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SAPPHIRE – AN APPROACH TO ANALYSIS AND SYNTHESIS

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ABSTRACT
The SAPPhIRE model uses constructs: **S**tate change, **A**ction, **P**art, **Ph**enomenon, **I**nput, o**R**gan and **E**ffect, to explain the causality of natural and engineered systems. The model has not been well understood and not tested for its capabilities to support analysis and synthesis. In this paper, we clarify the constructs of the model for a better understanding and demonstrate the capabilities of the model to support analysis and synthesis using examples. Results indicate that the model can be used to support analysis and synthesis. Other capabilities of the model are also demonstrated through the examples.

Keywords: Analysis, Synthesis, Physical laws, Physical effects, SAPPhIRE

1 INTRODUCTION
Analysis is a process of reasoning an artefact's behaviour from its given structure, deriving functionality from the behaviour and checking whether the derived functionality matches with the given, expected functionality. Synthesis is a process of deriving an artefact's behaviour from a given functionality and deriving a structure from the behaviour. In [1], both analysis and synthesis are observed to be present in designing, verified using protocol studies of designing sessions.
Physical laws and effects are principles of nature that govern a change [2] and are important in designing because they are one of the sources of innovation [3]. However, laws and effects are not used adequately in designing, (see Section 2.2 for more details). A model of causality – SAPPhIRE, is proposed in [2] that includes constructs - laws and effects. Therefore, it becomes important in the current context to encourage designers to use the SAPPhIRE model.
This paper is structured as follows: Section 1 gave an introduction, Section 2 reports important findings from literature, Section 3 briefs the research approach, Section 4 reports results and Section 5 concludes the paper.

2 LITERATURE SURVEY
The following sections report salient findings from literature:

2.1 Conceptual Design
Conceptual design is a phase of designing where principle solution(s) are developed. [4]. A lasting and successful solution (artefact) is more likely to come from the choice of the most appropriate principles, than from exaggerated concentration on technical details [4].

2.2 Physical Laws and Effects
Physical laws and effects are principles of nature that govern a change [2]. Natural laws comprise physical laws, effects and chemical processes, and these are representation of natural phenomena [3]. As a result, artefacts that embody natural phenomena also embody the natural laws. This is important because no technical system (artefact) can function contrary to the physical laws [5]. Natural laws are important for supporting the invention and development of artefacts because they help determine how the designer could add new constraints to the solution [3] and designing at the level of physical laws prevents a designer's fixation on adaptations of the existing solutions or composition of solutions from the existing components [5]. Physical laws and effects also support creativity and innovation [3, 5, 6]. Synthesizing 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 [3]. Therefore, in the current form, effect representations are ill-equipped in aiding synthesis in a substantial way. This inadequate representation has resulted in their insufficient usage while designing. This inadequacy has been verified empirically using protocol studies of designing sessions in [1] and [7], using novice and experienced designers.

2.3 SAPPhIRE Model of Causality

The SAPPhIRE model of causality includes constructs: **S**tate change, **A**ction, **P**art, **Ph**enomenon, **I**nput, o**R**gan and **E**ffect. The name SAPPhIRE is derived from the highlighted letters of the constructs. The term 'Effect' accounts for both, law and effect. The constructs are identified from different approaches in the literature: Function-Behaviour-State [8], Theory of Technical Systems [9], Domain Theory [10] and Metamodel [11]. The model, when put together in the form shown in Fig. 1, provides a rich description of functionality and behaviour of natural and engineered systems.

According to [2], a description of functionality can take different forms: an action description (e.g., cool body, move body, generate current, etc.), input-output of a system (e.g., temperature difference as input to heat transfer as output, acceleration as input to displacement as output, potential difference as input to current as output, etc.) and state changes (e.g., change in temperature, change in spatial location, change in current, etc). The SAPPhIRE model can describe functionality using its constructs action, state change and input together. The ability of the model to take functionality in its different forms and causally link them together provides a greater richness in the description of functionality. Physical phenomena and effects together are rarely supported by a single approach in the literature. The use of these constructs together and their links with functionality provides a richer description of behaviour.

The constructs of the model are found to be present in the natural ways of designing (i.e., when designers are not told to explicitly follow the model), as observed from protocol studies of various designing sessions [1].

The constructs of the model have been previously defined in [2] as follows:

- Parts: A set of physical components and interfaces constituting the system and its environment of interaction.
- State: The attributes and values of attributes that define the properties of a given system at a given instant of time during its operation.
- Organ: The structural context necessary for a physical effect to be activated.
- Physical effect: The law of nature governing a change.
- Input: The energy, information or material requirements for a physical effect to be activated; interpretation of energy/material parameters of a change of state in the context of an organ.
- Physical phenomenon: A set of potential changes associated with a given physical effect for a given organ and inputs.
- Action: An abstract description or high level interpretation of a change of state, a changed state, or creation of an input.

