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The Innovation Competencies - Implications for Educating the Engineer of the Future

Prof. William A. Kline, Rose-Hulman Institute of Technology

Bill Kline is Dean of Innovation and Engagement and Professor of Engineering Management at Rose-Hulman. He joined Rose-Hulman in 2001 and his teaching and professional interests include systems engineering, design, quality, innovation, and entrepreneurship.

Prior to joining Rose-Hulman, his industry experience includes roles as cofounder and Chief Operating Officer at Montronix and development manager at Kennametal.

Bill is a Phi Beta Kappa graduate of Illinois College and a Bronze Tablet graduate of University of Illinois at Urbana Champaign where he received a Ph.D. degree in Mechanical Engineering.

Mr. William D. Schindel, ICTT System Sciences

William D. Schindel is president of ICTT System Sciences, a systems engineering company, and developer of the Systematica Methodology for model and pattern-based systems engineering. His 40-year engineering career began in mil/aero systems with IBM Federal Systems, Owego, NY, included service as a faculty member of Rose-Hulman Institute of Technology, and founding of three commercial systems-based enterprises. He has consulted on improvement of engineering processes within automotive, medical/health care, manufacturing, telecommunications, aerospace, and consumer products businesses. Schindel earned the BS and MS in Mathematics.

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Abstract

Innovation is rapidly emerging as a critical competency for all types of organizations to ensure future success and prosperity. It is often included among the top strategic priorities for corporate leaders. This increased attention continues a trend of the last several years that highlights the importance of innovation as an organizational priority and suggests that engineering graduates must be prepared as skilled innovators in order to be successful in the technical workplace of today and the future.

This paper presents ideas, models, and new directions in engineering education. The paper proposes the types of educational processes envisioned to most appropriate to instilling the innovation competencies in engineering graduates. It is proposed that the innovation competencies are best taught and learned through a new and rebalanced combination of the teaching of content and an expanded concept of experiences. Characteristics and examples of these expanded experiences are presented using modeling concepts from the field of systems engineering where experiences are represented as learner interactions. These proposed experiences must be carefully crafted to be team based, focus on exploration and experimentation, and include interaction among multiple entities including a practice innovation system. These concepts have implications for both educators and business leaders in developing innovation competencies in both graduates and engineering professionals. Instead of differentiating between experiences in school versus professional practice, the educational system described here extends from school days into professional practice, serving practicing professionals as well as students.

This paper relies upon models of three distinct types of systems to provide an enhanced environment for education about and practice of the Innovation Competencies. The first of these are the Targeted Systems: the real, laboratory, or practice systems subject to innovation by learning students or practicing engineers, modeled by them as a central part of the Innovation Competencies. The second is the System of Education (itself a target of innovation), a model of which is summarized in this paper as a configurable reference model to illustrate the implied changes and advancements in different situations. The third is the System of Innovation, a model of which is referenced to understand the underlying framework in which all innovation occurs (effective or not; human-performed or not).

Introduction

Today globalization and connectivity mean that businesses and organizations compete in products and services not only for market share but for who will survive or perish. In several industries such as pharmaceuticals, strength in research and invention has long been a competitive advantage that enabled large and successful companies and industries to be created. In this and other industries, these traditional competitive advantages have eroded, barriers to entry have lowered, and the speed and intensity of competition has increased[1]. These trends suggest that the organizations that will survive and thrive in the future may be less dependent on invention of new ideas and technology and will be more adept at being innovative and nimble to create value to capture market and customer opportunities. With this perspective, we believe that engineering graduates must be prepared not only in their technical field of choice but also as innovators and technical leaders in order to be successful in this rapidly changing and complex workplace.

Current practices suggest that engineering graduates be proficient at both technical and professional skills[2]. Teaching of technical skills is often accomplished through graded courses delivering content in various disciplines. The addition of the professional skills to the ABET accreditation criteria required that new approaches be developed for teaching these skills[3]. These approaches have included complete courses, course modules, group exercises, and team projects. Experiential learning is often referenced as a technique for instilling both the technical and professional skills with high levels of complexity and fidelity being characteristics of a high quality experience.

Just as the competence in the 'professional skills' has become a requirement for graduates, it is proposed that Innovation Competencies are rapidly emerging as additional requirements for graduates. Recent work has reported on defining the Innovation Competencies, including an organizing framework, individual competency definitions, and associated rubrics being exercised in our institution to educate future innovators[4]. That work defined the educational outcomes sought, but not how to achieve them.

This paper proposes the types of educational interactions and processes we believe are most appropriate to achieving those outcomes within an overall reference framework. The education of engineering graduates occurs through a series of experiences ranging from attending classes, working in laboratories, participating in co-curricular activities, being part of industry-sourced pre-professional or professional experiences, to experiencing residence life on campus. It is proposed that the Innovation Competencies are best taught to and learned (by students and practicing professionals) through a new and rebalanced combination of the teaching of content and an expanded and defined set of experiences.

A model-based systems engineering framework has been developed to explore the innovation competencies and illustrate the proposed interactions in the educational system.

This paper is based on three main themes:

1. Effective innovation is facilitated by the Innovation Competencies, and these are in turn supported by the model-centric Systems Competencies, along with the Discovery Competencies and the Discipline Competencies;

2. Effective learning of the Innovation Competencies is facilitated by experiences during the learner's interactions either (a) with the explicit system models used by the System Competencies, or (b) with other actors, catalyzed by those system models;

3. In addition to their effectiveness in educating innovators, these models help "make room for themselves" in the time-constrained educational curriculum, by virtue of their support for other aspects of that curriculum.

Because the competencies of (1) are described at length elsewhere, the majority of this paper is concerned primarily with (2) and (3) above—the effective and efficient educational experience for acquiring or improving those competencies.

A Targeted Educational Outcome: The Innovation Competencies

The term innovation is widely used but lacks a common, precise definition. A review of the literature shows that there are many different definitions of innovation[5]. Most of these include elements of creativity, developing something new and different, and developing solutions that provide value to some user. Many universities focus on a mission of research and invention to creatively investigate problems and extend the boundaries of knowledge. These efforts often stop at developing new collections of knowledge and intellectual property. We believe that engineering education programs are ideally positioned to focus on the innovation and enterprising processes of developing these novel ideas into real-world solutions that provide benefit and value to some group of stakeholders. Based on this reasoning, we restate a definition of innovation from Schindel[4] - Innovation is defined as the ability to develop novel solutions to problems that create value and result in significantly enhanced stakeholder satisfaction.

Recent work has begun to explore and define engineering innovativeness and the innovation competencies[4,6]. The Innovation Competencies[4] for working in a technical environment are suggested to including three components - Discipline Competencies, Discovery Competencies, and Systems Competencies, in an integrated framework. Arranging these competencies in a 3-D "Innovation Competency Space", shown in Figure 1, is useful for understanding the activities of innovators and visualizing the day-to-day combinations that arise from all three areas.

The Discipline Competencies of Figure 1 are those specific to individual technical degree programs, such as EE, ME, ChE, CE, etc. This includes competency in the phenomena and technologies specific to a discipline.

The Systems Competencies of Figure 1 are concerned with:

- S1. Describing the target of innovation from a systems perspective;
- S2. Applying a system stakeholder view of value, trade-offs, and optimization;
- S3. Understanding system's interactions and states (modes);

- S4. Specifying system technical requirements;
- S5. Creating and analyzing high level design;
- S6. Assessing solution feasibility, consistency, and completeness;
- S7. Performing system failure mode and risk analysis;
- S8. Planning system families, platforms, and product lines;
- S9. Understanding roles & interdependencies across the innovation process.

The Discovery Competences of Figure 1 have been presented by Dyer[7] are concerned with:

- D1. Associating**:** Connect seemingly unrelated questions, problems or ideas from different fields into a single, coherent question, problem or idea.
- D2. Questioning: Develop questions that challenge the status quo.
- D3. Observing: Use observations of human behavior to develop new ways of doing things.
- D4. Experimenting: Develop new insights by provoking unexpected responses in an experiment or series of experiments.
- D5. Networking: Develop a broad and diverse network of associates to learn different perspectives and test new ideas.

