

CREATIVE CONCEPTUAL DESIGN: EXTENDING THE SCOPE BY INFUSED DESIGN

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CAD special issue on CD, in press

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ABSTRACT

Many methods that support human creativity by manual or computational means have been proposed in the past. They rely on the assumption that following a certain process of reasoning might lead to generating ideas considered creative. We start by defining creativity as a capability that enables the creation of systems that are patentable. We review the state-of-the-art of creative conceptual design and organize it with a framework. Subsequently, we present a method called infused design that guarantees generating design solutions by transforming systems and methods from remote disciplines. In many cases, these solutions would be deemed creative. Finding these systems and their transformations is done through a process based on the underlying discrete mathematical representation. This process is partially supported by a computer tool.

We describe the method of infused design and illustrate its operation through part of the results achieved until now, including designing a new active torque amplifier system. We

further demonstrate its benefits through other examples. We discuss the relation of infused design with other creativity or design methods and conclude with future developments of the method.

“A well-directed imagination is the source of great deeds.”

Chinese proverb

Keywords: creativity; conceptual design; graph representation; collaborative design; design support systems; framework; analogy

1 INTRODUCTION

Conceptual design is a central stage in product design; it determines the principles that govern the product. Decisions made in this stage have major impact on the final product quality, cost, and market success (Pahl and Beitz, 1996). But even high quality conceptual design leading to high quality products does not guarantee product success. If a company wishes to capture or maintain its market leadership, it must do better than that; it must develop breakthrough or radical innovations (McDermott and O’Connor, 2002).

Our position in this paper is that creative conceptual design (CCD) is central to developing innovative products. Therefore, studying and improving CCD is an important undertaking. However, creativity and innovation are elusive concepts; to some it is mysterious. There are more than 80 definitions of creativity in the literature (Dasgupta, 1994). A common definition of creativity is that creativity is the ability to generate new useful things that are characterized by being original and imaginative. The meaning of these properties is open to interpretations; therefore, for the purpose of this study we adopt a particular definition: CCD outputs a description of a device or a system that is or judged to be patentable. This definition concentrates on the engineering functionality of products rather than on their industrial design or

esthetics. We also focus on determining the principles that govern the product rather than a precise description of its structure and its detailed embodiment.

In section 2, we review the state-of-the-art of creative conceptual design. We provide a framework that helps organize previous work on the subject and helps locate areas of missing work. Rather than being exhaustive in the review, we mention representative studies that allow spanning the space of studies. A complete review deserves a separate study.

In section 3, we describe a method called infused design (ID) that provides a basis for extending creative conceptual design along several dimensions. Our method is independent of designers' personality, cognitive style, or other factors; it enables radical creativity demonstrated by generating designs that were not conceived before, by studying and exploiting designs from seemingly unrelated disciplines. It is built on a foundation that allows focused, partially computable, well-directed imagination.

Section 4 provides several examples that demonstrate these extensions. The discussion in section 5 elaborates on ways to integrate ID with other methods and further improve the support for creative conceptual design. Section 6 concludes the paper.

2 REVIEW OF CREATIVE CONCEPTUAL DESIGN

Creativity in general and in design or in conceptual design has been a topic of major attention over the years. Given the fascination with creativity and its foreseen economical value, it is no surprised that many researchers tried to understand it, find factors that correlate or enable creativity in different settings, and develop methods to enhance creativity. To illustrate, Smith, (1998) summarized 172 idea generation methods which could be perceived as the first and most critical part of creative design. The purpose of this section is to provide a brief overview of past research in relation to product design, organize it in a framework, and use this framework to identify interesting research topics.

2.1 A framework for organizing CCD studies

The framework defines a multidimensional space that allows classifying creativity studies.

Based on six dimensions:

1. *Actor complexity,*
2. *Product complexity,*
3. *Cognitive style or trait,*
4. *Cognitive process,*
5. *Problem structure and,*
6. *Design processes, practices, culture, or tools.*

The first dimension addresses the *actor complexity* reflected by the number of actors performing the design, their setup, e.g., whether collocated or distributed, etc. This dimension varies from a single designer to a distributed team. Single designers have been the subject of many studies on creativity. However, in contemporary product development practice, many creative solutions arise from collaborative work. This ‘single vs. many’ dichotomy echoes *product complexity* dimension that starts with a single device composed of few building blocks and ends with systems composed of many building blocks.

Studies of single designers have often dealt with the *cognitive style* or *trait* of people whereas the studies related to the creativity of groups have dealt with the cognitive style pool of group members. Cognitive style could be viewed as cognitive structure; its complement is the *cognitive process* which is the process used by designers to address design problems. The structure and process dimensions really use nominal scale; however, we turn them roughly into ordinal by ordering the approaches from least to most creative style and least to most creative process support.

Beside the contribution of designers to creative product design, the design context has major influence on the outcome. The context could be characterized by the *product complexity* whether a single device or a complex system; the *problem structure* (e.g., problem definition) which could invite or deter creativity; and the *design processes, practices, culture, or tools* available in the designers organization. These dimensions correspond to the designers' aspect dimensions. Together, the six dimensions span the space of studies on many product design topics including CCD.

2.2 Review of CCD studies

In dealing with creative conceptual design, our focus is on the findings of different studies and how they help us improve the state of creative conceptual design. More precisely, our interest is in the ability to design environments that foster creative conceptual design. The following review describes studies that span the space of possibilities; it is definitely not exhaustive. Some studies are roughly located in the framework shown in Figure 1.

2.2.1 Creative designers

The easiest way to influence the creativity of a design environment is to select creative designers that have greater chances to generate creative products. This however requires connecting two perspectives on creativity: creativity as *trait* or *style* and the product of creative acts. Measuring traits has been based on various psychological tests.

In most real world product development projects, teams are necessary to address the interdisciplinary nature of designs. But in relation to creativity, working in teams is often seen as a way to enhance creativity by forming social creativity (Fischer, 2000). Paulus (2000) suggested that when teams member differ in their background knowledge, their diverse perspective might lead to broad coverage of skills and constructive conflict. When such background knowledge overlap, analogies could emerge more easily and creativity could

improve (West, 2002). Without sufficient overlap, diversity could lead to communication problems, hampering the chance for creativity (West, 2002). Other models that explain the working of creative design teams have been proposed (e.g., Leifer, 1998; Fischer *et al.*, 2005) suggesting that communication means between designers, whether implemented in processes, tools, or settings are key to success. Such communication is often mediated by the creation of ‘boundary objects’ – concrete representations of the product that team members create, share, and evolve (Fischer *et al.*, 2005; Subrahmanian *et al.*, 2003).

In order to realize these ideas, diverse creativity tests have been developed for designers and teams. A variation on the Myers-Briggs Type Indicator test (Briggs Myers and McCaulley, 1985) was developed and used in creativity studies (e.g., Stevens *et al.*, 1999). The latter test was further developed to allow composing creative product development teams based on diversifying their knowledge, styles, or roles (Wilde, 2004). Creativity was measured by the winning of a particular design competition.

2.2.2 Cognitive strategies, methods, and tools (designers perspective)

Although cognitive style is commonly perceived as fixed, cognitive strategies could be altered by training (Ripple, 1989) and tools or methods could be implemented and used effectively. As previously mentioned, idea generation is fundamental to creativity in general and creative conceptual design, specifically. Given some statistics that on the order of 3000 raw ideas are required to generate one successful product in the market (Stevens and Burley, 1997), this task requires serious support. Many methods have been developed to assist in idea or concept generation including brainstorming (Osborn, 1953), TRIZ (Altshuller, 1988), or ASIT (Horowitz, 1999). There have also been numerous attempts to create creative programs or support human creativity by computational means. These range from support systems based on analogical reasoning (Qian and Gero, 1996; Goal, 1997), systematization of knowledge based,

e.g., on ontologies (Kitamura and Mizoguchi, 2004), to automated tools such as genetic-based approaches (Koza *et al.*, 2003, Pechter and Reich, 2003).

Some of the studies in the field of design by analogy attempted to simulate the process of designers arriving at solutions. Particularly, in this regard is the work of Gero dealing with situated analogy in design (Kulinski and Gero, 2001). Qian and Gero (1996) represented designs in the form of a function-behavior-structure model and used the matching between such graphs to retrieve previous designs. Another approach based on ontological systematization of functional knowledge (Kitamura and Mizoguchi, 2004) aims at transforming device descriptions between disciplines based on their functionality. However, its foundation does not support the kind of transformations presented later in this paper, e.g., between dual representations and transformation of solution principles rather than solutions. Many other models of creative designs have been proposed based on protocol studies or abstract conceptualization.

Since our subject is creative conceptual design, we need to review conceptual design methods and tools. Conceptual design could be decomposed into several activities: requirement analysis, product concept generation, and concept selection. The first and last activities enjoy the availability of numerous methods, for example, QFD (Akao, 1990) for requirement elicitation and translation; and Pugh's concept selection (Pugh, 1981) or AHP (Saaty, 1980) for concept selection. In contrast, there is no widely used method for concept generation (Hari *et al.*, 2001).

The predominant tool for concept generation has been morphological analysis (Pahl and Beitz, 1996) in which each requirement is potentially addressed by several functional solutions and the designers have to figure out manually which combination constitutes the better concept. Recently developed methods integrate several methods e.g., ICDM (Hari *et al.*, 2001), or

provide ways to integrate diverse knowledge into a shared workspace towards generating concepts, e.g., SOS (Ziv-Av and Reich, 2005).

Focusing more on mechanical or electromechanical devices, there has been significant work on the conceptual design of such devices given the ability to formalize them in different ways such as ontologies. Such design processes would start with a functional requirement and end with a concept that will have to be detailed further in subsequent design stages. These methods include genetic programming (Koza *et al.*, 2003), agents governed by simulated annealing (Campbell *et al.*, 1999) case-based reasoning (Han and Lee, 2006), hierarchical decomposition and re-composition (Chakrabarti, 1994; Chiou and Kota, 1999), and others.

Most of the aforementioned methods or software tools have been developed to support single designers. Supporting teams requires attending to additional issues including controversies. For example, empirical tests show that the perception of those engaged in collaborative problem solving (e.g., brainstorming) is that group work has an advantage over individuals (Paulus, 2000). Unfortunately, this perception is often wrong as in the case of brainstorming: Group performance could be even worse than individual performance (Paulus, 2000). The problems of team brainstorming could be explained by various psychological and social issues (Paulus *et al.*, 1993) and fortunately, they could be addressed successfully by electronic brainstorming tools that could lead to improved team performance over its members (Gallupe *et al.*, 1992).

Creative teams mostly require support for communicating and sharing ideas and knowledge (Fischer *et al.*, 2005; Reich *et al.*, 1997). Tools for supporting creative conceptual design of teams foster shared understanding, provide repositories of concepts, and may include communication means (Fischer *et al.*, 2005, Reich *et al.*, 1997).