Experience of using SAPPhIRE model by other researchers and designers suggests that there are difficulties in understanding the model. These difficulties maybe related to the definition of the constructs. The constructs require further clarification with respect to the following:

In the definition of parts: (i) What is a system? (ii) What is an environment? (iii) What is an interaction between a system and its environment? (iv) Why does a system and its environment interact?

In the definition of state: (i) What is an attribute? (ii) What is a property? (iii) Are they different? (iv) What is an operation of a system?

In the definition of organs: (i) Why is it defined on the basis of an effect? (ii) If this were to be defined on the basis of an effect, why is it defined before the definition of an effect? (iii) What is a structural context?

In the definition of an effect: (i) What is a change? (ii) What is nature? (iii) Where is this change happening? (iv) Why is this change essential?

In the definition of an input: (i) What are energy, material, and information requirements?

In the definition of phenomenon: (i) Why is it defined on the basis of effect, organ and inputs? (ii) What is a potential change? (iii) What is a change? (iv) Where is this change happening?

In the definition of action: (i) Why is it defined on the basis of a state, state change or input?

From the above issues we find that constructs are defined on the basis of other constructs or terms which are not defined earlier. This could be because the authors while constructing the original definition interpreted the involved terms to be standard ones that would be understood by all. However this is not the case in our experience. These issues may hinder an understanding of the constructs of the model and present difficulties in the usage of the model.

The model is explained as follows [2] (Fig. 1): parts create organs, which with the right input activate an effect; the effect creates a phenomenon, which creates a change of state; the state change with the right premises can be interpreted as an action or input or other state change. The model so far has only been used to explain the causality of natural and engineered systems, i.e., as a model of analysis and has not been explored in detail.

If we consider synthesis to be a reverse of analysis, then a (rearranged) model of analysis should also serve as a model of synthesis. This also has not been tested and explored with the SAPPhIRE model.

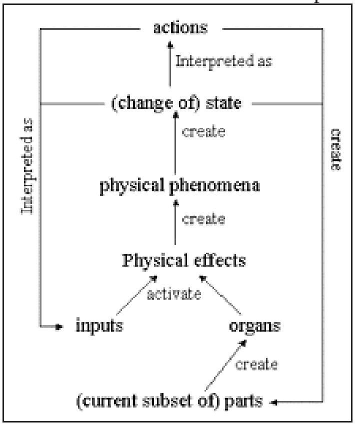

Figure 1. SAPPhIRE model of causality

2.4 Summary & Objectives

From the above sections (2.1-2.3) we observe that:

(a) Conceptual designing is an important stage in designing.

(b) Physical laws and effects are important in designing and can be used during the conceptual stage but currently are not adequately used.

(c) SAPPhIRE model of causality uses laws and effects but has not been explored in detail for analysis and synthesis.

(d) The lack of clarity in the current definition of the constructs of the model may hinder the understanding of the model.

Hence, the objectives of this paper are as follows:

(i) To clarify the constructs of the SAPPhIRE model.

(ii) To explore the model's capabilities in supporting analysis and synthesis.

3 RESEARCH APPROACH

The following research approach is adopted to tackle the objectives:

(1) To address the first objective, we refine the definition of the constructs of the SAPPhIRE model based on well-defined terms.

(2) To address the second objective we use the model to check if we can: (a) analyse four existing systems, and (b) (pseudo-) synthesize the same systems (we call it pseudo-synthesis because we already know one of the behaviours and structures of such systems from Step (a)).

4 RESULTS

4.1 Clarification of the Constructs

Before the constructs are defined, the following is a definition of some of the terms involved:

System: A subset of the universe which is under consideration. A system is characterized by its boundary called the system boundary (Fig. 2).
Environment: All the other subsets of the universe apart from the system constitute the environment. The system boundary demarcates the system from its environment (Fig. 2).
Universe: The system and the environment together constitute the universe.
Interaction: It is the communication between a system and its environment with each other to reach equilibrium. The equilibrium here refers to a balance in the properties of the system and environment. A system and its environment try to attain equilibrium because it is the most stable condition (Fig. 2).

