect to design theories. The first effort in theory-based analysis modeled a family of similar creativity assisting methods (ASIT and partially TRIZ, SIT, and USIT that all work by using various types of templates) within C-K theory. This analysis led to several insights including: ASIT provides a specific method to realize C-K; C-K theory captures ASIT fully; and C-K theory provides insights to extend ASIT. The analysis presented in the current paper applies the same methodology to illustrate the relationship between C-K theory and ID. As we shall see in the next sections, the analysis reveals new insights about C-K and ID.

3. BRIEF REVIEW OF C-K AND ID

3.1 C-K theory

C-K theory, at the core of its scope integrates creative thinking and innovation. It makes use of two spaces: (1) *K* – the knowledge space – is a space of propositions that have a logical status for a designer; and (2) *C* – the concepts space – is a space containing concepts that are propositions, or groups of propositions that have no logical status (i.e. are undecidable propositions) in *K*. This means that when a concept is formulated, it is impossible to prove that it is a proposition in *K*. Design is defined as a process that generates concepts from an existing concept or transforms a concept into knowledge, i.e., propositions in *K*.
Concepts can only be partitioned or included, not searched or explored in the C space. If we add new properties ($K \rightarrow C$) to a concept, we partition the set into subsets; if we subtract properties, we include the set in a set that contains it. No other operation is permitted. After partitioning or inclusion, concepts may still remain concepts ($C \rightarrow C$), or can lead to creation of new propositions in *K* ($C \rightarrow K$). The two spaces and four operators (including the $K \rightarrow K$) are shown in Figure 1.

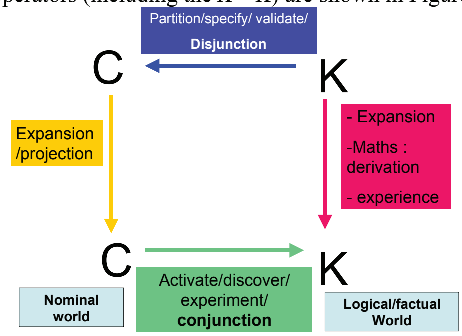


Figure 1: The design square modeled by C-K theory (Hatchuel et al., 2003)

A space of concepts is necessarily tree structured as the only operations allowed are partitions and inclusions and the tree has an initial set of disjunctions. In addition, we need to distinguish between two types of partitions: restrictive and expansive partitions.

- If the property added to a concept is already known in *K* as a property of one of the entities concerned we have a *restricting partition*;
- if the property added is not known in *K* as a property of one of the entities involved in the concept definition, we have an *expansive partition*.

In C-K theory, creativity is the result of two operations: i) using addition of new and existing concepts to expand knowledge; ii) using knowledge to generate expansive partitions of concepts.

3.2 Infused Design

Infused Design (ID) is a method that rests on a solid mathematical foundation for combinatorial representations of systems (Figure 2). ID has demonstrated new forms of creativity by generating designs that were not conceived before, by studying and transferring across disciplines designs from seemingly unrelated disciplines (Shai *et al*., 2008; Shai 2005a,b)).

The representations that are the foundation of ID are discrete mathematical models, called graph representations; they include Resistance Graph Representation (RGR), Potential Graph Representation (PGR), Flow Graph Representation (FGR), and others. These representations can represent diverse systems, e.g., RGR is isomorphic representation of both electrical circuits and indeterminate trusses (Shai, 2001b). These representations and their relations (see Figure 2), such as the duality between PGR and FGR allow for transforming automatically one representation to others connected to it (Shai, 2001a). Such transformations can be done automatically (Shai *et al*., 2008). The automated transformation in ID is provably mathematically correct as these transformations are guaranteed to produce the same behavior for the original and transformed representation. This is in contrast to other creativity assisting methods, such as analogy that do not guarantee that the transformation process across disciplines will lead to preservation of the behavior of the original representation.