2.2.3 Changing the problem structure

The product complexity is usually given by the problem definition, e.g., designing a device or a complex system are two different things. Such differences could be addressed by matching them with actor complexity. But for a particular problem, if we allow the development teams to modify it or if the problem is sufficiently open, then the available opportunity for creativity could be realized (Leifer, 1998; West, 2002).

2.2.4 Organizational culture, practices, and tools

Designers never work in isolation from a context. They are often part of an organization with knowledge, culture, and managerial practices. It is easy to kill creativity by focusing on productivity and efficiency (Amabile, 1998). However, practices that promote cultural values that foster creativity could exist or be nurtured (Amabile, 1998), and with the right strategies for uncertainty reduction including outsourcing and working with users (Von Hippel, 1986), and project management tools and attention to the people aspect, radical innovation could be supported (McDermott and O'Connor, 2002).

This dimension provides opportunity to see the interaction between some of the dimensions in the framework because its manipulation usually requires attention to other dimensions. There are several examples of successful integrations.

In the context of real demanding design tasks, teams created systematically (Wilde, 2004), that are coached (Reich *et al.*, 2006b) in a particular development process demonstrate consistently creative capabilities leading to creative products (Leifer, 1998). Creative team members that follow a well defined process led to better development performance in real projects (Stevens *et al.*, 1999). Finally, implementing creativity tool such as ASIT in the context of a comprehensive design methodology helped design teams achieve creative performance in demanding tasks (Reich *et al.*, 2006a). All these examples are far from perfect. There is much to be learned from them to further improve creative conceptual design of teams.

2.2.5 Analysis and future work

When mapping CCD studies onto the six-dimensional framework by assigning the value 1 to most simple and 9 to most complex values, this data could be analyzed. We perform this analysis using repertory grids (Kelly, 1955). Repertory grids represent objects of any kind (e.g., CCD studies) with different dimensions that might have different scales (e.g., discrete, ordinal). These grids could be analyzed and reveal insight into the space of objects; they could also assist in directing further exploration by pointing to additional objects and dimensions that could be added to the grid. Consequently, they could be used as research tools for review purposes and others, see examples in (Reich, 2000; Reich and Kapeliuk, 2005; Reich *et al.*, 2006b).

Figure 1 shows a partial analysis of a grid performed by the repertory grid tool WebGridIII (Gaines and Shaw, 1996). The figure shows a clustering of the dimensions (top right) and of the studies (bottom right). The first reveals that there are correlations between the complexity of the product and the complexity of the organizational processes used to develop it; more creative designers might use diverse strategies or methods; and more open problems are solved by more complex team structures. All these three correlations are familiar from practice but, more studies need to be mapped onto the framework to obtain better correlations. The preliminary correlations between the CCD studies are quite intuitive: studies (1), (2), and (3) are quite similar; (4) and (5) are similar; and (7) and (8) are similar. The method we present in this paper, ID, is quite different from the rest, thus it expands the scope of existing studies.

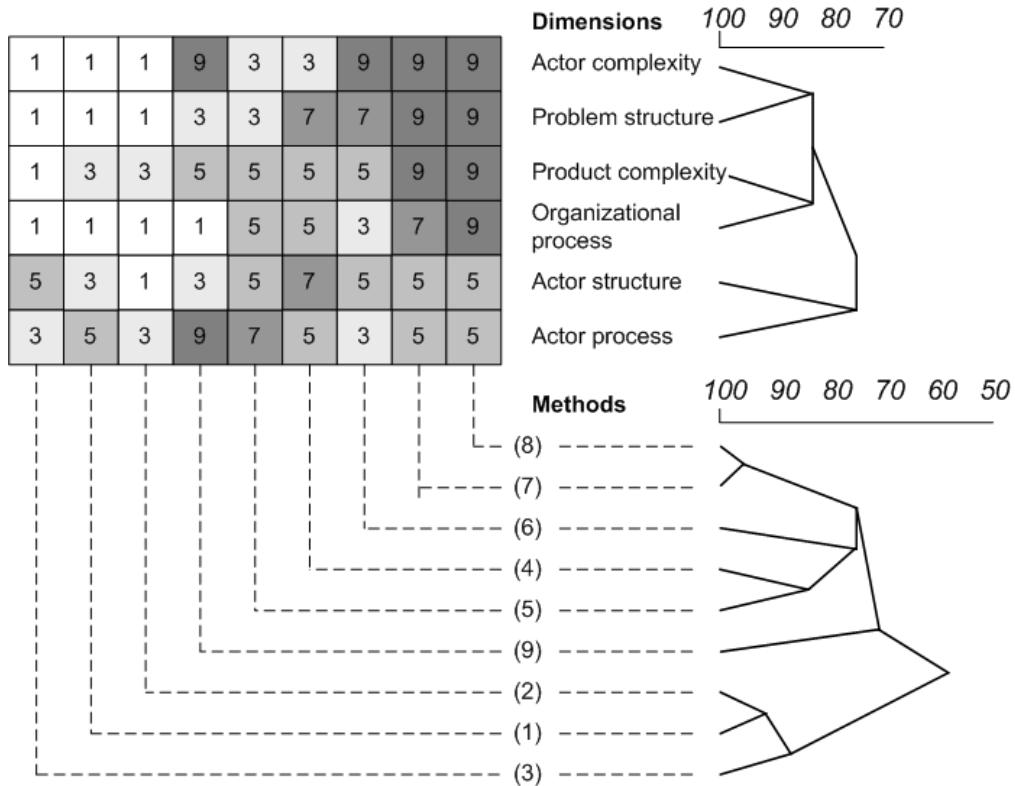


Figure 1: Preliminary analysis of the creative conceptual design framework. The numbers in the legend represent the following data points:

- (1) TRIZ-like methods: a single designer, knowing this method, could solve device-level problems, without needing organizational support
- (2) Use of genetic-based algorithms: automatically generating multidisciplinary devices
- (3) Research studies of a single designer performing a lab experiment over a short period of time (e.g., hours)
- (4) Small group of university students, organized in creative teams; with minimal knowledge of design tools, but with significant organizational culture and support, doing a complex device design whose problem statement could be altered (Leifer, 1998)
- (5) Small group of high school students; working in teams, with minimal technical knowledge but knowledge of a structured design process and tools; with considerable organizational support, doing a complex device design whose problem statement is fixed (Reich *et al.*, 2006a)
- (6) Brainstorming: group of designers works to create new ideas using the method and organizational cultural support
- (7) Studies of real industrial projects where experienced teams followed various structured organizational processes (e.g., Stevens *et al.*, 1999; McDermott *et al.*, 2002)

- (8) Practical goal: Practices for supporting industrial creative teams through design tools and organizational processes in breakthrough innovation projects
- (9) Infused design

Much more work is required to further understand creativity in general and CCD specifically. This work ranges from specific topics to overall integration of the various dimensions. An arbitrary collection of specific topics include: comparing between different idea generation methods (e.g., McKoy *et al.*, 2001), moving techniques for creative design of devices to systems; creating diverse teams with sufficient overlap to support communication (West, 2002), or maintaining a balance between creativity and effectiveness in development projects. Along with particular issues, controversies related to creativity tools need to be further studied and clarified. For example does brainstorming support group creativity or not and if it does, in which context? Or could creative cognitive style of people be altered?

Methodological issues in the study of creativity also exist. Given opinions that almost all creativity arise in social interaction (e.g., Fischer *et al.*, 2005), how much can be learned from few protocols of single designers? (Dorst and Cross, 2001). Another issue involves the ability to extract useful information for practical implementation from laboratory or even educational settings such as in (Leifer, 1998, Reich *et al.*, 2006a). Finally, the multiple perspective for studying creativity need to be sorted out to for allow cross fertilization (Sternberg, 2005).

A crucial issue for engineering that relates to the methodological issues is transforming the results of creativity studies into actionable knowledge that could impact practice; for example, using all this knowledge to inform the development of new creativity tools or support systems (Hewett, 2005) and understanding which type of computer tool might be appropriate for different design contexts (Lubart, 2005).

Finally, more theoretical work is needed to understand the phenomena of team CCD. We previously mentioned models of single designers, and there are models of team CCD (e.g., Leifer, 1998; West, 2002), where each addresses particular and sometimes overlapping dimensions. There is also a theory that places creativity at its core (i.e., C-K theory, Hatchuel and Weil, 2003). However, much better understanding of the interaction between the multiple framework dimensions is needed towards achieving creative conceptual designs in practice.

3 THE PROCESS OF INFUSED DESIGN

Shai and Reich (2004a) presented the ID process model (see later, Figure 4) further extended it in (Shai *et al.*, 2005). This section presents a revised version of the latter model.

3.1 Notation

In order to explain the nature of problem representation in ID we define a notation. In the notation,

- Capital letters denote sets or classes of problems or models
- Small letters denote single items or instances of classes
- Superscripts denote different types of models or representations
- Subscripts denote different sub-parts of a system

Any design team possesses a particular disciplinary perspective D consisting of:

- T - a set of alternative disciplinary terminologies (e.g., different ways to describe force, rod, connection, support, area that are used in structural engineering or resistor, capacitor, diode, current, voltage, and amplifiers in electrical engineering).
- M - the type of the combinatorial representation that governs the creation of a model (some of these types are more common than others within the perspective D).

The team can use a particular piece of knowledge and some primitive concepts to transform an initial problem information p into a model m described with a particular terminology t . The model and its terminology are denoted by the pair (m, t) . This pair is called the *representation of the problem*. The model of the problem m would subsequently be solved by some method sm . We proceed to describe the different ID activities with this notation.