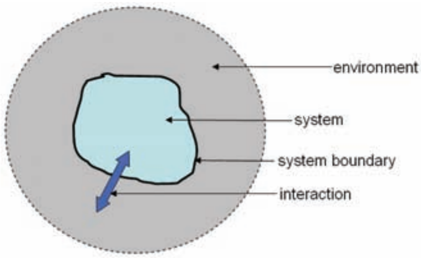

Figure 2. System, environment and interaction between system and environment

We now define the constructs of SAPPhIRE with the above terms and further, support the definitions with examples that will be detailed later.
Phenomenon: It refers to an interaction between a system and its environment. For example, heat transfer from a body to its surroundings, displacement of a body, flow of electric current, etc.
Effect: A principle of the universe that underlies/governs an interaction. For example, convection law underlies/governs heat transfer between a body and its surroundings, equations of motion underlie/govern displacement of a body, Ohm's law underlies/governs flow of electric current, etc.
State: It is a property at an instant of time of a system (and environment), that is involved in an interaction between a system and environment. As a consequence of an interaction, the property of a system (and environment) changes and this is called a state change. For example, temperature of a body decreases when heat is transferred from the body to its surroundings, spatial position of a body changes when the body gets displaced, value of electric current increases (zero to non-zero) in a resistor when there is a flow of current across the resistor, etc
Action: It is an abstract description or high-level interpretation of an interaction between a system and its environment. For example, heat transfer from a body to its surroundings can be interpreted as cooling of the body (temperature drop in a body can be interpreted as cooling of the body), displacement of a body can be interpreted as movement of the body (change in spatial position of a body can be interpreted as movement of the body), flow of current can be interpreted as generating current (change in current can be interpreted as generating current), etc.
Input: A physical variable that comes from outside the system boundary which is essential for an interaction between a system and its environment. This quantity can take the form of material, energy or information. This quantity also activates the underlying/governing principle. For example, positive temperature difference between a body and its surroundings is required for a heat transfer from the body to its surroundings, acceleration has to be applied on a body to displace the body, a potential difference has to be applied across the ends of a resistor for a current to flow through a resistor, etc.
Organ: A set of properties and conditions of a system and its environment required for an interaction between them. These are also required for activating the effect and remain constant during an interaction. All the other requirements apart from the input required for activating the effect comprise the organ. For example, for a transfer of heat from a body to its surroundings through convection (principle), requires a fluidic nature of the surrounding medium, surface area of the body through which heat can get transferred and heat transfer coefficient (a function of the fluid medium and geometry of the body) apart from temperature difference between the body and its surroundings (input), for displacing a body by the second equation of motion (principle) requires the body to be initially at rest (another case with body having non-zero initial velocity is also possible), Newtonian conditions (applicable to bodies that travel less than the speed of light) and degree of freedom in

direction of acceleration apart from application of acceleration for some time interval (input), to produce a flow of current across a resistor by Ohm's law (principle) requires maintaining constant temperature, closed circuit, resistance of the resistor and the use of Ohmic material apart from potential difference across the resistor (input).

Parts: A set of physical components and interfaces that constitute the system and its environment. For example, a body surrounded by a medium, a body lying on a ground, a resistor connected to a battery through conductor wires, etc.

4.2 Explanation of the SAPPhIRE model with new definitions

The set of components and interfaces that constitute a system and its environment (parts) create a set of properties and conditions (organ). When the system and its environment are not in equilibrium, there is a transfer of a physical variable in the form of a material, energy or signal (input) across the system boundary. This physical quantity in combination with a particular set of properties and conditions, together activate a principle (effect). This principle is responsible for an interaction (phenomenon) between the system and its environment. The interaction between the system and its environment changes a property of the system (and environment) (state change). The change in property can be interpreted at a higher level of abstraction (action).

4.3 Testing the capabilities of the model for analysis

The following section demonstrates the analysis capabilities of the model with a few examples. The objective of this section is to check if the model can be used for analysis i.e., from given parts and action, reason organs, effect, input, phenomenon and state change and link the state change to action to check if the required action is achieved.

<u>Example 1: How does a hot body cool down?</u> (see Fig. 3 and Fig. 4)

Consider a body kept in a medium [parts]. The relevant properties and conditions that can be derived from the part are: fluidic property of the medium, surface area of the body (A), and the heat transfer coefficient between the body and the surrounding medium (h – function of the geometry of the body and the nature of the surrounding fluid) [organ]. Assume that the body is at a higher temperature as compared to the medium ($T_b>T_s$). The temperature difference between the body and the medium (T_b-T_s) [input] and the organ activate the convection heat transfer law ($Q = hA(T_b - T_s)$) [effect]. This effect creates a heat transfer from the body to the surrounding medium [phenomenon]. The phenomenon decreases the temperature of the body [state change]. This state change can be interpreted as cooling of the body [action].