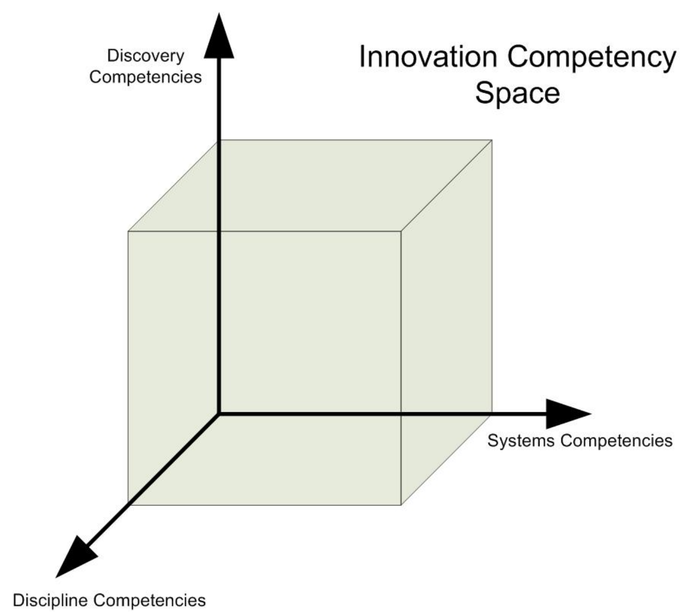


Figure 1: The 3-D Innovation Competency Space (From Schindel [4])

In particular, the model-based approach to the System Competencies is key to much of what follows in this paper.

Game-Changer: Learner Interaction with System Models

This paper is concerned with optimizing the educational experience for future innovators. It is not simply about new ways to educate to perform the old ways of doing innovation. It is about new ways to educate to perform innovation in new ways[8,9,10,11]. Among other potential benefits of the approach described here is educational efficiency: the ability, within the limited time available for an educational program, to accomplish a more effective outcome.

The "game changer" in this ecosystem is its focus on how the objects of innovation (targeted systems) are represented (and perceived) in context, using "system models", and the learner's interaction with those models and other actors. Explicit system models become the basis for the Innovation Competencies, which are performed and demonstrated using System Models[4]. Because the previous report focused on the definition of the Innovation Competencies and their expression using system models, this paper assumes that background and focuses on the system of education using them.

Because these explicit models are in the form of tangible artifacts, the innovator (whether student or professional practitioner) can interact with the model[12]. Likewise, the innovator's colleagues (be they teachers, coaches, stakeholders, or other colleagues) likewise interact with the model while interacting with each other—the model becomes a literal catalyst for enabling improved team interactions[10,13,14].

Throughout this paper, by "system" we mean a set of physically interacting components, as illustrated in Figure 2.

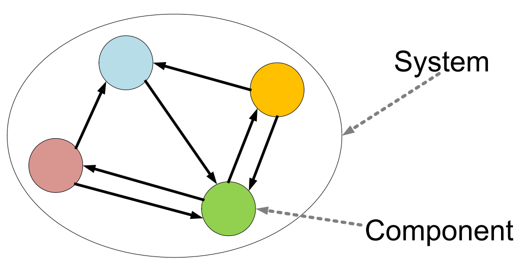


Figure 2: The System Perspective

There are three different modeled systems involved in this framework:

- **System 1--The Innovated System**: The object of an innovation is a new or modified system (commercial product or service, student project device, etc.) intended to provide its stakeholders with enhanced value. The System Competencies are practiced using explicit models of System 1—The Innovated System, in its environmental context. These competencies frame the Innovated System as an element of a larger system; they describe the stakeholder values associated with the Innovated System; they describe the modes and states of the Innovated System; they describe the design of the Innovated System; they describe the failure modes of the Innovated System; etc. Model-based artifacts enhance assessment of individual learning and the learning process, on a simpler, more objective, and explicit basis—whether by teacher, learner, or other assessor. Refer to the model-based rubrics of Appendix 1.

- **System 2—The System of Education**: This is the system for delivering education, and we are specifically concerned here with education of innovators. In particular, the interaction models of the System Competencies are key to representing a range of possible educational experiences future learners may have. The System of Education model is sufficiently general that it can represent educational processes that do not use model-based Systems Competencies, as well as those which do--this system may or may not use the System Competencies approach to innovation, but we assert that it is more effective when it does so. In the latter case, we can expect to see the System 1 models appearing "inside" the System 2 model, as in a learner's practice innovation exercise. The many other dramatic developments in education (inverted classrooms, on-line education, etc.) readily justify the use of System 2 models to describe and understand the educational revolutions that are afoot.

- **System 3—The System of Innovation**: This is the system of the total innovation process, whether human-performed or otherwise. It is represented by commercial enterprises, markets, competing nations and societies, biological ecosystems, production processes, educational experiments and assessments, variation and selection processes, innovation regulation, and other aspects. Skilled or not, individual innovators and teams operate within the System of Innovation. An innovator skilled at the highest levels will understand how to play the game effectively within the System of Innovation. A particular System of Innovation need not be based on the Innovation Competencies, but we argue that the more effective ones (even in the natural world) are. The System of Innovation includes the (optional) ability to represent (model) the Innovated System. So, models of System 1 may, but need not, appear inside the models of System 3, and 2. Likewise, we are interested in educating future innovators about the System of Innovation itself, and encouraging their reflection on their own performance of it. So, we expect models of System 3 to appear inside the models of System 2.

All these systems are represented using the same underlying system modeling framework, the S*Metamodel[15] of Appendix 5.

The System of Education: A Configurable Reference Model

Through innovation processes, system families evolve to optimize their fit to the stakeholders benefitting from system selection[8,9]. This applies to systems found in nature, to human-engineered product lines (e.g., consumer products, military systems), and to systems of education. In the case of education of future innovators, there are multiple types of “customers” and settings; accordingly, no single System of Education configuration will be optimized for all stakeholder situations or markets. Accordingly, this paper describes a configurable reference model for the System of Education of innovators. In addition to being configurable for different stakeholder situations, it may also be configured differently to experiment in support of different theories of what would be superior. This paper offers some suggestions on rebalanced configurations of this reference model, for the Ideal Educational Experience of future innovators in different situations.

The process of educating engineering graduates is comprised of a series of experiences ranging from attending classes, working in laboratories, participating in co-curricular activities, being part of industry-sourced pre-professional or professional experiences, to experiencing residence life on campus. Depending upon the nature of the educational process, some of these may or may not be present, and their balance may vary. However, in all configurations the learner’s experiences may be characterized based upon learner physical interactions with other entities. These other “actors” may be teachers, lab equipment, models, references, fellow learners, simulated clients, social actors, recordings, etc.

System interactions involve the exchange of forces, energy, or mass flows between interacting entities, with one entity changing the state of another. In many important cases, the exchange of information is paramount, represented symbolically by the energy, mass, or force exchanged. In modeling educational experience, we can expect that many (but not all) of the important interactions will be information-centric. (If only information exchange were required, our schools would not be air-conditioned, use comfortable seats, provide food and beverage services, or offer opportunities for exercise. Indeed, some educational platforms are configured just that way.)

Figure 3 summarizes the setting for these interactions, in the form of a domain model focused on the Learner (a student or practicing professional), interacting with other actors (that may include other Learners). The domain model is one “view” of the integrated configurable System of Education model discussed by this paper. Definitions of the entities in this view may be found in Appendix 2.

Interaction exchanges occur over the relationship lines shown in Figure 3, and a list of such interactions is provided in Appendix 3. Each interaction may be modeled in detail, as illustrated later in this paper. Note that Figure 3 includes system interfaces. Definitions of Domain Model components are provided in Appendix 2.