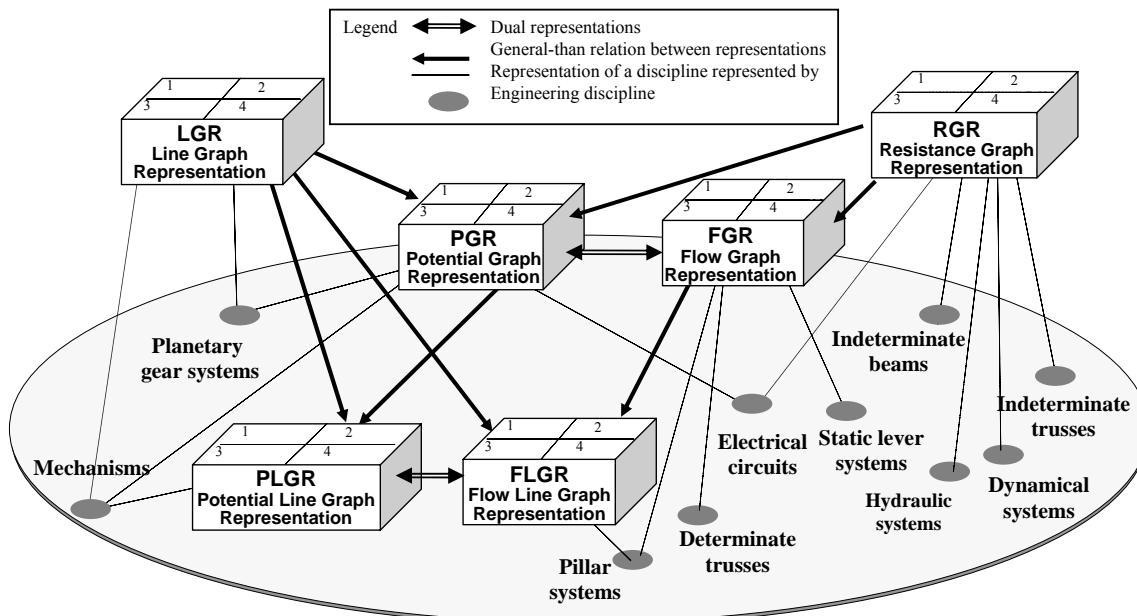


Figure 2: Map of graph representations, their interrelations, and association with engineering systems (Shai and Reich, 2004b)

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. For example, a FGR representation of a truss is shown in Figure 15 of the appendix and a PGR representation of a linkage is shown in Figure 16. In the FGR representation, m is the graph model, Figure 15(b), and t is the terminology used to describe such models including: joint = vertex, edge = rod, unit vector for each edge = rod orientation, etc.

These representations can represent diverse systems, e.g., RGR is the 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 transforming automatically one representation to others connected to it (Shai, 2001a). Shown in the appendix, such transformation could be done automatically. Since these transformations guarantee that each representation has the same behavior, the automated part of ID is provably correct. This is in contrast to other methods such as design by analogy or design based on ontology which do not guarantee that the transformation process between disciplines will be successful.

3.2 ID process

Design starts with a written, verbal, problem description, abstract idea, or in some other unspecified manner. The initial information is limited, uncertain, and ill defined. Problem formulation is a process of creating a product specification, ps , from the initial problem information, p . Problem formulation is quite informal and involves (1) making assumptions about the focus of the problem and the importance of different aspects; (2) information consolidation from diverse structured and unstructured sources; and (3) authoring the specification. The product specification might include, in addition to the verbal description, drawings, computer models, physical objects, and other available information. It could be incomplete or even inconsistent, thus requiring future revisions.

The system being developed could be composed of many components j , $j=1,\dots,m$, each with its own representation i , $i=1,\dots,n$. We denote component j in its representation i with (m_j^i, t_j^i) . These indices are independent since one component might have several representations at different times for different purposes; furthermore, several components might have the same

representation. ID can proceed by integrating the different components representations (m_j^i, t_j^i) , $j = 1, \dots, m$ into subsystems with a single representation (m_j^{n+1}, t_j^{n+1}) that could be assembled into the complete system or product representation (m^{n+1}, t^{n+1}) as shown in Figure 3.

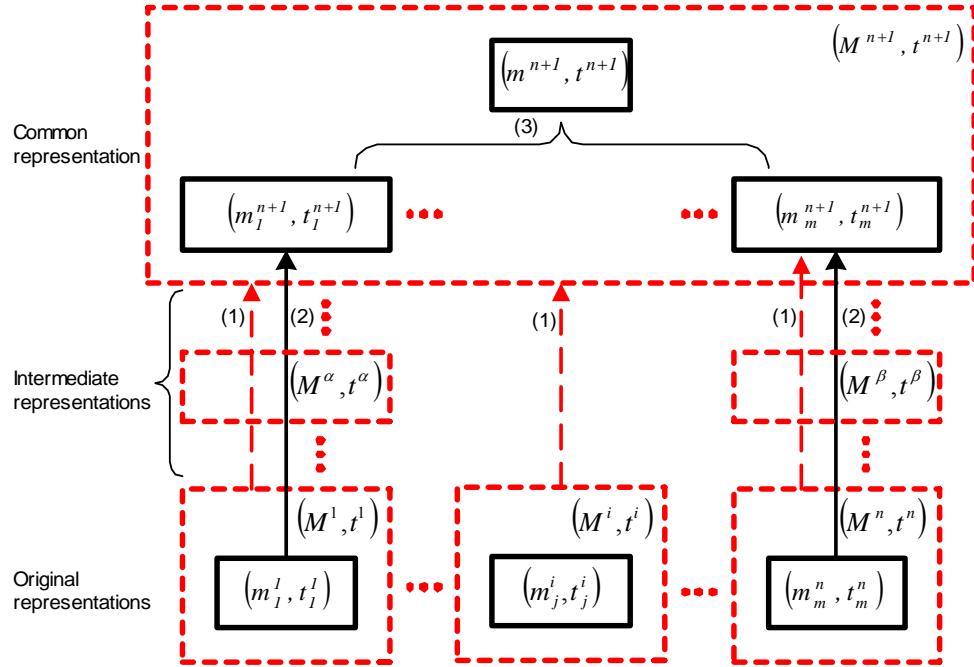


Figure 3: Transforming diverse subsystems representations into a common system representation
(Shai and Reich, 2004a)

In the figure, the dashed boxes refer to representations such as RGR, FGR, or PGR that are depicted in Figure 2; the solid boxes denote specific models of the components. The integration is accomplished by identifying a common representation composed of model type and terminology (M^{n+1}, t^{n+1}) that can accommodate all the original representations. Step (1) in Figure 3 shows this move from the original representations, through intermediate representations, e.g., (M^α, t^α) , to the common representation. Subsequently, the original models (m_j^i, t_j^i) ,

$j = 1, \dots, m$ are transformed into the common representation (m_j^{n+1}, t_j^{n+1}) (step 2); and the models can be combined into the complete system model (m^{n+1}, t^{n+1}) (step 3).

To better illustrate Step (1), consider the following example. Members of the multidisciplinary team start by using their customary disciplinary model and terminology for each discipline $(M^1, t^1) \dots (M^n, t^n)$, e.g., PGR for mechanisms and FGR for static systems, see appendix for examples. In order to integrate all the disciplinary representations they need to search for one common representation (M^{n+1}, t^{n+1}) that accommodates all the original representations. This representation must have known mathematical relation such as duality or generality with the original representations. This search could be done without considering the particular problem at hand. It is performed following relations found in previous studies that are depicted in Figure 2. For the 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. The search is therefore trivial; furthermore, it could be automated.

The common representation (M^{n+1}, t^{n+1}) allows borrowing solutions or solutions methods from different disciplines. For example, suppose one of the problems p of one practitioner is found to be very difficult in his discipline (see Figure 4).

Step (1): The problem is modeled by the practitioner in m^0 , a model of the model type M^0 .

We can denote this process by $p \xrightarrow{D} m^0$, clarifying that m^0 is created from p by some disciplinary perspective D .

Step (2): A common representation (M^{n+1}, t^{n+1}) is found between the problem representation and other disciplinary representations. The problem model is automatically transformed from m^0 to m^1 and onwards, while modifying the terminology.

Step (3): A reference discipline is selected and the problem model could be automatically transformed into model m^3 described by its disciplinary terminology t^3 .

Step (4): Team members who are experts in that discipline can now locate design solutions s^3 for the problem and model it in the disciplinary representation.

Step (5): Once the solution is modeled, it could be automatically transformed in the opposite direction, resulting in solutions representations to the original problem s^0 .

Step (6): To complete the process, this representation has to be implemented in the original discipline by the practitioners.

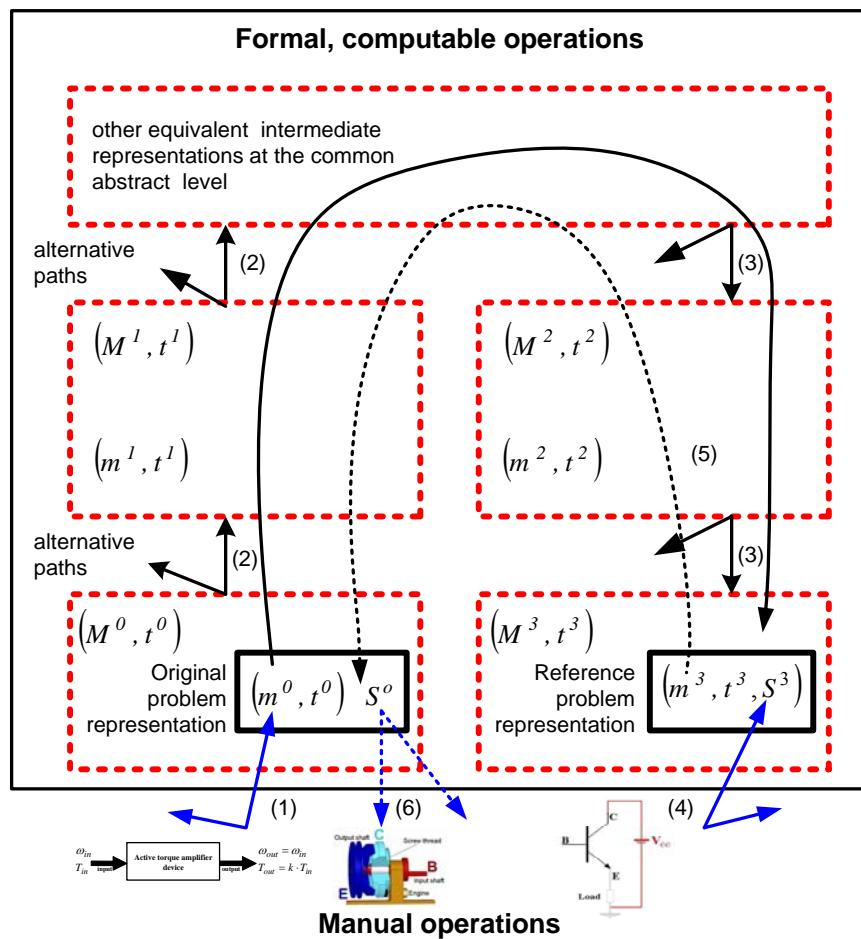


Figure 4: Infused design process model (modified from Shai and Reich, 2004a)

Figure 4 makes explicit the formal and computable operations of ID which involve transformations between graph representations and the manual operations of ID which deal with transformations between physical/disciplinary models and graph representations,

There are several decision points in the ID process that are critical to understand and appreciate. These decision points appear in steps (1), (2), (3), (4), and (6) and are denoted by multiple arrows:

Step (1): When representing the problem, there could be several options, i.e., different graph representations with which to represent the engineering system; which of the options should be selected?