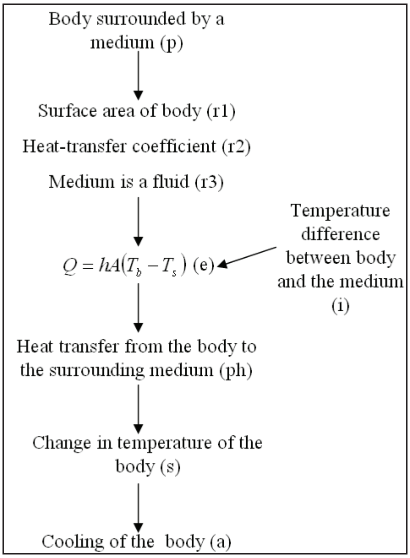

Figure 3. Example 1

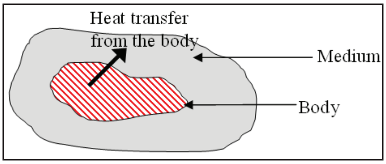

Figure 4. Example 1

Example 2: How does a body move under the application of acceleration? (see Fig. 5 and Fig. 6)
Consider a body lying on a ground [parts]. The relevant properties and conditions that can be derived from the parts are: body has a degree of freedom to displace in a direction (all directions except downwards where the movement is resisted by the ground) of applied acceleration and, the body and ground are initially at rest, i.e. at time, t=0 [organ]. Apply an acceleration (a) on the body for time duration (t) [input]. The organ and the input together activate the second equation of motion ($x = ut + 0.5at^2$ reduced to $x = 0.5at^2$) [effect] (A separate case where the body has non-zero initial velocity can also be considered). The effect creates a displacement of the body [phenomenon]. The phenomenon changes the spatial location of the body relative to a fixed global reference [state change]. This state change can be interpreted as a movement of the body [action].

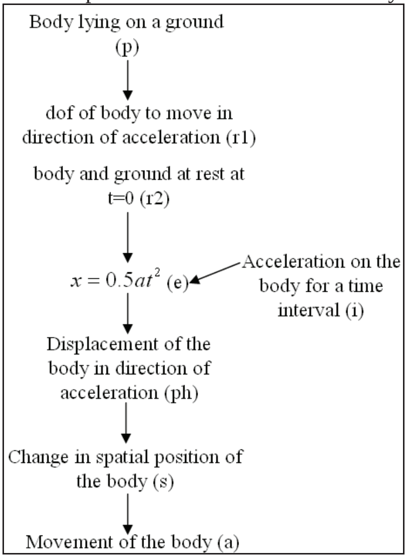

Figure 5. Example 2

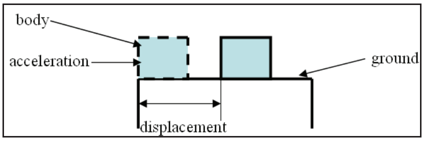

Figure 6. Example 2

Example 3: How is an electrical current generated? (see Fig. 7 and Fig. 8)
Consider a resistor connected to a battery through conductor wires [parts]. The relevant properties and conditions that can be derived from the parts are: resistance of the resistor (R), ohmic material of conductor wires and resistor, closed circuit and maintenance of constant temperature [organ]. Let us apply a potential difference (V) [input] across the resistor through a battery. The input and the organ activate Ohm's law (different version) ($I = (V/R)$) [effect]. This effect creates a flow of current across the resistor [phenomenon]. The phenomenon creates a change in current across the resistor,

from zero initially to some non-zero value [state change]. This state change can be interpreted as generation of current in the circuit [action].