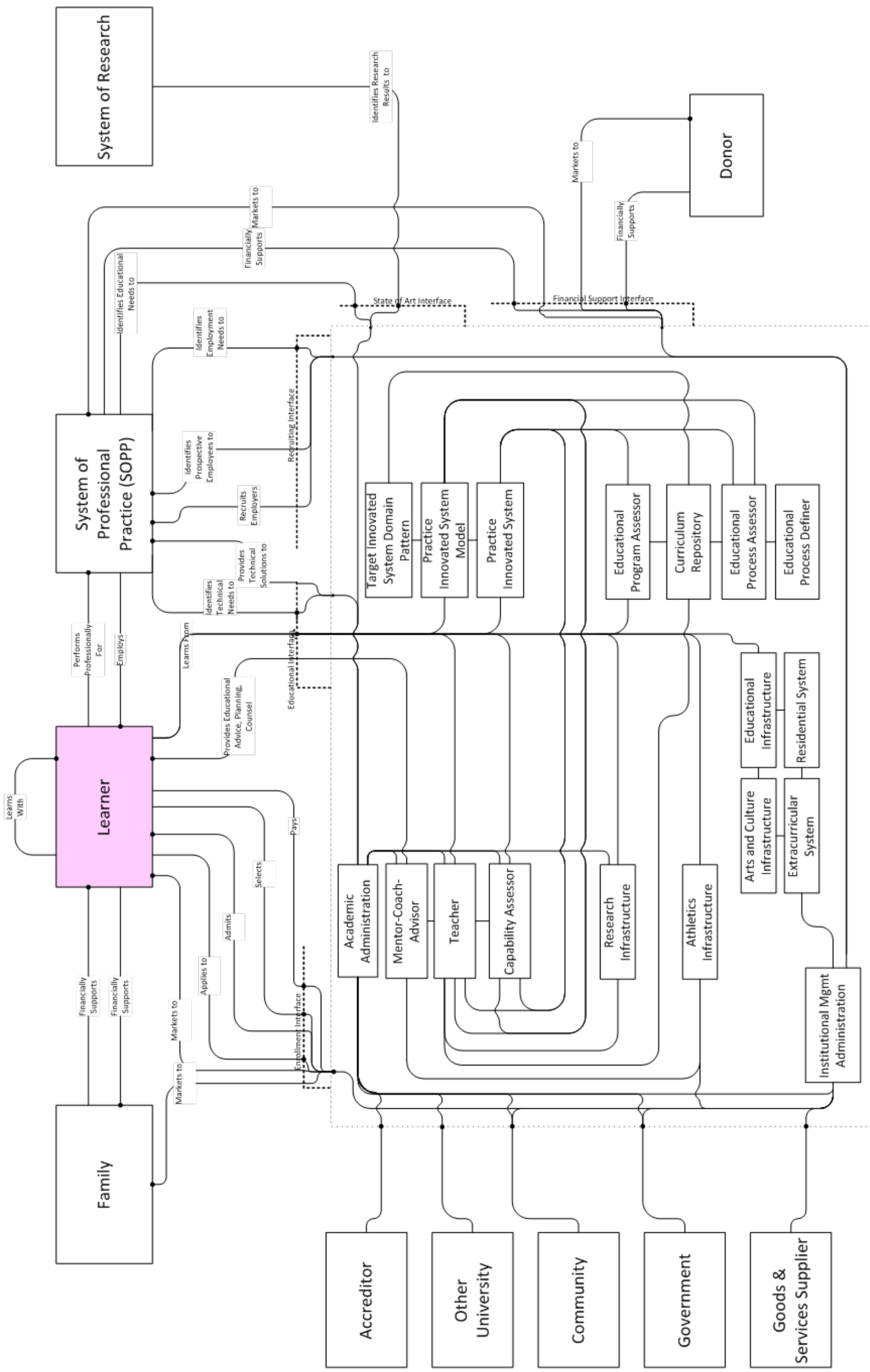


Figure 3: System of Education Domain Model

Experience has shown that System Interfaces and Systems of Access are important aspects of systems, including those involving humans. Emerging on-line educational offerings and electronic media are prominent examples, as are web-based course management software platforms.

Although Interactions are a central part of the System of Education model, they are not a direct representation of stakeholder value, such as would be perceived by the Learner, Employer, or other stakeholder. Indeed, exactly the same learner interaction may have different value to different learners. Accordingly, the Stakeholder Feature Model represents and is focused on stakeholder value. A Feature Model for the System of Education is shown in Figure 4. Definitions of all features are provided in Appendix 4. The features in the dark boxes are explored in more detail later in the paper.

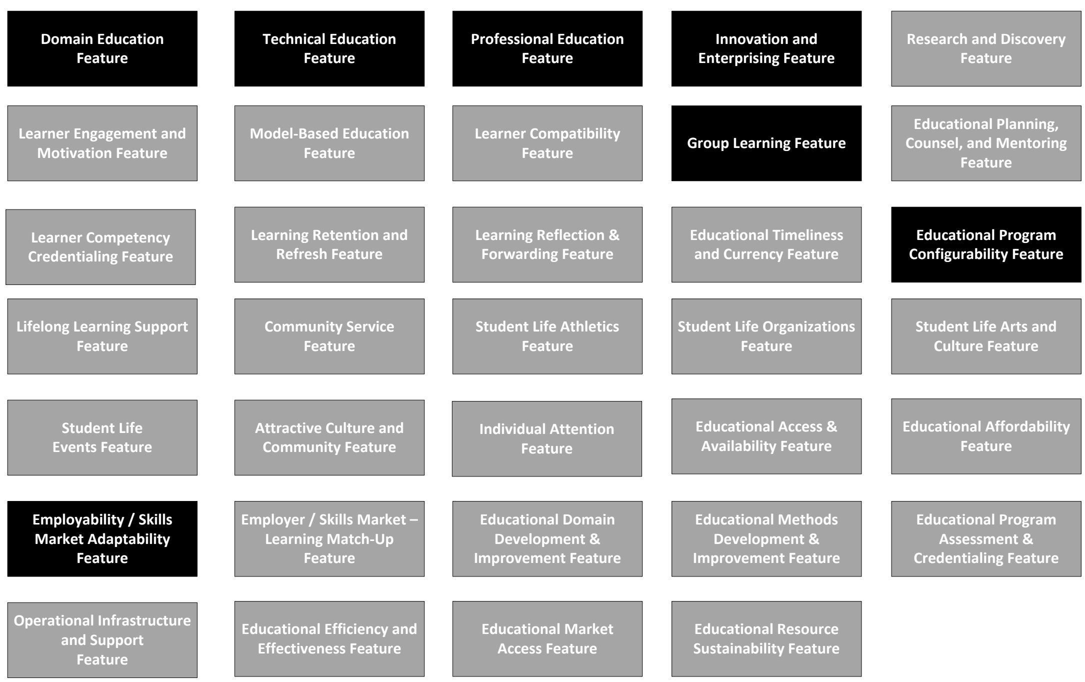


Figure 4: Stakeholder Features of the System of Education

System Interactions represent and model pure objective behavior and are devoid of value. We can design systems to deliver those interactions, but they don't tell us whether it would be a good idea. By contrast, Features model pure subjective value, and Features are the subject of any optimization, selection, or trade-offs. However, Interactions and Features are associated with each other and there is value in modeling which Interactions have the potential to impact each Feature. A limited example is provided by Figure 5.