The choice of representation often depends on the level of detail required. This is a general modeling problem in any domain and in particular in engineering. For example, a structure could be modeled as a truss if its members' connections are flexible or as a frame if they are stiff. Since this is the first step of the process, it influences the difficulty and success of the process.

Moreover, different representations enable revealing different properties of the engineering system. For example, if we deal with kinematical system, choosing PGR enables to reflect the properties of the linear velocities of the system, while choosing PLGR enables to concentrate upon the angular velocities.

There could also be different modeling choices at different levels of granularity. For example, a lattice boom of a crane could be modeled as a frame to analyze its internal forces or as a bar to analyze the complete crane. In the present complexity of the infrastructure of ID (see Figure 2), it is possible to check multiple representations of a device.

Step (2): After a problem is represented, there could be alternative paths in which it could be transformed into intermediate representation (M^{n+1}, t^{n+1}) , which one should be selected?

The obvious answer is trying all representations. Since the representations are discrete models, the process could be automated so that only computational resources are necessary. As seen in Figure 2, currently most disciplines could be transformed to one (e.g., static lever systems) up to three representations (e.g., mechanisms). Therefore, it is quite easy to try all the possibilities. Even if multiple paths are selected in the hierarchy, the combinations do not grow significantly; the hierarchy is limited in size so that the number of paths through different representations is rather small.

Minimizing the paths traversed is not a necessary goal. Intermediate representations have built in knowledge that could be used to shed a new light on the present problem, as was done in the process of revealing the equimomental line in statics (the dual of instant center from kinematics) using the duality between FGR and PGR and the duality between PLGR and FLGR (Shai and Pennock, 2006).

Step (3): Another issue is which reference discipline should be selected in order to search for a solution?

The answer is similar to the previous question. The preferred solution is trying as many solutions as possible. Therefore, the more reference disciplines are explored, the higher the potential to find good results. Given the size of the present hierarchy, the number of options is small enough to be familiar to a team of practitioners so that they can make a judgment based on their collective expertise how to prioritize the reference disciplines. However, in the future, as we try increasingly complex designs and as more disciplines are added and since this approach is founded on discrete mathematics, this step could be automated.

Step (4): This step exhibits the same line of reasoning about alternative representations as in Step (1). In addition, another situation arises when a device does not easily transform into the graph representation. For example, a transistor is a device with three interfaces thus cannot be added as a primitive to any graph representation which comprises devices with two interfaces. Electrical engineers encounter this problem when they use graph representation to solve analog circuits. They had to create a model of a transistor that is composed of other components with two interfaces each. This model is quite complicated and introduced difficulties for solving circuits yet it is necessary. It is plausible that new devices that are introduced in some discipline would have to be modeled approximately to allow their representation by graphs.

Step (6): When translating the solution back, there might be (parts of) devices that do not have immediate mapping in the source domain. Realizing these fragments of graph representations in the source domain requires domain knowledge to find the physical principle that could govern the implementation as well as an effective embodiment. For example, realizing current source controlled current (ideally) from electronics in mechanics is not trivial since there is no such primitive design available. Consequently, a subsystem that replicates the current source controlled current (CSCC) behavior needs to be designed and implemented in order to map electrical circuits that include CSCC into solutions for problems in mechanisms.

Each of these decision points becomes a source of creativity. While ID does not help in this act, it certainly focuses the attention on the precise points where creativity is required. This focusing is illustrated in section 4.1 that deals with creating a new concept in engineering that is being employed for devising a new mechanical amplifier device.

4 EXAMPLES

This section provides several examples that demonstrate the way ID extends CCD. The first example shows how a new patentable device is developed by ID and consequently demonstrates the basic premise of the approach.

The second example shows how devices from diverse disciplines are derived from a single device in a way that guarantees the functionality of the new devices. This demonstrates breadth of the method: once a new principle is discovered, it could be used to generate diverse creative devices. The equivalence between these diverse disciplines, which is made explicit in Figure 2, allows transforming knowledge from diverse disciplines to assist in solving a particular problem. As more perspectives or disciplines are available through more participants, better solutions could be devised.

The third example shows that not only can ID support creative design of devices; it can also support creative formation of new knowledge. In the fourth example, this new knowledge in turn, extends the scope of ID by bringing downstream concerns into the conceptual stage.

4.1 Design of an Active Torque Amplifier Device

This example demonstrates how ID is used to generate a new device that is patentable. This establishes the basic claim of the method.

4.1.1 Function

There are many mechanical devices that generate an amplified input at the output. Examples include gear systems and levers. In each of these devices, there is a conservation law that governs the device behavior. In a gear system, the angular velocity could be amplified but the power remains constant, therefore, the external moment is reduced. In a lever, the force is amplified but the energy remains the same so that the distance traveled is reduced. Suppose we wanted a device

that amplifies the input moment and maintains the angular velocity. This statement is the problem definition p . Figure 5 presents a schematic description of the function of the required device. This model m^0 , expressed by the domain terminology t^0 (angular kinematics), is the translation of the problem definition p . Obviously, to realize such a device we would need an external power source to support the additional power required at the output. This need will be satisfied automatically when we transform a solution from any discipline.



Figure 5: Functional description of the proposed device

Therefore, the device possesses at least two interfaces: the input shaft and the output shaft. The properties are as follows:

1. The angular velocity at the output shaft is kept equal to the angular velocity supplied at the input shaft.
2. The torque exerted by the output shaft is equal to the torque applied at the input multiplied by a constant k . Constant k is the pre-designed structural property of the device, and can reach values of several hundreds in accordance with the requirements of the selected application.

Consider an example of the active torque amplifier with amplification ratio $k = 100$. Suppose one rotates the input shaft with angular velocity of 1 rad/sec . By property 1, the output shaft will also be forced to rotate with the same angular velocity. Suppose that in order to rotate the load connected to the output shaft with this angular velocity, a torque of 100 Nm is to be exerted on it by the output shaft. Thus, according to property 2, the torque to be applied to the input shaft would equal to $1/k \cdot 100 \text{ Nm} = 1 \text{ Nm}$. To balance the torque difference, external engine would have

to supply the remaining $99Nm$. As a result, despite the heavy load connected to the output, one can easily rotate it with the desired angular velocity by applying a small torque. On the other hand, due to the constant ratio between the input and the output torques, one still “feels” the output resistance at the input.

Such a mechanism could be useful for many practical applications that would value the advantage of the “feeling” property in addition to the amplification. Practical applications include a working tool, such as a precise screwdriver, or drill that enables performing manually controlled rotational motion, while the device supplies any power necessary to overcome resistance at the output; various rescue equipment tools; and a new concept for a power steering wheel mechanism, depicted in Figure 6.

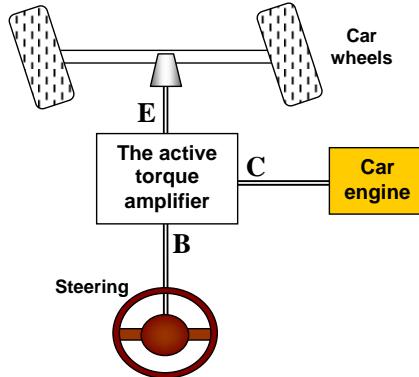


Figure 6: A simplified principle sketch of the new concept of the power steering wheel mechanism employing the active torque amplifier

In the proposed concept, the steering wheel is connected to the input of the active torque amplifier, while its output is connected to the differential rotating the car wheels. The external source shaft of the active torque amplifier can be connected through a proper transmission to the car engine or to an additional dedicated engine, such as the one used today for the hydraulic steering wheel. This way the torque applied by the driver upon the steering will be amplified and

applied to rotate the wheels to the desired angle. Such a concept for the power steering offers a number of advantages:

- No need for special pumps and hydraulic fluids to operate the power steering wheel.
- The “feeling” property allows the driver to feel higher resistance at the output, thus it will be harder for him to rotate the steering at higher velocities.
- No need for electronic control components.
- Relatively small number of parts, which are easy and cheap to manufacture.

4.1.2 The process used to develop the device

The device was designed through the following steps that correspond to the steps in Figure 4.

Step (1): Representing the problem

Figure 5 is a visual representation of the desired device. A formal representation of the problem in the mechanism discipline could be:

Design a device S that has the following two interfaces:

| | Interface Role | w | T |
|---|----------------|-----------|-----------|
| 1 | Input | w_{in} | T_{in} |
| 2 | Output | w_{out} | T_{out} |

Step (2): Exploring alternative paths

The next step is finding alternative paths that may lead to solutions in different disciplines. From Figure 2 we observe that there are multiple paths that could be explored from the mechanisms representation to various intermediate representations including:

1. Mechanisms → PGR → FGR. The latter involves transforming between dual representations, see appendix for this example.

2. Mechanisms → PGR → FGR → RGR. The latter involves transforming between one representation to its generalization.

3. Mechanisms → LGR.

Each of these intermediate representations, M^i , may expose new opportunities. In particular, the LGR representation allows access to the following disciplines: planetary gear systems, pillar systems (through FLGR), electrical circuits (through PGR), and static lever systems and determinate trusses (through FGR). Within this representation, designers can find representations of all the devices known to date. If one of these representations possesses the function modeled by (m^1, t^0) , the search for solutions has been successful.

Steps (3) and (4): Selecting reference disciplines

As mentioned in the previous subsection, from each visited intermediate representation, there are reference disciplines that could be accessed. Each such reference discipline could be a source for solutions. Even if solutions are represented at intermediate representations, the device in the reference representation contains additional knowledge beyond its representation. In our case, out of all existing devices, designers could detect two that match the required functionality. This could be done automatically by matching the formal representations of the devices. In this case, we merely need to find 2 interfaces in each device that match the definition in step (1). The complexity of this matching increases with the number of interfaces. Performing it efficiently for large devices remains a topic for future research.

1. The electronic transistor that could be accessed through the PGR representation. In this case, the model (m^1, t^0) would be translated into the PGR representation, M^2 with its own terminology t^2 (i.e., potential difference, ...). From the model, the translation would lead to model m^3 of type M^3 in the terminology t^3 of electrical circuits.

2. The hydraulic Valvistor that was developed by Vickers (1993) that could be accessed through the RGR representation.

Seemingly, we have two solutions that could be used to develop creative devices. However, these devices are isomorphic. This means that if their models are translated into the same model type M^4 of RGR through a sequence of translations, these models would be isomorphic from a graph theory perspective. Consequently, we select to continue the design with the transistor knowing that transforming the transistor back to the original domain involves only one intermediate representation.

Step (5): Finding alternative paths for transforming solutions back

This step is similar to step (b). In the particular example, only one path has been explored from electrical circuits (m^3, t^3) back to PGR (m^2, t^2) , see Figure 7. The figure shows the correspondence between the parts of the transistor and the graph in this discipline. This translation could be done automatically but presently is done by hand.