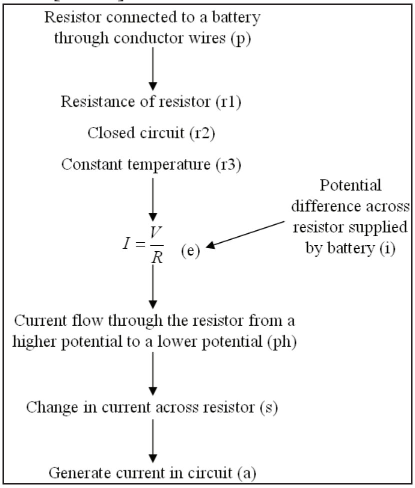

Figure 7. Example 3

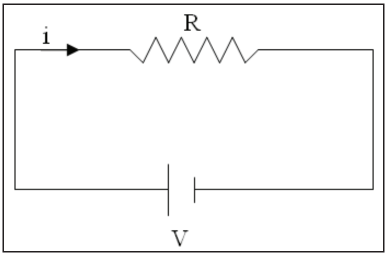

Figure 8. Example 3

<u>Example 4: How does a body move under the application of a force?</u> **(**see Fig. 9 and Fig. 10**)**
Consider a body lying on a ground [parts]. The following relevant properties and conditions can be derived from the parts: mass of the body (m) [organ]. Let a force (F) be applied to this body for a time duration (t) [input]. The input and the organ activate Newton's 2nd law of motion ($a = (F/m)$) [effect]. This effect creates an accelerated motion of the body [phenomenon] in the direction of the force and this motion lasts as long as the force is applied. This accelerated motion is interpreted as if an acceleration is applied on the body in the direction of force for the same time duration [input]. The other set of relevant properties and conditions that can also be derived from the parts are: existence of degree of freedom to displace in the direction of acceleration, body and ground initially at rest (t=0) [organs]. The latter input and organs activate the 2nd equation of motion ($x = 0.5at^2$) [effect]. This effect creates a displacement of the body in the direction of applied acceleration [phenomenon]. The phenomenon creates a change in the spatial position of the body relative to a fixed global reference [state change]. This state change can be interpreted as movement of the body [action].
The following observations can be drawn from the demonstration with the above examples:

(a) The SAPPhIRE model can be used as a model of analysis.
(b) The model can support analysis of multi-domain systems. Examples from thermal, mechanics and electrical domain are shown. Similar approach can also be extended to other domains like fluid, electronics, etc.
(c) The model can support analysis of simple and complex systems. A simple system here represents a single instance of SAPPhIRE being used to explain the causality, as shown in examples 1-3. A complex system here represents multiple instances of SAPPhIRE being used to explain the causality, as shown in example 4. For complex systems, phenomenon of a

SAPPhIRE instance which is like an output of an effect of the same SAPPhIRE instance becomes an input to an effect of the next SAPPhIRE instance. This chain repeats until the overall behaviour can be explained to link it to the overall action. For every instance of SAPPhIRE, relevant organs are derived from the same set of parts.

(d) The use of the model for analysing a system, requires information about both the system and its environment to analyse the system. For instance in example 1, it is mandatory to know that the medium has fluidic properties and the nature of the fluid medium which helps in determination of the heat transfer coefficient and the selection of the convection heat law.

(e) The model can support a quantitative analysis of a system. For instance in example 2, if one knows the magnitude and direction of the applied acceleration and the duration of this application, then one can calculate the distance moved from the 2nd equation of motion and check this displacement with the actual one.

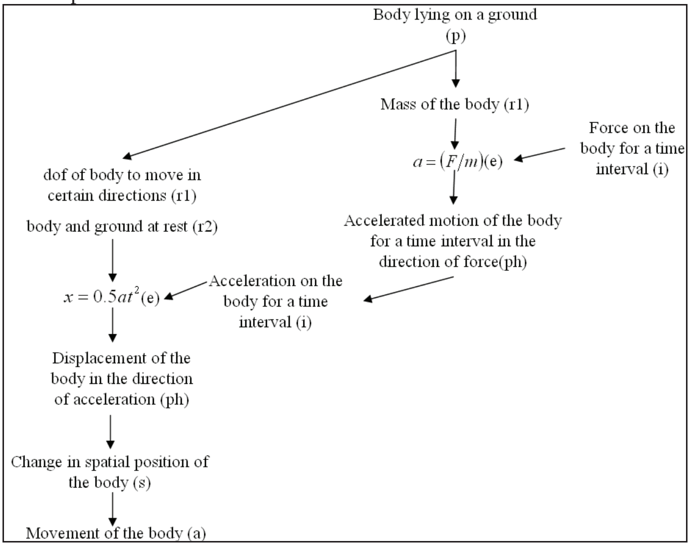

Figure 9. Example 4

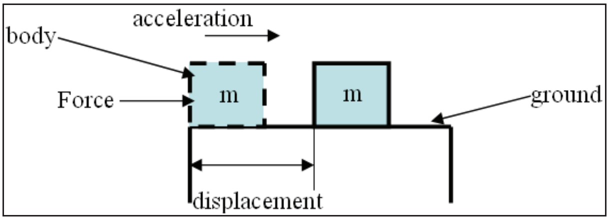

Figure 2. Example 4

4.4 Testing the Capabilities of the Model for Synthesis

This section demonstrates the synthesis capabilities of the model with a few examples. The objective of this section is to check if the model can be used for synthesis i.e., given an action, determine possible state changes, phenomena, effects, inputs, organs and parts that satisfy the given action.

