Understanding and Supporting Evolution of Engineering Designs

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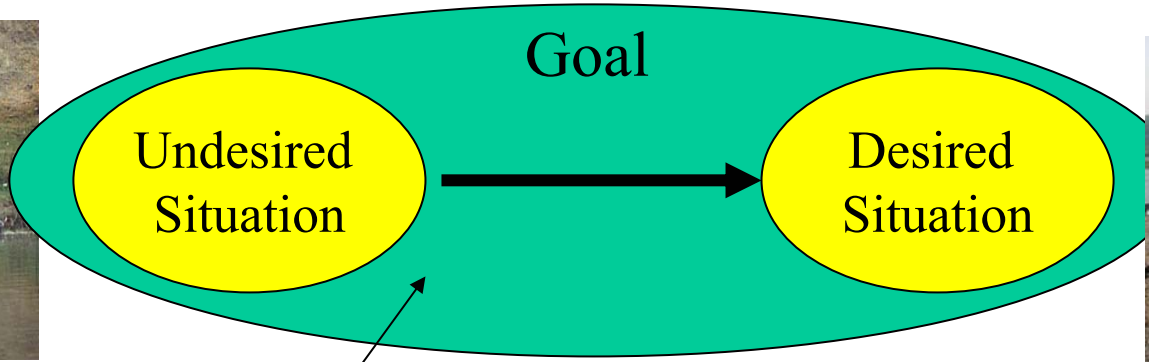
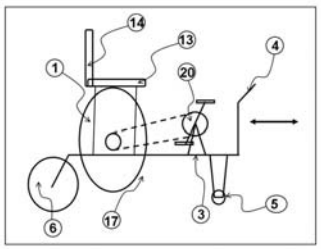
What is design?





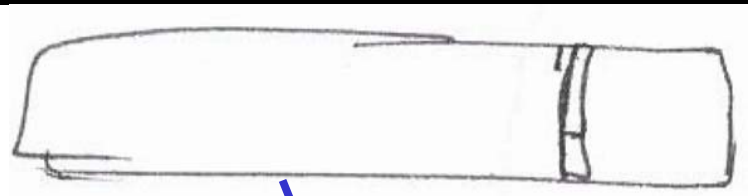
Implemented and utilized as intended

- Design: **Plan** of a system, its implementation and utilisation for attaining a goal: change undesired to desired
- Designing: **How** a design is developed
- Designs can be for: technical systems (power plant), educational systems (Montessori Method), aesthetic systems (logo designs, advertisements), legal systems, social, religious or cultural systems, theories, Models, etc.

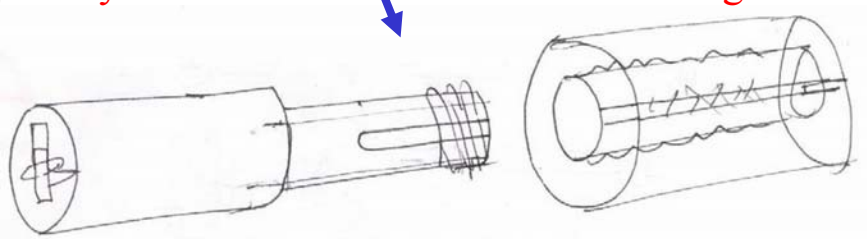
Evolution of Engineering Designs

6.32	S1	First the problem is that executives requires exercises
6.45	S1	and why they require we don't know
6.48	S1	and because they are busy
6.57	S1	and they are reluctant to spend money to buy expensive gym equipment for personal use
7.01	S1	so they are miser
7.04	S1	miser, do not want to spend money for equipment
7.17	S1	which means that the assumption is they know that they have to do some exercise but they are not doing
7.23	S1	and they think that gymnasium equipment is very expensive and I don't need to buy
7.3	S1	because they are quite expensive probably
7.34	S1	well there are some personal use equipment available but they are expensive, ok
7.4	S1	this is a fact
7.44	S1	privacy is not there in gymasium
7.52	S1	privacy is not there means lot of people are feeling, feeling what
8.03	S1	feeling shy of going there, body building exercise probably
8.09	S1	why they don't do exercise wearing the full dress (smile) strange
8.15	S1	current equipment occupies lot of space ok
8.28	S1	and usually are not portable
8.34	S1	these are problems with current equipment
8.39	S1	so the requirements are external requirements, some are constratints
8.46	S1	apart from the solution of the problem, requirements are that
8.52	S1	it should be easily setupable
9.07	S1	it should be setup easily and portable
9.12	S1	and should help in complete workout of the body
9.27	S1	ya
9.29	S1	first of all the thing is that whether we really achieving that

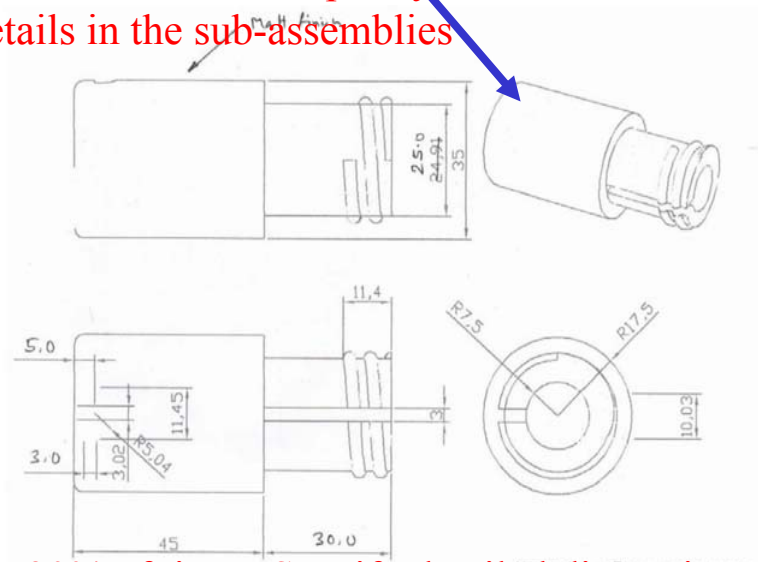
First 20% of time: understand the problem and identify the constraints



Next 30% of time: Specify ideas, spatial layouts and sub-assemblies of the design



Next 20% of time: Specify the interface details in the sub-assemblies



Next 30% of time: Specify detailed dimensions, materials and manufacturing tolerances

Essential Features of Design

- Design: Intentional constructions; **Plans for achieving goals**
- Designing: Goal-oriented processes of **how** designs are developed

- Initially: Predominantly only **goals** are known
- Finally: Both goals and **plans** are known and more clearly

- Co-evolution: **both** goals and plans evolve together, one influencing the other

- But: Designing does **NOT** guarantee that designs will work: some designing may be better than others in achieving goals

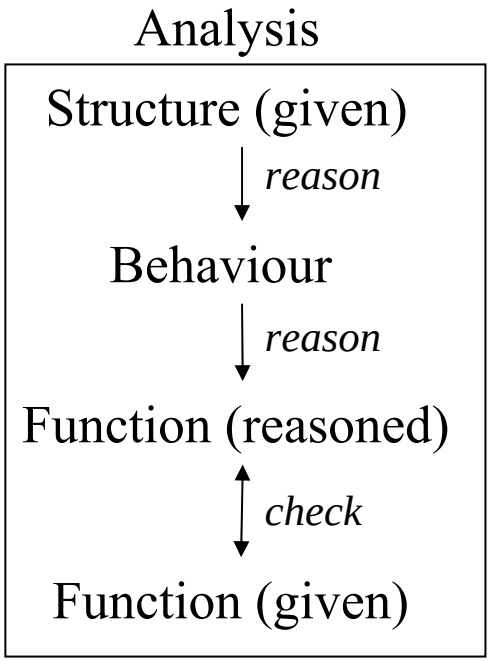
What do we want to do?

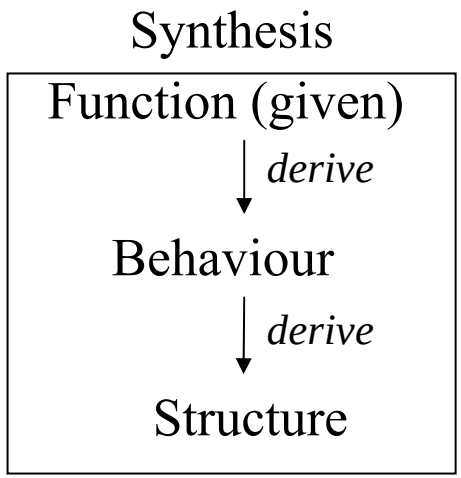
- Support: Design of novel technical systems
- Develop: A framework and methods for designing better

- Understand: How technical systems are designed: Model
- Identify: Where they may be scope for improvement

- Understand: How things work: how systems achieve their goals
- Develop: A model of causality for working of technical systems

Analysis and Synthesis





Overview

- SAPPhIRE: A model of how things work
- GoS Model: How people design (how designs evolve)
- Novelty-SAPPhIRE: Where one could improve upon how people currently design things
- GoS Framework: How people should design
- Idea-Inspire: How to inspire novelty in designs

SAPPhIRE Model

Definition of Constructs

System [Pahl & Beitz, '96]

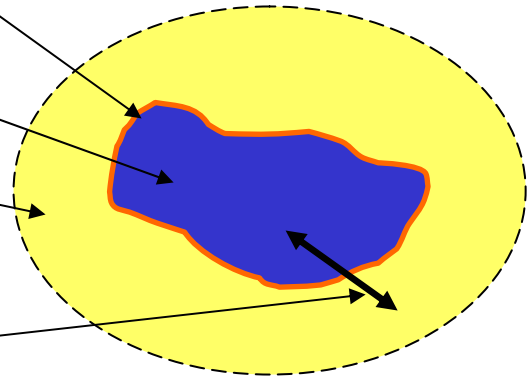
- A subset of universe under consideration
- Characterized by a boundary called the system boundary

Environment [Pahl & Beitz, '96]

- All other subsets of the universe apart from the system.
- System boundary separates environment from the system

Universe

- Constitution of system and environment.



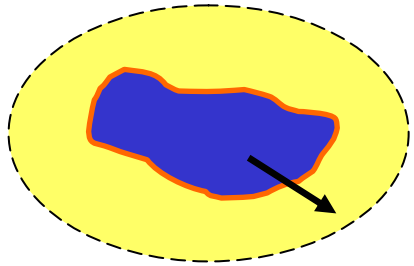
Interaction

- Communication between a system and its environment with each other to reach equilibrium.
- Equilibrium is the most stable state

Definition of Constructs (contd.)

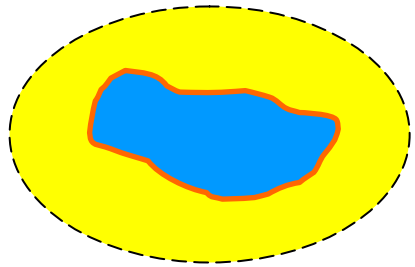
Phenomenon: Interaction between system and environment

Eg. Heat transfer from a body to its surroundings



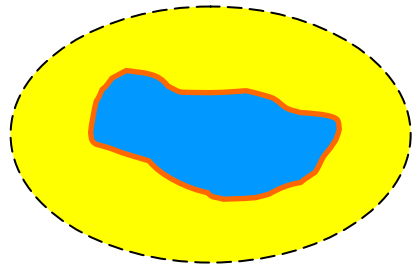
State change: Change in property of system (and environment) due to the interaction

Eg. Decrease (increase) in temperature of body (surroundings)



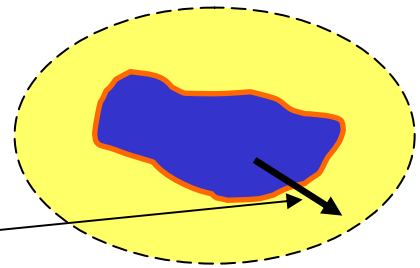
Action: Abstract description or high-level interpretation of an interaction

Eg. Cooling (Heating) of body (surroundings)



Effect: Principle of universe underlying an interaction

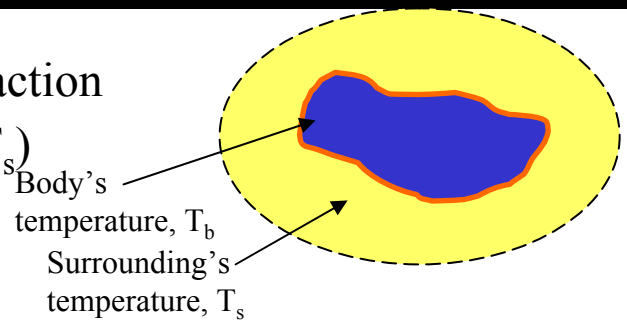
Eg. Convection heat transfer [$Q=h.A.\Delta T$]



Definition of Constructs (contd.)

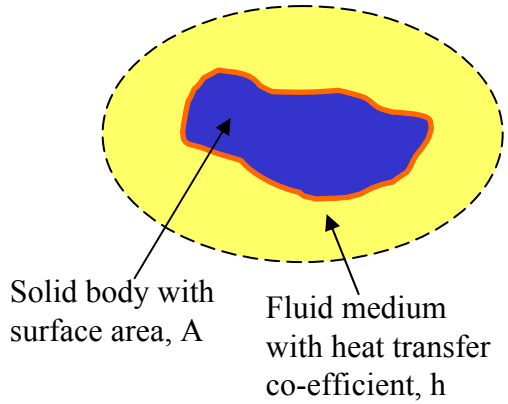
Input: Physical quantity or variable which is essential for an interaction

Eg. Temperature difference between body and surroundings, (T_b-T_s)



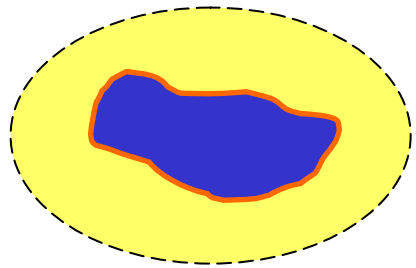
Organs: Set of properties and conditions of system and environment that are required for an interaction

Eg. Need for surface (area of body), heat transfer co-efficient (between solid and fluid medium)



Parts: Set of components and interfaces that make the system and environment relevant for the interaction

Eg. Solid body held in an air medium



SAPPhIRE model of causality

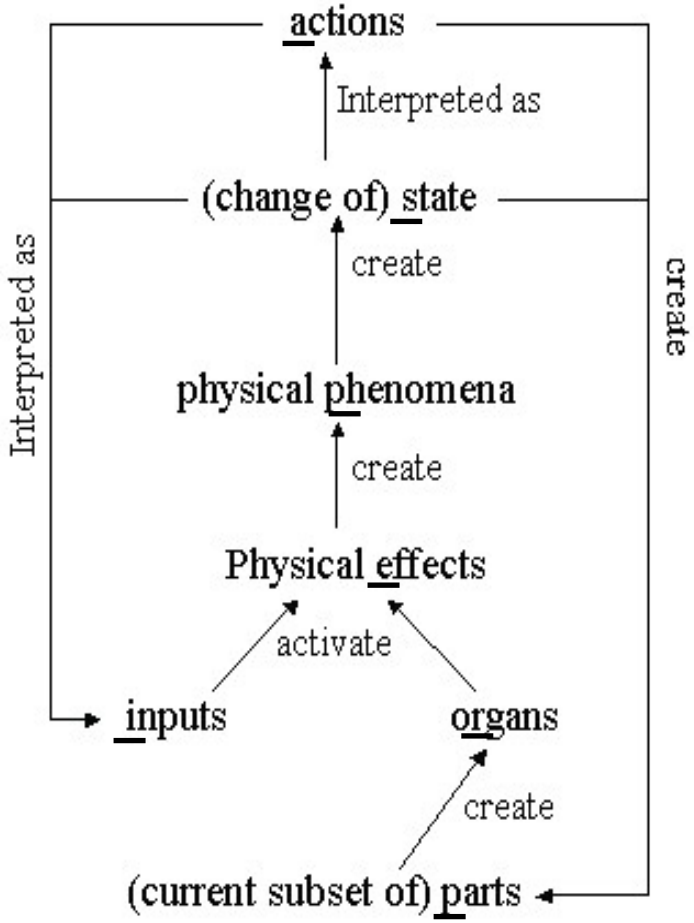
- Uses: **S**tate change, **A**ction, **P**arts, **Ph**enomenon, **I**nput, o**R**gan and **E**ffect

- Constructs inspired from FBS-model [Umeda et al., '96]; Theory of TS [Hubka & Eder, '02]; Domain Theory [Hansen & Andreasen, '02]; Metamodel [Tomiyama et al., '89]

