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COMPUTATIONAL SUPPORT OF SYNTHESIS AND ANALYSIS OF BEHAVIOUR OF ARTEFACTS USING PHYSICAL EFFECTS: SOME CHALLENGES

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1. Introduction

Many researchers stressed the importance of physical effects in the synthesis and analysis of artefacts. Murakoshi and Taura [1998] feel that synthesising artefacts directly from physical effects is hard since effects have been created and described by scientists primarily for explanation of phenomena rather than for synthesising artefacts that embody these phenomena – and synthesis using them requires more than straightforward application. Therefore, in the current form, effect representations are ill-equipped in aiding synthesis in a substantial way. However, a detailed study, of why this should be the case and to what extent we could support analysis and synthesis directly using physical effects, is yet to be carried out. In analysis, visualisation of qualitative state changes using a structural level of artefact description is possible using 'envisionment'[de Kleer and Brown, 1984; Forbus, 1984; Kuipers, 1986]. These, however, do not deal much with the functionality (or intended, higher level behaviour) of artefacts, which must also be part of analysis. Also, the description used in qualitative reasoning is far less detailed than that which an artefact description must be at in order to be implementable – a requirement of the design process. The goal of this work is to support behavioural analysis and synthesis of artefacts directly using physical effects.We ask two broad questions:

- Why is it hard to design or explain directly using physical effects?
- Given this, what can still be done in terms of supporting the above activities?

2. Research Methodology

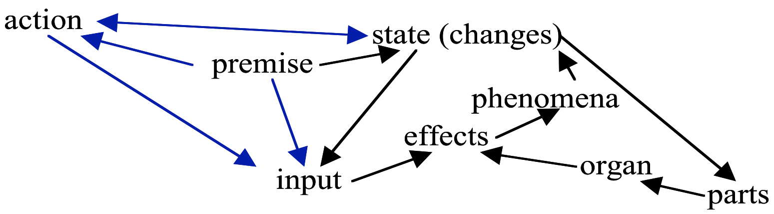
In order to investigate the first question, we use a current model for representing device functionality to explain known functionality of given artefacts, and identify if and when we run into difficulty and why (given function and structure of an artefact, we try to explain how the functionality is achieved using physical phenomena & effects). Given the above explanation, we ask if it is possible to start with the functionality and without the artefact description, and whether it is possible to identify or construct the artefact description, and then see if we run into difficulties and why (given the function of an artefact, we try to synthesise a description of the artefact so as to fulfil this functionality).

To investigate the second question, we ask which of the activities, with which we have difficulties in the process of linking function to form, could be at least partially supported, and how.

3. SAPPHIRE Model of Causality

Need fulfilment should be explicable by some theory for device causality. We use the SAPPHIRE model of device causality, see Figure 1 [Chakrabarti et al., 2005] as such an explanation model. The goal of designing is to fulfil a need by a technical system that can be made. This indicates two delimiting levels of its description: a need description and an implementation description. Need can be described in several ways, such as an action description, e.g., ‘store information’ or ‘apply force’ [e.g., in Umeda et al, 1996]. Another, often more well defined description is using input/output of a system [e.g., in Pahl & Beitz, 1996]. Another description is using state changes [e.g., Hubka & Eder, 1988]. Often the need would be described first using actions, and then interpreted into the others by making some assumptions or premises. For instance, in a recent innovation attempt, a micro memory device facilitates storage of information by forming a dent in a silicon-based material. Here the presence or absence of the dent signifies presence or absence of memory. Having made explicit this premise that ‘presence/absence of a dent is taken as presence/absence of information’, changing the state of a location within the object from one of not having a dent to one of having a dent could be taken as a derived description of its functionality. A state change is achieved by means of various phenomena (physical processes) that are brought into being by physical effects. A physical effect requires some conditions for it to work (described by Taura as ‘constraints’). Some of these are inputs (and therefore provided by previous state changes within or around the system) and the rest are what we call organs. Organs are the physical contexts needed for the effect to be activated.