<u>Example 1: How to cool a body? (see Fig. 11)</u>

We take the requirement of cooling a body as an action. A body can be cooled down by many alternatives: reducing the quantity of heat in the body, reducing the temperature of the body, etc. [state change]. Each of the state change can be accomplished by many alternative phenomena, for instance, quantity of heat can be reduced by increasing the heat transfer. Each phenomenon can be accomplished by multiple alternative effects. For instance, heat transfer can be accomplished by conduction, convection or radiation laws. Each effect requires its own set of conditions and properties. For instance, conduction requires a solid medium with thermal conductivity (K), area of cross-section

(A), thickness (x) and a contact with the body to be cooled [organ]. The input to the effect is a temperature difference between the body and the solid medium. Each set of organ can be embodied by multiple alternative set of parts as shown in Fig 11.

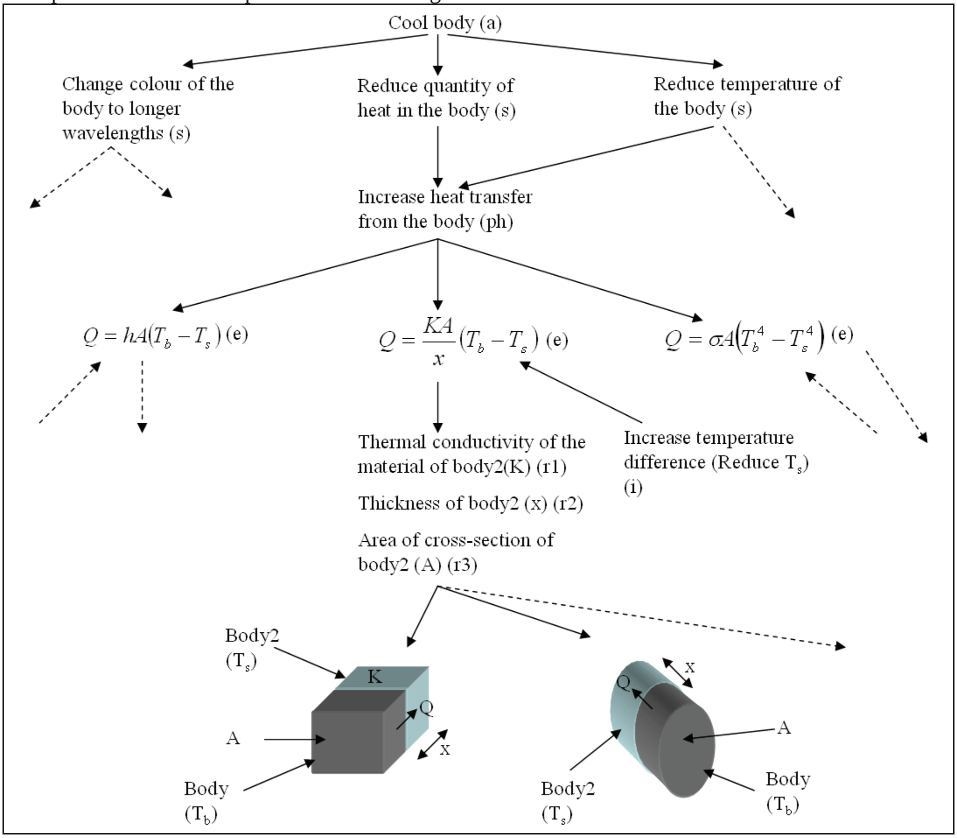

Figure 3. Example 1

<u>Example 2: How to move a body? (see Fig. 12)</u>

The requirement of moving a body is taken as an action. The different means of moving a body are: changing orientation of the body, changing position of the body, changing both-orientation and position, etc [state change]. Each state change can be accomplished by multiple alternative phenomena. For instance changing position can be accomplished by sliding, running, jumping, etc. Each phenomenon can be satisfied by multiple alternative effects. For instance, sliding by the 2^{nd} equation of motion. This law requires an input of acceleration to be applied on the body for time duration and the other conditions are that there should be a degree of freedom in the direction of acceleration and the body should be initially at rest for this version of the law. The organ can be embodied by multiple alternative set of parts as shown in Figure 12.