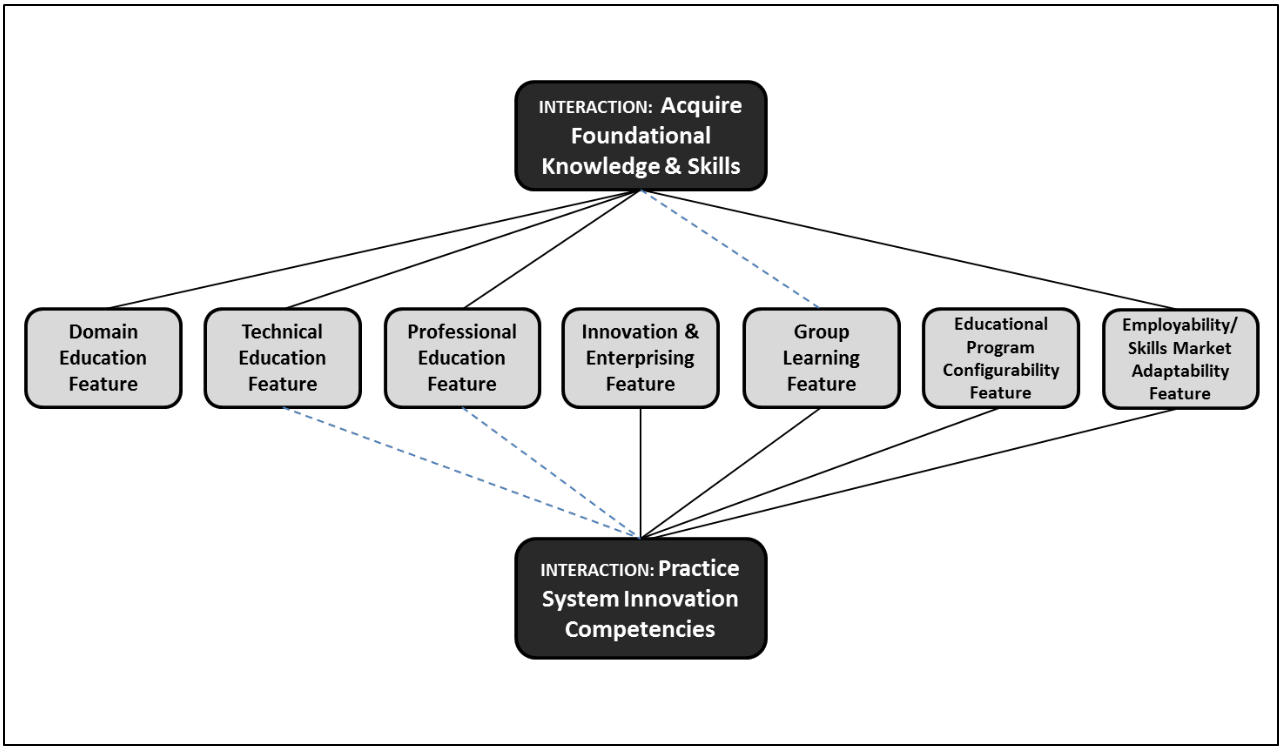


Figure 5 : Feature-Interaction Associations **(Selected Interactions and Features)**

As noted above, Interactions describe behavior of the system, and each interaction may be illustrated in detail by tracing it out using the Domain Diagram in Figure 3. Figure 6 and 7 below illustrate the 'Acquire Foundational Knowledge and Skills' and 'Practice System Innovation Competencies' Interactions. Figure 6 illustrates the traditional 'Acquire Foundational Knowledge and Skills' with the Learner interacting primarily with the Teacher and the Curriculum Repository through the Instructional System of Access. One of the main roles of the Teacher in this interaction is being an instructor. The Learner may also interact with a Practice System which traditionally may be a laboratory setting designed to reinforce learning of curriculum. Figure 7 illustrates a proposed 'Practice System Innovation Competencies' Interaction with the Learner interacting primarily with the Practice Innovated System, System Stakeholders, and other Learners. A Teacher/Mentor is also involved in this interaction and plays a role not of instructor but coach. The Learner also interacts with and develops a mental model of Practice Innovated System at the same time.

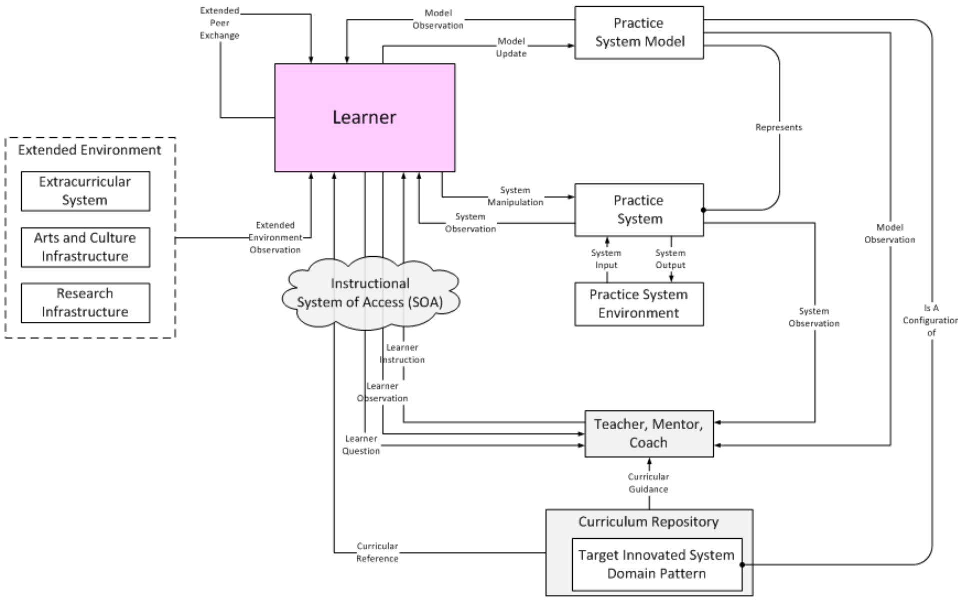


Figure 6: Illustration of 'Acquire Foundational Knowledge and Skills' Interaction

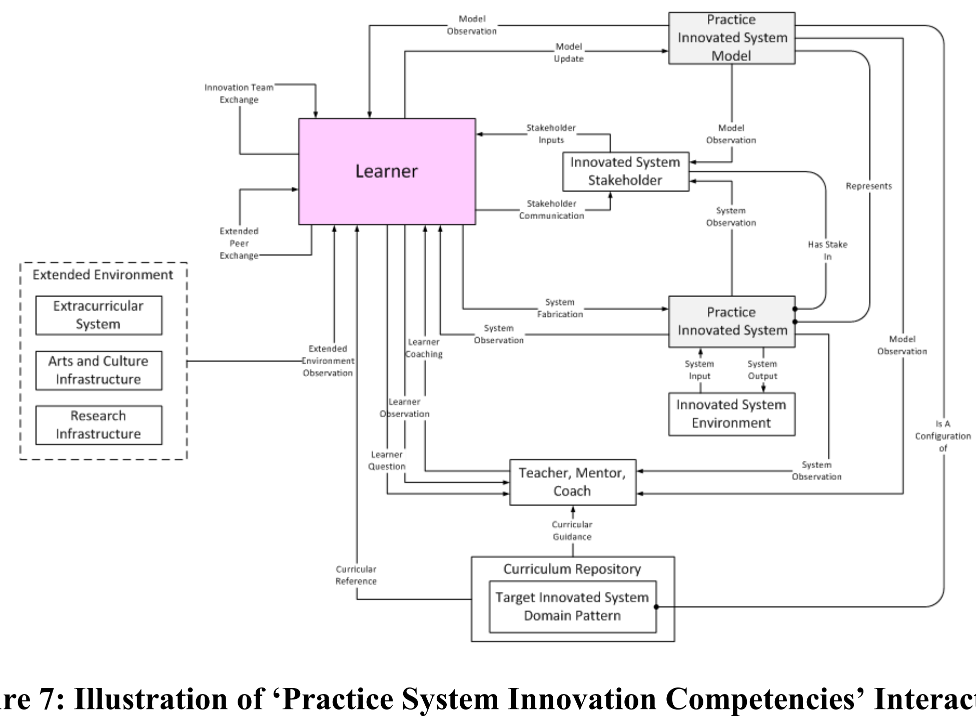


Figure 7: Illustration of 'Practice System Innovation Competencies' Interaction

Interacting entities fulfill Functional Roles in their interaction, and these roles are parameterized by attributes which technically characterize the performance, reliability, or other aspects of the objective behavior of an interacting entity. In a system models, such objective technical attributes are coupled to the Feature Attributes, which express stakeholder value. The resulting coupling shows how different technical behaviors will be valued differently by stakeholders, as illustrated by Figure 8.