Figure 1 SAPPHIRE Model of Causality



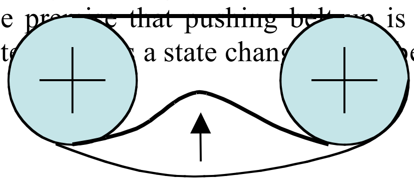
For instance, causing the dent requires deformation of the object and could be achieved by Stress-Strain effect, activated by providing stress at the location. Providing stress would require providing force to the object (input) and constraining the object so that it cannot move (organ). This constraint has to be physically embodied – in terms of components, to a level at which the system is implementable – we call these parts and relationships. These constructs together form the SAPPHIRE model of causality, in which parts create organs which with right inputs activate effects which activate phenomena which create state changes which with the right premises are interpreted as actions or inputs or other state changes. ‘S’ stands for State-change, A for Action, P for Parts, P for Premise, H for pHenomena, I for Input, R for oRgan, and E for Effects.

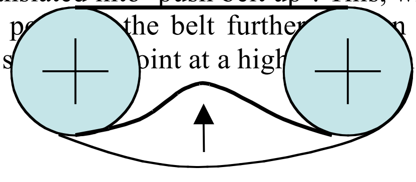
4. Why is it hard to design or explain directly using physical effects?

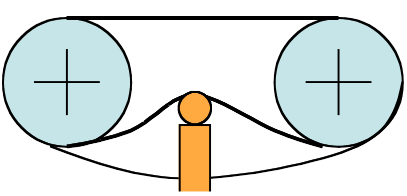
We take two example sets to ask this question. The first contains belt tensioner designs, whose primary function is to tighten the belt of a belt-pulley system (Sections 4.1-4.2). The second set contains handle designs for a carrier bag (Sections 4.3-4.4). The Questions we ask are: how can we explain how these artefacts work to fulfil their function, and how could we analyse/synthesise these?

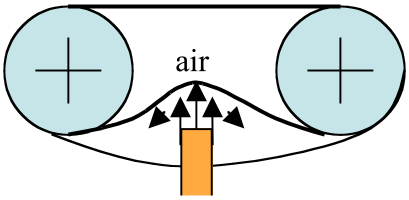
4.1. Belt Tensioner Example: A Roller-Spring Belt Tensioner

The high level function or need of a belt tensioner is to increase the efficiency of motion transfer between belt and pulley. With the understanding that motion transmission between belt and pulley is due to friction between them, and more friction means less slip (premise), one could ‘translate’ this into a required action ‘prevent slip’ between belt and pulley. Assuming that high tension in belt would increase friction (premise), this action ‘prevent slip’ could be translated into ‘increase tension’ on belt. Further, assuming that tension can be increased by pushing belt up so that its length is increased thereby stressing the belt (premise), the above action could be translated into ‘push belt up’. This, with the premise that pushing belt up is changing location of some p the belt further n be int a state chan belt point at some location to s oint at a high ’.









2a Roller-Spring belt tensioner **2b Air-Jet Belt Tensioner**

Figure 2 Belt tensioners

This state change could be achieved by the phenomenon ‘upward movement of belt’ – which is a special case of Newtonian motion. Therefore, Newton’s laws (effect) can be applied to make the movement possible. Newton’s laws of motion require a force input in the direction of movement, in this case upward, and inertia of the particle, in this case the belt. Note that belt already has the inertia, but upward force is not available in the current state, and must be provided. This can be described by a state change: ‘no upward force on belt at a location to upward force on belt at that location’. This can be achieved by the phenomenon of ‘force transfer’ and in many ways, including using a solid rod with a roller to provide the force to the belt, Figure 2a. This would require providing a force to the roller and constraining the roller to have no freedom of movement upwards against the belt. However, it is not clear what the effect exactly is behind force transfer. It is probably the fact that two objects cannot be at the same place at the same time, and the above condition ensures that this is exactly what is attempted when a force is applied on the other solid object (the tensioner). This upward force can be provided by a spring that is already in a deformed state, and it will work using Hooke’s law – when deformed, the spring (with stiffness – an organ – achieved by the one end of the spring fixed to the ground and the other to the tensioner – the parts) provides force of resistance. The roller tensioner has the advantage that its energy dissipation due to friction is small due to the use of rolling friction.

Note that several difficulties might be faced in forming this explanation, particularly computationally: First, ‘translating’ high level descriptions of purpose to lower level descriptions (e.g., ‘prevent slip’ to ‘push belt up’) requires making assumptions about the translation that are non-unique and informal. This cannot be done by the computer in an automated sense, as the description compresses a detailed explanation into a hint – for human consumption – which expanded in a logical way would be tedious.