- Provides a rich description of functionality and behaviour

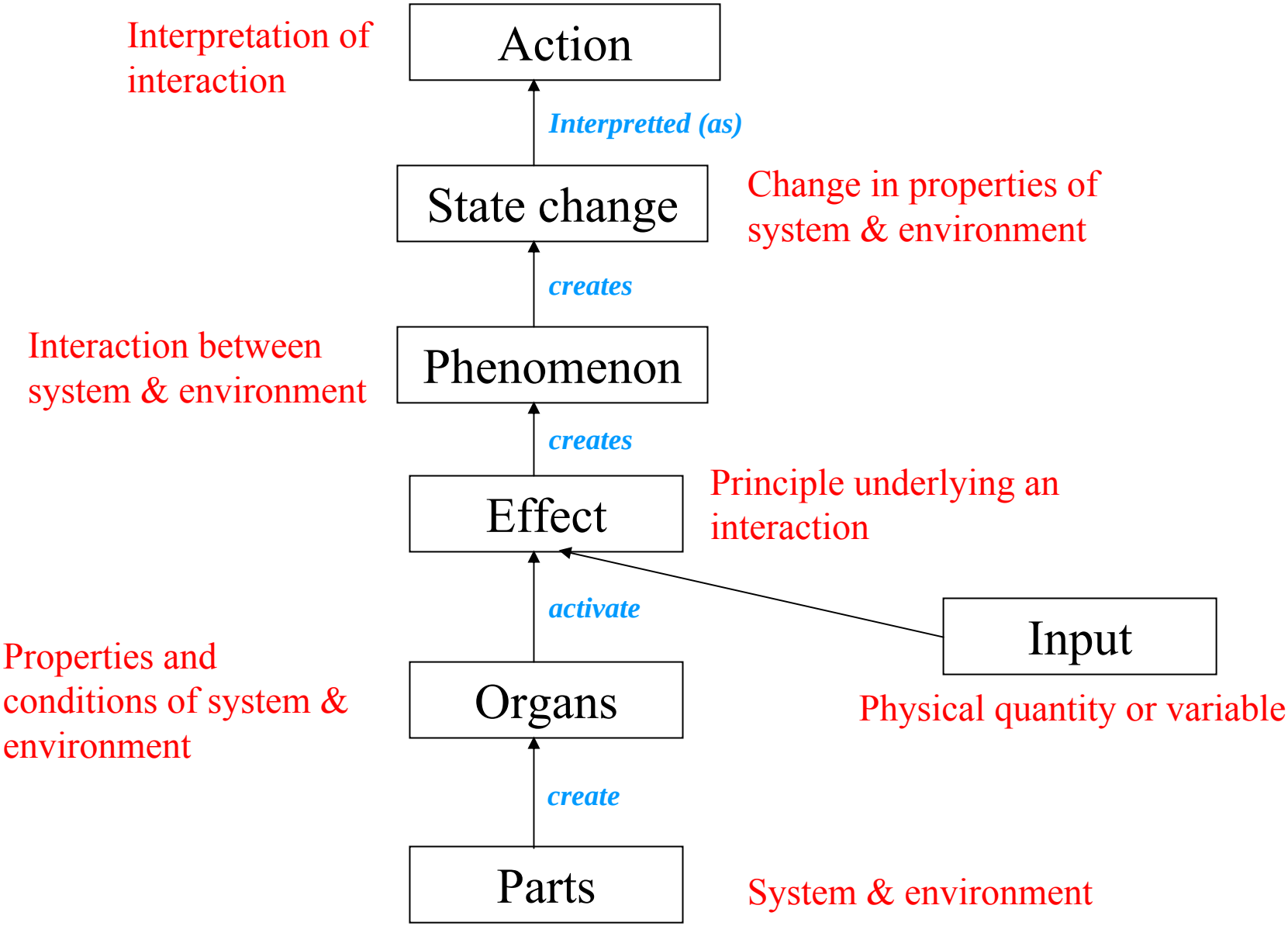
- Used as a model of causality for natural and engineered systems

[Chakrabarti et al., '05]



[Chakrabarti et al., '05]

SAPPhIRE model of Analysis



Analysis – Example 1

Example 1: How does a body move under the application of acceleration?

Body lying on a ground (p)

↓

dof of body to move in direction of acceleration (r1)

body and ground at rest at t=0 (r2)

↓

$x = 0.5at^2$ (e) ← Acceleration on the body for a time interval (i)

↓

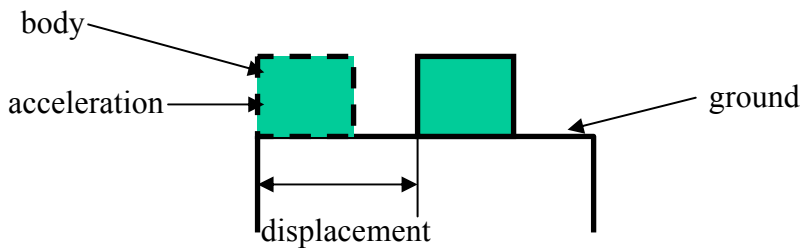
Displacement of the body in direction of acceleration (ph)

↓

Change in spatial position of the body (s)

↓

Movement of the body (a)



Analysis – Example 2

Example 2: How is an electrical current generated?

Resistor connected to a battery through conductor wires (p)

↓

Resistance of resistor (r1)

Closed circuit (r2)

Constant temperature (r3)

↓

$I = \frac{V}{R}$ (e) ← Potential difference applied across resistor by battery (i)

↓

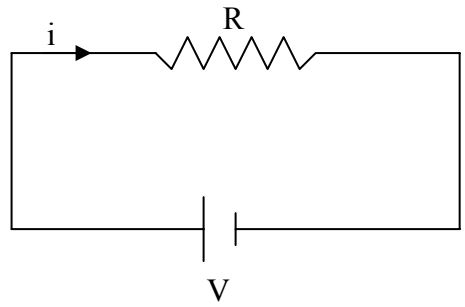
Current flow through the resistor from a higher potential to a lower potential (ph)

↓

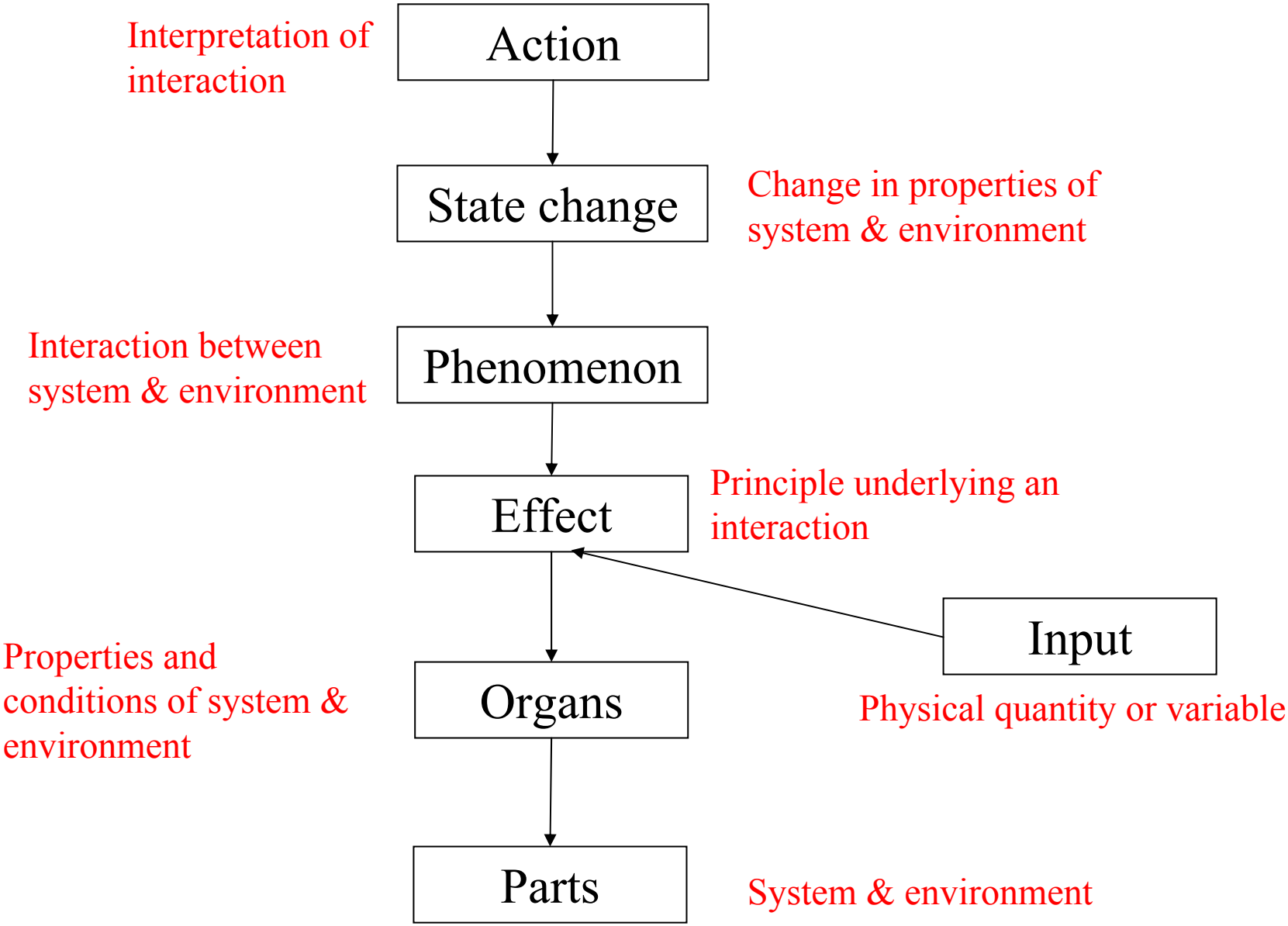
Change in current across resistor (s)

↓

Generate current in circuit (a)

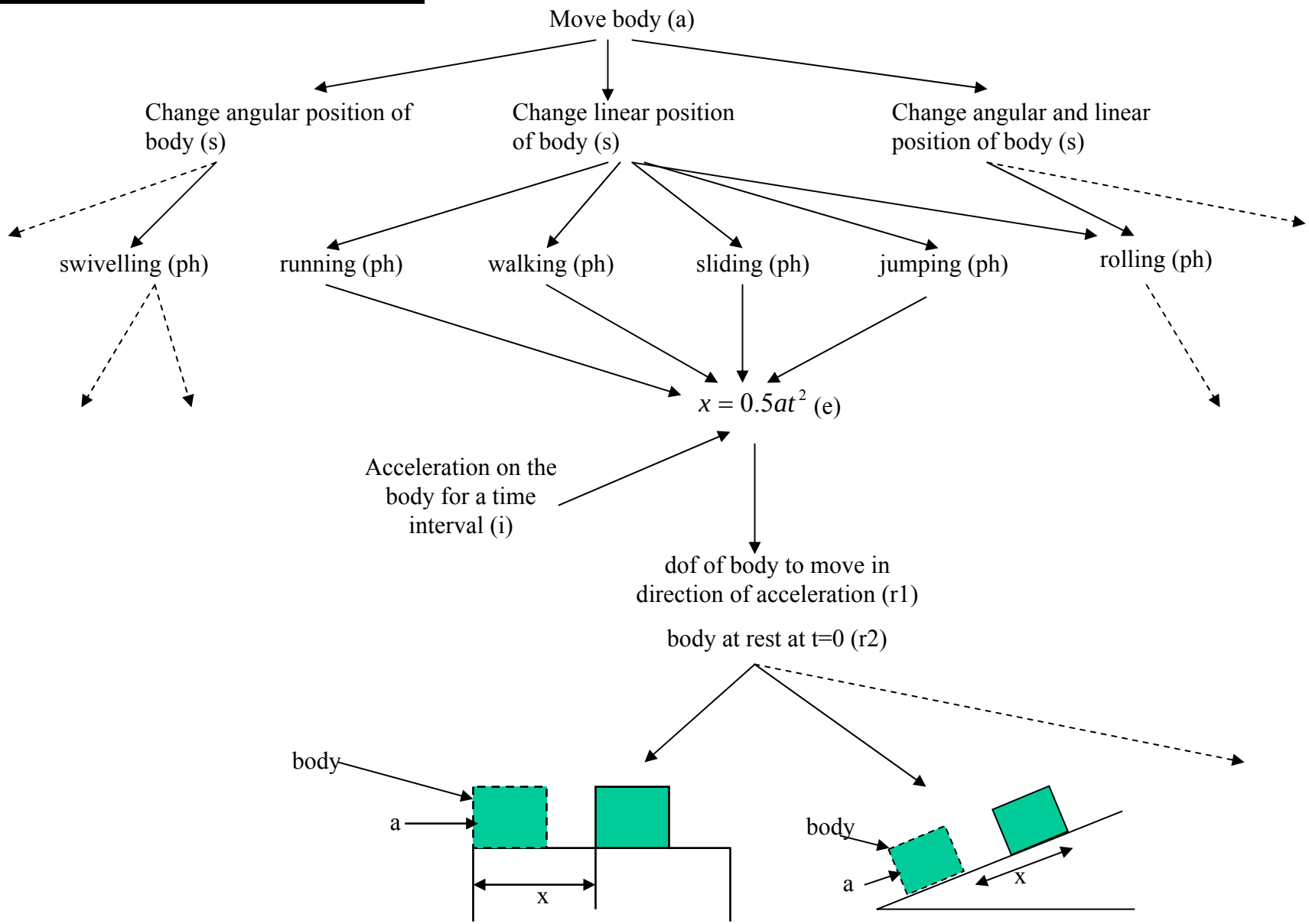


SAPPhIRE model of Synthesis



Synthesis – Example 1

Example 1: How to move a body?



Synthesis – Example 2

Example 2: How to generate electrical current?

Generate electrical current (a)

Increase current from I→I+ΔI (s)

Increase current from 0→I (s)

Flow of current (ph)

$I = \frac{q}{t}$ (e)

$I = \frac{V}{R}$ (e)

Potential difference (i)

Resistance (R) (r1)

Closed circuit (r2)

Constant temperature (r3)

Use of Ohmic materials (r4)

Electromagnetic induction (ph)

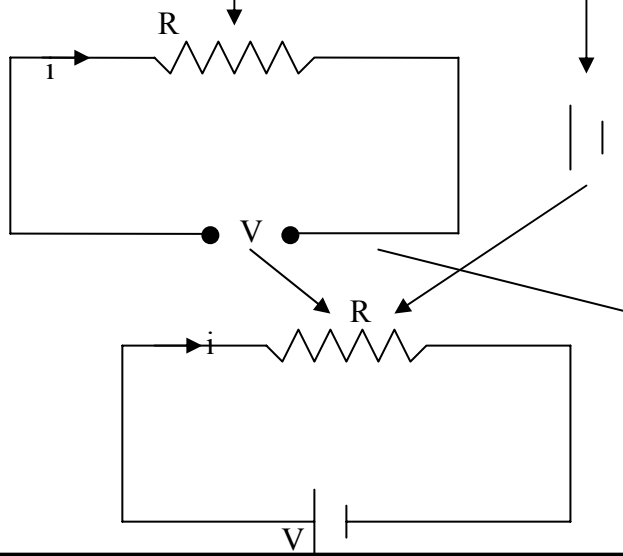
$V = N\frac{d\phi}{dt}$ (e)

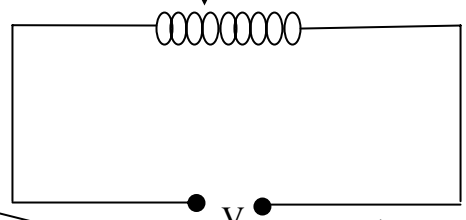
Coil (r1)

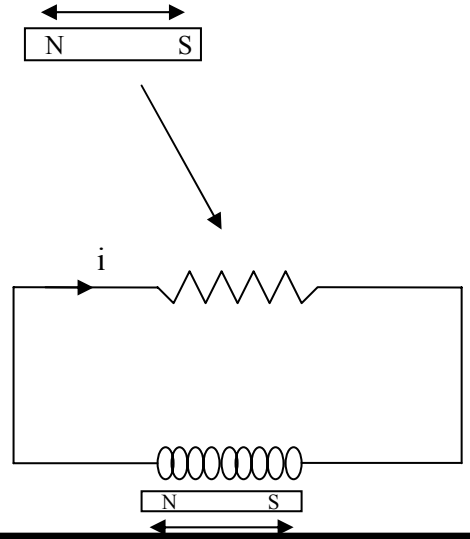
Coil has N turns (r2)

Flux linked to the coil (r3)

Rate of change of flux (i)







Model of Designing

Literature Survey

- Conceptual design:
  - solution concepts developed to meet requirements [*Pahl & Beitz, '96*]
  - most creative stage
  - most changes are best effected and less expensive
  - majority of design's total life-cycle cost committed in this phase [*Chakrabarti et al., '02*]
  - early phase of design→difficulties owing to open-endedness
  - less attention paid into supporting the stage.
- Activities and outcomes:
  - important as they influence aspects like requirements identification & satisfaction [*Cooper, '91; Nidamarthi, '99*].
- Physical laws/effects:
  - principles of nature that govern a change [*Chakrabarti et al., '05*]
  - designing with laws/effects can help produce novel and creative artifacts [*Chakrabarti et al., '97; Zavbi & Duhovnic, '97; Murakoshi & Taura, '98*]

Literature Survey (contd.)