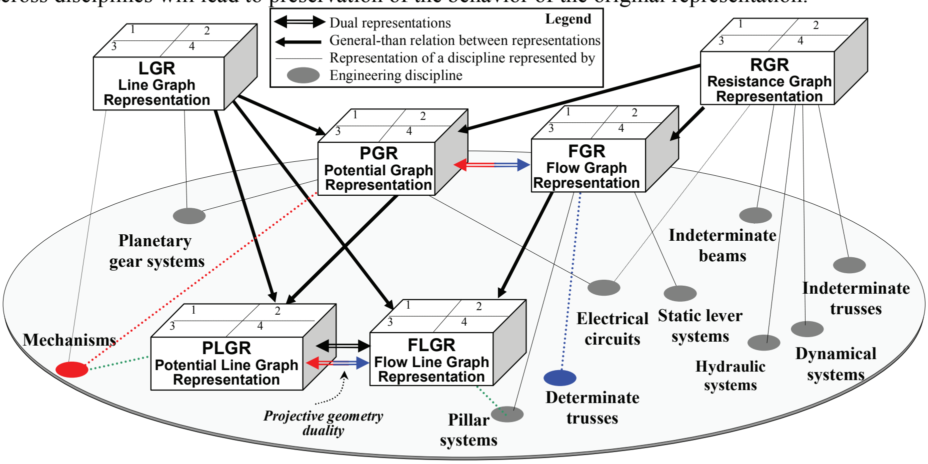


Figure 2: Map of graph representations, their interrelations, and association with engineering systems (Shai and Reich, 2004b). The map includes the relations between mechanisms and determinate trusses that are used in this paper.

To better illustrate the process, consider an example where all the disciplines that participate in the design are assumed to be modeled in Figure 2. A discipline that is still not represented cannot participate in the process. Members of the multidisciplinary team start by using their customary disciplinary model and terminology for each discipline, e.g., PGR for mechanisms and FGR for static systems. In order to integrate all the disciplinary representations they need to traverse the map of representations to find one common representation that accommodates all the original representations. For this particular example, according to Figure 2, PGR, FGR and RGR could serve as the common representation because PGR and FGR are dual and because RGR is more general to both.

Once the common representation is found, there is a path in the representations map that allows transferring knowledge from one discipline to the other. This knowledge includes solutions or solution methods.

4. GENERATING NEW ENTITIES AND METHODS BY INFUSED DESIGN

Figure 2 shows the path that was employed for revealing a new concept in statics – the face force concept – from the ID perspective. The process followed several steps.

Step 1. The first step was the observation that when using duality between the PGR and FGR representations to transform mechanism to determinate trusses, two basic concepts in mechanisms – *joint linear velocity and instant center* – do not have a corresponding entity in determinate trusses. Since the correspondence between trusses and mechanisms implies that for each entity or variable in one system there exists an entity or variable in the other, shown in Table 1, and possessing the same value. This absence could mean that we simply are not aware yet of this concept or that we need to elaborate with a richer modeling of the duality. Let us begin with joint linear velocity and let us introduce the notion of "face force". To illustrate this new entity, Figure 3(a) shows a part of a mechanism with joints and their linear velocities and Figure 3(b) shows a set of face forces in the dual truss that are equal to the linear velocities of the corresponding joints in the mechanism. This correspondence includes the values and directions of the velocities and forces. A more general view appears in Figure 4 showing a truss (a) and its dual mechanism (b). The dimensions are determined by the duality relations. The corresponding joints and faces are marked with the same symbols (the dual is marked with ', e.g., A and its dual A').

Table 1: Duality between trusses and mechanisms: the duality relation between these two engineering systems implies the complete correspondence between the variables describing them. While the relative link velocity in the mechanism corresponds to the rod force in the truss, there is no existing variable corresponding to the joint velocity.

Dual systems	**Mechanisms**	**Determinate trusses**
1	Relative velocity in a link	Force in a rod
2	Velocity	Force
3	Point (Joint)	Face (or contour of rods)
4	Joint linear velocity	*unknown entity – face force*
5	Instant Center	*unknown entity – equimomental line*

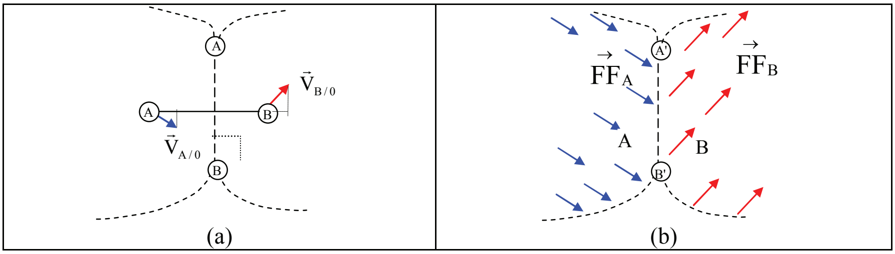


Figure 3: The dualism between joint velocities in a mechanism and the face forces in the dual truss. (a) The primal mechanism and its linear velocities. (b) The corresponding dual truss and its face forces.