<u>Example 3: How to generate electrical current? (see Fig. 13)</u>

We consider the requirement of generating a current as the action. The action can be accomplished by alternative state changes: increasing current from zero to non-zero or non-zero to higher value, etc. Each state change can be accomplished by alternative phenomena, for instance, flow of current to increase current from zero to non-zero. Each phenomenon can be accomplished by alternative effects: ohm’s law, charge-current effect, etc. Ohm’s law requires a potential difference as an input and the organs are resistance (R), maintenance of constant temperature, use of Ohmic materials and closed circuit. Each organ can be accomplished by alternative parts and here it is embodied by a circuit containing a resistor connected to the voltage source by conductor wires. The potential difference which is the input to the Ohm’s law can be supplied from a battery or by electromagnetic induction through a coil whose associated flux changes with time. This flux change maybe accomplished by a moving magnet.

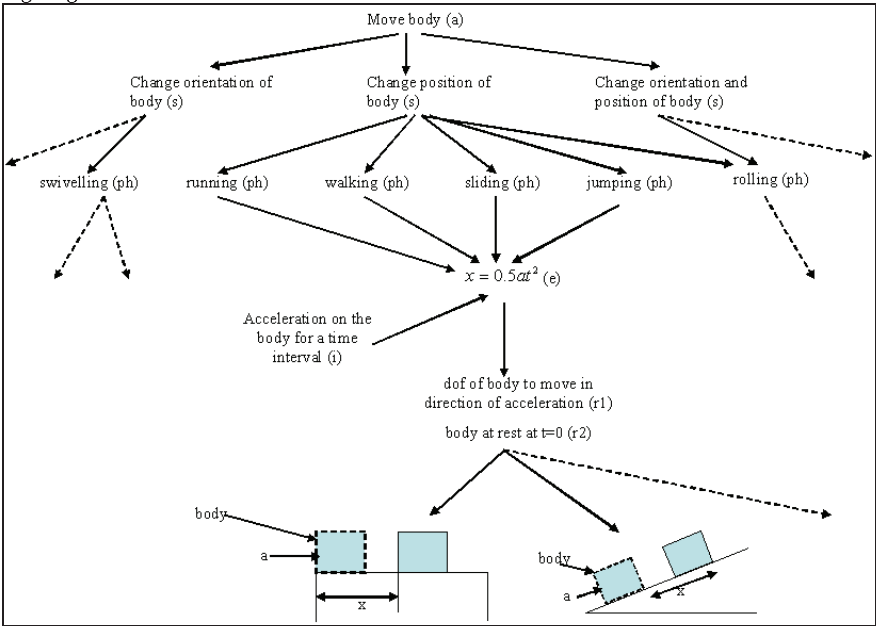

Figure 4. Example 2

<u>Example 4: How to move a body? (see Fig. 14)</u>

This is a special case of example 2 to show the other capabilities of the model. Moving the body is a requirement which can be accomplished by alternative solutions at action-level: loading the body followed by transporting the body and unloading the body, change physical form of the body followed by transportation and changing back to the original form, etc. Each action can be accomplished by multiple state changes and so forth as shown in the other examples.

The following observations can be drawn from the demonstration with the above examples:

(a) The SAPPhIRE model can also be used as a model for synthesis.

(b) The model can support synthesis of multi-domain systems. Examples from thermal, mechanics and electrical domain are demonstrated. Similar approach can also be extended to other domains like fluid, electronics, etc.

(c) The model can support synthesis of simple and complex systems. A simple system is demonstrated using examples 1 and 2. A complex system is demonstrated in example 4.

(d) The use of the model for synthesis of a system, helps develop information about both the system and its environment. For instance in example 1, the model develops information that there is a need for another solid medium with cross-sectional area, thickness and thermal conductivity properties which has to be in contact with the body to cool the body by means of conduction law.

(e) The model can also enable a quantitative synthesis of a system. For instance in example 2, if a body has to be displaced by a certain distance in a particular direction, then the magnitude and direction of acceleration to be applied and the duration of its application can be computed using the approach. Note that there is a certain trade-off that is required between time and acceleration to achieve the required displacement which is left to the discretion of designer.

(f) The capability of the model to support complex systems also adds to the complexities to be handled by the designers. The approach allows linking of several SAPPhIRE instances and the chain or network becomes more complex when there are a large number of instances interlinked. An approach to terminate a chain is shown in example 3 (Fig. 13) where the potential difference (input to the first SAPPhIRE instance) can be supplied by a battery (constant potential difference). This input can also be achieved through electromagnetic means (varying potential difference).