- Physical laws/effects (contd.):
  - synthesizing artifacts directly from effects is hard – created for explanation of phenomena than for synthesizing artifacts that embody the phenomena [*Murakoshi & Taura, '98*]
  - not adequately represented in current design models/frameworks
- Requirements & Solutions: Critical aspect in design
  - Requirements initiate a design task [*Cooper, '91; Pahl & Beitz, '96*]
  - Requirements fulfillment (solutions) → design success criterion [*Blessing, '94*]
- Need for a model
  - includes:
    - ✓ activity elements
    - ✓ outcome elements (especially laws and effects)
    - ✓ requirement-solution elements
  - explain traits of conceptual designing
  - address novelty at the conceptual-stage

Research Methodology

- Development of a Model
  - Use literature to identify activity, outcome and requirement-solution elements
- Empirical Validation of the Model
  - Use protocol studies of designing sessions to check whether the model is a part of natural way of designing

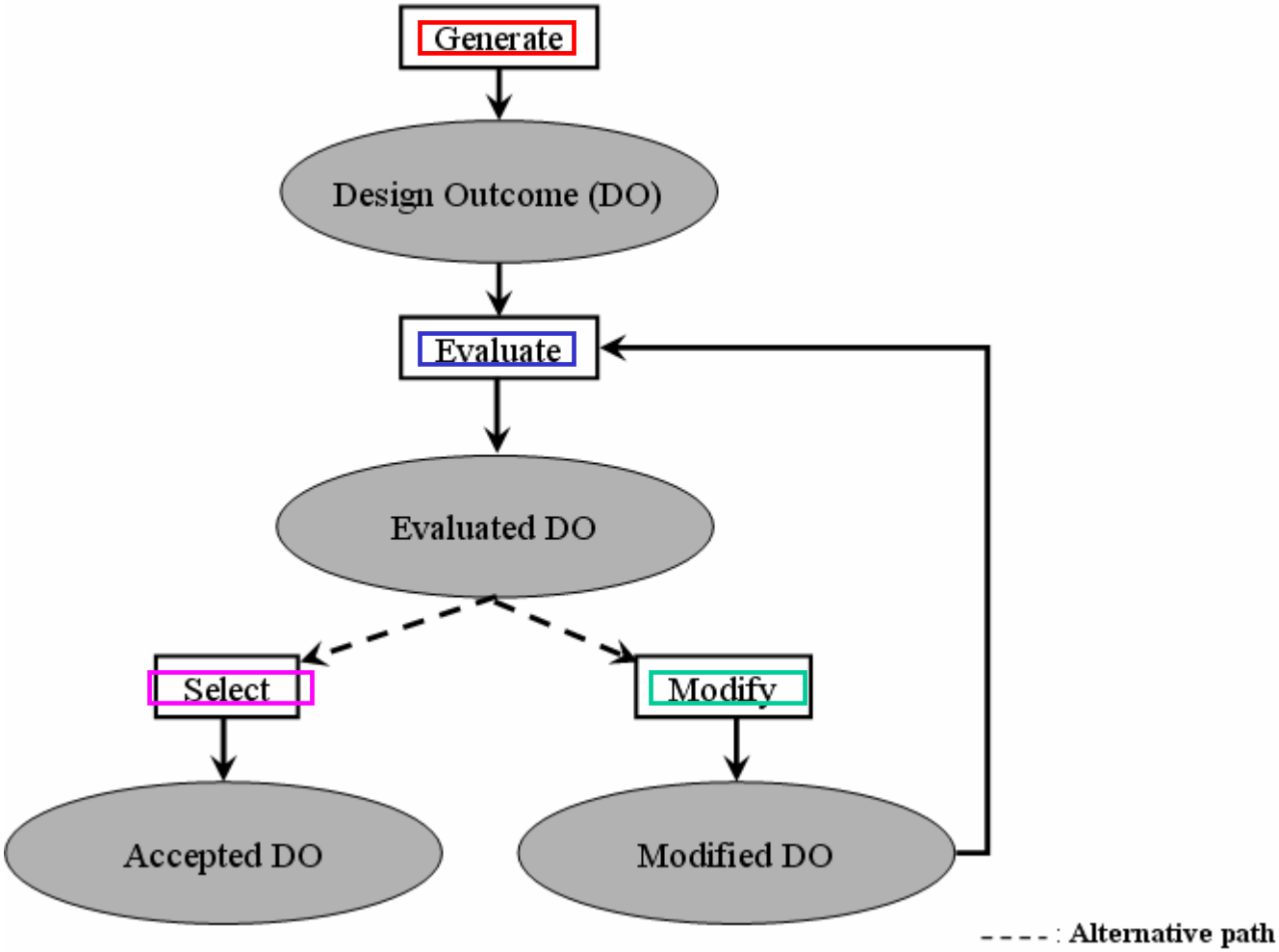
Model Development

- Activities in design:
  - Test-Operate-Test-Exit [*Miller et al., 1960*]
  - Formulate, Synthesise, Analyse, Evaluate, Document and Reformulate [*Gero, 1990*]
  - Construct-Develop-Evaluate-Accept-Reject [*Visser, 1990*]
  - Generate-Evaluate-Decide [*Stauffer & Ullman, 1991*]
  - Generate-Evaluate-Select [*Blessing, 1994*]
  - Analyse, find, select, evaluate, upgrade, improve, eliminate, check etc. [*Pahl & Beitz, 1996*]
  - Generate-Evaluate-Modify [*Chakrabarti et al., 1997*]
  - Generate, form, revise, justify, synthesise, specify, analyse, assess, evaluate etc. [*Smithers, 1998*]
  - Identify-Analyse-Choose & Generate-Evaluate-Select [*Nidamarthi, 1999*]
  - Explore-Generate-Evaluate-Communicate [*Cross, 2000a*]
  - Clarify, define, analyse, evaluate, assess, develop, divide etc. [*Cross, 2000c*]
  - Define, Find, Describe, Evaluate and Select [*Lossack, 2002*]
  - Formulate, Generate, Evaluate and Guide [*Campbell & Rai, 2003*]
  - Generate, Synthesise, Select and Shape [*Zeiler et al., 2007*]

- Generalised Activity model: **G**enerate-**E**valuate-**M**odify-**S**elect (**GEMS**)

Model Development (contd.)

GEMS activity model



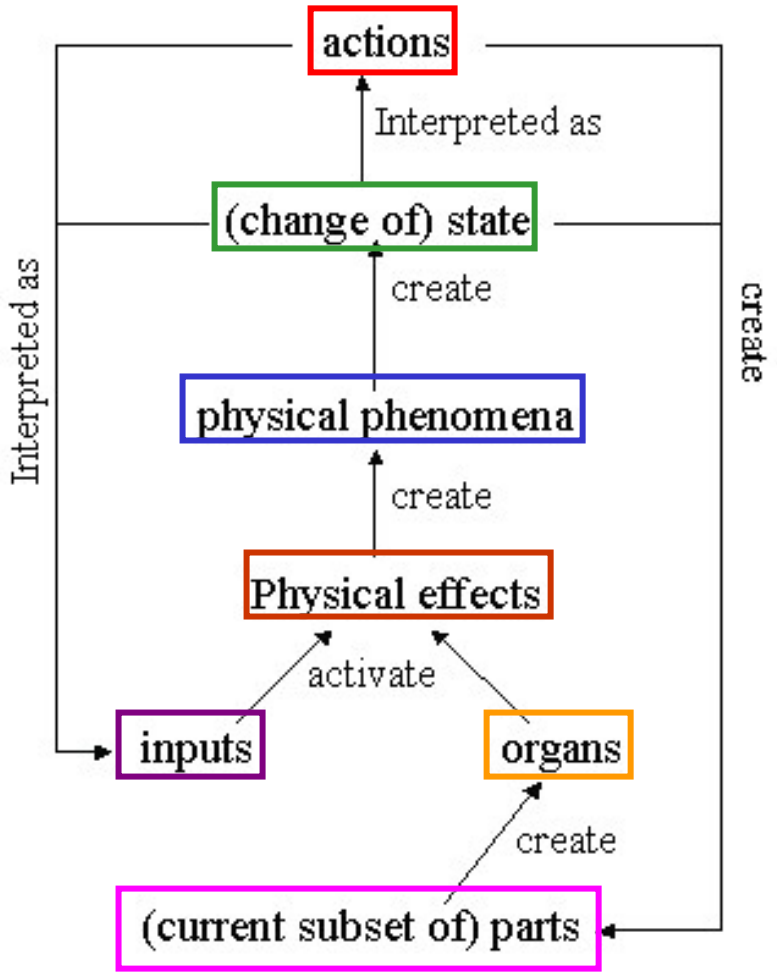
Model Development (contd.)

- Outcomes in design:
  - Function and means [*Hubka, 1967*]
  - Function, expected/actual behavior and structure [*Gero, 1990*]
  - General Design Theory (ideal) – function, attribute [*Reich, 1995; 2002*]
  - Problem, requirement, function, concept and detailed design [*Blessing, 1994*]
  - Function structure, working principle, working structure, solution principle, concept, layout, production and assembly document [*Pahl & Beitz, 1996*]
  - Function (input-output) and solution principle (physical laws and effects) [*Chakrabarti et al., 1997*]
  - VDI 2221 – task, function structure, solution principle, module, layout, production and operating documents [*Cross, 2000c*]
  - Theory of TS -process, function, organ and part (sketch layout, dimension layout, detailed part drawing) [*Hubka & Eder, 2002*]
  - Domain Theory-transformation, organ (wirk elements) and part (part and assembly relations) [*Hansen & Andreasen, 2002*]
  - Structure (components and their relationships), behaviour (state and active functions) and function (input-output) [*Bhatta & Goel, 2002*]
  - Requirement, function, physical principle and embodiment [*Lossack, 2002*]
  - SAPPhIRE model – action, state change, phenomenon, effect, input, organ and part [*Chakrabarti et al., 2005*]
  - Need, specification, function structure, principle solution, structure, form and product [*Zeiler et al., 2007*]
  - Function, physical law, basic schemata and structure [*Rihtarsic et al., 2008*]
- Primary interest in designing using laws & effects

Model Development (contd.)

- **SAPPhIRE** model
  - elements – **A***ctions*, **S***tate change*, **Ph***enomena*, **E***ffects*, **I***nputs*, o**R***gans* and **P***arts*
  - explains behavior of natural and engineered systems
  - elements created by integrating design outcomes from existing models

  [*Chakrabarti et al., '05*]
  - supports analysis and synthesis
  - not tested for its designing capabilities
  - Design: Need→Form
    - Functional-level **(Need): A, S, I**
    - Behavioural-level: **E, Ph, R**
    - Embodiment-level **(Form)**: **P**



- Outcome model: **SAPPhIRE**

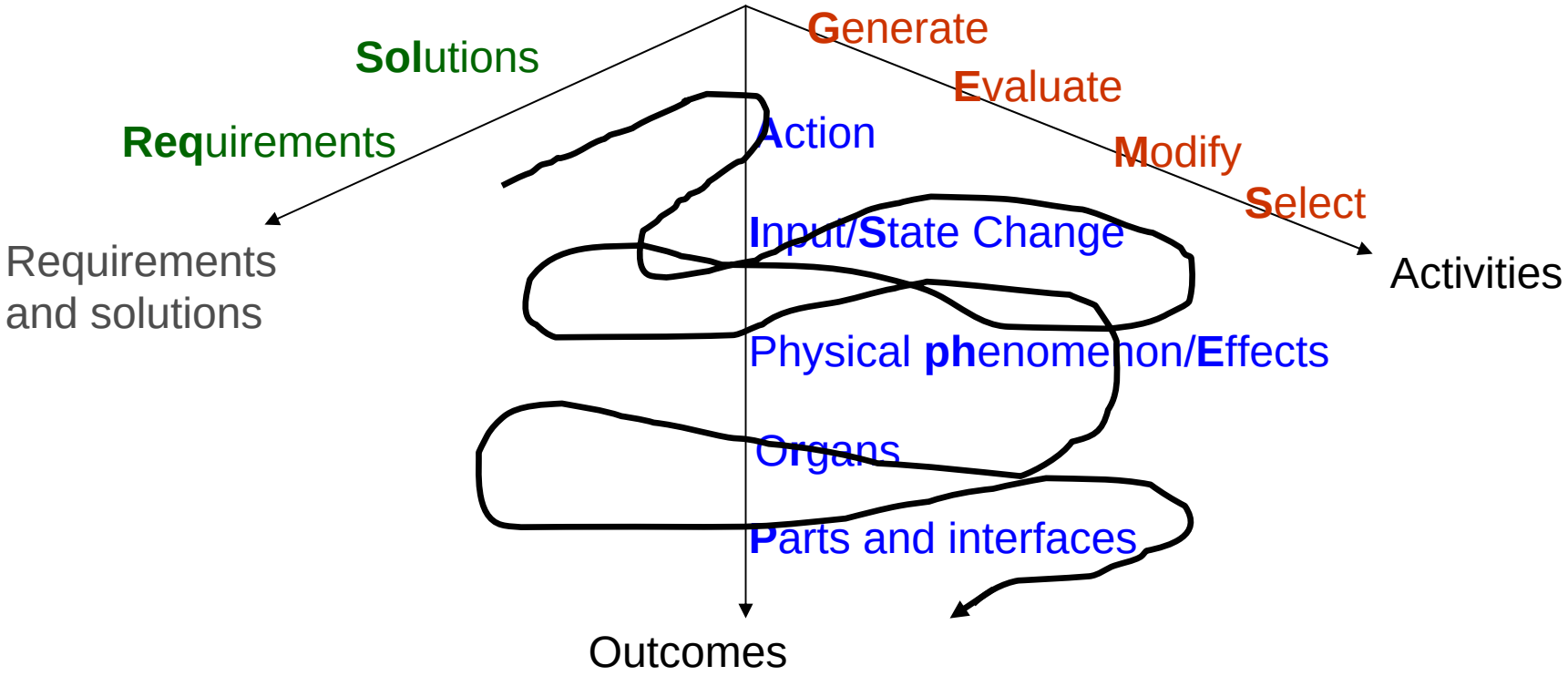
Model Development (contd.)

- Requirement-Solution in design:
  - Function and means [*Hubka, 1967*]
  - Problem and solution [*Visser, 1990*]
  - Constraint and proposal [*Stauffer & Ullman, 1991*]
  - Proposals of problem and requirement, and proposals of function, concept and detailed design [*Blessing, 1994*]
  - Specification (requirement)-solutions at different abstraction levels- function structure, solution principle, preliminary layouts, form designs [*Pahl & Beitz, 1996*]
  - Problem and solution (co-evolve) [*Maher et al., 1996*]
  - Requirement and solution (co-evolve) [*Nidamarthi, 1999*]
  - Problem and solution (co-evolve) [*Cross, 2000a*]
  - Problem, solution and information [*Hubka and Eder, 2002*]
  - Problem and solution [*Lossack, 2002*]
  - Problem and solution [*Campbell & Rai, 2003*]

- Model of requirement-solution: co-evolving requirement and solution

Model Development (contd.)

- Integrated model of designing: GEMS of SAPPhIRE as req-sol



Validation of the Model of Designing

Empirical Validation

- Compatibility with natural way of designing, look for
  - ✓ Activities: **G, E, M, S** (and others , if any).
  - ✓ Outcomes: **SAPPhIRE** (esp. effects/laws)
  - ✓ Requirements/Solutions
- Video-Protocol Analyses of design sessions

Empirical Validation (contd.)

- Design methods

Method	Description
M1	Functional analysis
M2	Ideal design approach
M3	Innovation situation questionnaire

- Design problems

Problem	Goal
P1	To develop a conceptual solution for keeping the university campus free from dry leaves
P2	To develop a conceptual solution for a locking system that does not require any physical key or numbers to remember

- Teams (PDM: Product Design & Mfg)

	T1	T2
M1	P1	P2
M2	P2	P1
M3	P1	P2

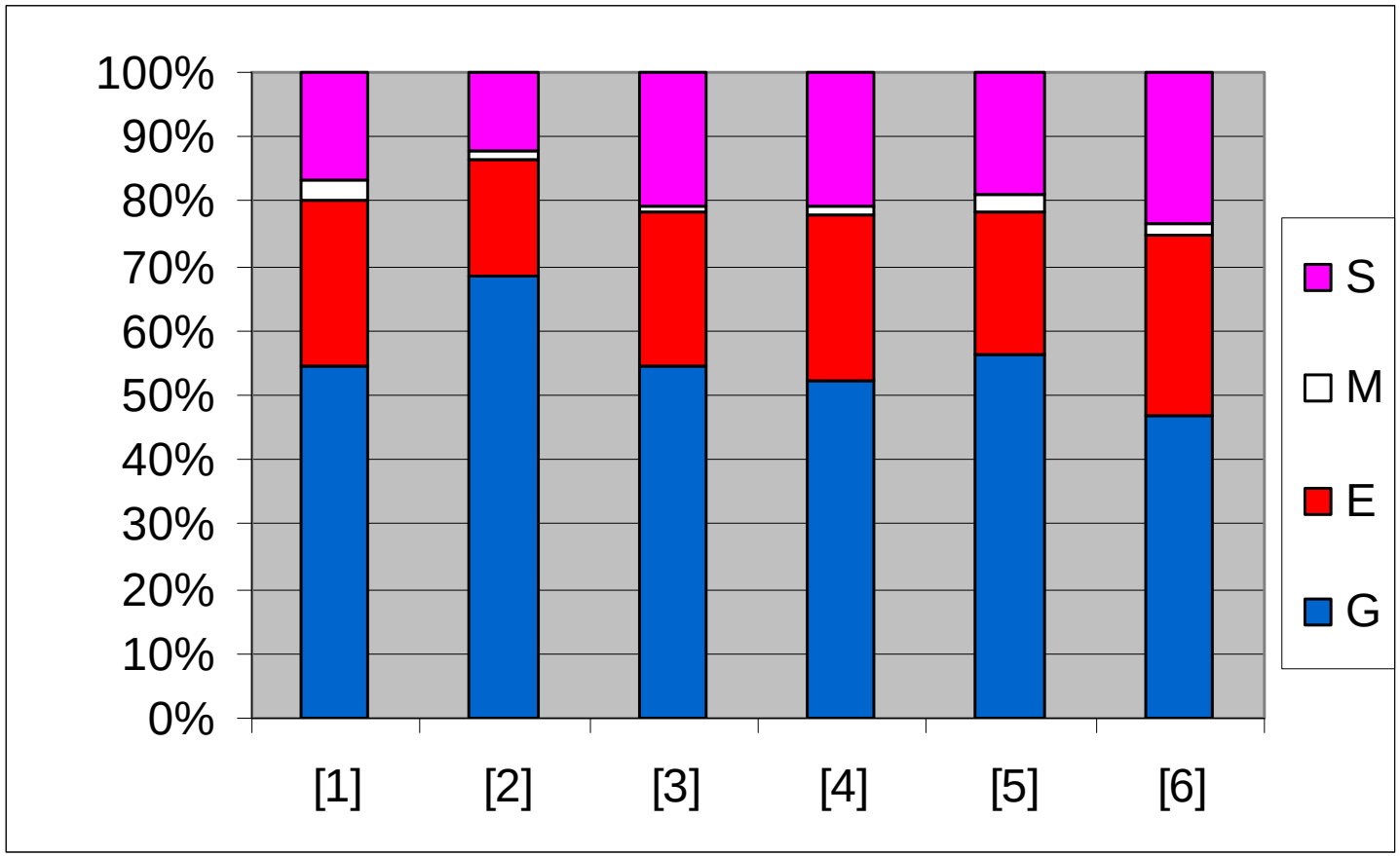
Team	Member	Education		Experience
		Bachelors	Masters	
T1	D11	Mechanical	PDM	Novice
	D12	Mechanical	PDM	Novice
	D13	Mechanical	PDM	Experienced
T2	D21	Mechanical	PDM	Novice
	D22	Mechanical	PDM	Novice
	D23	Architecture	PDM	Novice

Empirical Validation (contd.)