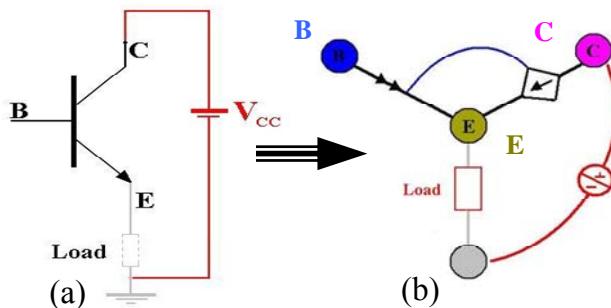


Figure 7: Finding one alternative path. (a) the transistor modeled in (m^3, t^3, S^3) ; (b) the translation of (m^3, t^3, S^3) into (m^2, t^2, S^2) of PGR

Step (6): Implementing the solution principles in the source domain

When transforming devices from one reference discipline into another through the intermediate representations, new opportunities are opened for the designer since for the same device representation, different devices can be constructed. For the given design case, the device from the reference discipline is one dimensional (electronics) while the source domain consists of a number of dimensions. For the given design problem, two options were applied: linear and angular dimensions. The availability of multiple options demonstrates one of many potential applications of the proposed technique. These options could be codified for each case and maintained for future reference; for example, when moving from one dimensional space into multidimensional such as kinematics, the translation could be implemented into linear or angular dimensions.

The designer can transform one device from the target domain (m^3, t^3, S^3) and get several devices $(m^0, t^0, S_1^0), \dots, (m^0, t^0, S_n^0)$ that are all isomorphic to the same device. This translation is done manually and involves creativity in embedding the elements and relationships that appear in the graph into 3-dimensional physical media. Each such device gives a different perspective and new insight on the new device and even on the reference device. For example, the reported invention was found to possess a novel self controlling mechanical principle that has never been reported in the literature. The mechanical engineers in our group had difficulties in capturing and understanding the idea underlying this device and understanding how it works. The possibility of constructing two devices, one linear (Figure 8) and the other angular (Figure 9), enabled understanding its behavior using the former which also helped implementing the latter to become a practical application in industry. We skip the details of the linear device and elaborate next on the particular implementation and operation of the final solution.

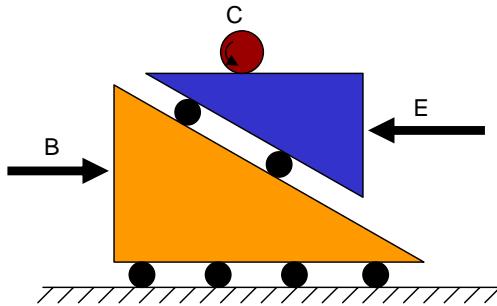


Figure 8: Linear Active force amplifier schematic drawing

This proposed product is one of a number of new concepts that have been developed in the last decade through the same technique and are about to be introduced to industry.

4.1.3 Structural and behavioral description of the device

Figure 9 presents a schematic drawing of the proposed device. The device is comprised of only three solid parts: B, C and E and its performance does not require any additional control or electronic components. As the device has been obtained by transforming knowledge of the electronic transistor, there is a complete correspondence between the behavior of the abovementioned parts and base, collector and emitter of the transistor. Part B is the input shaft, part E is the output shaft and part C is the shaft connected to the external power supply with high angular velocity. The rotation axis of B is connected to E by a screw thread. When B is rotated at angular velocity ω , the screw thread causes E to displace towards C and to attach to it. When C and E are attached, the friction between them causes E to rotate as well. When E reaches an angular velocity higher than that of B, the screw thread will cause E to displace right and to detach from C. Thus E will constantly attach itself to C in order to keep its angular velocity equal to that of B.

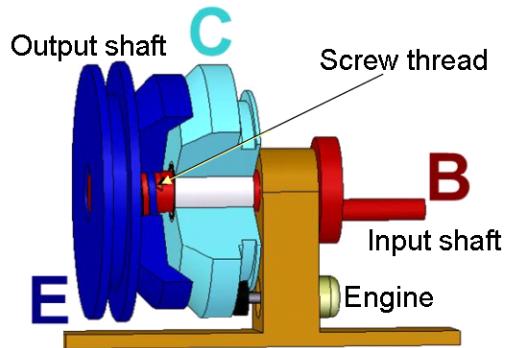
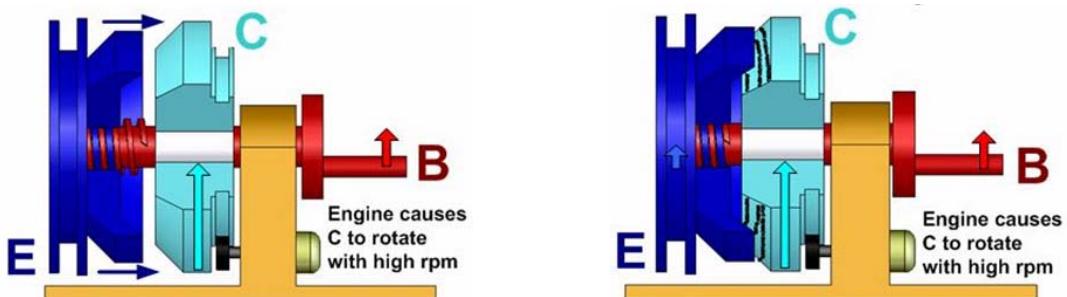


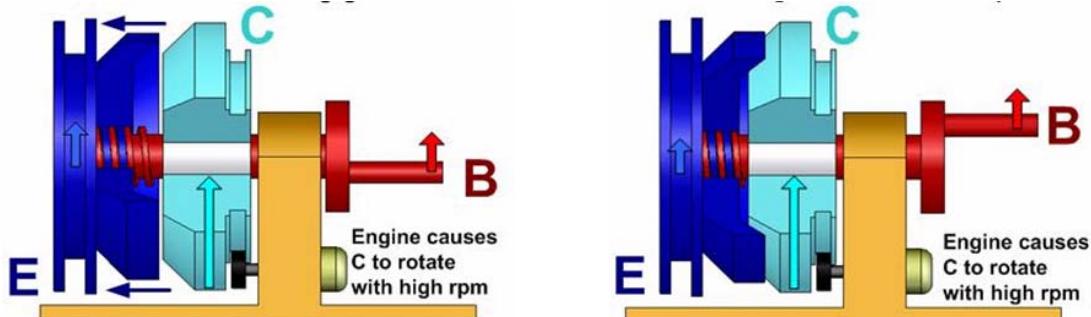
Figure 9: Active torque amplifier schematic drawing

The torque transmission from C to E is determined by the corresponding friction coefficient and thus is constant subject to the material properties and the form of the interface surfaces. Furthermore, one can see from the sketch that the output torque equals the sum of the torques applied to B and to E. Figure 10 summarizes the four stages of the working principle of the active torque amplifier.

Accordingly, the function of the new mechanical device can be outlined by two relations: (a) the angular velocity of the output shaft is kept equal to the angular velocity of the input shaft and (b) the torque applied by the output shaft is equal to the torque applied upon the input shaft multiplied by a high constant coefficient. This function maps the function of the electronic transistor, where the voltages upon the base and the emitter are kept approximately equal, while there is a high constant ratio between the base and the emitter currents.



- a. Disengaged mode: Rotation of B causes E to moveb. Push mode: C causes E to rotate through towards C friction



c. Free rotation mode: When E starts to rotate faster than B, it moves left and disengages from C.

d. Push mode: When E starts to rotate slower than B, it moves right and returns to push mode

Figure 10: The four stages of work of the active torque amplifier

The above principle description covers the one direction of action of the active torque amplifier (say counter clockwise). In order for the device to handle the rotation in both directions by means of the same principle, a number of additional simple parts are to be added to the device, but the principle of work remains the same.

A prototype of an active torque amplifier with amplification ratio of about 100 was constructed and successfully tested at the Mechanism Laboratory of Tel-Aviv University (Figure 11).

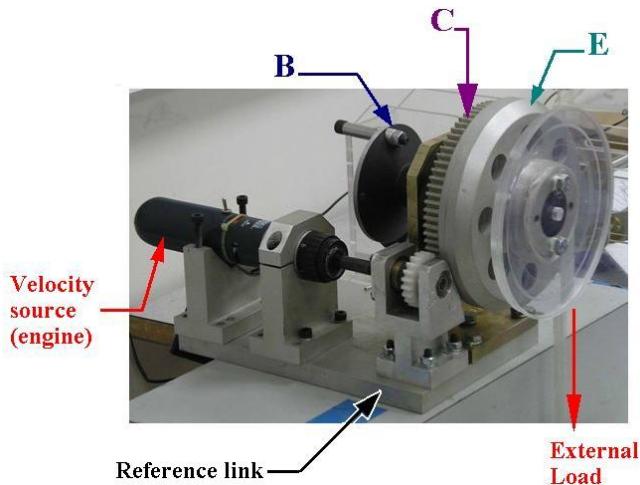


Figure 11: Active torque amplifier device constructed in the Mechanism Laboratory at Tel-Aviv University

4.2 Equivalent systems

This example expands on the previous one by showing that the process exemplified above can be replicated to diverse domains, leading each to new creative designs. Shown in Figure 12, is a simple known electrical rectifier circuit that is transformed into three different disciplines: a gear system, a hydraulic system, and a structure, to obtain the corresponding rectifying function.