Second, sometimes humans hint at many related effects occurring as a result of the mentioned main effect, and assume that mentioning the main effect would suffice for them all. For instance, changing location of belt - we described - could be achieved by Newton’s laws of motion. However, given a force applied on the belt, all it ensures is that it would have an acceleration. This acceleration must operate over a finite period of time to change the velocity of the belt, and this must operate over time to change the location. In translating change of state, not all states are clearly or explicitly mentioned, and the state changes may need multiple phenomena or effects to be achieved.

Third, often the effects have to be made specific to the situation at hand. For instance, the belt movement in this case is upward which brings specific constraints and inputs necessary and is a special case of Newton’s laws of motion. Generalisation or specialisation of effects in order to apply them is part of the process of explaining or synthesising behaviour using physical effects. Fourth, sometimes it is unclear what the effects behind phenomena are. In such cases identifying conditions to invoke the phenomena becomes difficult, and is hard to handle computationally.

Fifth, alternative causal forms of the same effect may exist, and often specific ones must be used to invoke the phenomena desired, e.g., Hooke’s law relates stress to strain or force to deformation, and can be interpreted in several ways. From the conditions of stress (and an object with young’s modulus) or force (and stiffness), consequences of strain or deformation respectively can be obtained.

Sixth, there could be many means of providing a condition, e.g., stiffness could be provided by a plate, a beam, a stack of thin sheets of metal, a coiled wire, in simply supported, cantilever or other constraints, so as to transmit forces of various forms (torsion, compression, bending etc), could be used. This forms a many-to-many mapping between conditions and artefact description.

Finally, ‘deriving’ the spring-roller artefact from the conditions of rolling friction, or even its ‘common’ embodiments, is hard as the mapping is non-unique and indirect. The typical situation describing rolling friction is a wheel rolling and moving forward on a static ground. In the current embodiment ground moves forward and the wheel rolls without moving as a whole. This is a complex transformation of the typical case that must be made in order to get to the current artefact description.

4.2. Belt Tensioner Example: An Air-Jet Belt Tensioner

The roller-spring belt tensioner has a drawback: vibration. The forces between the belt and the tensioner vary with time, and when there is a difference in forces provided to the pulley (or belt) and that resisting it, this acts like an unbalanced force on a spring-mass system (the tensioner/belt has a mass and a stiffness), and vibration phenomenon takes place. The ways of reducing vibration are to reduce variability of force, or eliminate force, mass or the spring. Mass could be eliminated by using a magnetic device to provide the force, or by a jet of air along the surface of the belt to create lift leading to tensioning, or by eliminating force transfer between the two systems. However, force transfer from pulley to belt is required for tensioning, although eliminating force transfer from belt to tensioner could be considered, thereby eliminating vibration of the tensioner. The air-jet tensioner (see Figure 2b) achieves this by hitting the belt with an air-jet to transfer momentum to the belt, and since rate of change of momentum is force, this provides force to ‘push belt up’. By Newton’s third law pf motion, the air that transfers its momentum gets the same force back from the belt, but the incoming air from the tensioner ensures that this force is not transferred to the tensioner. Since air has much lower friction than solids, this also substantially reduces friction between belt and tensioner.

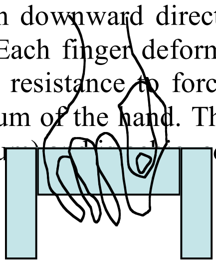
Providing explanation or synthesising this system has the following difficulties:

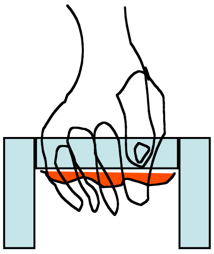
The first difficulty is that eliminating force is a very unintuitive concept since tensioner is designed to provide force, and hence seeing that at least the force from belt to tensioner could be eliminated is very hard since in the spring-roller design (solid to solid contact) Action-Reaction law ensures that providing force to belt is equivalent to providing force to tensioner also.

Modelling how this air-jet system works is difficult, since there are several phenomena involved (how air jet transfers force, how air jet gets force back, and how it moves away from the tensioner), where each requires different conditions to be applied. For instance, explaining how air jet transfers force to belt requires viewing air as an ensemble of particles or a continuum, and applying momentum conservation effect. Understanding how force is transferred requires viewing that the overall force as a sum of the individual momentum changes imparted. Understanding how the jet moves away from tensioner (and belt) requires viewing both the incoming jet and deflected jet as an ensemble of particles, and then thinking about the interaction of a particle from each jet. Choosing the right viewpoint is a difficult task even for humans.