- Individual activity
  - **G***eneration*, **E***valuation*, **S***election* and **M***odification* identified

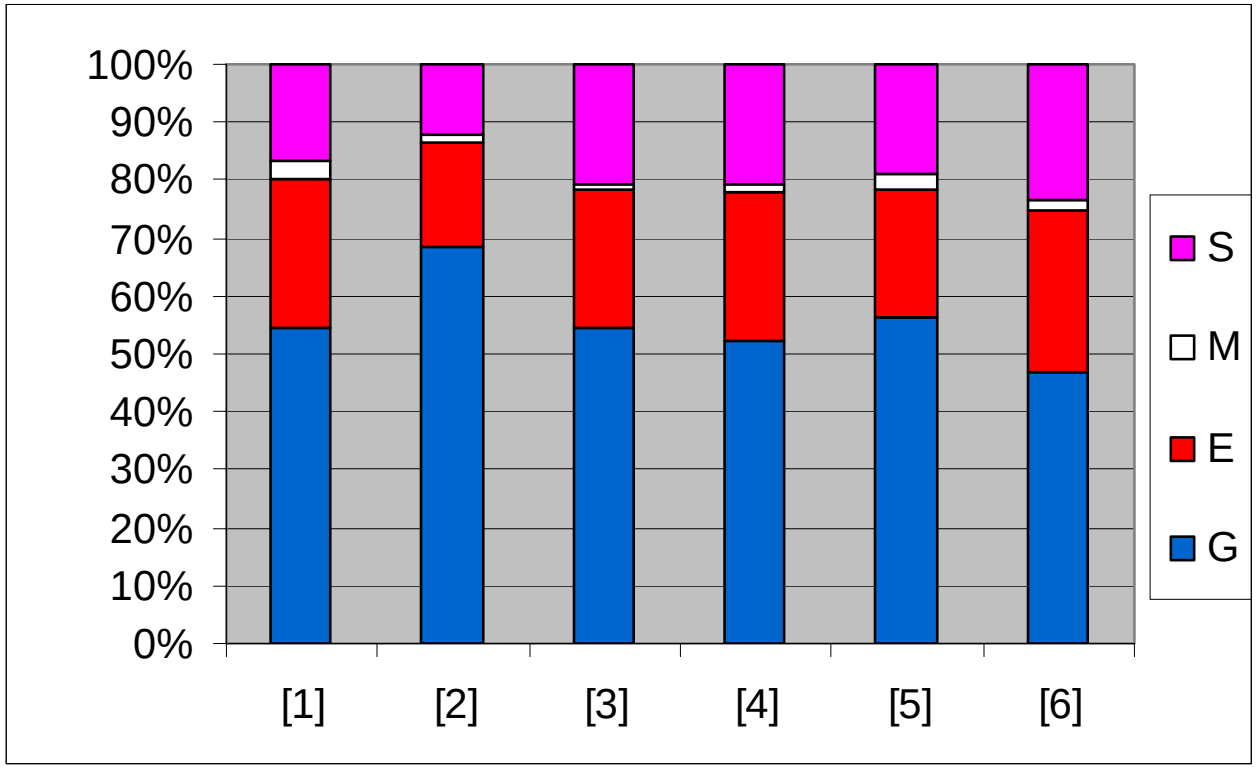
Activity	Code	Protocol Instance
Generate	G	D: So, what has to be achieved is that the campus has to kept free from dry leaves *(Generation: Campus to be kept free from dry leaves)* *[Episode: Designer defines the purpose of design exercise by generating a requirement]*
Evaluate	E	D: Is sweeping okay? *(Evaluation: Checking the worth of sweeping)* *[Episode: Designer generates an idea for clearing-off dry leaves and estimates its worthiness]*
Modify	M	D: Instead of manual sweeping, collection is a better term *(Modification: Change from 'manual sweeping' to 'collection')* *[Episode: designer generates a solution for clearing dry leaves (manual sweeping) and then feels collection maybe a more general term]*
Select	S	D1: Some secret code is required because each individual will have it differently D2: Yeah *(Selection: D2 accepting the solution proposed by D1)* *[Episode: First designer generates a solution to have a safe, private locking system which is accepted by the second designer]*

Empirical Validation (contd.)



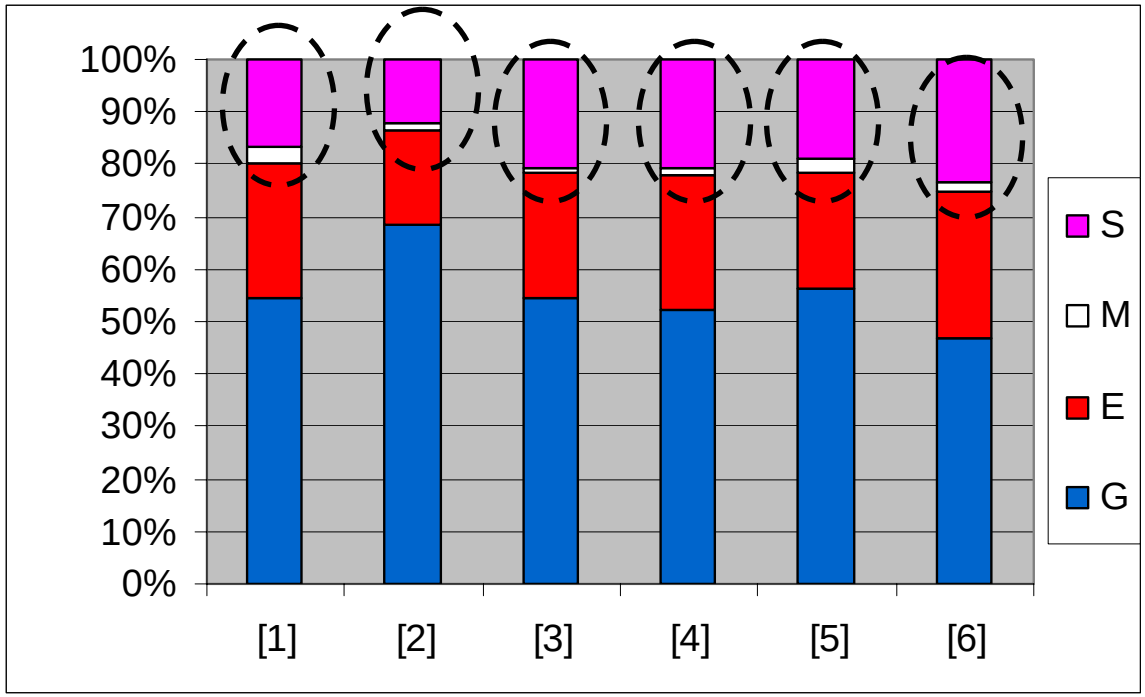
#G>#E>#S>#M

Empirical Validation (contd.)



#E=#(S+M) (approx.) → *S or M generally after E?*

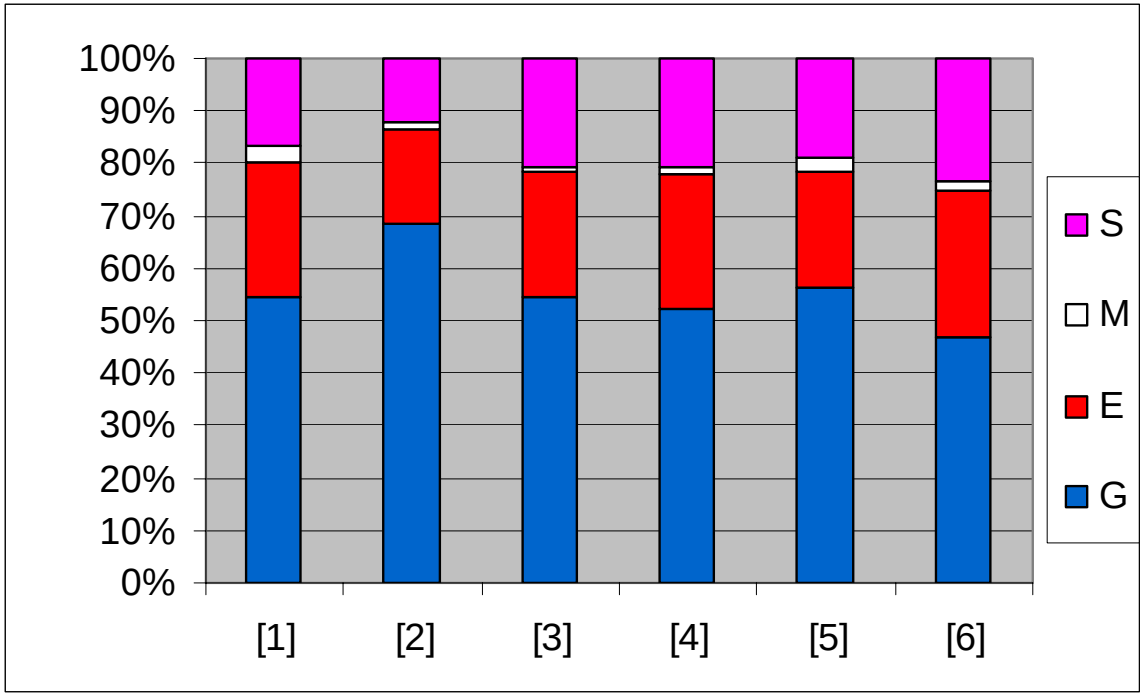
Empirical Validation (contd.)



#M<#S

- *Objective of design exercises: original design and not redesign?*
- *Shorter duration (45 min) of protocols? – designers preferred to accept solutions with lesser iterations?*

Empirical Validation (contd.)



No explicit 'rejection' observed → *short time duration?*

Empirical Validation (contd.)

- Activity-patterns

Activity Pattern	Instance from protocol
G	D: system's primary useful function-it should lock when it is required to lock and open when it is required to open *(G: function of lock)* *[Episode: A designer states the purpose of a locking system, before designing it]*
GE	D: Why don't we have an implanted, body-planted chip? *(G: implantation of body-planted chip & E: worthiness of implanted body-planted ship)* *[Episode: A designer generates an idea for a key to a locking system, which the user can carry anywhere, without having to remember/forget that he/she has the key]*
GES	D1: Concept is to sense something from the physical body and then process it, and operate D2: (thinks) Yeah *(G: sense something from physical body and process; E (implicitly-D2's thought process):(worthiness of) sense something from physical body and process; S: sense something from physical body and process)* *[Episode: Designer 1 generates an idea for sensing something from one's body, to operate locking system and designer 2 supports)*
GEM	D1:Those (existing locking systems) structures have components, it has got levers D2: (thinks) It has got plungers actually *(Evaluate and Modify)* *(G: levers in existing locking systems; E: locking systems (to check whether they have levers or anything else; M: levers →plungers)* *[Episode: Designers analyze the structure of the locking system]*

Empirical Validation (contd.)

Activity pattern	[1]	[2]	[3]	[4]	[5]	[6]
G	166	144	97	74	181	98
GE	29	11	5	8	4	10
GEM	11	3	0	1	10	3
GES	49	19	28	34	88	73
GESE	1	1	0	0	0	0
GEMES	2	0	0	1	1	1
GESES	11	4	4	5	2	3
GESEM	0	1	1	0	0	0
GESESE	0	0	0	0	0	1
GEMESES	1	0	1	0	1	0
GESESES	2	1	4	1	0	3
GESEMES	1	0	0	0	0	0
GESESEM	0	0	0	1	1	1
GESEMEM	0	0	0	0	0	1
GESESESE	0	0	1	0	0	0
GESEMESESES	0	0	0	0	0	1

#G > #GES > #GE > #GEM

Empirical Validation (contd.)

Activity pattern	[1]	[2]	[3]	[4]	[5]	[6]
G	166	144	97	74	181	98
GE	29	11	5	8	4	10
GEM	11	3	0	1	10	3
GES	49	19	28	34	88	73
GESE	1	1	0	0	0	0
GEMES	2	0	0	1	1	1
GESES	11	4	4	5	2	3
GESEM	0	1	1	0	0	0
GESESE	0	0	0	0	0	1
GEMESES	1	0	1	0	1	0
GESESES	2	1	4	1	0	3
GESEMES	1	0	0	0	0	0
GESESEM	0	0	0	1	1	1
GESEMEM	0	0	0	0	0	1
GESESESE	0	0	1	0	0	0
GESEMESESES	0	0	0	0	0	1

Almost all patterns culminate in selection *(natural)* or modification

Empirical Validation (contd.)

Activity pattern	[1]	[2]	[3]	[4]	[5]	[6]
G	166	144	97	74	181	98
GE	29	11	5	8	4	10
GEM	11	3	0	1	10	3
GES	49	19	28	34	88	73
GESE	1	1	0	0	0	0
GEMES	2	0	0	1	1	1
GESES	11	4	4	5	2	3
GESEM	0	1	1	0	0	0
GESESE	0	0	0	0	0	1
GEMESES	1	0	1	0	1	0
GESESES	2	1	4	1	0	3
GESEMES	1	0	0	0	0	0
GESESEM	0	0	0	1	1	1
GESEMEM	0	0	0	0	0	1
GESESESE	0	0	1	0	0	0
GESEMESESES	0	0	0	0	0	1

Patterns culminating in modification not subjected to any evaluation

→*Evaluated and selected, both implicitly*

Empirical Validation (contd.)

Activity pattern	[1]	[2]	[3]	[4]	[5]	[6]
G	166	144	97	74	181	98
GE	29	11	5	8	4	10
GEM	11	3	0	1	10	3
GES	49	19	28	34	88	73
GESE	1	1	0	0	0	0
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GESEM	0	1	1	0	0	0
GESESE	0	0	0	0	0	1
GEMESES	1	0	1	0	1	0
GESESES	2	1	4	1	0	3
GESEMES	1	0	0	0	0	0
GESESEM	0	0	0	1	1	1
GESEMEM	0	0	0	0	0	1
GESESESE	0	0	1	0	0	0
GESEMESESES	0	0	0	0	0	1

Certain patterns (GE, GESE, GESESE) culminate in evaluation

→*Implicit selection?*

Empirical Validation (contd.)

Activity pattern	[1]	[2]	[3]	[4]	[5]	[6]
G	166	144	97	74	181	98
GE	29	11	5	8	4	10
GEM	11	3	0	1	10	3
GES	49	19	28	34	88	73
GESE	1	1	0	0	0	0
GEMES	2	0	0	1	1	1
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GESEM	0	1	1	0	0	0
GESESE	0	0	0	0	0	1
GEMESES	1	0	1	0	1	0
GESESES	2	1	4	1	0	3
GESEMES	1	0	0	0	0	0
GESESEM	0	0	0	1	1	1
GESEMEM	0	0	0	0	0	1
GESESESE	0	0	1	0	0	0
GESEMESESES	0	0	0	0	0	1

Patterns have multiple evaluations, selections, and modifications

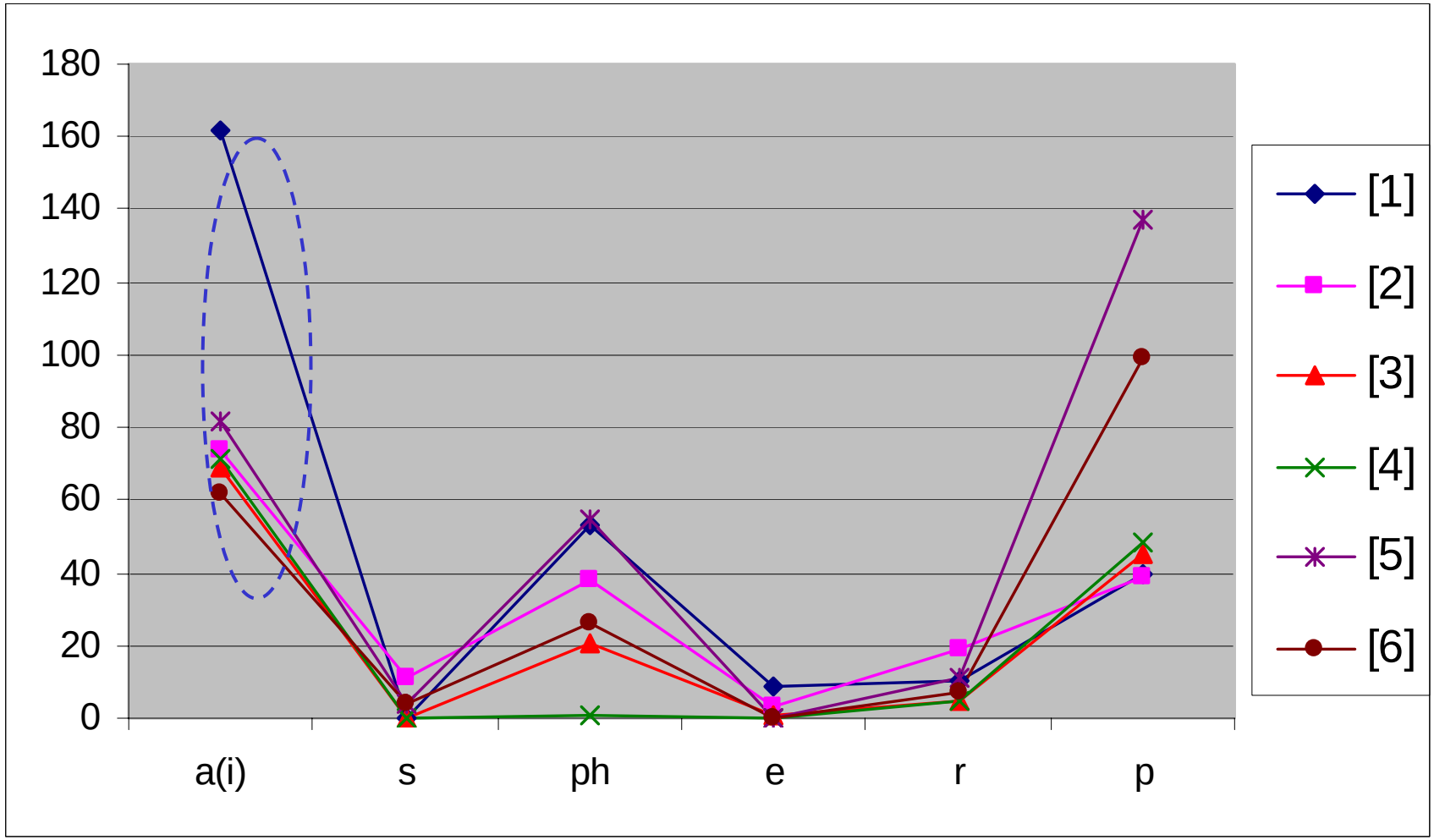
- *Design problem solved by a team, each member adds his/her own point(s) of view?*
- *Emphasizes iterative nature of design?*

Empirical Validation (contd.)