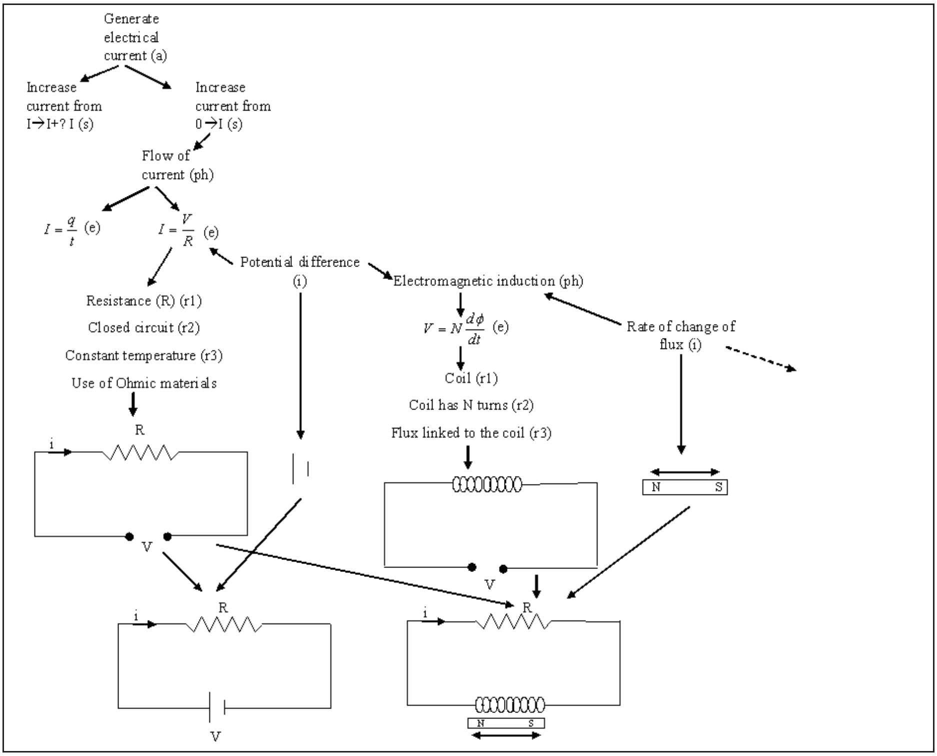

Figure 5. Example 3

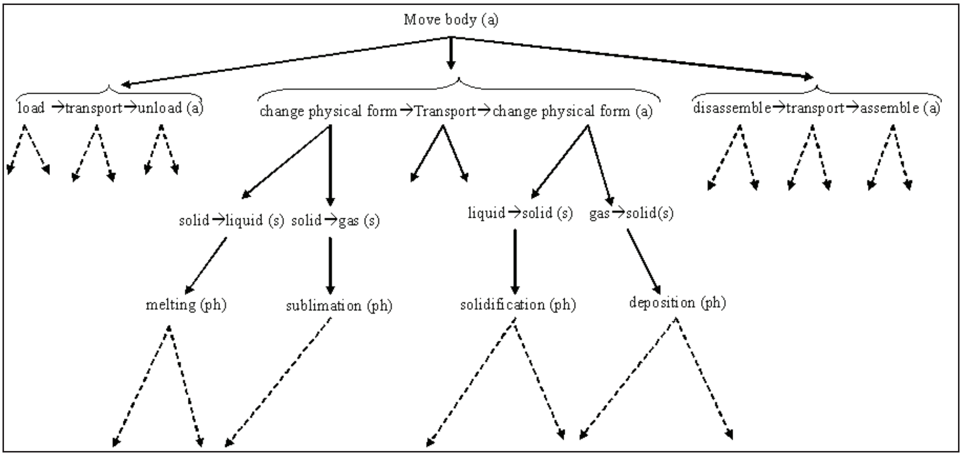

Figure 6. Example 4

(g) The use of the model allows many-to-many mapping, i.e. actions can be satisfied by multiple alternative state changes, state changes can be satisfied by multiple alternative phenomena and so forth. For an effect that satisfies a given phenomenon, there is only a unique combination of input and set of organs that can satisfy the effect. This many-to-many mapping produces a large number of alternative solutions from which the designer can select the most promising ones.

(h) The model supports both – 'AND' and 'OR' analogies. The 'AND' analogy is demonstrated in Example 4 (Fig. 14) where each action alternative has a series of actions to be fulfilled to satisfy the overall action. The 'OR' analogy is demonstrated in all the examples where multiple alternatives exist at all the levels of the constructs.

(i) The model is currently limited to supporting only conceptual and early embodiment stages.

5 SUMMARY

The following are the highlights of this paper:

(a) The definition of each construct of the model is refined to provide more clarity in understanding the constructs and using the model.

(b) The analysis and synthesis capabilities of the model have been demonstrated using examples.

(c) Some analytical and synthetic features of the model have been derived from the examples.

(d) The model in its current form can support only conceptual and early embodiment phases and needs to be extended to support other detailed phases.

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