Step 2. Now that we have introduced the new entity called Face Force, designated by the letters FF, and defined solely by its duality with the joint velocity in the mechanism model, we want to understand better its nature and meaning by giving to it some more attributes. Since we are referring to the new entity as some kind of a 'force,' we expect it to apply along some line of application. In addition, we expect it to be related to other variables through quantitative equations that reflect the physics of the system. Let us investigate what can be concluded from the above table.

1. The relative velocity of a link whose end joints are A and B (see Figure 3(a)) is the difference between their corresponding linear velocities, i.e., $\vec{V}_{A/B} = \vec{V}_{A/0} - \vec{V}_{B/0}$.
2. Let A' and B' be the faces in the dual graph corresponding to joints A and B (see Figure 3(b)). It is proved (Shai, 2001) that the force in rod (A'B') is equal to the relative velocity of the corresponding link (AB) because these variables are dual (see Table 1), i.e., $\vec{F}_{A'B'} = \vec{V}_{A/B}$.
3. Since the new variable, face force, by accepting the existence of the new entity in the dual, is equal to the linear velocity of the joint in the primal system it follows that $\vec{V}_{A/0} = \vec{FF}_{A'}$ and $\vec{V}_{B/0} = \vec{FF}_{B'}$.
4. From the above analysis, it follows that the force in a rod is equal to the difference between its two adjacent face forces; in the given example, $\vec{F}_{A'B'} = \vec{FF}_{A'} - \vec{FF}_{B'}$

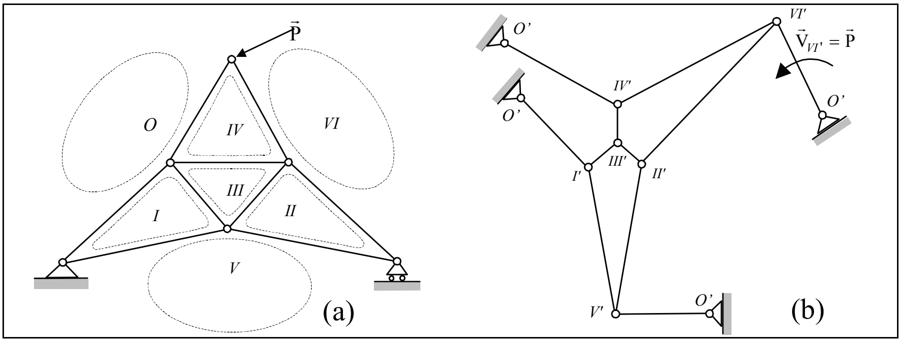


Figure 4: The dualism between joint velocities in a mechanism and the face forces in the dual truss. (a) The primal truss and its face forces. (b) The corresponding dual mechanism.

In this step, we can say that we have "revealed the existence" of the face force and "discovered" how it relates to the forces in the rods. Or, we can more precisely say that we decided to introduce a new entity that was not in the dual and found its properties that could be deduced from the dual equations. However, part of any force definition, its acting line, cannot be discerned from the duality relationship between the representations PGR and FGR. In addition, the last unknown entity in the dual, corresponding to the instant center in the primal, remains unknown.

Step 3. An elaboration of the location of the face force to complete its definition requires new knowledge. For this, we use one of the strengths of Infused Design – multiple representations, e.g., mechanisms could be represented by LGR, PGR, and PLGR. Moreover, The PGR and FGR are representations that deal with knowledge related to things that happen in the elements; in statics these would be forces in the rods and in kinematics, the velocities of points in links. In contrast, PLGR and FLGR deal with knowledge related to the relations between the elements.[3] Consequently, employing both representations might give access to more knowledge.

Furthermore, abstract domains such as kinematics and statics are embedded within numerous systems, e.g., statics within determinate trusses, pillar systems, indeterminate beams and more. Since there are a number of representations associated with each domain, we have a new possibility to deal with the same systems and concepts from diverse perspectives. From experience of using ID, including the present study, there are many cases where knowledge is implicit in one representation and explicit in the other. This unique property is totally different from other known methods used in the design community, such as bond graph, where only one representation is used.