- Outcomes

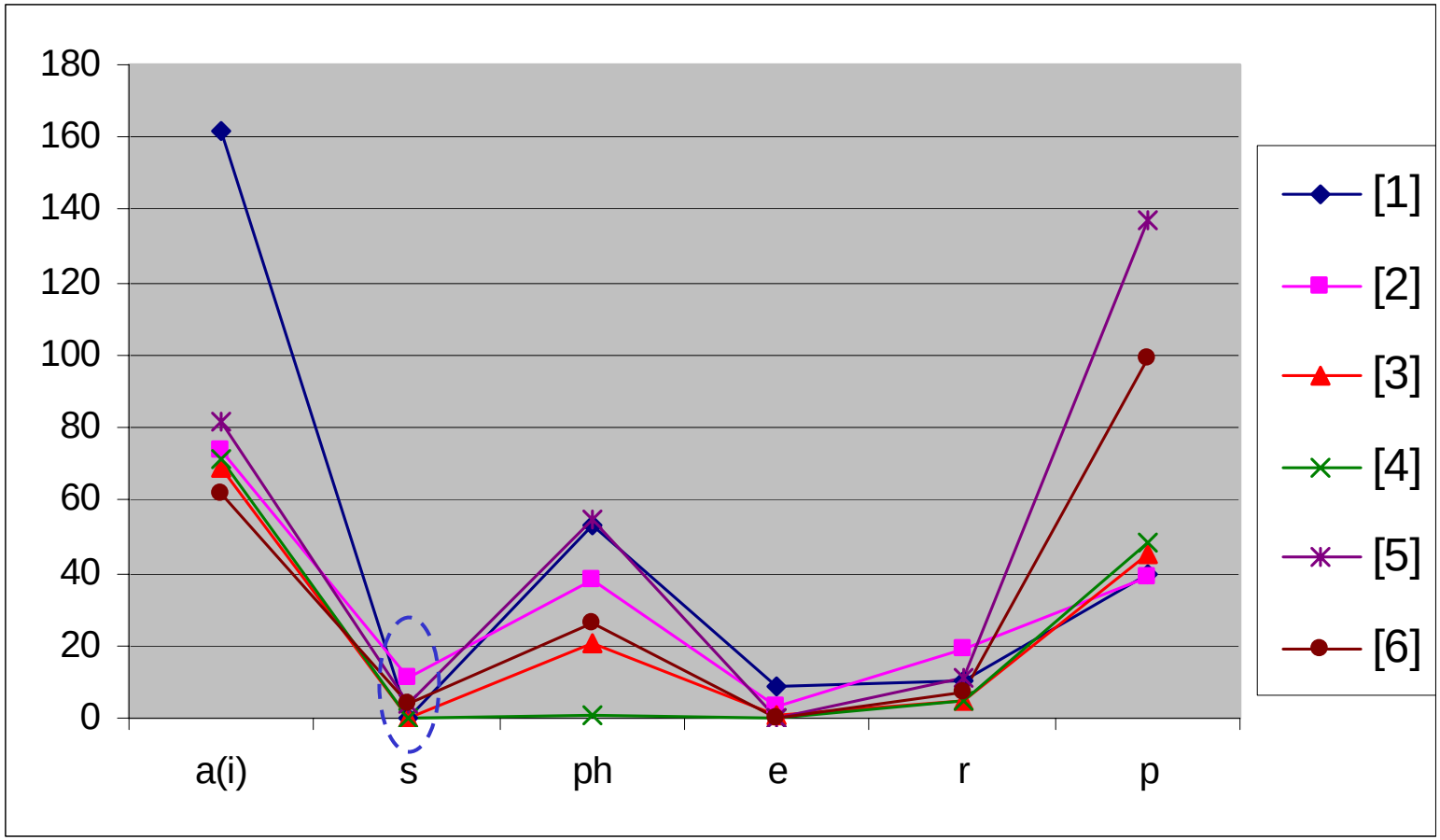
SAPPhIRE	Instances
a (i)	D: So, what has to be achieved is that the campus has to be kept free from dry leaves *(Action: Interpreted as dry leaves → no dry leaves)* *[Episode: Designer states the requirement to be fulfilled i.e., keep the campus free from dry leaves and at a higher level of abstraction, closer to the problem]*
s	D: System's primary useful function is that it should lock when it is required to lock and open when it is required to open *(State change: unlock → lock or lock →unlock)* *[Episode: Designer stating the purpose of the lock, which has to be designed and is closer to a solution]*
p	D: transportation can be done by carrying the bins and baskets manually, small trucks or tractors *(Part: Bins, baskets, small trucks, tractors)* *[Episode: Designer generates ideas for transporting dry leaves from one place to another]*
ph	D: So, the functions that the system will take care of are: cleaning, loading, transportation, unloading and disposal of dry leaves. *(Ph: cleaning, loading, transportation, unloading, and disposal)* *[Episode: Designer generates the process of keeping the campus free from dry leaves]*
r	D: So input is gravity, self-weight, weak link *(Organ: Weak link)* *[Episode: designers reasoning the factors responsible for the fall of a leaf]*
e	D: Because, of the force of gravity-gravitational force (D2 writes on the paper) *(Effect: Newton's law of gravitational force)* *[Episode: Designer explains the cause of fall of a leaf]*

Empirical Validation (contd.)



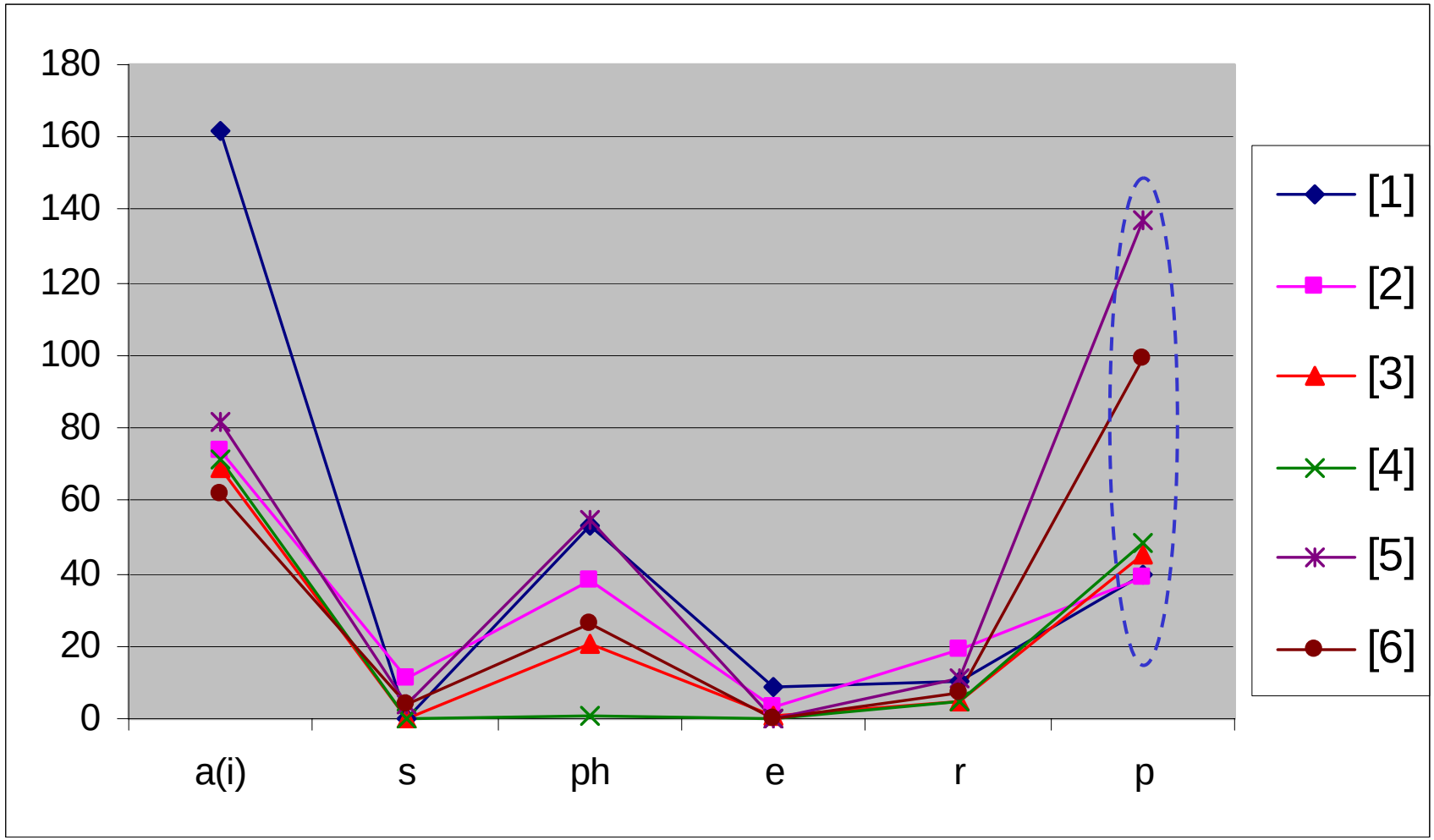
High incidence of action-level descriptions→*derived directly from design problem*

Empirical Validation (contd.)



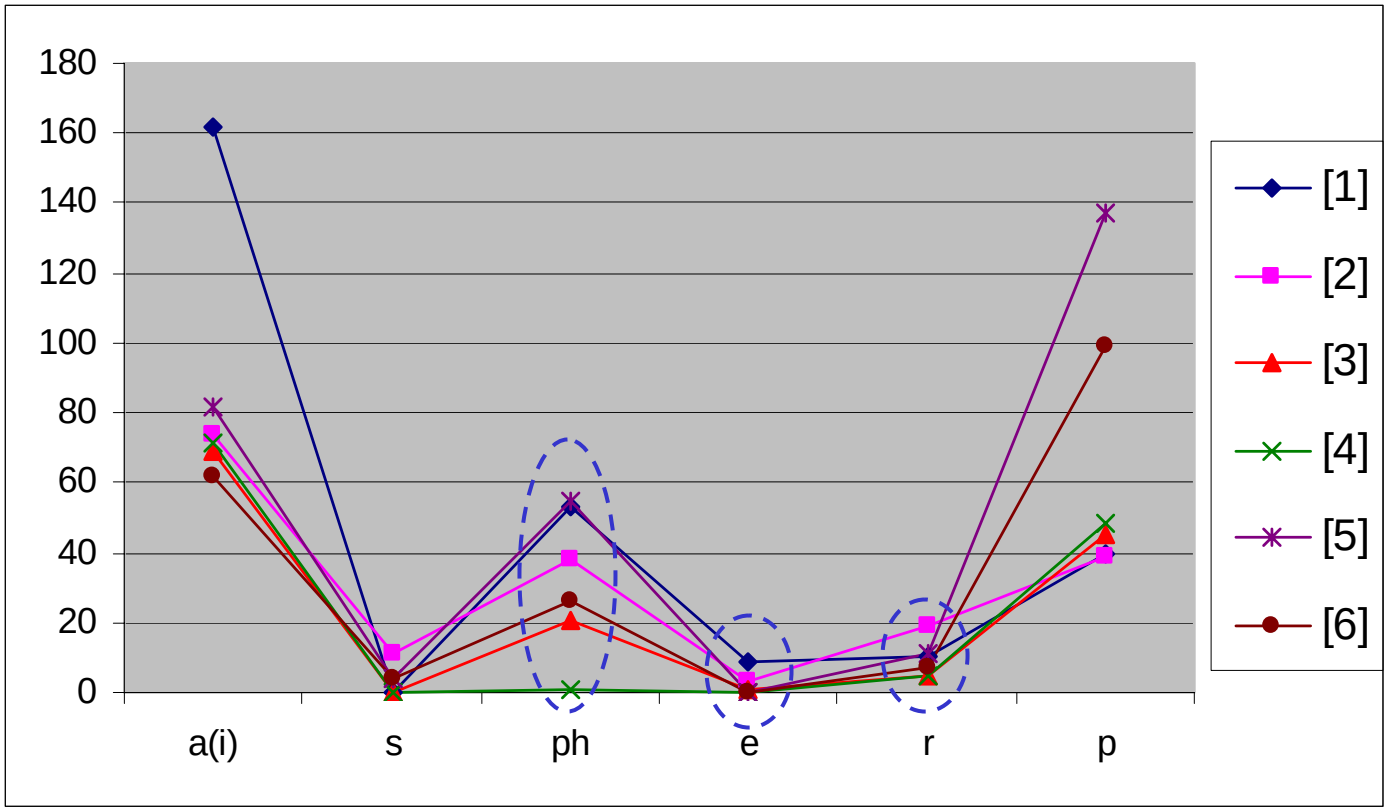
state change-level descriptions few in number → *Another way of expressing 'action' and could have been included under it?*

Empirical Validation (contd.)



High number of part-level descriptions→ *Designers possess better knowledge?*

Empirical Validation (contd.)



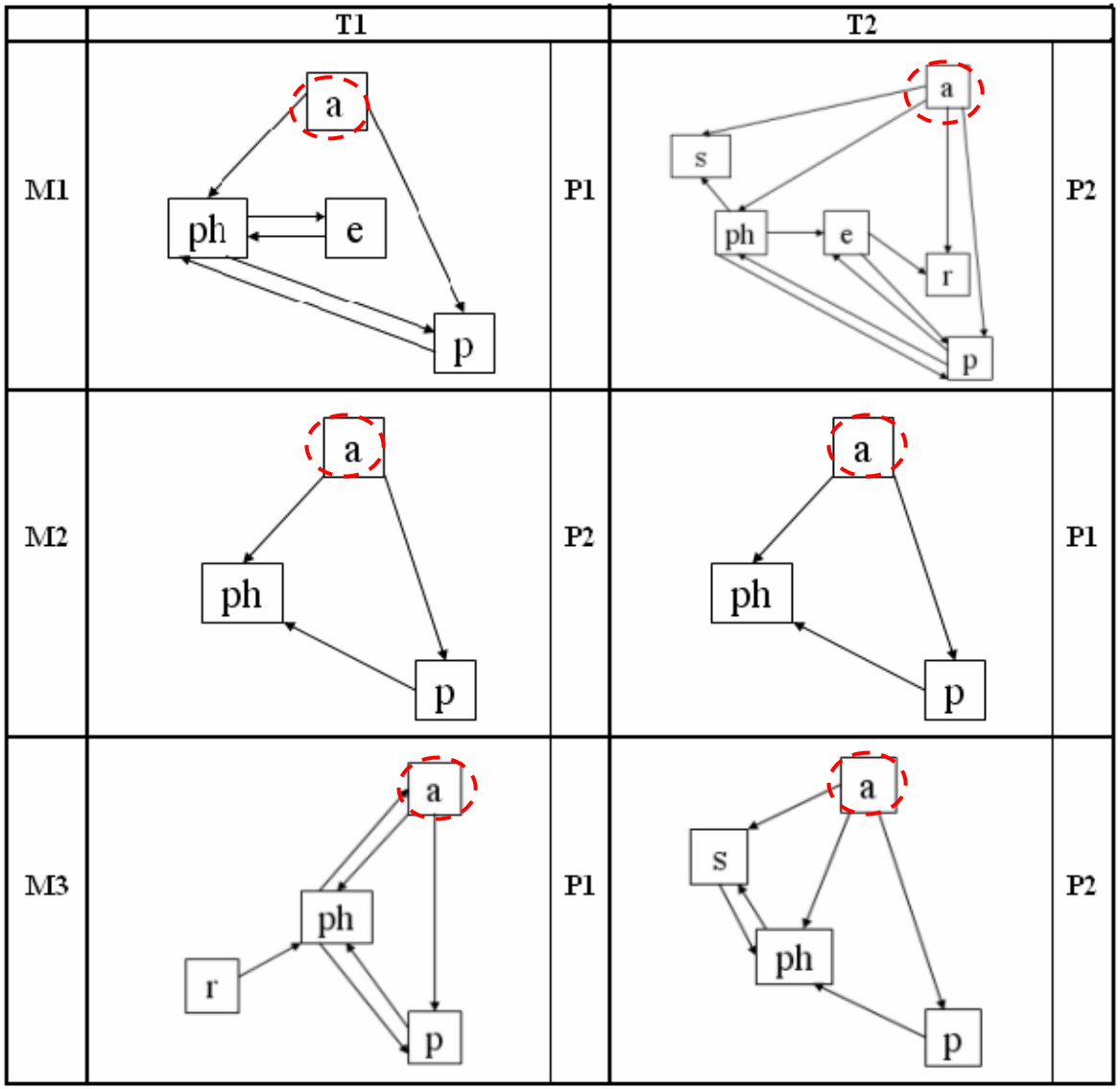
Low numbers of phenomenon-, effect- and organ-level descriptions

- *Not a part of natural way of designing?*
- *Methods did not specify use of effects?*
- *Designers lacked effects/laws knowledge? – require support?*
- *Designers did not know how to use them? – require support?*

Empirical Validation (contd.)