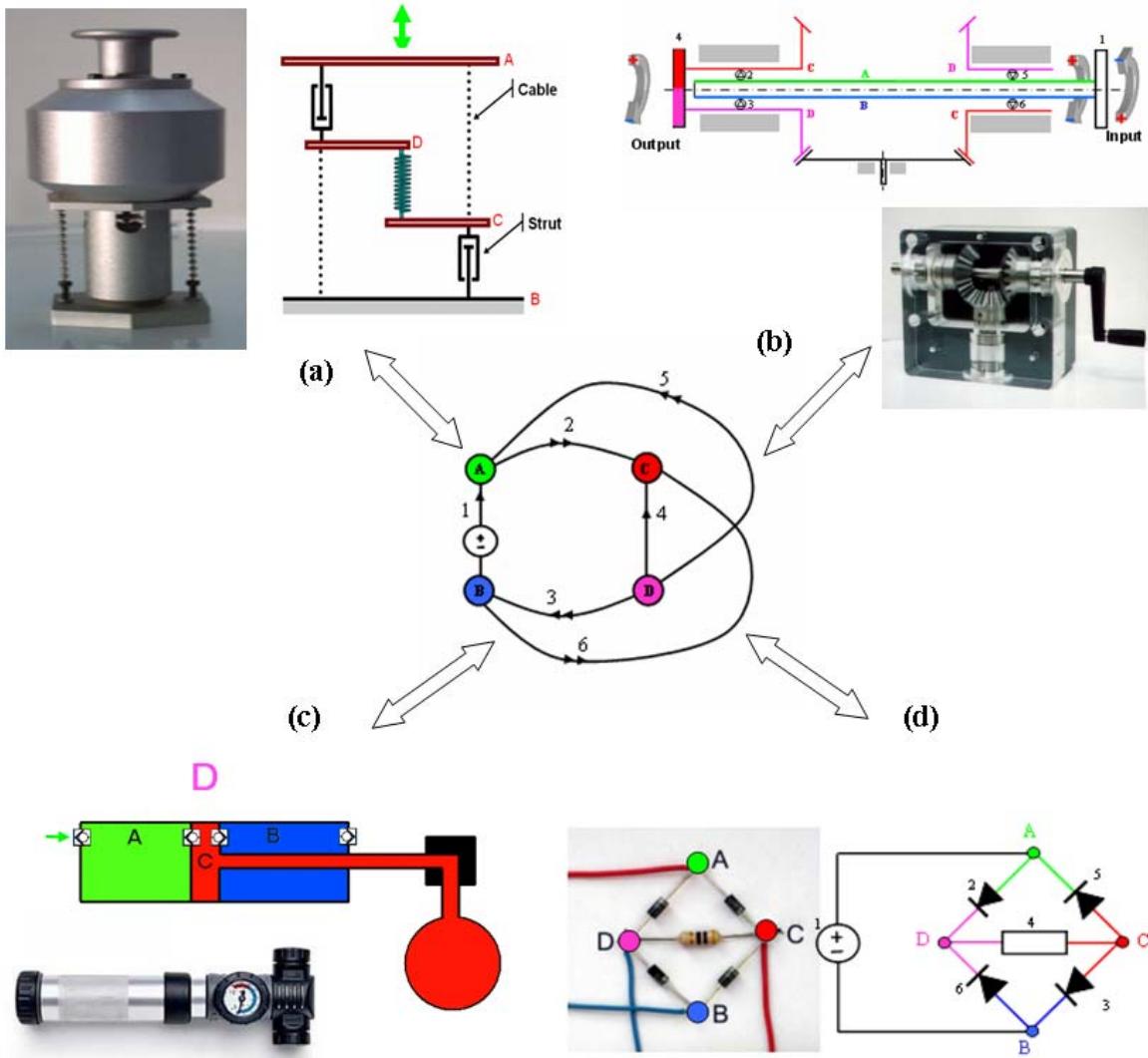


Figure 12: Equivalence between diverse disciplinary devices: (a) force rectification in statics, (b) unidirectional gear train in kinematics, (c) double action bicycle pump in pneumatics, (d) diode bridge in electronics

As in the previous example, ID provides precise equivalence and guarantees structural implementation through the common graph only by matching the desired function with available functions. It should be noticed that during the transformation process, the behavior is not being taken into consideration, and only at the end, after the new device is built, the behavior is tested and works as expected if the proper transformation was done.

Moreover, even faulty behavior is transformed. To clarify this issue, let us examine the behavior of the diode bridge and the unidirectional gear train when the input source is wrongfully connected, for example at the output. In the diode bridge, when the input source is located between junctions C and D and the positive potential is connected to D then nothing will happen in the circuit and zero voltage will be measured at the input (now output) port (junctions AB). But, connecting the negative potential to D will result in a short circuit. For the unidirectional gear train, one can easily verify that the output (link 4) could rotate clockwise without resistance while the driving link (link 1) remains still; while trying to rotate link 4 counterclockwise is not possible since the system is in a locked position.

Comparing any two systems appearing in Figure 12 will show correspondence between the behaviors both in correct and faulty modes.

4.3 Extending creativity: adding knowledge to devices and systems

This example shows that ID enables transforming not only devices, but also concepts, ideas, and methods thus yielding new methods and concepts in other engineering disciplines. The following example demonstrates the process of deriving a new concept in statics, termed – 'face force,' which was transformed from kinematics using the route described in the map (Figure 13). Presently, these derivations are done manually.

As appears in Figure 13, the representations that correspond to mechanisms in kinematics are PGR (Potential Graph Representations) while the representations corresponding to determinate trusses in statics are FGR (Flow Graph Representations) which are proved to be dual graphs, thus every linkage is dual to a determinate truss and vice versa. This equivalence between the systems yielded equivalence between the concepts in these two engineering domains. For instance, the relative linear velocity of a link was proved to be the counterpart of the force acting in the corresponding rod in the dual determinate truss. Applying this equivalence enabled to reveal a

previously unknown counterpart of the absolute linear velocity of a linkage joint in statics, which is a new type of force variable termed 'face force' (Shai, 2002). The face-forces act in each face of the static system and possess the properties of potential, similarly to a mesh current variable in electrical circuits. Figure 13(a) depicts a four bar linkage superimposed upon its dual truss. It is highlighted in the figure, that the absolute linear velocity of each revolute joint is identical to the face force acting in its corresponding face of the dual truss, shown in Figure 13(b).

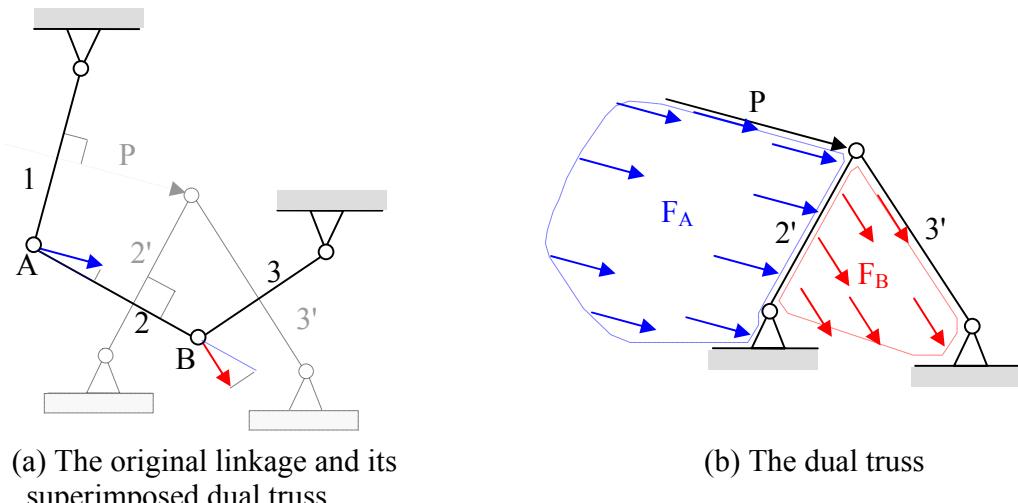


Figure 13: The kinematic system (linkage) and its dual static system (determinate truss)

4.4 Addressing downstream concerns: finding locking positions of linkages

This example demonstrates how the discovery of the face force allows the development of a tool that aids the design process. Knowing the locking positions in advance is essential for engineers for diverse applications, such as for toggle mechanisms (Sclater and Chironics, 2001), for deployable structures and for preventing entering to such positions when a continuous motion is needed. In application that locking is undesired, it could emerge after the detailed design or even production since it was not foreseen to occur. This situation would require product redesign.

The new concept – face force and its further developments – can help the designer avoid being in such situations.

The essence of a linkage being in a locking position is that the driving link cannot move, thus it exerts force, which produces internal forces in the links of the linkage. Therefore, the problem of finding the locking configurations becomes a problem of finding the configurations, where the forces in the links, produced by the driving link, can be found in static equilibrium. Since the face force possesses properties of both forces and potentials, it is possible to choose arbitrarily a face force for each face of the linkage so that they define a feasible configuration of the forces in the links. Since the forces in the links are vectors, the inclinations of the links can be determined from the force diagram.

Figure 14(a) shows the topology of a mechanism for which arbitrary face forces are assigned as shown in Figure 14(b), which in turn, define the directions of each link in the locking position. Analysis of this result, together with tools transformed also form statics, which due to length limitation of the paper are not described, enables the engineer to characterize the configuration in which the linkage will be in a locking position. In this case, as shown in Figure 14(c), the engineer can characterize that when the intersection points of the links (or their continuations): 2 and 4; 5 and 9; and 6 and 8 are collinear, then the linkage is in a locking position and there are internal forces in all the links.

It is important to notice that this characterization applies to any configuration of the linkage, i.e., lengths, angles etc. Furthermore, the design tools used in this example were derived through the transformations between statics and kinematics.

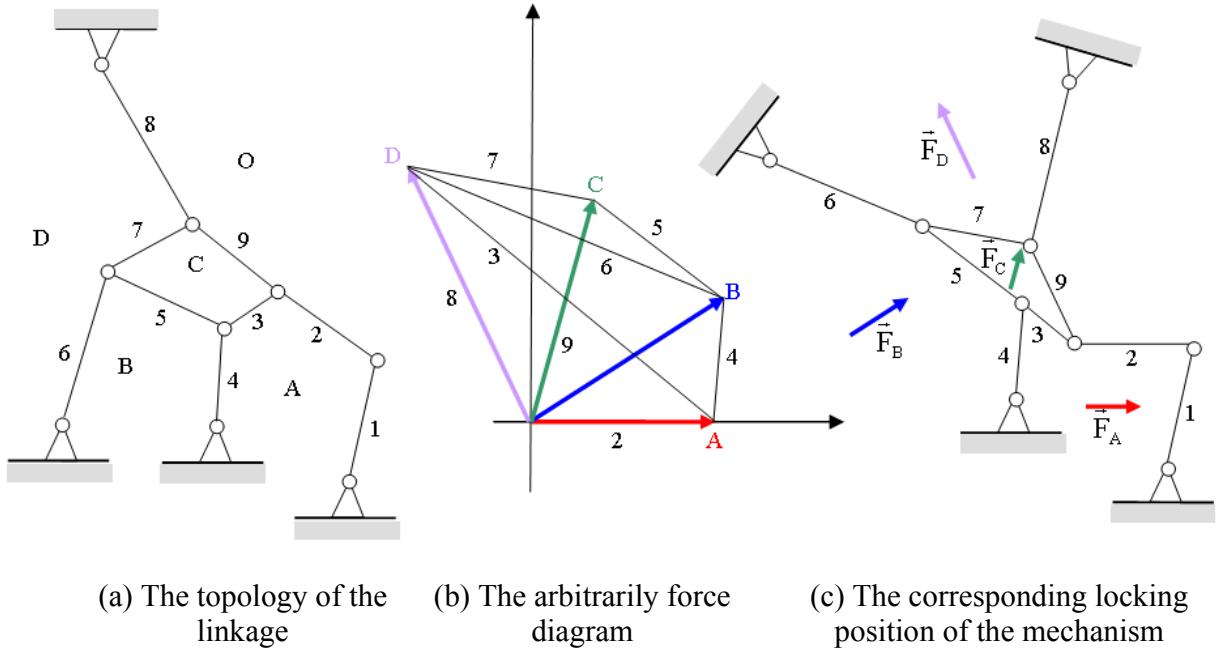


Figure 14: Example of finding the locking configuration through the face forces

5 DISCUSSION

5.1 Scope of infused design

ID (Shai and Reich, 2004a, b) leads to generating creative products by transforming products from one discipline to another. One of the advantages of ID or creativity is that during the transformation process, no analysis procedure is used, and the properties of new engineering systems are revealed only after the final step, when the device has been constructed from the graph. Furthermore, the mappings in ID are founded on discrete mathematics and are not heuristic. This means that transformations between representations could be automated. Another major difference between ID and analogy-based approaches is that ID does not rely on surface structural similarity but on various formal principles. It could map domains that are similar but also domains that are dual in the mathematical sense. This allows obtaining surprising results.