4.3. Carrier Bag Handle Design: Rigid Handle

The primary function of a carrier bag handle is to enable the hand to hold the weight of the bag in a comfortable way. We take the premise that holding is attaining a state at which an object previously not held is now held, and the state of being held is one in which the object under the applied force (weight carried) is not allowed to move. This could be achieved by the phenomenon of force equilibrium, in which the balance of force applied to the handle is zero. This is a particular form of the Newton’s laws of motion in which motion state is the same as before. In this case, one of the forces applied is the weight, and the other is by the hand, and the two must cancel each other. Force from the bag is transferred to the handle (see Figure 3a) using stiffness of the handle (as a beam with high stiffness using Hooke’s law – the force-deformation version, and Spring phenomenon, and the resulting low deformation that can be explained using Hooke’s law – the stress-strain relationship). Since the hand (and fingers) is under the handle, there is no degree of freedom between handle and fingers in downward direction, and since weight is applied in that direction, it is transferred to the fingers. Each finger deforms under the bit of the force it experiences (Hooke’s law again), and as a result its resistance to force increases, eventually becoming equal to the force applied – leading to equilibrium of the hand. This force is reacted back to the handle with equal magnitude (leading to its equilibriu[illegible]d by the Newton’s third law of action and reaction.





3a Rigid Handle for a Carrier Bag **3b Bag with Fluid Filled Handle**

Figure 3 Rigid Handle for a Carrier Bag

One issue with this design is that since the handle shape is rigid, its own deformation is little, while the hand shape in contact with handle - which is dissimilar to the handle shape and is softer – deforms substantially and non-uniformly, eventually to conform to the shape of the handle. This may lead to some portions of the hand to deform well beyond a stress that is comfortable (note that the effect underlying this phenomenon is unclear). The difficulties in forming this design or explanation are:

The first is clarifying what discomfort means. This is difficult since one is not sure what effects the phenomenon of discomfort is based on, and how to identify the conditions under which it may apply.

A particular difficulty in identifying the conditions for discomfort is that one must take a 'micro' view of each finger as the situation rather than the 'macro' view of the whole hand or handle in order to appreciate what is going on. Yet another difficulty is that the same change can be described using different forms of the phenomena involved. For instance, the change of 'movement to no movement' could be described by Newton's laws of motion, or the phenomenon of equilibrium.

4.4. Carrier Bag Handle Design: Flexible, Fluid-filled Handle

In order to remove the drawback, we can envisage a change that leads to the two shapes (hand and handle) to be the same and supply uniform pressure to the hand. One possible way of achieving this is to have a rigid handle with a shape conforming to that of the hand. One issue with this is that when this shape comes in contact with the hand it still deforms it (although less than a less conforming shape) non-uniformly (since deformed shape of the hand under uniform stress depends on the magnitude of the force resisted and specific initial configuration of the hand which vary from one load or hand to another) leading to some level of discomfort, since stress generated is non-uniform and may exceed comfort limit. A further solution to this could be to have the shape having a little more flexible material with conforming shape of the hand, so that when pressed it could deform a little to accommodate the change in shape of the hand without providing too much force to the hand.

Yet another design could be a fluid filled flexible handle, the connection being made through pressure or stress (in the function) and Pascal's Law of constant pressure in fluid (in physical effect) to its conditions – confined fluid. However, even this suffers from a drawback. When force is applied on the handle (by the hand), and it is supported at the interface between handle and bag, the handle is like a beam with distributed force in its middle, leading to deformation of the whole beam – aka handle – away from the hand. At the local level of interaction between handle and hand, some deformation could occur between the hand and the handle. The overall deformation of the handle is the sum of these two deformations. For many parts the deformation away from the hand is greater than the local deformation, leading to portions of the handle losing contact with the handle, while other portions leding large deformation to the hand (beyond comfort limit) – leading to similar drawback as before.