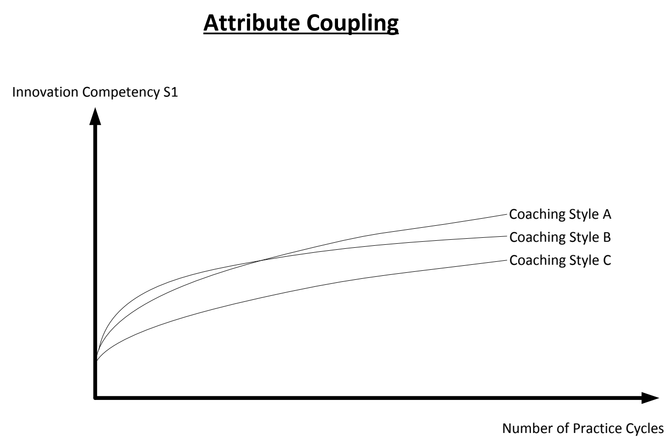


Figure 8: Example Attribute Coupling

Systems of Innovation: Maps versus Itineraries

A recent exhibition of "A World Without Maps" at NYU's Institute for the Study of the Ancient World[16] suggested that the ancient world likely used "itineraries" (step-by-step procedures to move from one geographic place to another) instead of "maps" (explicit and integrated representations of underlying geographic representations). This is analogous to the current situation in innovation of complex systems: The innovator wishes to evolve a system from one "place" in system configuration space to another (improved) place in system configuration space. However, an explicit and integrated map of system configuration space is usually not available to the innovator, who instead follows a "cook book" procedure of some sort that has been used in the past to advance from one system configuration to another.

For the geographic traveler, interacting with a real map (and the visible surroundings) yields a better result than interacting with an itinerary (procedure). However, the traveler must have available, and have some familiarity with, a map of the territory.

In like manner, we would have the innovator interact with an explicit and integrated map of the system configuration territory, along with other actors relevant to the innovation process. This involves more than drawings of physical equipment or lists of system requirements, although they are a part of the model. The System # 1 models referenced above are that map, addressed by the System Competencies, based on the underlying Metamodel[4,15] of Appendix 5. The System of

Education model accordingly reflects at least the option for the Learner to practice both map (model) use in innovation, as well as map-making (model-making).

Discipline Competencies (Figure 1) typically include a portion of this map, as in learning the underlying phenomena and equations (quantitative relationships) specific to a discipline (e.g., mechanical engineering, electrical engineering, etc.). However, these are much less than the whole system map. The System Competencies (Figure 1) focus on filling out and using the rest of that systemic model (map). This frequently requires exercising the Discovery Competencies (Figure 1) to fill in blanks in the model revealed by the System Competencies.

Innovation is inherently iterative in nature[9,10]. Some of this iterative cycle involves interacting with pilot designs, breadboards, stakeholders, and mock-ups. But those interactions are not necessarily the most efficient path through innovation, as discovered again and again by those who build prototypes without exploring requirements and key design relationships. The model scope covered by the System Competencies is the smallest possible model scope sufficient for effective innovation purposes[15]. In considering the enlarged system model, our point here is that the innovator interacts with that model—it is not just stared at passively. Both the model and the innovator typically change state in those interactions, which may also include physical equipment, stakeholder, and other actors. The System of Education Model thus shows interaction of the Learner with the System #1 Model (see Figure 7), fundamental to "practicing" the innovation process. What the Learner is acquiring in this process is familiarity with the System Competencies (the core of the System #3—the System of Innovation), not just more knowledge of System #1 (the Innovated System). This includes the Learner reflecting on those interactions, and any available coaching available from the Teacher/Mentor/Coach shown in the SOE model in Figure 7.

System Patterns

The Innovation Competencies collectively emphasize building skills in general innovation. However, many businesses are built around specific application/market domain patterns[17] such as automotive vehicles, aircraft, communication systems, weapons defense, earthmoving, agricultural systems, etc. Engineering educators may argue that it is not the role of undergraduate engineering education to emphasize these systems, versus the more fundamental physical laws or technologies upon which they are founded. Nevertheless, current engineering education appears to recognize at least some obligation to teach some mechanical engineers about vehicles, some chemical engineers about reactors, some electrical engineers about power supplies, etc.

The optimum balance of emphasis of more general System Competencies versus more specific System Patterns may fairly be debated, and the configurable System of Education model is only intended to provide a reference framework that can be used to consider different balance configurations. Whatever that balance may be, a key realization should be that the Domain Patterns can be learned as nothing more than configurable models of the target system model elements called for by the System Competencies. That is, learning the Stakeholder Feature Space, key Interactions, fundamental Couplings, critical Failure Modes, and other aspects of the "smallest model" is still the right approach, whether it is for vehicles, aircraft, information processing systems, or other domain patterns. The System of Innovation model accordingly reflects a (configurable) degree of Learner interaction with System Patterns.

Balancing Interaction Experience, from Classroom through Professional Practice

It is proposed that some increase is desirable in the balance of Learner time spent on the interactions of the System of Innovation—including interactions with the explicit system models called for by the System Competencies. The configurable System of Education reference model permits the expression of that increase, but does not demand it, as it can also represent other SOE configurations.

The explicit nature of the SOE model also helps us express the "limited space" constraints of the educational curriculum and its time budget. Although this normally suggests looking for subjects to trade out or de-emphasize, it should be noted that many of the traditional Discipline Competency subjects already in the curriculum can be expressed in System Model and System Pattern form that improves familiarity with the System Competencies, and may yield efficiencies that free up time for increased innovation practice.

In any case, it is not the position of this paper that "perfect system models" should be pursued by Learners practicing the System Competencies. Rather, the assertion is:

- Innovation, and related learning, are not as effective in the absence of explicit Stakeholder Feature models, even if imperfect;
- Innovation, and related learning, are not as effective in the absence of explicit models of the scope of System Interactions, even if imperfect;
- Innovation, and related learning, are not as effective in the absence of some degree of verification that the innovation being implemented is at least generally consistent with the description of the System Competencies model.

Like all innovations, the System of Education must itself be innovated through experiments and iteration. The SOE model can guide our planning of experiments, but in the end we must carry out those experiments.

Examples and Experiences at Rose-Hulman

Previous sections have described the nature of high quality educational experiences to develop the innovation competencies and we now present three example courses and programs from Rose-Hulman.

Multidisciplinary Grand Challenges Course – A summer course focused the analysis, design, and documentation of a system using solar energy to address a theme of the Grand Challenges with use targeted for Kenya. The course was co-taught by three faculty members and combined material from three courses including design(Mechanical Engineering), science(Physics), and technical communication(Humanities and Social Sciences). The twelve students received credit for three courses (12 credits). Unique aspects of the course are that it began with loosely defined scope for the practice innovated system which was applying solar energy to address one of the Grand Challenge themes for use in Kenya. Students worked in teams and identified three initial prototype concepts focused on water purification and improved ventilation. The teams combined ideas and converged on a solar energy collector for water purification that could be built with materials in the target region. To represent local stakeholder and cultural perspectives, a student from partner school in Kenya was brought to our university to work with the student design teams in the early stages of the project.