As mentioned before, mechanisms are also represented by PLGR, indicated in the figure by dashed green line, which in turn, enables accessing another representation – FLGR through another type of relation – projective geometry duality. This new channel between kinematics and statics enables exposing new knowledge that was not known before, partly because the relation between the representations is based, this time, also on projective geometry. This second duality principle and its corresponding analogies are shown in Table 2. The PLGR and FLGR representations and their duality enabled revealing the corresponding analogy of *relative instant center in statics* (see Table 1), another new concept that was not known before.

Step 4. Let us check what can be concluded from basic text books in kinematics and statics about the instant center and its possible dual concept. Note that this analysis relates kinematics and statics in general and not the particular systems of mechanisms and determinate trusses.

1. Every link has a single point around which the link rotates. This point is called the absolute instant center.
2. The linear velocity of every point of the link due to its rotation can be calculated when the angular velocity value and the distance between the absolute instant center and the point is given.
3. Every two links have a point where their absolute linear velocities are the same. This is called: relative instant center.
4. The linear velocity of a link at the absolute instant center is equal to zero.

[3] In 2-dimensional kinematics and statics, both representations could be used.

Since in the projective geometry duality (Table 2), angular and linear velocities correspond to force and moment respectively, the previous 4 statements translate to the following 4 statements, which are well known in statics:

5. The moment exerted by a force is equal to zero along its acting line.
6. The moment at every point in the plane due to exerting a force can be calculated when the force and the distance between the line of the force action and the point is given.
7. There exists at least one point upon which two forces exert the same moment – their intersection point and the moment is equal to zero.
8. The moment exerted by the force along its line of action is equal to zero.

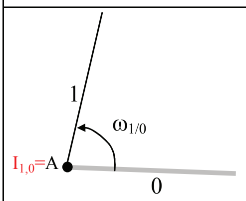
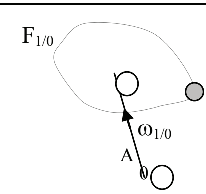
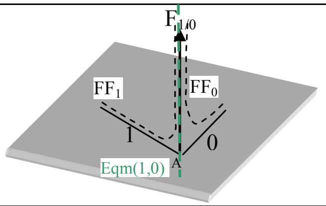
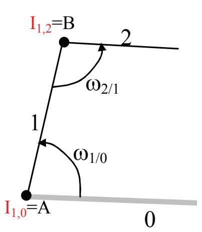
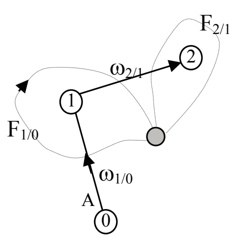
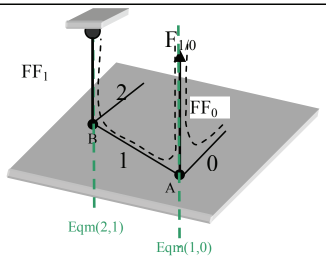
These statements were subsequently used to focus the analysis between the dual systems.

Table 2: Projective geometry duality between mechanisms and pillar structures

Dual systems	**Mechanisms**	**Pillar Systems**
1	linear velocity	moment
2	angular velocity	force
3	point (joint)	line

Step 5. Now, using the duality between PLGR and FLGR, let us examine the duality between kinematics and statics, this time between mechanisms and pillar systems. Using another type of static system may enrich the available knowledge with new concepts or perspective. We assume that concepts derived from this specific analogy, will transfer to all statics and kinematic systems. As will be shown in this section, this duality enabled highlighting the relation between instant centers and a new concept of equimomental lines.

Suppose we have a four bar linkage, Figure 5, Let us follow the process of composing it, step by step, from its components and look simultaneously at the process of constructing its dual pillar system. This process simulates the process of exposing the counterpart of instant center in kinematics in statics.