Altogether, as partially demonstrated, there are significant consequences to what could be done with ID compared to other methods.

The ID process presented here extends the previous by including also transformations between the formal representation of the concept and the representation of the physical embodiments (e.g., Step (6), Figure 4). In the case of the mechanical amplifier, the embodiment of the representation in physical material involved experimentation and creative thinking focused on how to implement a physical principle in the desired domain. We could foresee additional devices arising from additional creative embodiments presently unknown. The value of ID is in focusing designers on the truly creative steps while allowing for mechanizing the rest.

ID brings all knowledgeable engineers to be fruitful participants in any design project. Its foundation serves as a common language that is continuously extended with additional concepts (e.g., face force). Furthermore, the available designs and those that are continuously created with ID serve as ‘boundary objects’ that together with the new concepts expand and enhance communication channels between multidisciplinary professionals. There is nevertheless, a difference between the contributions of different engineers for different projects. For example, in designing the mechanical amplifier, the mechanical engineer has the central role. Steps (a), (b), and (d) are all part of the mechanical engineer contribution. In particular, step (d) can be completed solely by one that has significant mechanical design expertise.

It turns out that ID subdivides design activities into those that could be formalized and done automatically and those that embody significant creative design expertise (Figure 4). This subdivision allows creating a true collaboration between decision support systems for design and design professionals, where each perform the most suitable task. This issue is further discussed later.

Although not shown here, ID could be used to represent thus generate multidisciplinary devices (Shai and Rubin, 2003) and complex devices from simpler ones by connecting them and condensing the result (Gorodetsky, 2004). This allows addressing complex functionality requirements since for specific complex functionality; it is unlikely that equivalent devices would exist in other disciplines.

5.2 Integration with other methods

ID could be integrated with other design or even creativity methods whether they address device or system level perspectives. We illustrate several such integrations here. Among the illustrations, we select TRIZ and axiomatic design as they could be perceived as complementary methods (Lee and Ahn, 2006). Axiomatic design could be used to define and analyze multi functional systems but lacks synthesis assistance and TRIZ could be used to address few functions but it lacks system level perspective. ID could integrate with each and both and deliver added value.

TRIZ-like methods. ID and creativity methods such as TRIZ or ASIT are natural candidates for complementing each other. ID could get help from such methods in the following way. If no solution for a given problem exists in other disciplines that could be transformed by ID, there could be at least two solution paths. First, if by considering functionality, there is a similar but not equivalent device in one discipline, it could be transform to the desired domain and TRIZ could be used to improve it to the desired functionality. Second, if no similar device exists, a suitable device could be created using methods such as TRIZ. The effort spent on this process could be amortized by sharing the new concept with all other disciplines.

ID could also support TRIZ-like methods. If TRIZ is used to design multifunctional system, TRIZ would be best at assisting the design of few-function devices. ID could be used to integrate

simple devices (even if they are multidisciplinary) by combining their graph representations and condensing them.

Axiomatic design. ID could also be used with evaluative methods such as axiomatic design. For example, it is currently known from electrical engineering that there are only two conceptually dissimilar rectifying devices. If one is using axiomatic design to design a system and rectifying function is required, it could be realized by one of the available concepts. Multiple function systems requirements could also be matched directly with available solutions or synthesized from simpler devices and condensation. For example, it could be difficult to create an efficient device for two functions in one discipline. The complex device could be transformed into another discipline, condensed there, and the result transferred back to the original discipline (Dagani, 2004). Axiomatic design could guide the condensation toward minimizing information content while maintaining the independence of the functional requirements as much as possible.

System-level tools. Since ID can be used on devices or systems whose behavior could be formalized by graph representation, it could benefit from integration with general system-level synthesis tools such as SOS (Ziv Av and Reich, 2005). SOS uses existing building blocks to compose systems that address diverse customer and manufacturer's objectives. The building blocks could be devices or systems that perform desired functions. In case the overall product concept created by SOS is not satisfactory, focused search could be done to replace sub-optimal devices with better solutions derived by ID. More complex search for better building blocks could be done to replace multiple building blocks with better devices created by ID. Note that an integration of ID with TRIZ and axiomatic design could work as well with SOS in the same way.

Genetic-based approaches. A final example of integrating ID with device-level perspective comes from genetic programming approaches and simulated annealing that have been used to generate mechatronics and other devices from functional descriptions (e.g., Koza *et al.*, 2003).

These methods work by evolving representations of the designed product until its behavior approximately matches the desired function. ID can be used to model mechatronics and more complex multidisciplinary product concepts. Its integration with generative approaches could be used to generate devices from scratch (Pechter and Reich, 2003), thus providing means to enrich the base for other uses of ID.

5.3 Future work

In the future, we intend to develop a computational system that would support all the formal steps of ID, relieving designers to focus on the essence of the creative activities. In addition, once a solution is created in a particular discipline, its representation would be recorded with its engineering knowledge that is not expressed in the graph representations (e.g., manufacturability). When the hierarchy grows and more problems and solutions are introduced, it will be necessary to support this process with an information system. Case-based reasoning could be used to index and retrieve solutions (Reich and Shai, 2000); indexing might benefit from functional ontology at the level of systems (Kitamura and Mizoguchi, 2004). Altogether, a system such as *n*-dim (Reich *et al.*, 1999) is an excellent candidate for integrating all these support mechanisms. Note that although we might use such indexing mechanism which is heuristic, once a solution is found, it is transformed back into the original problem automatically as discussed above.

We intend to demonstrate the creative conceptual design of complex system level products that could include multidisciplinary components or subsystems. This demonstration would be based on the ability of the underlying representation to represent multidisciplinary systems (Shai and Rubin, 2003).

We further intend to explore integration with other design methods such as those described before. In doing so, it would become clearer what are the benefits and limitations of the various methods and how they could work better together.

The utility of ID is derived not only by its mechanisms but also by the disciplines that get connected by the graph representations (shown in Figure 2). We intend to continue and establish additional connections with other disciplines to leverage their collective knowledge.

5.4 The framework after introducing ID

Not only designers need to be creative, researchers developing creativity methods need to be creative as well. Therefore, it is important to continually, propose, develop, and test new methods that extend the scope of CCD. ID extends the scope of CCD in several ways (see also Figure 1).

In the actor aspect of the framework, ID displays several new properties. ID works well with a single designer who is familiar with the foundation of the method and working with a repository of past designs; it works better with a group of people from different disciplines where each is in charge of her disciplinary designs; and it could also work with several designers from each discipline providing different experiences regarding physical embodiments and other issues outside the scope of ID. The use of ID creates common language and invents new conceptual terms (e.g., face force) that could subsequently be used to enrich communication. Consequently, ID can be used and it supports diverse user compositions. ID has been used by designers without attention to cognitive style. We believe that traditionally “less creative” designers could still derive significant benefit by using ID.

In relation to the product context of the framework, ID makes also significant contribution. The most unique aspect of ID is the capability to transfer knowledge between disciplines. As demonstrated by the face force and the locking device examples, such transfer provides significant value to designers. This capability adds another dimension to the framework.

Otherwise, ID is quite independent of the problem structure and organizational processes and culture.

6 CONCLUSIONS

This paper has two main contributions. The first contribution presented a framework for organizing studies on CCD and reviewed representative studies that span this space. The result of this review is a list of research needs classified into several categories. This framework can serve to focus on many potential studies, for example, there could be many studies that check the interaction between any two dimensions.

The second contribution is the presentation of ID as a method for supporting CCD. The ID process was reviewed and revised compared to its previous presentations, including decision points along the process, and the parts that could be automated. Several significant examples were presented to show the value of the revised ID method and its future potential. We also presented ways in which ID could integrate with other tools. In doing so, we follow the aforementioned hypothesis that combining diversity of skills, styles, or knowledge could engender creativity. Similarly, the integration of diverse CCD tools, could lead to the emergence of new interesting capabilities. We concluded the discussion on ID with a list of future research issues.

Together, the framework and ID provide new ways at looking at CCD.

ACKNOWLEDGMENTS

Part of this research was supported by the Fleischman Research Grant. We thank the reviewers for their comments on the draft of this paper.

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Appendix

This appendix provides the main terminology related to graph representations, demonstrating how the ID process is computerizable and highlighting the ability to perform transformations between different engineering systems.

Definition: A Flow Graph Representation (FGR) is a directed graph G, where each edge is assigned a vector variable called flow. The flow variables are subject to the **Flow Law**, stated as follows:

Flow Law: The vector sum of the flows in every cutset of G is equal to zero.

The flow law may be recognized as a generalization of the well-known Kirchhoff's Current Law (KCL). Note that KCL is restricted only to one dimension which is appropriate for electrical circuits, while the flow law is multidimensional and can be used for two or three dimensions which are appropriate for trusses and other engineering systems.

FGR can be used as a mathematical model mapping the physical behavior of various types of engineering systems such as: electronic circuits, statical systems (trusses), hydraulic systems, etc.

For example, Figure 15(a) shows a truss with two rods and one external force P . Its FGR, shown in Figure 15(b), is constructed in a systematic way. A vertex is associated to each joint (vertex A to joint A and vertex O to the two supports) and an edge to a rod (marked 2 and 3 on the graph, corresponding to the rods). The unit vectors associated with the edges are also depicted in Figure 15(b). The unit vector \hat{i}_x corresponding to edge x is oriented in the same angle as rod x and is drawn beside its corresponding edge.

The third edge in the graph denotes the external force P . In this graph, the spanning tree (a tree containing all the vertices) is of size one, so edge 2 was chosen to be the spanning tree with a single branch and is denoted by a dashed line.