Branam Innovation Center – The Branam Innovation Center (BIC) houses eight competition teams including EcoCar, Formula SAE, Human Powered Vehicle, Concrete Canoe, Chemical Car, and Robotics. Many universities participate in competition team projects and we have found they can be a very good experience for instilling the innovation competencies. Students voluntarily join the teams and form multidisciplinary teams. The teams are supervised by faculty and staff mentors. The BIC is equipped with onsite prototyping facilities to encourage rapid experimentation and prototyping. The competitions inherently present a number of challenges that provide opportunity to exercise the discipline, discovery, and systems skills.

Rose-Hulman Ventures – The Rose-Hulman Ventures (RHV) program operates like an on campus engineering consulting enterprise. Corporate partners specify and provide financial support for technical projects to be worked on by student interns and staff project managers. At any time, the RHV program houses some 25 projects with 60 paid student interns and 12 staff members working on them. In some ways, this is an ideal program for instilling the innovation competencies. The projects brought forward by the corporate partners provide the practice innovated systems. The number, diversity, and natural rotation of projects provide a very rich and synergistic environment to practice a combination of the technical, professional, and innovation competencies.

Conclusions and Future Activity

This paper has proposed that innovation is an emerging organizational competency and that engineering graduates should be prepared with the Innovation Competencies to be successful in this workplace of the future. It is proposed that the Innovation Competencies be taught in part through traditional courses with curriculum content but also that a significant portion of the education be provided through an expanded concept of learner experiences.

A systems engineering approach has been used to develop a comprehensive model for a generic System of Education that can be configured to represent a traditional residential university or other educational models. The desire to prepare graduates with the Innovation Competencies has been represented and visible in new features, interactions, and other elements being added to the model.

The new experiences proposed to educate graduates in the Innovation Competencies have been represented as Interactions in the model framework. The proposed interactions have been shown to involve different system actors and information exchange compared to a traditional classroom, content focused experience. In particular, these experiences should be team based, focus on exploration and experimentation, and include interaction among multiple entities including a practice innovated system.

It has been noted that there are three systems models under consideration – a model for the Innovated System, one for the System of Education, and perhaps less apparent, one for the System of Innovation.

The model based system engineering methodology is a valuable approach for representing educational systems, processes, and interactions. In particular, it is useful for modeling educational experiences in the form of interactions of materials and information among system elements. Further application of this approach is proposed to explore its utility in a broader context.

This paper has proposed new future directions, modeling approaches, and types of educational processes most appropriate to instilling the innovation competencies in graduates. At this time, only preliminary results are available from programs aligned with providing the proposed experiences. Further conceptualization and implementation of programs is needed to assess the utility of the proposed approaches.

Appendix 1: Model-based Rubrics – from Schindel, et al. ref. 4.

System Competency		Model-Based Assessment Rubric	
S1	Describing the target of innovation from a systems perspective	S1R1	Domain diagram and definitions are available, showing that the subject system is understood to be itself part of a larger system.
		S1R2	What percent of external domain actors are identified by the domain model?
		S1R3	Logical architecture diagram is available, showing that the subject system' external behavior is understood to emerge from the interactions of a set of decomposed subsystems.
		S1R4	What percent of the subject system's external behavior is covered by the logical subsystems / logical architecture model?
S2	Applying a system stakeholder view of value, trade-offs, and optimization	S2R1	A stakeholder model is available, identifying and defining the classes of stakeholder with a stake in the subject system.
		S2R2	What percent of the total set of classes of stakeholders in this system are represented by the stakeholder model?
		S2R3	A system feature model is available, identifying and defining, in stakeholder terminology, the aspects of system behavior that carry stakeholder impact, positive or negative.
		S2R4	A stakeholder-feature association trace is available, showing which features are of interest to each stakeholder class.
		S2R5	To the extent that the interests of stakeholders are quantified or further identified by parameters, the features have defined feature attributes identifying and defining those variables.
		S2R6	What percent of the total set of stakeholder interests are covered by the features and their attributes?
		S2R7	Stakeholder features are explicitly traced to the system external interactions that deliver on or have stakeholder-impacting aspects.
		S2R8	What percent of the features are fully covered by the interactions associated with them?
		S2R9	Does the design solution selection rationale demonstrate optimization with respect to the (possibly weighted) stakeholder feature value space?
S3	Understanding system's interactions and	S3R1	An interaction model is available identifying and defining the different physical interactions the system has with its environment over its life cycle.

System Competency		Model-Based Assessment Rubric	
	states (modes)	S3R2	A state model is available, identifying and defining the different modes of externally visible system behavior in interacting with its environment over its life cycle, including state definitions and association with external interactions.
		S3R3	What percent of the total set of interactions the system has with its environment are included in the system interactions model?
		S3R4	What percent of the total set of system states or modes are included in the system state model?
S4	Specifying system technical requirements	S4R1	The externally visible behavior of the system, interacting with its environment, is fully specified by system requirements statements associated with each modeled interaction.
		S4R2	System external interactions are individually modeled by interaction diagrams showing the related system input-output exchanges with external actors.
		S4R3	For each modeled interaction, a set of associated system requirement statements is provided that are objective, testable, atomic, descriptions of the required system input-output behavioral relationships.
		S4R4	Key attributes (parameters) further characterizing the requirements are included with the system requirements.
		S4R5	Attribute value dependency couplings of requirements attributes and feature attributes are identified and characterized, showing how stakeholder feature satisfaction varies with respect to change in technical requirement attribute values.
S5	Creating and analyzing high level design	S5R1	A physical architecture model is provided, identifying and defining physical subsystems or components and their arrangement into physical relationships with each other.
		S5R2	System black box requirements are traceably decomposed to white box requirements that are objective, testable, atomic descriptions of internal functional roles.
		S5R3	The decomposed white box requirements are explicitly allocated to the components of the physical architecture which are responsible for meeting those requirements.
		S5R4	Key attributes (parameters) of the physical architecture are identified and defined.

System Competency		Model-Based Assessment Rubric	
		S5R5	Attribute value dependency couplings of physical architecture attributes and requirements attributes are identified and characterized, showing how system behavior varies with respect to change in physical component attribute values.
S6	Assessing solution feasibility, consistency, and completeness	S6R1	Based upon a review of the modeled design, would the decomposed white box requirements, if met, satisfy the parent black box requirements?
		S6R2	Based on a review of the modeled design, are the physical subsystems or components capable of meeting the white box requirements that have been allocated to them?
		S6R3	Based on a review of the modeled design, have design margins or gaps for each of the requirements attributes been identified?
		S6R4	Have any additional parasitic behaviors of the selected physical components or subsystems been identified and included in the model?
		S6R5	If fabricated, assembled, integrated, or otherwise constructed, is the implemented system solution consistent with the modeled system design?
		S6R6	If fabricated, assembled, integrated, or otherwise constructed, does the implemented system solution meet the modeled system requirements?
S7	Performing system failure mode and risk analysis	S7R1	Have the impact effects of not delivering each of the stakeholder features been identified, including the severity of those impacts?
		S7R2	Have the counter-requirements associated with each of the modeled system black box requirements been identified for use in risk analysis?
		S7R3	Have the failure modes of the design components or subsystems been identified?
		S7R4	Have the failure modes associated with external human actors been identified?
		S7R5	Have the failure modes associated with external processes been identified?
		S7R6	Have the failure modes been associated with related counter requirements?
		S7R7	Have the failure modes been associated with probabilities of their occurrence?
		S7R8	Have the counter requirements been associated with the related impact effects?
		S7R9	Have the relative risks, based on probability and severity, been estimated?