Outcome-patterns

Start with action-level description



Empirical Validation (contd.)

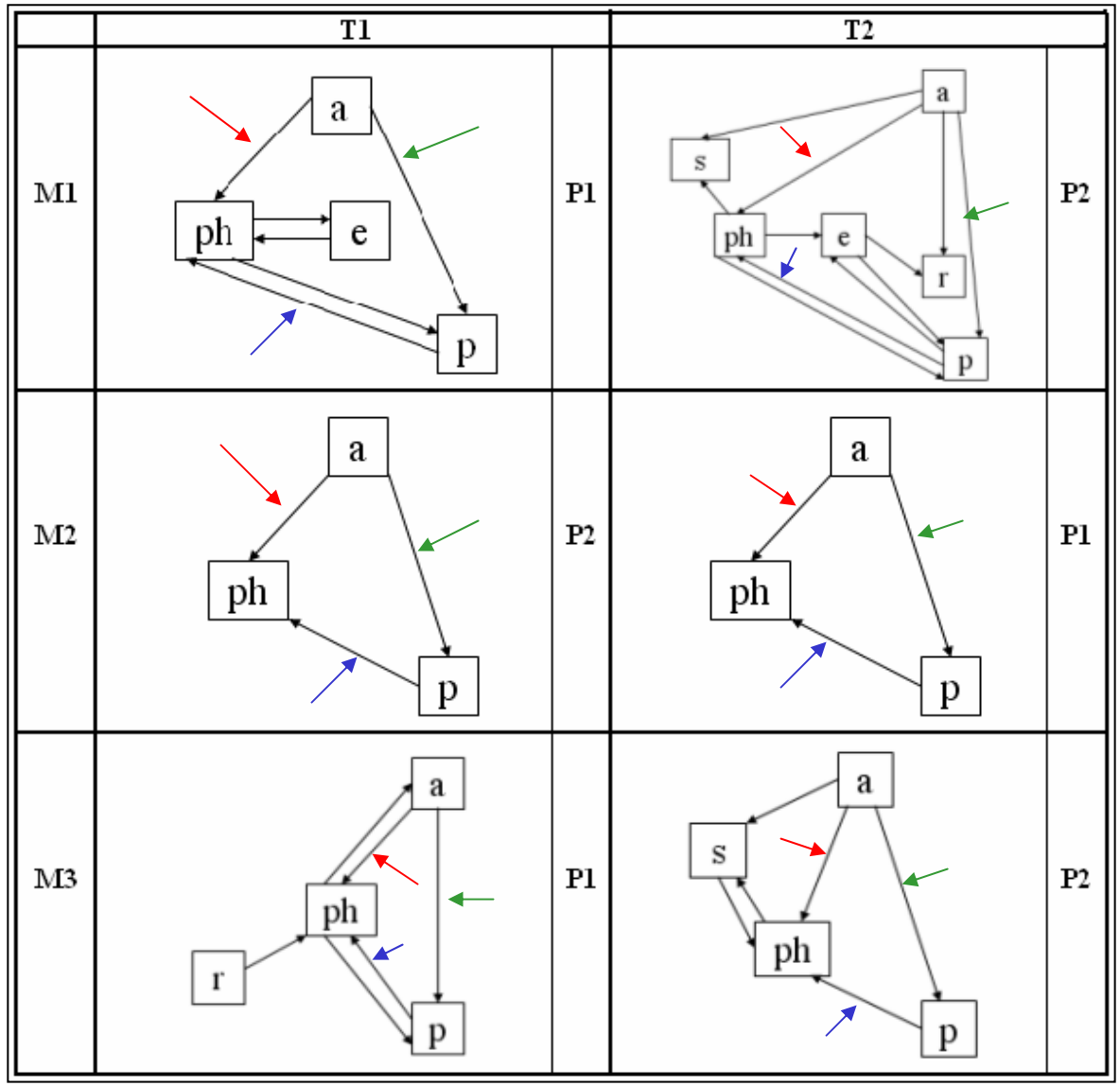
Outcome-patterns

All cases,

A→Ph

A→P

P→Ph

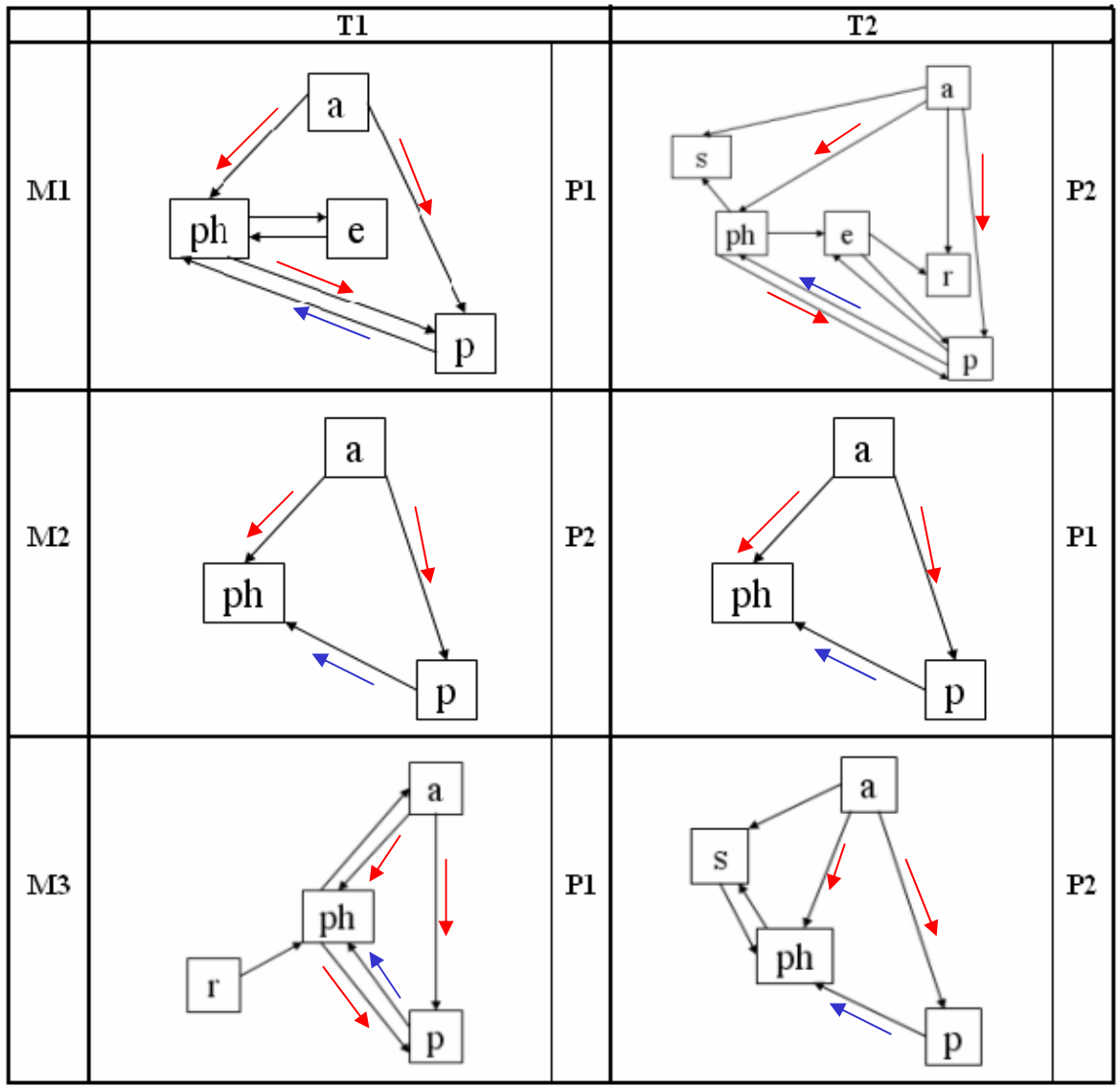


Empirical Validation (contd.)

Outcome-patterns

Synthetic nature

Analytical nature

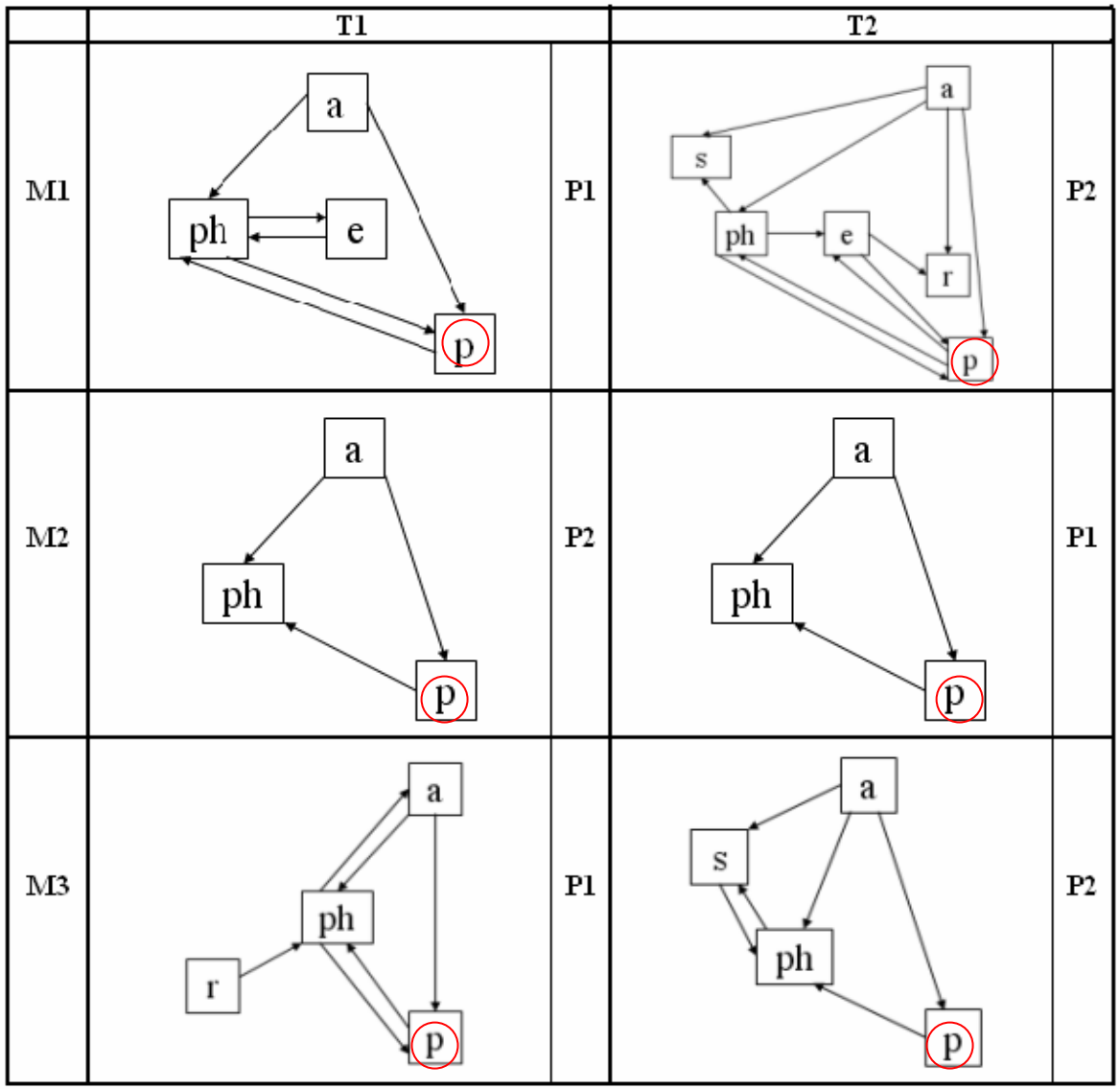


Empirical Validation (contd.)

Outcome-patterns

All cases,

- Design solutions culminate in part-level descriptions
- Parts not detailed to level of manufacturability
  - ✓*Designers given little working time (45 min)?*
  - ✓*Instructed to develop conceptual solution only?*

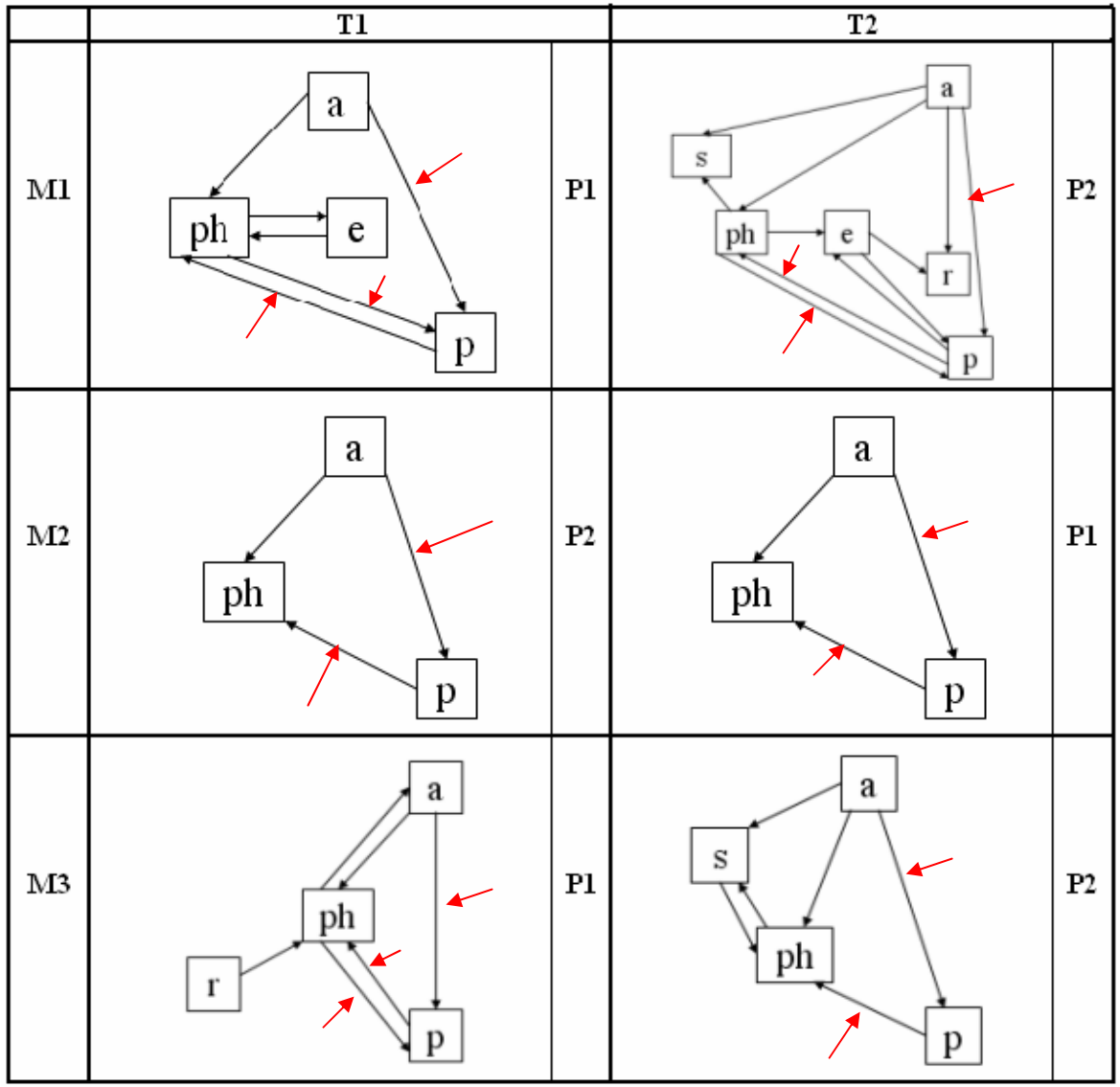


Empirical Validation (contd.)

Outcome-patterns

In A→P, Ph→P, P→Ph, transitions bypassing intermediate-levels of abstraction

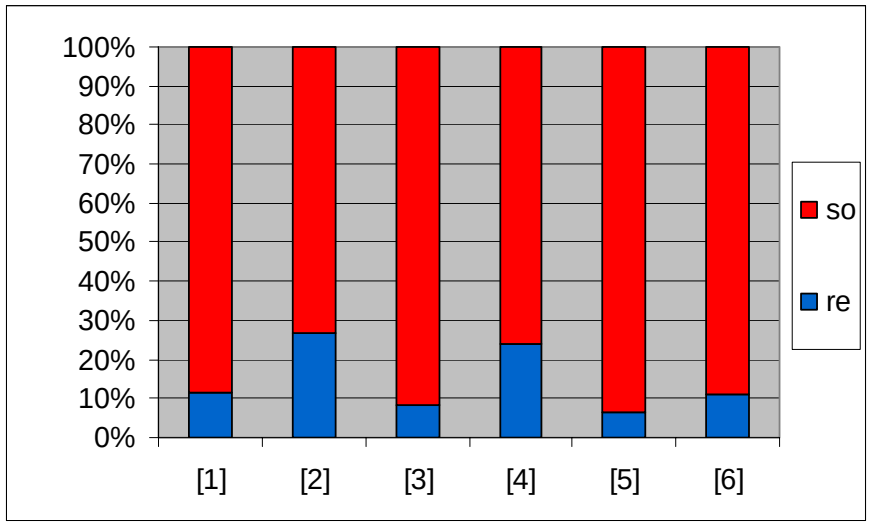
✓ *Strong part-level knowledge of designers?*



Empirical Validation (contd.)