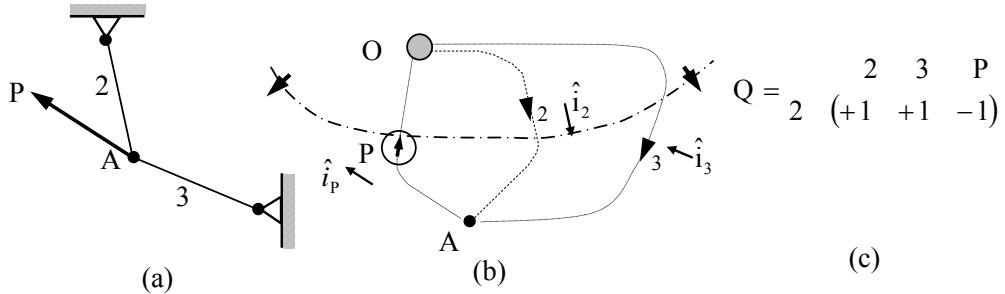


Figure 15: A truss and its corresponding FGR. a) The truss. b) The corresponding FGR in which edge 2 (the dashed line) was chosen to be the branch that defines the cutset. c) The corresponding cutset matrix of the graph.

Usually, the data structure used to represent this graph is the cutset matrix Q (Balabanian and Bickart, 1969). A cutset, defined by a branch, is a set of edges that partition the graph into two parts, one containing the tail vertex of that branch and the other its head vertex. In the cutset matrix Q , each row corresponds to a cutset defined by the corresponding branch. The matrix entry ij is +1 if edge ' j ' belongs to the cutset and with the same direction as the cutset (if its

tail/head vertex is in the same part of the graph as the tail/head vertex of branch 'i' defining the cutset), otherwise it is -1 . If edge 'j' is not included in the cutset, the entry is zero. The cutset matrix of the graph in Figure 15(b) appears in Figure 15(c). The matrix consists of one row related to branch 2 and the other two edges are included in that cutset. Thus, the entries corresponding to these edges are $+1$ (or -1), since the edges are in the same (or opposite) direction as the cutset, respectively.

With the cutset representation, the flow law can be written as:

$$\mathbf{Q} \cdot \vec{\mathbf{F}} = \mathbf{0}, \quad (1)$$

where $\vec{\mathbf{F}}$ is the vector of flows in the edges.

The second graph representation that we introduce in the appendix is the Potential Graph Representation (PGR), shown in the map of representations (Figure 2) to be dual to the FGR.

Definition: Potential Graph Representation is a directed graph G , where each vertex is assigned a vector variable called potential and each edge is assigned a vector variable called potential difference. The potential difference of an edge is equal to the potential of its head vertex minus the potential of its tail vertex. The potential variables are subject to the **Potential Law**, stated as follows:

Potential Law: For every circuit in the graph, the vector sum of the potential differences of the circuit edges of the circuit is equal to zero.

This law is a vectorial generalization to several dimensions of KVL (Kirchhoff's Voltage Law) which by itself is stated only for a one dimensional (scalar) system.

PGR can be used as a mathematical model mapping the physical behavior of various engineering systems, for which the potential law is sufficient for their analysis, such as: the kinematics of mechanisms, electronic circuits, and more.

Similar to FGR, PGR is constructed systematically. For a linkage, see Figure 16(a), the PGR is constructed algorithmically by associating a vertex to each joint and an edge for a link. If two vertices have the same potential at all times, they are contracted to one vertex, as shown in Figure 16(b). The information about the geometry is augmented to the graph by associating a unit vector to each edge indicating the direction of the relative linear velocity of the corresponding link. In the linkage appearing in Figure 16(a), a unit vector shown in Figure 16(b) is perpendicular to the link and is designated by $\hat{\pi}_x$ for a link 'x'.

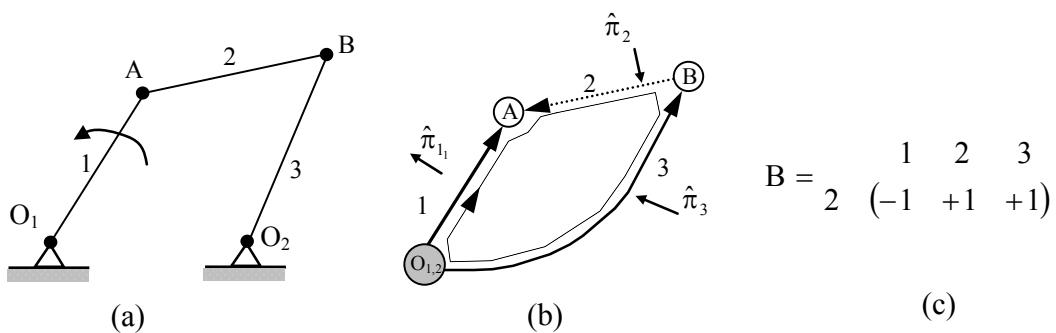


Figure 16: A linkage and its corresponding potential graph representation. a) The four-bar linkage. b) The corresponding PGR in which $\{OA, OB\}$ are the branched thus chord – AB defines a circuit for which the corresponding equation can be generated. c) The corresponding circuit matrix of the PGR.

Usually, the data structure used for this graph is the circuit matrix B (Balabanian and Bickart, 1969). The circuit matrix is constructed also by means of the spanning tree: the chords (any edge that is not included in the spanning tree) define the circuits, so that each circuit includes a single chord and a number of branches of the spanning tree. For example, the PGR (Figure 16(b)) of the linkage (Figure 16(a)) contains only one chord thus the circuit matrix contains only one row (Figure 16(c)). As the process of constructing the circuit matrix is similar to that of the cutset matrix explained above, it will not be introduced here in details. Moreover, due to a mathematical correlation there is a well known procedure enabling to deduce the circuit matrix from the cutset matrix for a given graph by using the following equation (Balabanian and Bickart, 1969):

$$B = (-Q_c^t \mid I), \quad (2)$$

where Q_c is the sub-matrix of the cutset matrix containing all the rows and those columns corresponding to the chords, and I is the unit matrix.

In the circuit matrix B , each row corresponds to a chord and the columns to the edges, thus the potential law can be reformulated as follows:

$$\mathbf{B} \cdot \vec{\Delta} = \vec{0} \quad (3)$$

where $\vec{\Delta}$ is the vector of potential differences.

The process of constructing the dual system through the graph representations

It has been mathematically proven (Shai 2002) that PGR and FGR are graph representations that are dual to one another. Section 3.1 indicated that when two graph representations are dual, it is possible to construct, in a systematic way, the dual engineering system that usually belongs to another engineering domain. Below we explain, through an example, the process of constructing the dual truss for a given linkage.

Step 1: Construct the graph representation of the given engineering system, in this case the PGR of the linkage. The PGR contains both the topological information in the form of the graph structure and the geometry information of the linkage in the form of the unit vectors perpendicular to the links and associated with the graph edges.

Step 2: Construct the dual graph by applying the following algorithm:

- a. For each face (a closed circuit without inner edges), associate a vertex in the dual graph.
- b. For each two adjacent faces, associate an edge between the two corresponding vertices in the dual graph.

Step 3: Transfer the geometry information from the PGR to the dual graph FGR by associating the unit vectors to each corresponding edge in the dual graph. The physical interpretation of the unit vectors is transferred from indication on the perpendicular direction to the link to the indication on the orientation of the corresponding dual rod in the truss. This step is performed by applying the following equality for all the edges of the graph: $\hat{\pi}_x = \hat{i}_x$

Step 4: The dual graph is proved to be FGR and since it possesses both the topology and the geometry, one may use it to construct the dual engineering system – the dual truss.

Figure 17 demonstrates the above process and shows how the linkage of Figure 16(a) (also Figure 17(a)) is transformed into its dual truss of Figure 15(a) (also Figure 17(f)).

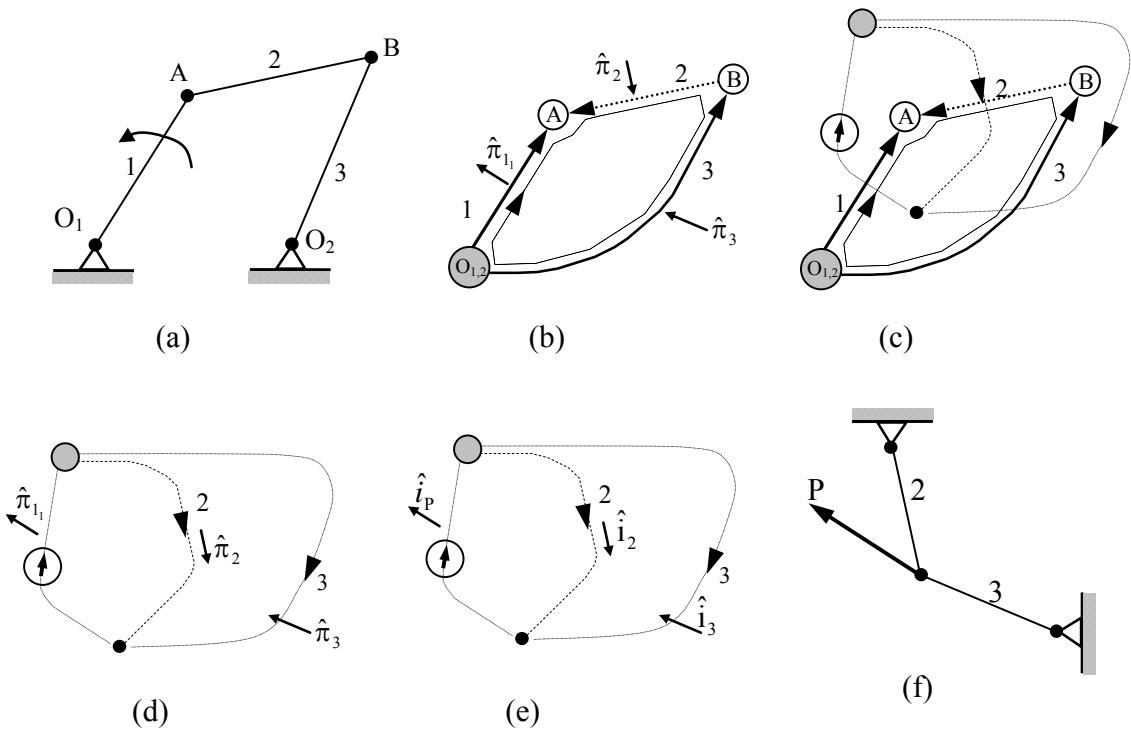


Figure 17: The process of constructing the dual truss from a given linkage.

a kinematical linkage, (b) A graph representation of the linkage without unit vectors (the topology of the PGR). (c) The topology part of the PGR and its dual graph superimposed. (d) The unit vectors of the PGR are associated to the corresponding edges in the dual graph. (e) Changing the physical interpretation of the unit vectors thus now the dual graph becomes FGR. (f) The dual truss corresponding to the FGR appearing in (e).