The primal kinematic mechanism	The PLGR and its dual FLGR	The dual static pillar system
		
Link 1 is rotating around the ground link, link 0, and its angular velocity value is $\omega_{1/0.}$ The value $\omega_{1/0}$ can be any number and joint A is the locus of the Absolute Instant Center $I_{1,0}$.	The dual FLGR (dashed lines) is a loop, meaning, there is no constraint on the value of the force $F_{1/0}$. The value $F_{1/0}=FF_1-FF_{0.}=\omega_{1/0}$.	Since face 0 is one of the two faces adjacent to bar A, line A is an absolute equimomental line $I_{1,0}$. This means that the location of FF_0 is known and it acts along line A.
		
The relative instant center $I_{2,1}$ is the joint B, but the absolute instant center is unknown at this stage.	In FLGR, there are two independent forces.	The relative equimomental line Eqm(2,1) is along line B. The location of absolute equimomental line is unknown at this stage.

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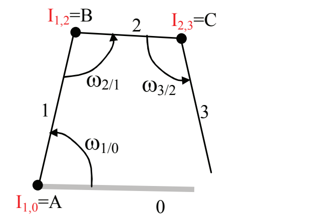
<td>
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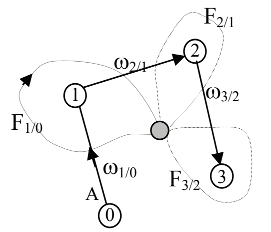
<td>
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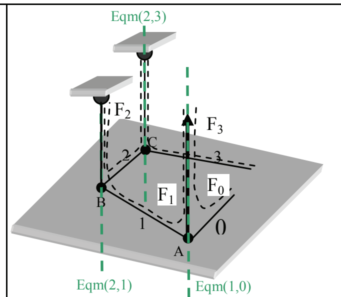
<td>
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<tr>
<td>All the three relative angular velocities are independent.</td>
<td>The three flows in FLGR are independent.</td>
<td>Another equimomental line related to face 2 is known, this time Eqm(2,3), along line C.</td>
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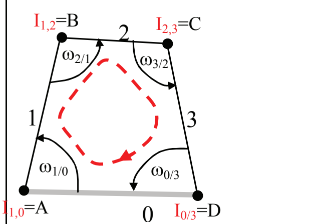
<td>
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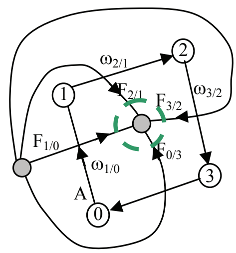
<td>
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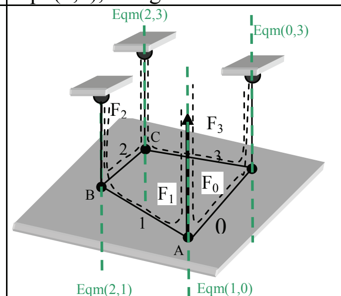
<td>
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<tr>
<td>Now, the four relative angular velocities are dependent since they should satisfy the circuit/potential law. Except absolute instant center, $I_{2,0}$, the others are known.</td>
<td>The dual four forces are dependent since they should satisfy the flow/cutset law.</td>
<td>The four forces are dependent since they all should satisfy the cutset/ flow law. All the equimomental lines are known except the absolute equimomental line $I_{2,0}$, where FF_2 acts, is unknown.</td>
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</table>

Figure 5: The process of composing a mechanism and its dual pillar system through the duality between the PLGR and FLGR.

From the figure, it is clear that the locations of the pillars are exactly the locations of the instant centers of the mechanism. Thus, we expose the meaning of the dual of the instant centers in statics. Furthermore, part of the joints are relative instant centers and some absolute instant centers (those joints that connect the link to the ground), thus we reveal the difference between the dual of relative instant centers (relative equimomental) and the dual of the absolute instant centers (absolute equimomental) in statics.

Step 6. Now, that the counterpart of relative instant center in statics is known from Figure 5, we introduce the definition of relative instant center as appears in any textbook in kinematics (Erdman and Sandor, 1997) for defining its dual in statics.

Definition: Relative instant center of links x and y, $I_{x,y}$, is a point where the links, having angular velocities ω_x *and* ω_y respectively, have the same linear velocity.

When we transform this definition into statics, we derive a new entity, *eqm(x,y)*, defined as follows (maintaining the phrasing in the previous definition as much as possible):

Definition: The new concept, *equimomential line – eqm(x,y)* is a line where upon each point, the forces having values F_x and F_y exert the same moment.

or phrased differently,

Definition: The new entity, *equimomential line – eqm(x,y)*, is a line where upon each one of its points, the forces F_x and F_y exert the same moment.