- Re-So

Content	Code	Instance
requirement	re	D: So, our main focus will be here (points at the paper and shades a part in the sketch), wherever people want to access, those places need to be kept clean. *[Designer creates a requirement by identifying the areas to be cleaned]*
solution	so	D': This is a net-arrangement (pointing at the sketch) and this is a vacuum cleaner (pointing at the sketch) *[Designer generates a solution for collecting dry leaves and storing in a net-arrangement]*



Empirical Validation (contd.)

- Sources of Re
  - Method
  - Designer
  - Problem

Source	Code	Instance
Method	re(met)	D: Next step is criteria for selecting solution concept-desired technological characteristics, desired economic characteristics, desired timetable, expected degree of novelty, and other criteria (reads from the instruction-sheet) *[Designer reads out the requirement specified by method (ISQ) from the instruction-sheet i.e., to generate evaluation criteria-technological, economy etc.]*
Designer	re(des)	D: So, it (lock) should not be electricity dependent or it can have its own battery, why not? *[Designer creates a requirement that the locking system should not be electricity-dependent, but, however, it can be battery-powered]*
Problem	re(pro)	D': So, what has to be achieved is that the campus has to kept free from dry leaves. *[Designer spells out the objective of the design exercise i.e. to keep university campus free from dry leaves taken directly from the problem given]*

- Re-So relationships
  - Re-Re: E/M/S of Re
  - Re-So: G of So to Re
  - So-Re: G of Re to So
  - So-So: E/M/S of So

Relationship	Instance
re-re	D: Now there is a constraint, no physical key, no code, in the sense alpha-numeric. D: I have a doubt, is alpha (numeric) also included in this? *[Designer 'D' develops a requirement for conceptual solution of a locking system and clarifies (evaluates) by asking whether if 'alpha-numeric' is also included in the requirement]*
re-so	D': If humans are there then, supervising can be done by cameras like its done here (points at the camera) *[Designer D proposes to use cameras as solution for a requirement of supervising]*
so-re	D': unloading and disposal, these are the areas to be satisfied by the system *[Designer D identifies 'unloading' and 'disposal' as requirements, which were previously developed as solutions for the primary useful function]*
so-so	D: Can it be a keyboard password? D': Yes, it can be a keyboard password. *[Designer 'D' clarifies whether 'keyboard password' can be used as a solution for the locking system and is accepted by another designer D']*

Empirical Validation (contd.)

- Combined activity-outcome

	G	E	M	S
a(i)	520	245	23	184
s	19	6	1	5
ph	194	91	7	72
e	13	1	0	1
r	57	25	1	20
p	408	124	10	101

Action- and part level descriptions: many instances of G, E, M & S → *designers did not face difficulty at this level?* → *strong knowledge?*

Empirical Validation (contd.)

- Activity-Outcome

	G	E	M	S
a(i)	520	245	23	184
s	19	6	1	5
ph	194	91	7	72
e	13	1	0	1
r	57	25	1	20
p	408	124	10	101

State-change level descriptions: less instances of G, E, M & S → *little differences between action and state change?* → *another way of expressing 'a'*

Empirical Validation (contd.)

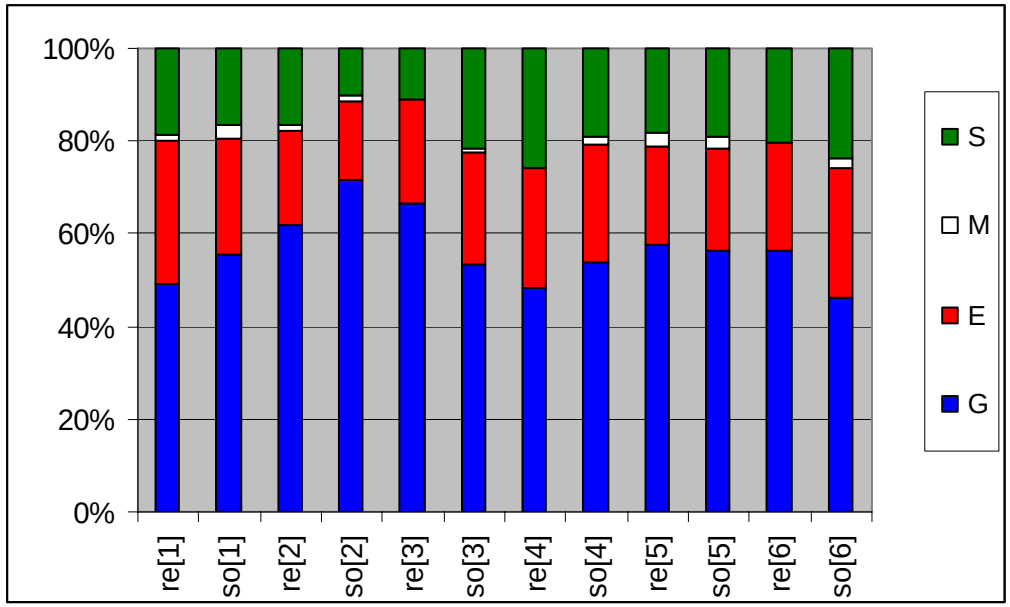
- Activity-Outcome

	G	E	M	S
a(i)	520	245	23	184
s	19	6	1	5
ph	194	91	7	72
e	13	1	0	1
r	57	25	1	20
p	408	124	10	101

Phenomenon-, effect- and organ-level descriptions: less instances of G, E, M & S → *Designers faced difficulty at these levels?*

Empirical Validation (contd.)

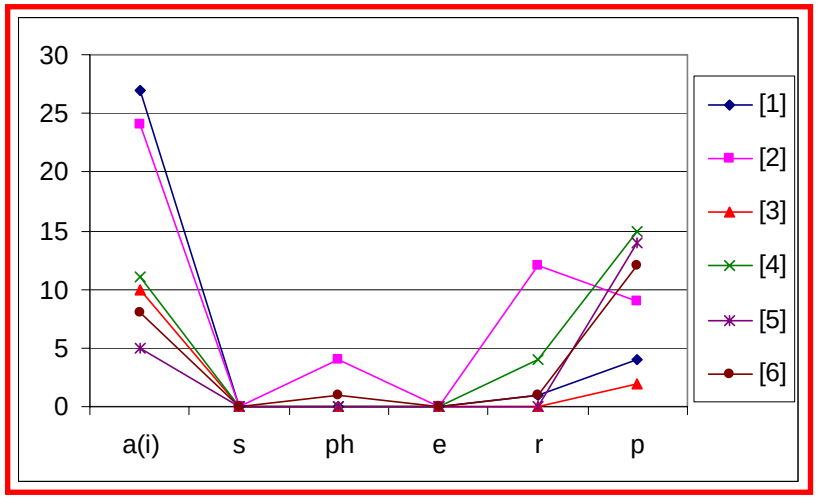
- Activity-(Req-Sol)

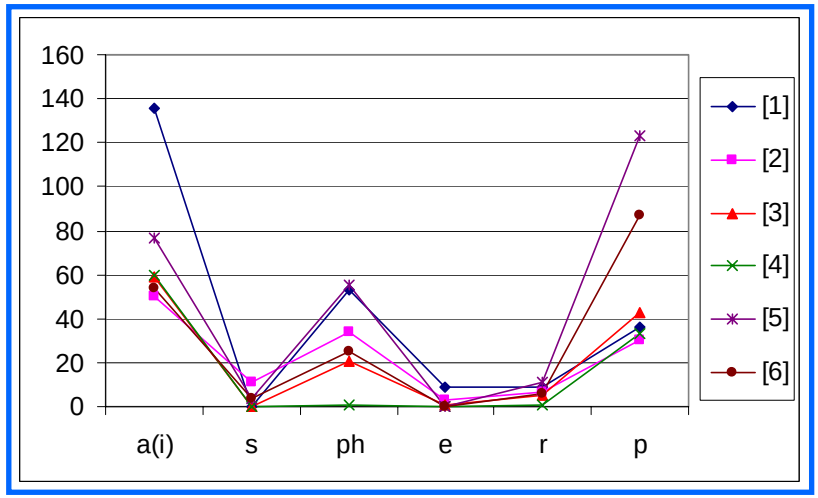


Similar patterns as observed for individual activity

Empirical Validation (contd.)

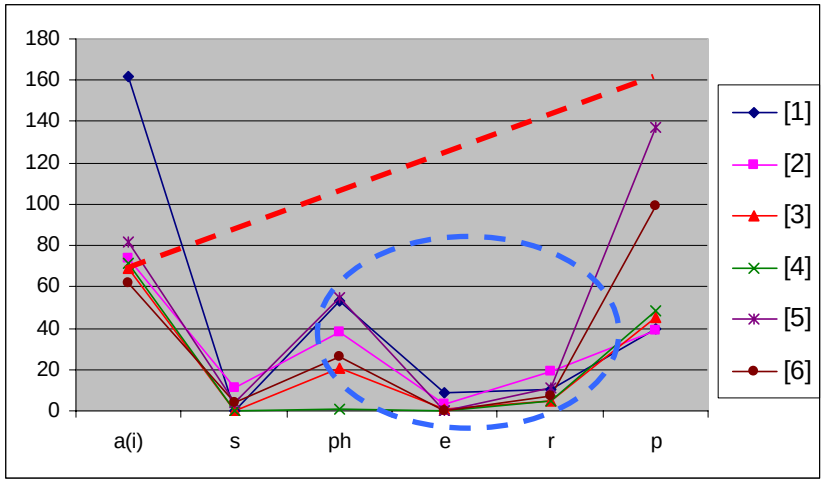
- Outcome-(Req-Sol)





Similar patterns as observed for individual outcomes

Empirical Validation (contd.)



- Expected: a single-many mapping from higher to lower levels of abstraction
- Expectation not met due to less use of ph-, e- and r-level descriptions → novelty inhibition?
- Designers not equally proficient with activities at all levels of outcomes for requirements and solutions!
- **Framework: GEMS of SAPPhIRE (as re-so) → GEMS at all levels of SAPPhIRE for both Re and So.**

Novelty-SAPPhIRE Relationship

Literature Survey

- Novelty
  - resembles
    - something not formerly known [*Sternberg & Lubart, 1999*]
    - unusualness or unexpectedness [*Shah et al., 2003*]
  - one of the measures of creativity of engineering products [*Shah et al., 2003; Lopez-Mesa & Vidal, 2006; Sarkar, 2007*]
  - importance
    - new ideas improve product quality in competetive market [*Molina et al., 1995*]
    - creative products used to increase products' price and gain larger market share [*Ottosson, 1996; Zimmerman & Hart, 1998*]
- Physical laws and effects
  - principles of nature that govern a change [*Chakrabarti et al., 2005*]
  - help synthesise novel products [*Zavbi & Duhovnic, 1997; Murakoshi & Taura, 1998*]
    - not tested empirically

Research Questions

- Is there a relationship between novelty and the constructs of the SAPPhIRE model, especially effects?
- If a relationship exists, how strong is this relationship?

Definitions

- Concept
  - solution that satisfies an overall function
  - Eg. vacuum cleaner to clean dust
- Idea
  - solution at a particular abstraction level that is a constituent of a concept
  - Eg. suction at phenomenon-level, dust-collecting chamber at part- level, etc. are constituents of a vacuum cleaner
- Idea group
  - collection of ideas at the same abstraction level
  - eg. {suction, blowing, etc} at phenomenon-level, {chamber, tubing, etc} at part-level, etc.
- Idea Space (IS)
  - collection of idea groups at all abstraction levels
  - eg. IS=[{suction, blowing, etc} at phenomenon-level, {chamber, tubing, etc} at part-level, {remove dust, gather dust, dispose dust} at action-level, etc]

Definitions (contd.)

- Size of idea group
  - number of ideas in that group of IS
- New Concept Space (NCS)
  - set of all concepts produced during designing to satisfy a function
  - Eg. NCS={magnets to clean magnetic dust, charged bodies to clean charged dust, etc.} for cleaning dust
- Existing Concept Space (ECS)
  - set of all concepts for a given function that existed even before the first concept was produced in NCS
  - Eg. ECS={broom, vacuum cleaner, mop, etc.} for cleaning dust

Definitions (contd.)

- Variety of Concept (V)
  - measure of a difference of the given concept from the other concept(s) produced before in that concept space
  - measured in terms of difference at highest abstraction level – a:7, s:6, i:5, ph:4, e:3, r:2, p:1
  - V(first concept)=0
  - Eg. charged bodies different from magnets at effect-level, V(charged bodies)=3
- Variety of Concept Space (V(CS))
  - average of the variety of all concepts in that concept space
  - Eg. If NCS={magnets, charged bodies}, V(NCS)=(0+3)/2=1.5

Definitions (contd.)

- Novelty of concept (N)
  - measure of a difference between the concept and: (a) concepts in the ECS that satisfy the same function and (b) concept(s) produced before in that concept space
  - measured in terms of difference at highest abstraction level – a:7, s:6, i:5, ph:4, e:3, r:2, p:1
  - magnets different from {broom, vacuum cleaner, mop, etc} at effect-level (N=3)
  - charged bodies different from {magnets} and {broom, vacuum cleaner, mop, etc} and magnets at effect-level (N=3)
- Novelty of Concept Space (N(CS))
  - average of the novelty of all the concepts in that concept space

Definitions (contd.)

- Variety of idea space
  - measure of a difference of all the ideas from each other in that idea space

$$V(IS) = \sum_{j=a}^{p} w_j (n_j - 1)$$

  - n_a, n_s, n_i, n_{ph}, n_e, n_r, n_p: no. of ideas at the action, state change, input, phenomenon, effect, organ and part-level
  - w_a, w_s, w_i, w_{ph}, w_e, w_r, w_p : weightage at the action, state change, input, phenomenon, effect, organ and part-level (7, 6, 5, 4, 3, 2, 1)

Research Approach

- Validate hypothesis using empirical studies
  - using existing protocol studies of designing sessions
  - designers follow natural way of designing
    - do not make explicit use of SAPPhIRE model

	Designer	Problem
Experienced	E1	P1
	E2	P2
	E3	P2
	E4	P1
Novice	N1	P1
	N2	P1
	N3	P2
	N4	P2

problem	objective
P1	To design a m/c to make holes in any direction in 3-d, subject to constraints..
P2	To design a device to clean utensils, subject to constraints..

Research Approach (contd.)

- Validate hypothesis using empirical studies (contd.)
  - Identify concept(s)
  - Identify idea(s)
  - Estimate ECS
    - www: How stuff works, Wikipedia, etc.
  - Estimate variety & novelty of each concept
    - Modified form of method of [*Chakrabarti & Sarkar, 2007*]
      - Use only SAPPhIRE constructs with quantitative scale
  - Estimate variety & novelty of concept space
  - Compute size of idea groups & variety of idea-space
  - Compute correlation values
    - Determine: degree of relationship between variety/novelty & abstraction levels
      - Variety of concept space – size of idea groups at different abstraction levels
      - Novelty of concept space – size of idea groups at different abstraction levels
    - Test hypothesis
      - Variety of concept space – Variety of idea space
      - Novelty of concept space – Variety of concept space
    - Pearson's correlation to compute correlation values

Results

	Experienced				Novice			
	E1	**E2**	**E3**	**E4**	**N1**	**N2**	**N3**	**N4**
s(a)	9	8	7	6	6	7	13	12
s(s)	1	0	0	1	2	0	0	0
s(i)	1	1	1	2	0	0	0	1
s(ph)	32	7	12	5	9	3	11	7
s(e)	1	0	0	0	0	0	2	0
s(r)	19	2	1	4	1	2	5	1
s(p)	40	20	16	14	25	9	9	18

Ideas at different abstraction levels

	s(IS)		
Designer	**s(a+s+i)**	**s(ph+e)**	**s(r+p)**
E1	11	33	59
E2	9	7	22
E3	8	12	17
E4	9	5	18
N1	8	9	26
N2	7	3	11
N3	13	13	14
N4	13	7	19

Categorised ideas at different abstraction levels

- designers not told about SAPPhIRE model
- a+s+i ~ function; ph+e ~ behavior; r+p ~ structure
- results valid in a more generic sense

Results (contd.)

Designer	V(CS)	N(CS)
E1	4.44	3.89
E2	3.88	3.13
E3	3.75	2.92
E4	3	2.57
N1	2.42	1.58
N2	3.14	2.14
N3	4.54	4
N4	3.69	3.54

Variety and Novelty of concept space

	V(CS)	N(CS)
s(a+s+i)	0.66 (0.90-0.95)	0.82 (0.98-0.99)
s(ph+e)	0.60 (<0.90)	0.56 (<0.90)
s(r+p)	0.33 (<0.90)	0.33 (<0.90)

- Correlation values [variety/novelty of concept space – size of categorized idea space]
  - Variety: decreases with decrease in abstraction level
  - Novelty: decreases with decrease in abstraction level
- Signifies importance of higher abstraction levels (and not just effects)
- Establishes relationship between novelty & SAPPhIRE constructs

Results (contd.)