System Competency		Model-Based Assessment Rubric	
		S7R10	Have detection and mitigation strategies for the failure modes and effects been described?
S8	Planning system families, platforms, and product lines	S8R1	Has the range of configured stakeholder configurations to be satisfied been modeled?
		S8R2	Have product line configuration rules for system features been modeled?
		S8R3	Has configuration of external system environments across different configurations been modeled?
		S8R4	Has configuration of the system state model for different configured features been modeled?
		S8R5	Has variation in configured interactions with respect to configured features been modeled?
		S8R6	Has variation in system requirements and their attributes been modeled across the range of configurations?
		S8R7	Have interfaces been modeled to minimize impact across varying configurations?
		S8R8	Have variant product lines, archetypes, and sub-families been identified to globally optimize Return on Variation across the system family, platform, or product line?
S9	Understanding roles & interdependencies across the innovation process	S9R1	Are the roles and interdependencies of the team members responsible for different aspects of the innovation process identified, described, understood, and agreed upon?
		S9R2	Is the innovation process, and its allocation to different organizations, partners, team members, and information systems described as a modeled system?
		S9R3	Are the goals of the innovation process identified, used to configure instances of the process, and known to the organization?

Appendix 2: Domain Diagram Definitions

Domain System Name	Domain System Definition
Learner	A person who acquires learning, experiences, advice, and counsel from the System of Education.
Family	Immediate family related to the Learner, who support and are supported by the Learner's activities.
System of Professional Practice	The system of people and entities that may hire Learners upon graduation and perform engineering and techncial activities for commercial benefit.
System of Research	The people, equipment, facilities, and infrastructure that develops research results, new learning, and scholarship that supports the System of Education and society.
Donor	A person or entity that provides financial support to the System of Education
Accreditor	An agency that reviews and accredits the programs and offerings of the System of Education.
Other University	The group of educational entities that the system of education may interact with.
Community	The body of people and infrastructure surrounding and sharing common interests with the System of Education.
Government	The group of people and infrastructure that makes laws affecting and may support the activities of the System of Education.
Other Goods and Services Supplier	The group of entities external to the System of Education that provide goods and services to support its activities.
System of Education	A logical system responsible for supporting learning by and improved employability of the
Academic Administration	The group of people that provide oversight and support for the mission of the System of Education.
Mentor-Adviser-Coach	A person with unique credentials who provides learning and experience opportunities, advice, and counsel to Learners.
Teacher	A person with unique credentials who provides learning and experience opportunities related to curriculum, advice, and counsel to Learners.
Capability Assessor	A person who assesses the performance and competence of Learners and provides feedback on these assessments.
Target Innovated System Domain Pattern	The pattern that can be developed for the Practice Innovated System.
Practice Innovated System Model	The model that the Learner develops of the system that they can interact with and develop the competencies of innovation.
Practice Innovated System	The entity or system that the Learner can interact with and develop the competencies of innovation.
Research Infrastructure	The system of people, equipment, and infrastructure to support processes of discovery and extending the boundaries of knowledge.
Educational Program Assessor	The group of people and infrastructure that assess educational curriculum and programs and report on findings.
Curriculum Repository	The collection of information, content, and materials that the System of Education draws upon to provide learning experiences.
Educational Process Assessor	The group of people and infrastructure that assess educational processes and report on findings.
Educational Process Definer	The group of people and infrastructure that develop educational rules and processes.
Athletics Infrastructure	The system of people, equipment, and infrastructure to support athletics activities and competitions.
Educational Infrastructure	The system of people, equipment, and infrastructure to support the delivery of learning opportunities.
Residential System	The system of people, facilities, and infrastructure to support the living needs of the Learner.
Extracurricular System	The system of people, facilities, and infrastructure to provide social and cultural opportunities to the Learner.
Institutional Mgmt Administration	The system of people, facilities, and infrastructure to support the planning and operational needs of the system of education.

Appendix 3: Learner Interactions: Definitions

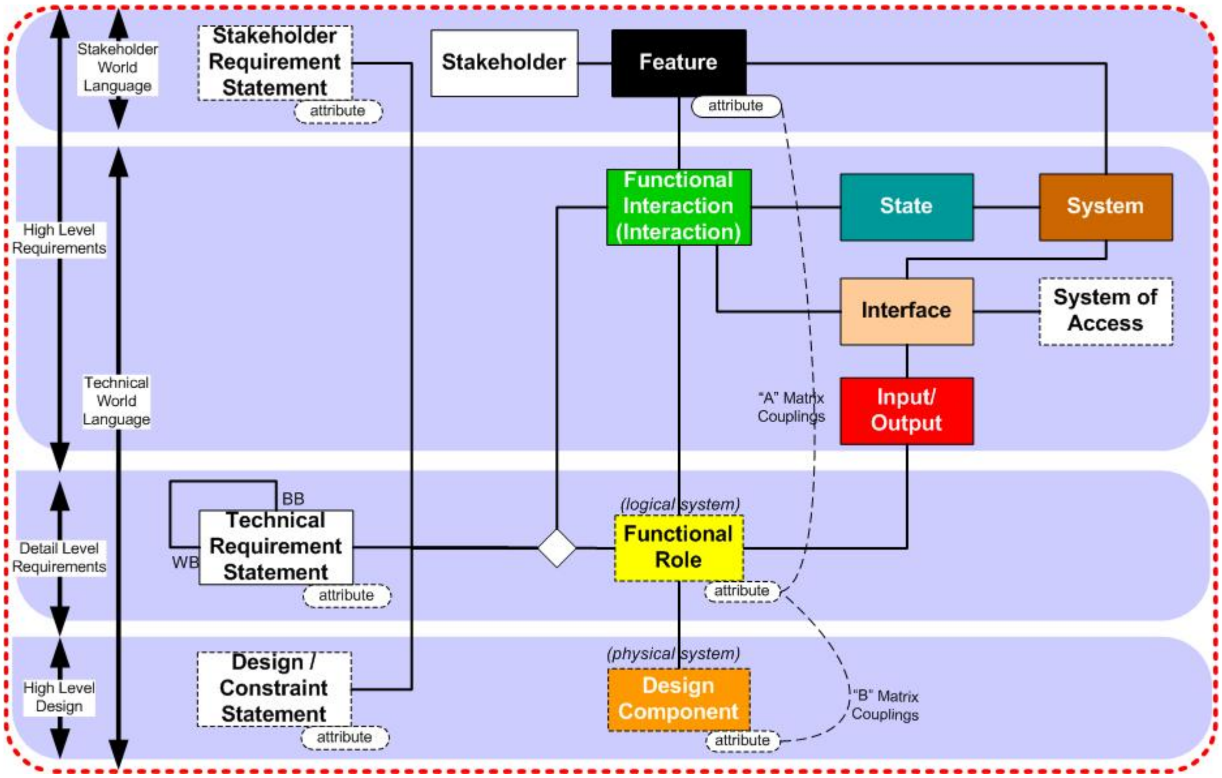
Interaction Name	Interaction Definition	Learner	Mentor/Coach	Teacher	Other Learners	Educational Infrastructure	Capability Assessor	Practice Innovated System	Curriculum Repository	Athletics Infrastucture	Research Infrastructure	Residential System	Arts / Culture Infrastructure
Acquire Foundational Knowledge and Skills	The interaction during which the Learner learns foundational knowledge and curriculum.	X		X		X			X				
Learns with Other Learners	The interaction during which the Learner learns with other Learners	X			X								
Practice System Innovation Competencies	The interaction during which the Learner interacts with a practice innovation system	X	X	X	X			X					
Performs Research	The interaction during which the Learner performs research activities using the research system infrastructure	X		X							X		
Learns from Educational Infrastructure	The interaction during which the Learner uses items in the educational infrastructure	X				X							
Advising on Academic Matters	The interaction during which the Learner receives advising and counsel on academic matters	X		X									
Assess Capability	The interaction during which the Learner receives assessment feedback	X	X	X									
Participates in Athletics	The interaction during which the Learner participates in athletics training and competitions	X	X							X			
Learns from Residence Life	The interaction during which the Learner inhabits and learns from residence life	X	X		X							X	
Learns from Arts and Culture	The interaction during which the Learner learns from arts and culture	X											X