There is full correspondence between instant centers in kinematics and equimomential line in statics, thus such correspondence should exist for any of their special cases. In kinematics, for instance, there is a special case of instant center, called: *absolute instant center*, defined as follows (Erdman and Sandor, 1997).

Definition: *Absolute instant center*, $I_{x,o}$,is a point in which the linear velocity of link *x* is equal to zero.

Transforming this special entity into statics yields:

Definition: *Absolute equimomential line*, *eqm(x,0)*, is a line in which the moment exerted by force *x* is equal to zero.

From the physical point of view, this is the line where the force acts, thus along this acting line it exerts a zero moment.

Step 7. Till now, we have seen transformation of variables from kinematics into statics. Now we will show that the transformation through the duality enables also to derive new theorems in statics from kinematics. Let us transform the known Kennedy theorem in kinematics into statics yielding a new theorem in statics.

Kennedy Theorem: Suppose we have three links, *x*, *y,* and *z*, then the three relative instant centers: $I_{x,y}$, $I_{y,z}$ and $I_{x,z}$ are collinear.

Applying the dual projective geometry to the Kennedy theorem and using the duality relation that maps collinear points into lines that all intersect at the same point, yields the following new theorem:

Dual Kennedy theorem in statics: suppose we have three forces: F_x, F_y and F_z, then the three relative equimomential lines *eqm(x,y)*, *eqm(y,z)*, and *eqm(x,z)* should intersect at the same point.

Now, we are ready to refer to the original question of the location where the face force acts. Following the definition of equimomential line, every force, in particular face force, acts along the absolute equimomential line. Now, we are facing with a need to come up with an algorithm to find the needed equimomential lines. Following the idea introduced in the paper, we transfer the problem to kinematics where there exists a known method, Kennedy Circuit method, for finding all the instant centers the dual to the equimomential lines. Now, what is left to do is to transform back the method from kinematics into statics yielding an algorithm for finding all the equimomential lines, as appears in (Shai and Pennock, 2006).

Proposition: From the physical point of view, the equimomential line of two forces is a line defined by the vector difference between these two forces.

Proof: Equimomential line of two forces is a line where the moments exerted by these two forces along each point on the line are the same. This property can be written as follows:

$$\mathbf{r}_1 \times \mathbf{F}_1 = \mathbf{r}_2 \times \mathbf{F}_2 \tag{1}$$

Any two lines in the plane, in generic position, always have a crossing point. Let us designate this point by *o*. The two forces exert the same moment at the crossing point – zero moment. Thus, the equimomential line should pass through this crossing point.

Let us choose an arbitrary point along the equimomential line (Figure 6), let us designate it by *p*, and **r** to be the radius-vector from *p* to the crossing point - *o*, i.e., $\vec{r} = \langle p, o \rangle$. The moment exerted by the two forces at point p is:

$$\begin{aligned} (\vec{\mathbf{r}} + l_1\hat{\mathbf{e}}_1) \times (F_1\hat{\mathbf{e}}_1) &= (\vec{\mathbf{r}} + l_2\hat{\mathbf{e}}_2) \times (F_2\hat{\mathbf{e}}_2) \\ \vec{\mathbf{r}} \times (F_1\hat{\mathbf{e}}_1 - F_2\hat{\mathbf{e}}_2) &= 0 \end{aligned} \tag{2}$$

which means that the direction of the equimomential line is the same as the direction of the vector difference of the forces $\mathbf{F}_1$ and $\mathbf{F}_2$.

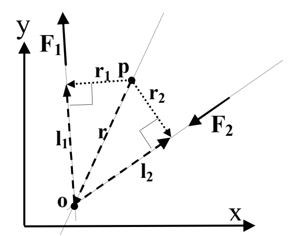

Figure 6: Geometry description of the equimomental line.

We now conclude this exercise in infused design by illustrating that two new entities were generated with their associated meaning and valuable methods. Such discovery has not taken place till now and the authors are not aware of any result reported in the literature that using systematic method led to such discovery. Furthermore, even the presentation of these new entities and their meaning (without describing the way they were discovered) led to enthusiastic response in the mechanical engineering community. Establishing the 'face force' variable is not only important from the theoretical point of view, but has practical analysis applications as well (Shai, 2002).