Yet another proposal is one that prevents the deformation of the beam as a whole, for instance by providing a beam of high stiffness (leading to low deformation as a result of force applied) and providing the flexible fluid-filled material at the interface region between hand and handle – retaining the local deformation that leads to a deformed shape of the handle with uniform pressure. This can be achieved in many ways: using a bagful of balls, powder, air or a liquid – any composition (artefact description) that can provide deformation to the bag with uniform pressure resistance (organ).

A major difficulty in forming the above designs or explanations is how to model the effect of applying load on the various designs, especially how they interact with the hand. Note that modelling requires identifying conditions and consequences of the hand-handle interaction at a detailed and microscopic level. Particularly difficult is modelling of the second potential solution: flexible, fluid filled handle, which requires reconciling changes from phenomena at both macro and micro levels to derive the overall change in deformation. Note that it is possible to come across various phenomena the basis (effects) of which may unclear. Premises are often made to wade through these (such as the discomfort phenomenon). Another difficulty is the transition between variables or parameters of importance: for discomfort stress is the parameter, but here pressure applied is equivalent to stress.

5. Summary of Difficulties

In order to discuss the difficulties in analysis and synthesis of artefacts from physical effects, we have placed the essentials of an effect or phenomenon against the essential aspects of function and form in an artefact. Any artefact has at least two levels of functional description: one within its environment and the other outside. The first is termed here as changes required, and the second, the need or high level function, those that are indirectly attended to by means of the changes required. An effect or phenomenon has at least three components: *conditions* needed to activate the effect/phenomenon, the *effect/phenomenon*, and the *consequences* of the effect/phenomenon – the changes it provides. Since the changes desired are to be provided by the changes possible by the phenomena and their conditions must be embodied in the artefact, there are four possible transitions: high level function to necessary changes (Transition 1), changes necessary to phenomena/effects that provide the changes (Transition 2), phenomena/effects to conditions for their activation (Transition 3), conditions to their embodying artefact description (Transition 4). The difficulties, identifed in the examples, are as follows.

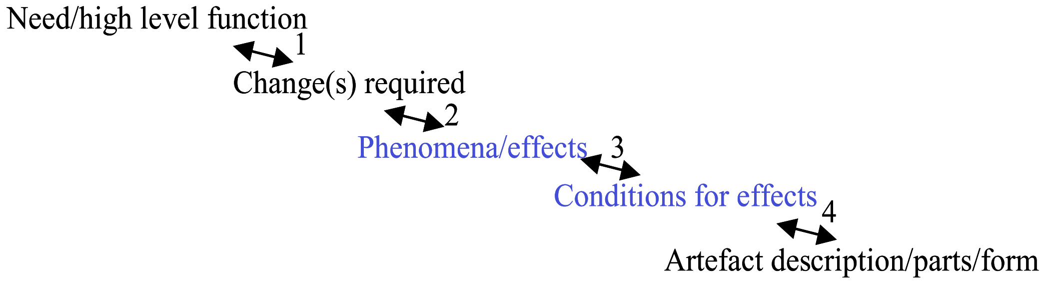


Figure 4 Various Transitions Within From Function to Form

5.1. Transition 1: Function to change required

There is often a difference in the levels of abstraction of high level functions and changes required, and there is a many to many mapping between high level function and changes (ie, the same function can be satisfied by different changes, and same change may satisfy different functions). Therefore, without making premises (the modelling of which is highly complicated as they contain incomplete knowledge and pointers to knowledge that humans are assumed to possess) the mapping cannot be uniquely specified. Similar idea is echoed in Umeda et al. [1996], where they take function as a subjective choice of state change. Also, many change-alternatives are possible for a given function (e.g., 'prevent slip' by 'increase belt-tension', or 'increase friction-coefficient between belt-pulley').

5.2. Transition 2: Change to Phenomena/Effects

A many-to-many mapping exists between phenomena/effects and changes required. This is partly due to multiple phenomena possible using the same effect, and resulting multiple changes since the same effect can have multiple causal forms (eg, Hooke's law as providing motion resistance, or energy storage or deformation). Murakoshi and Taura [1998] have spoken about some of these mappings. Moreover, a change may be effected by an aggregation of phenomena/effects, e.g., addition of global and local deformations to provide the change in a fluid-filled handle. Note that often a designer has knowledge of devices only, and the underlying phenomena or effects are unclear; conversely, sometimes knowledge is available of phenomena and not effects (e.g., the effect behind the phenomenon of force transfer is unclear). This may prevent reasoning from being carried out from effects, or could make conditions hard to identify computationally. Also, it may be inefficient to explain/design for a change directly using effects if this is possible using device level information. There is a trade-off between novelty achieved and process efficiency: using effects increases novelty but at the cost of efficiency, and it is vice versa for device level reasoning. That there may be several alternative phenomena/effects to effect a change (e.g., push belt by a roller, air jet, aerofoil lift, or magnetic attraction) is good and could be utilised in enhancing synthesis.