Appendix 4: Stakeholder Features: Definitions and Attributes

No.	Feature Name	Feature Definition	Feature Attributes
1	Domain Education Feature	The capability to deliver educational programs in particular domains.	Primary Key: Educational Program Name(s); Enrollment Capacity; Accreditation
2	Educational Timeliness and Currency Feature	The capabilty to deliver educational programs that are current with the state of the related domain art, and first available on a timely basis with respect to changes in the domain state of the art.	
3	Learner Compatibility Feature	The capability to delivery educational program services that fit the learning style, capabilities, and situation of the targeted learners.	Primary Key: Learner Compatibility Issue
4	Educational Planning, Counsel, and Mentoring Feature	The ability of the system to provide learners with planning, counsel, and mentoring relevant to the planning and guidance of the learners' individual interests, situations, and programs of learning.	
5	Learning Retention and Refresh Feature	The ability of the system to assist learners in retaining or refreshing the competencies they acquire from the educational programs of the system.	
6	Learner Engagement and Motivation Feature	The capability of the system to excite, engage, and motivate learners and learning.	
7	Model-Based Education Feature	The capabilty of the system to provide educational services that are based upon explicit system model-based representations of the domain systems which are the subject of an educational program.	
8	Educational Access & Availability Feature	The capability of the system to make the educational services it offers highly accessiable and available to the learners it targets.	
9	Educational Affordability Feature	The capability of the system to make the educational services it offers financially affordable by the learners it targets, with due consideration of the perceived value delivered and the means and financial resources available to the targeted market.	
10	Educational Efficiency and Effectiveness Feature	The capability of the system to deliver education that is perceived as efficient and effective by the targeted learners, in consideration of the time and effort required of them.	
11	Learner Competency Credentialing Feature	The capability of the system to provide access to effective credentialing service that indicates the capabilities of learners, for parties who need that credentialing.	
12	Employability / Skills Market Adaptability Feature	The ability of the system to adapt its educational offerings to the needs of employers and markets it targets.	
13	Employer / Skills Market-Learning Match-Up Feature	The ability of the system to provide employers and learners with match-up services that introduce learners to potential employers.	
14	Learning Reflection & Forwarding Feature	The ability of the system to encourage its learners to eventually become sources of future educational offerings themselves, based upon their expertise and experience.	
15	Lifelong Learning Support Feature	The ability of the system to provide educational services to learners throughout their lives.	
16	Educational Program Assessment & Accreditation Feature	The ability of the system to assess its own educational programs, and to win and maintain program and overall accreditation from issuing agencies.	
17	Educational Program Configurabilty Feature	The ability of the system to tailor and otherwise configure its educational offerings to varied or changing markets, channels, learners, employers, and needs.	
18	Educational Program Development & Improvement Feature	The ability of the system to develop new or improved programs of education on a timely basis to address market needs.	
19	Educational Methods Development & Improvement Features	The ability of the system to develop new or improved methods of education on a timely basis to address market needs.	
20	Educational Resource Sustainability Feature	The ability of the system to operate on a sustainable basis with respect to its financial, human, material, and other resources.	

21	Group Learning Feature	The ability of the system to deliver learning experiences that include educationally effective interactions between individual learners.	
22	Educational Market Access Feature	The abiilty of the system to access targeted market segments for its educational services and programs.	Primary Key: Educational Market Name(s)
23	Individual Attention Feature	The ability of the system to deliver educational services such that the experiences of individual learners lead to perception of a high degree of individual attention to their interests and needs.	
24	Technical Education Feature	The capability to deliver educational programs to achieve ABET objectives A,B,C, E, and K	
25	Professional Education Feature	The capability to deliver educational programs to achieve ABET objectives D, F, G, H, I, and J	
26	Operational Infrastructure and Support Feature	The capability of the system to support the facility, utility, financial, and benefits needs of …..	
27	Research and Discovery Feature	The capability of the system to conduct inquiry and experiments in particular domains using the scientific method.	
28	Community Engagement and Service Feature	The ability of the system to provide activities and services that are aligned with the needs and interests of community members.	
29	Innovation and Enterprising Education Feature	The capability of the system to deliver programs and experiences to develop and intgrate the discipline, discovery, and systems competencies.	
30	Student Life Athletics Feature	The ability of the system to provide athletic training and competition experiences that learners may voluntarily particpate in.	
31	Student Life Organizations Feature	The ability of the system to provide organization, group, and club experiences that learners may voluntarily participate in.	Professional, organizational, social
32	Campus Life Arts and Culture Feature	The ability of the system to provide arts and cultural experiences that learners may voluntarily particpate in.	
33	Campus Life Attractive Culture and Community Feature	The ability of the system to provide an attractive culture and sense of community for the campus.	
34	Campus Life Events Feature	The ability of the system to provide enriching campus events for the benefit of community members.	

Appendix 5: S*Metamodel and Definitions – from Schindel ref. 7.



Term	Definition
	Terms for Systems
System	A collection of interacting Components.
Component	A part of a system, capable of interacting with other components.
Interact	Two components are said to interact if one impacts the state of the other, through exchange of energy, force, mass flow, or information.
Sub-system	A Component of a system, which is itself a system.
Logical System	A system identified solely by its externally viewable (input-output) behavior.
Physical System	A system identified solely by its physical identity or make-up. Physical Systems are design components that fulfill Functional Roles allocated to them.

Term	Definition
Terms for System Behavior	
Functional Interaction (Interaction)	An interaction of Systems, expressed as an external (outcome) relationship in which at least one system affects the state of another system, through the exchange of energy, force, mass, or information.
Functional Role (Role)	The behavioral description (and therefore a Logical System) of a part played by a System in a Functional Interaction.
Stakeholder Feature (Feature)	A collection of Functional Interactions that has stakeholder value or provides a valuable service.
Input-Output	That which is externally exchanged between interacting elements. Abbreviated as I-O. Flow of Energy, Force, Mass, or Information.
Architectural Relationship	A relationship that summarizes the architectural significance of a set of interactions between systems.
System of Access	A System providing the means of access for interactions between other Systems.
Interface	The association of a System with a set of its Functional Interaction(s), Input-Output(s), Architectural Relationship(s), and System(s) of Access.
Terms for Modeling System States or Modes	
State	The condition of a system that determines its interactive behavior, viewed externally from the system. A system mode. A situation.
Sub-state	A state that occurs during, but not necessarily throughout, another state.
Event	Describes an occurrence that triggers a transition from one modeled state to another.
Terms for Modeling Hierarchies, Relationships, and Attributes of Classes	
Class	A set of things that are considered “similar” to each other by virtue of their membership in the class.
Superclass, Subclass	A class is a superclass of another class (called a subclass) if the latter is a special case of the former. Viewed as sets, a subclass is a subset of a superclass.
Relationship	A statement about several classes that may be true or false. If true, the classes are said to be in that relationship with each other.
Hierarchy	A sequence of classes, related to each other sequentially by the same type of relationship.
Class Hierarchy	A General-Special hierarchy, in which each progressive layer is a more specialized case of the layer above it. (“Is a type of”)
Containment Hierarchy	A Whole-Part hierarchy, in which each progressive layer is a part of the layer above it. (“Is a part of”)
Metaclass	One of the S* foundation classes used to formally describe systems and system related information. Metaclasses include System, Functional Interaction, State, Feature, Interface,

Term	Definition
	Input-Output, etc.
Attribute	A property or characteristic of a class, capable of taking on values to describe instances of the class.
Terms for Managing and Applying System Patterns	
S*Model	A model conforming to the S*Metamodel
S*Pattern	A configurable, re-usable S*Model.
Attribute Coupling	A description of how attribute values impact or are related to each other.
Terms for Modeling System Requirements and Designs	
Stakeholder	A Person or Organization most directly impacted by a System.
Requirement Statement	A (prose form, typically) behavioral description relating a Functional Role's Inputs, Outputs, and Attributes, describing the intended or expected behavior of a system.
Design Component	A Physical System that is within a Subject System's Physical System Containment Hierarchy and to which is allocated Functional Roles.

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