5. MODELLING THE "FACE FORCE" DISCOVERY WITH A C-K PERSPECTIVE

We now show how C-K could model the previously described ID discovery process. A complete general analysis requires a separate study, but on the example of the truss-mechanisms duality, we can highlight several remarks on the design logic of scientific discovery. The present analysis follows the 7 steps of the discovery process.

Step 1: The first step of identifying the missing concept could be understood as:

1. Analysis of K reveals omission of knowledge k_m: the duality between trusses and mechanisms shows unknown entities related to trusses. The dual provides a basis for a specific K-K operator that allows the identification of potentially missing knowledge. The missing knowledge k_m is not understood in its 'neighborhood' (discipline); it has no identifiable meaning in existing practice.

k_m is used to generate a new concept called Face Force: i.e. a force that is intentionally designated as the dual of joint velocity [$K \rightarrow C$]. This is clearly an expansive partition in K of "face" or "force" and the complete definition of a Face Force is not decidable at the beginning of the process.

Remark I: The embedded scientific knowledge in the duality equations is used not only to map the corresponding entities from the primal to the dual of what is known but also to reveal what is unknown.

Step 2: Once in C, different knowledge sources are used to elaborate the concept of the 'face force'. Past studies (i.e., previously generated knowledge) help elaborate the concept so it is related to the force in rods. [$K \rightarrow C$]

Step 3: Relevant knowledge is searched to find potential sources of knowledge to elaborate the concept. [$K \rightarrow K$] Through another representation, pillar systems become interesting candidate source of knowledge.

Remark II: these knowledge expansions are guaranteed to generate knowledge without contradictions, without need to check this property. Otherwise, knowledge elaboration might lead to contradictions that are impossible to remove automatically.

Step 4: Additional knowledge is gathered by further elaboration of the mechanism-pillar system relation. [$K \rightarrow K$] It becomes clear that there is useful knowledge in this domain to elaborate the face-force concept.

Step 5: This step further elaborates the concept face-force by adding the concept of equimomental line. [$K \rightarrow C$]

Step 6: Through a specialization of the new concept of equimomental line [$K \rightarrow C$, conjunction], a concept of absolute equimomental line is created which provides the final missing part in completing the definition of the face force concept. This step moves the concept into the K space [$C \rightarrow K$].

Step 7: This step also discovers a new method in the target discipline. From the representation, the transfer of methods between disciplines is guaranteed to work. There is no apparent generation of a concept in C in this step; therefore, it could be described as a more classic deductive process from $K \rightarrow K$, even though in C-K, such process is not supposed to generate new knowledge.

Remark III: From a C-K perspective, discovery occurs when a new concept is formed and subsequently, transferred to K. A jump from K to K in a way that creates a new method seems impossible. The explanation would suggest that the representation map in Figure 2 could be considered as supporting $K \rightarrow K'$ 'macro' operators (like duality) where knowledge from one discipline K is transferred to knowledge in another discipline K'; this allows forming new paths $K \rightarrow C \rightarrow K'$ that implicitly create new concepts.

Remark IV: As can been seen above, the expanding of K by new knowledge is done in a systematic way by using additional representations of the mechanisms and trusses. Usually the expansion is of K by new knowledge is derived from experiments or other external sources. Such expansion is not guaranteed to generate consistent knowledge. In fact, taking a body of knowledge and attempting to check its consistency is intractable computationally. ID opens a new way for expanding K by augmenting existing disciplinary K with K from other, seemingly unconnected, knowledge sources. Yet, ID serves as a new bridge to connect pieces of seemingly disparate knowledge in a consistent manner, so that they could be brought into C for generating new concepts. Initially, these new concepts do not have understandable meaning in the discipline of the dual although some elements of their definitions (assured existence with some meaning) is guaranteed by ID operators. Thus, the interpretation of ID with C-K theory throws an interesting light on scientific discovery, which in this case is clearly a design process (i.e., it needs a C-space); however, the K expansion is controlled by special $K \rightarrow K$ operators that warrant consistency and compatibility: the new objects have to obey to pre-established knowledge and these rules warrant some aspects of their existence. Clearly, the face force is still a force in the classic sense even if its formation and action line are unique.