	V(CS)
V(IS)	0.65 (0.90-0.95)
N(CS)	0.95 (>0.99)

- Correlation values
  - V(CS)-V(IS)
  - N(CS)-V(CS)
- Validates the hypothesis: V(IS)→V(CS)→N(CS)

Main Findings

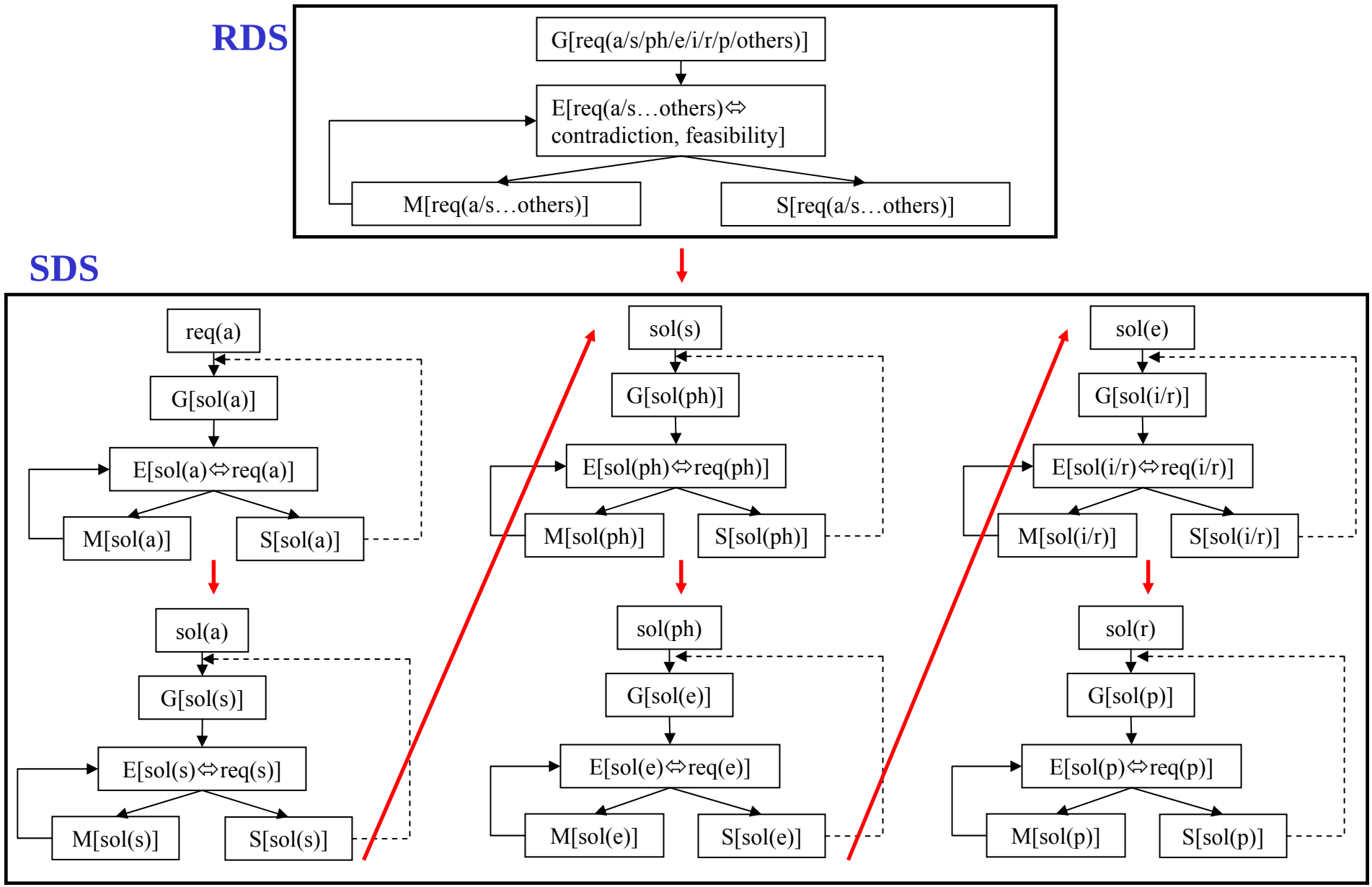
- Relationship between novelty and SAPPhIRE constructs – higher abstraction level important
- V(IS)→V(CS)→N(CS); empirically verified

Framework for Designing

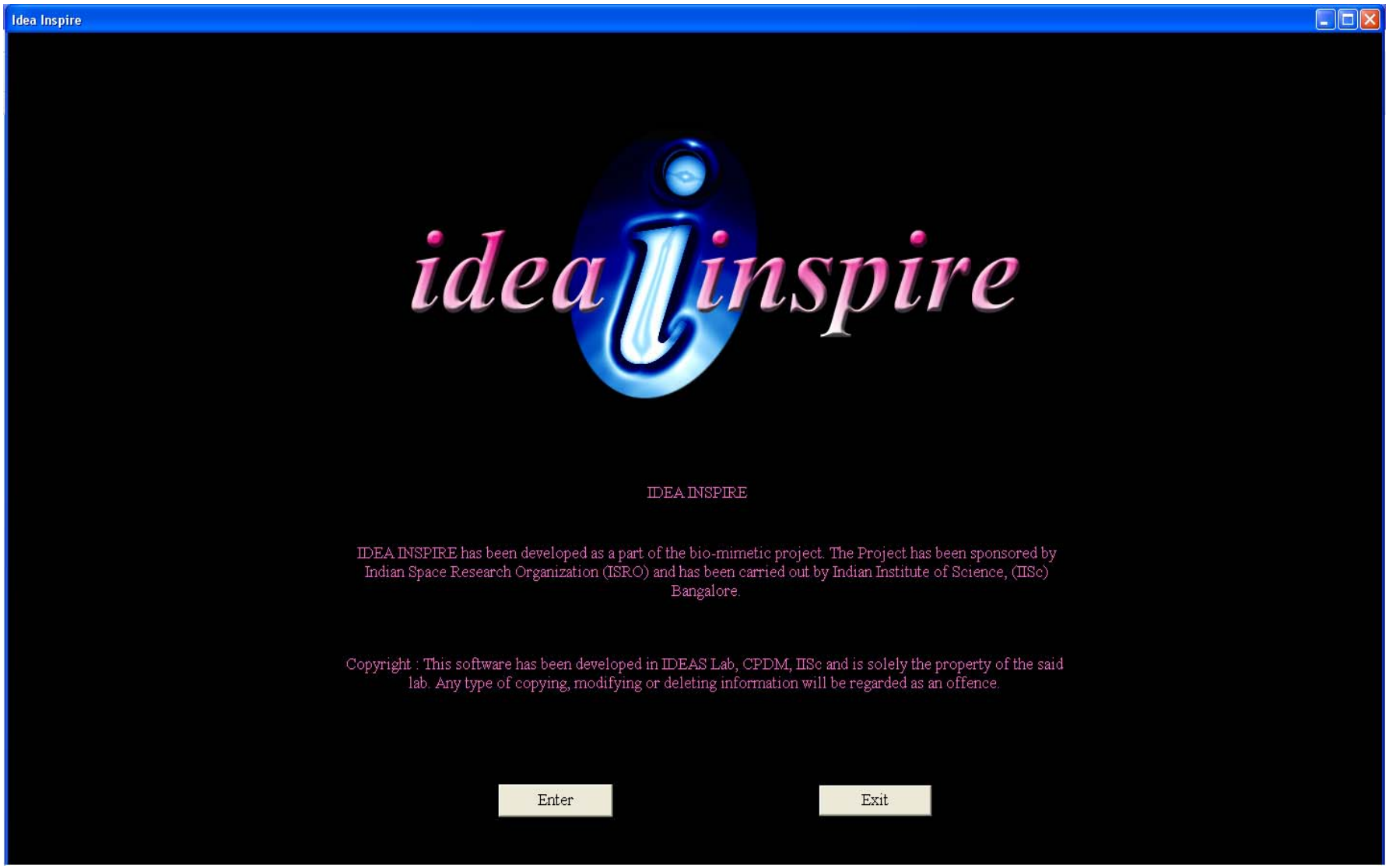
Framework for Designing

- GEMS of SAPPhIRE as req-sol
  - Prescriptive framework for designing
  - Supports development of novel designs
  - Addresses:
    - Task clarification stage
    - Conceptual design stage
    - Early embodiment design stage
  - Integrates:
    - Activities (GEMS)
      - **G**enerate, **E**valuate, **M**odify and **S**elect
    - Outcomes (SAPPhIRE)
      - **S**tate change, **A**ction, **P**arts, **Ph**enomenon, **I**nput, o**R**gan and **E**ffect
    - **Req**uirements and **Sol**utions (req-sol)
  - Divided into:
    - Requirements Development Stage (RDS)
      - Requirements at different levels including SAPPhIRE are developed
    - Solutions Development Stage (SDS)
      - Solutions at different levels of SAPPhIRE are developed

Framework for Designing (contd.)



IDEA-INSPIRE


Idea Inspire
idea inspire
IDEA INSPIRE
IDEA INSPIRE has been developed as a part of the bio-mimetic project. The Project has been sponsored by Indian Space Research Organization (ISRO) and has been carried out by Indian Institute of Science, (IISc) Bangalore.
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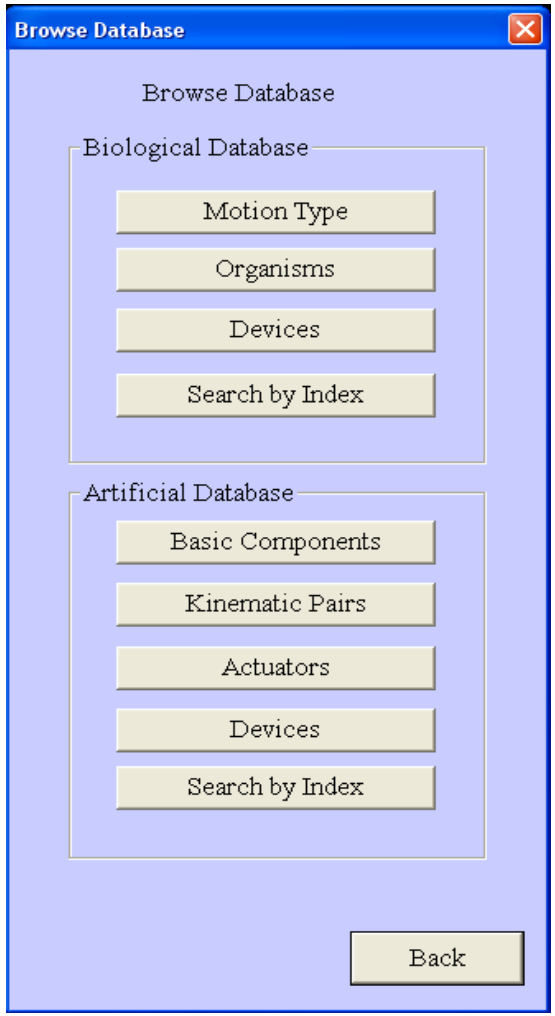
Enter
Exit

- IDEA-INSPIRE can be used in two modes:
  - Browse database
    - Used when the problem is not well-defined
    - Entries of natural and engineered systems in database can inspire designers to pursue solution
  - Solve problem
    - Used when the problem can be defined using the constructs
    - Software searches for analogous solutions

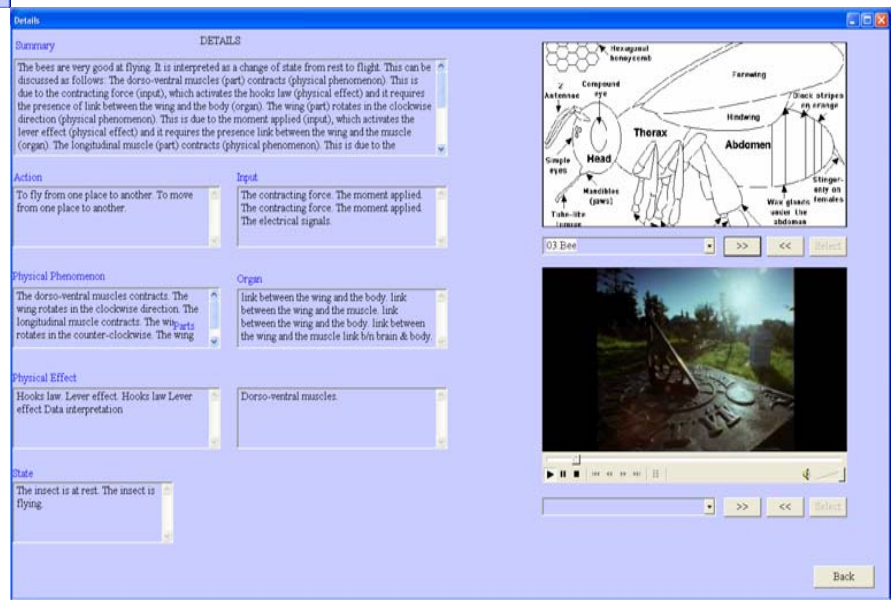
Browse Database



Example of a Natural system: **Bee**

← FBS-description

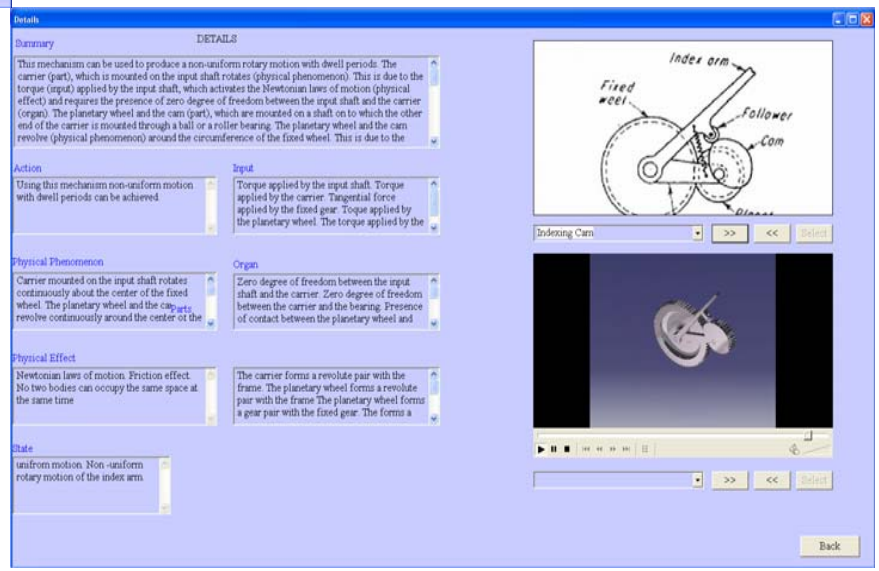
SAPPhIRE-description →



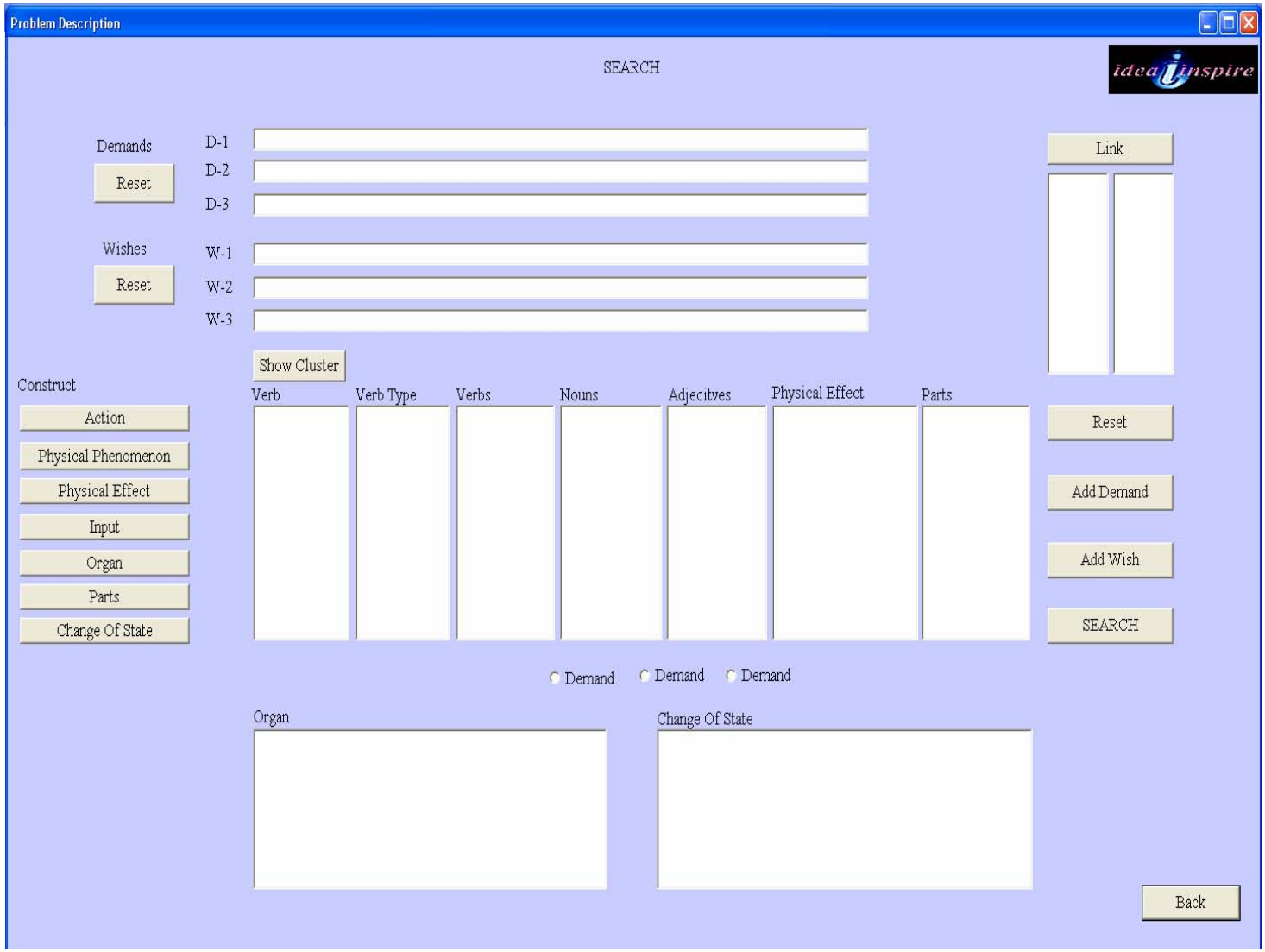
Example of an Engineered system: Indexing Cam

← FBS-description

SAPPhIRE-description →



Solve Problem



Thank you!

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