Sometimes different parameters may have to be 'equated' in order to make the connection between a change and an effect (e.g., stress for discomfort and pressure for Pascal's law); at others, connection would involve apparently non-logical steps (e.g., eliminating force from belt to tensioner is non-intuitive as it seems equivalent to eliminating force from tensioner to belt if Newton's third law is applied without thinking deeper). Often special or generalised cases [see Murakoshi & Taura, 1998] or forms of phenomena have to be used (e.g., upward belt movement as a special case of movement).

A given phenomenon may involve aggregation of multiple effects (e.g., energy dissipation by friction as a phenomenon would require laws of friction combined with thermodynamical laws. Another difficulty is the existence of multiple viewpoints for the same phenomenon/effect. A typical, known viewpoint may be inappropriate in the current situation, e.g., air-jet force transfer to the belt may be easier to explain with an Eulerian view, and force non-transfer to tensioner with the Lagrangian view.

5.3. Transition 3: Phenomena/Effects to Effect-Conditions

Conditions for an effect/phenomena may often be non-unique. For instance, conditions for Newtonian laws of motion may be the presence of an unbalanced force and a particle with inertia on which this force operates, or a force in a given direction on a particle having inertia with a degree of freedom in than direction. There may be different views of the same situation (e.g., zoom in/out views as in whole hand versus fingers, or the soft part of fingers) leading to different sets of conditions. Sometimes there is no formal definition of a condition; (e.g., conditions that create discomfort under tactile pressure). This is especially true when some phenomena are known in an experiential sense but the underlying effects are unknown, leading to conditions being only vaguely known (e.g., if we keep on increasing pressure it will eventually cause discomfort; but the underlying effect is unknown).

5.4. Transition 4: Conditions to Artefact Description

There is a potential many-to-many mapping between conditions and artefact description. Sometimes a structural description representing a condition for a given effect might have to be substantially modified in order to represent the same condition for the same effect in providing a different change (e.g., rolling friction in car requiring the roller to rotate and move while road remains static, while in belt and tensioner for the roller to rotate and remain static as a whole while for the belt to translate).

6. Discussion and summary

The report summarises a study of several artefacts to identify the difficulties associated with their synthesis and analysis directly using physical phenomena/effects and what could be done to support a designer in synthesis and analysis of these artefacts. The study highlights some major reasons as to why analysis/synthesis using physical phenomena of effects is difficult, and in some cases impossible.

Given the above difficulties, to what extent can we support synthesis and analysis for designers? Probable routes are the following. Supporting synthesis requires that given the required functions, designers are supported to construct structural descriptions of artefacts that could fulfil the function. The transition from function to change required, is a many-to-many mapping, and requires making assumptions or premises that are too difficult or too inefficient to model in detail. This transition is therefore better left to designers to handle. The transition from change to phenomena or effects could be supported by a database of physical effects and phenomena that have links to the changes they could cause. Even though they would not be able to carry out the task for a designer, a designer could be given hints of what potential effects could be relevant for a given change, e.g., ‘provide force’ by magetic attraction, spring-force, aero-foil, air-jet, liquid-jet, etc. The step from effects to conditions could be aided by providing in the database of phenomena and effects explicit conditions that must be present for the phenomena or effects to work. The step from conditions to artefact description could be supported by linking several specific artefact options to the generic conditions of the effects.

Supporting analysis requires that, given an artefact description and its functions, designers are aided in linking the artefact behaviour to its functions. This, however, is too complex a task to be handled by computers alone, as it is often difficult even for the designers. Supporting this could, however, be done by linking the change necessary for the intended functions to all alternative phenomena and effects to which they could be linked (e.g., linking force to all force-related phenomena), so that given a specified function, potential phenomena could be suggested to the designer and the designer left with the task of checking if any of these are likely to occur in the given situation.

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