6. DISCUSSION: SCIENTIFIC LOGIC AS CREATIVE DESIGN

This study has several contributions to design theory, practice, and science in general.

a) Creativity in Science as a design process

In relation to design theory, we need to ask 'Do I know more on C-K or ID from the analysis?' First, in the context of our study of creativity theories and methods, we find that C-K could model the particular ID process presented in this paper. In addition to a previous study (Reich *et al*., 2008b), this strengthens the claim that C-K as a design theory embeds creativity as an inherent part. But the study offers deeper insight as C-K theory was applied primarily to model the creative design of engineered artifacts, not scientific results (Hatchuel and Weil 2008). The study of ID offers a direct opportunity to extend C-K theory towards the generation of symbolic artifacts like scientific entities. The previously established correspondence between C-K theory and forcing in modern set theory (Hatchuel and Weil, 2007) opened this line of development, as Forcing is a method to design new infinite sets (extension models for Set theory) which are also scientific objects. A simpler example of design as a scientific logic can be also found in the formation of complex numbers through the introduction of the new concept of $i = \sqrt{-1}$. It may be interesting to remark that the introduction of such complex numbers comes from a duality principle between the real and the imaginary roots of the polynomial functions (Van der Waerden, 1985). As is the case with the concept of "face force" in this paper, most roots of polynomial equations were unknown in the world of the real numbers. The design of complex numbers as a well defined number field created a new source of knowledge that was consistent with real numbers and could generate new roots for any polynomial function.

In this paper, we cannot do complete justice to the conjecture that creativity in science through the creation of symbolic artifacts is a design process. ID and other examples are convincing enough to open a new research program on C-K theory as a model for analyzing and interpreting the logic of scientific discovery.

b) Knowledge-based systems with embedded C-K logic: A new type of design support systems

First, ID raises a new issue in knowledge management within C-K or any other theory or practical design support system. Managing a knowledge base, including its consistency is a challenging task. Operators that extend knowledge and maintain its consistency could be extremely powerful.

Second, intricate knowledge bases include significant hidden insight that could be discovered, leading to the formation of new concepts and potentially after further expansions to new surprising knowledge. Operators that create such new concepts, first operate from K to K trying to identify disjunctions, "holes" or interesting unknown objects. This requires a revision, re-interpretation or enrichment of $K \rightarrow K$ operators. As such, ID is both a special organization of engineering knowledge and a design support method.

As a scientific knowledge, ID provides an interesting multilevel structure.

Level 1: Graph theory (or matroid) is the highest level and the least specific form of knowledge.

Level 2: Flow graphs and Potential graphs are not implications of graph theory, but its combination with specific algebras (flows, potential or even durations in transport problems) which are added to the graph structure. Truss-mechanism duality appears at this level as shown in figure 2.

Level 3: engineering specialties are at the lowest level; they also introduce new additional knowledge to reach some sort of embodied form of knowledge (materials, fluids, energy…) which appear as isolated domains.

The classic logics of engineering design and computation tend to favor a design process that stays at the embodiment level of this structure where solutions seem "realistic," "concrete," or testable. ID allows to avoid such "embodiment trap:" it offers to travel horizontally, at level 2, in Space K. yet with a rigorous and controlled sets of operations. Actually, analogies and metaphors are well known sources of creativity through jumping from one domain to another. They may generate new concepts, but without any consistent source of K or method for K-Expansion that could provide the progressive elaboration of these concepts. ID avoids such potentially misleading and useless generation of concepts; it helps to think out of the engineering boxes, in a controlled and rigorous manner. The concepts generated through duality can be clearly designed at the intermediate level of the graph algebras. They also could offer an important design support at the embodiment level if there is at least one tractable solution in one of the embodiment domain. If the latter exists, its dual might be identified and it might serve as consistent design candidate, i.e., concept that is close to be perceived by experts as a solution. Sometimes identifying a solution at the embodiment level might not be easy (Shai *et al*., 2008).

While ID has been shown to support creative design and create new scientific knowledge, its interpretation with C-K theory helped to identify the point where creativity occurs. More generally, ID may be a special case of a new type of knowledge-based methods of systems (or meta knowledge based systems) that possesses an embedded C-K logic inside; another approach is explored by Kazakci *et al*. (2008). The general and complete characterization of this type of hybrid structures between scientific consistency and design logic is yet to be explored and will be pursued in future research

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