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Towards Defining the Systems Habits of a 'Primed' Student Engineer

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Abstract. In this paper, the philosophical underpinnings of a systems approach to engineering are described. These "habits of thought" capture fundamental ways of thinking that—when used together—distinguish systems engineers from traditional, discipline-based engineers, with particular attention to a 'pre-awareness' level of the Systems Thinking competency within the INCOSE competency framework. By discussing the philosophy for a systems-level approach to engineering, the foundational aspects from systems engineering and the broader systems sciences important in an undergraduate program can be discussed. Through this paper, systems principles—or habits—are proposed, essential for creating modern engineers who can shape the engineering profession into the future.

Introduction

The field of Systems Engineering is typically taught at the postgraduate level, or learned later in an engineer's career through professional development and real-world experience. This is commonly explained through the belief that in order to appreciate a systems-level approach to engineering problem solving, an engineer must have a certain level of expertise in a discipline or technical area, alongside a background of professional experience. For this reason, undergraduate systems-based engineering programs are not commonplace, in favour of traditional engineering disciplines. However, there is an established viewpoint that systems-level concepts are intuitive, and a recognition that a systems approach to problem solving is a skill required broadly in the global future workforce.

It is well established that the future engineer needs to be proficient with a broad range of problem-solving skills in order to approach future complex problems (King, 2008), and that universities should equip graduates with the right mix of skills for their professions ten and twenty years into the future (Gardner in Spike Innovation 2015, p.4). This paper argues that the fundamental ways of thinking required to take a systems approach to problem solving are readily generalisable to the problems that future engineers will encounter. The concept of 'habits' takes inspiration from the work that the Waters Centre for Systems Thinking (2010, 2019) has done towards defining the habits of systems thinkers, more readily associated with the systems thinking seen in system dynamics modelling.

This paper aims to provoke a discussion to define a set of philosophical underpinnings of the Systems Thinking competency relevant to systems engineering at an undergraduate level. The discussion is pitched at a conceptual level and at an audience of practicing systems engineers, so it is assumed that the philosophies discussed are known and spend little time justifying their use or historical context.

Whilst a coherent and finite set of ideas are presented, it is readily acknowledged that this is prototype argument. The focus is not on the requisite content knowledge or necessary systems processes familiar to practicing systems engineers, but rather the underlying principles, habits and ways of thinking familiar to those practicing systems engineering. Discussing the philosophy for a systems-level approach to engineering provides more freedom to explore the foundational aspects for educating a generation of engineers who naturally adopt a systems point of view, and hence avoid the problems that systems engineering aims to overcome, without being limited by the detail of specific systems engineering processes.

The 'Primed' Student Engineer

The INCOSE Competency Framework (Presland *et al* 2018) furnishes this discussion with a comprehensive concept inventory for systems engineers at various levels of competency. The 'awareness' level of the competencies provides a clear starting point for our investigation into the habits. However, the context for this investigation is at a 'pre-awareness' stage: what desirable habits of thinking can be developed so that the student engineer will be 'primed' to apply a systems approach to their discipline engineering, or indeed become a systems engineer. This clearly situates this discussion not in the content of systems engineering, but rather how the systems approach can benefit all student engineers.

The 'primed' student engineer (PSE) is the persona used to explore the systems engineering (SE) ways of thinking. The PSE is a newly-minted graduate engineer of a discipline-based engineering degree, such as a mechanical, electrical, civil or chemical engineering program. We focus particularly on the Australian context, where undergraduate engineering students graduate with an Honours degree recognised by the Washington Accord (2014); however, there are parallels to other education system where students exiting engineering programs have limited exposure to engineering practice or profession, but have typically studied the foundations of engineering science, based in applied physics and mathematics, participated in team design activities, majored in an engineering specialisation, and completed a major research project.

<u>Teaching the processes and practices of SE at an undergraduate level as a separate matter is challenging</u>, as often students do not have the depth of experience necessary to understand how to apply these processes and practices or even why they would be useful; for example, being comfortable with spending time and energy gathering requirements before generating a solution. Students can understand this idea in an academic sense, but typically do not encounter situations where this is put into practice in favour of sandboxed learning experiences. Having not experienced being part of a professional engineering workforce, it is commonplace for students to have the misconception that professional engineering work is made up almost entirely of engineering science activities—solitary technical work of design (Trevelyan 2010), such as calculating the forces in structures, or analysing the performance of an electrical circuit—without consideration of broader skills such as communication, strategic thinking and technical leadership.

However, the education of PSEs needs to be far more forward-looking. SE is increasingly important as our technological systems become further intertwined. The ways in which societies live and work are rapidly changing, and that technological systems underpin this change, such as systems that support improved human health, the emergence of intelligent networks, smart urban infrastructure, changes brought about by global climate change and political instability, responses to humanitarian crises, all alongside extraordinary scientific advances (CEDA 2015, FYA 2015). The PSE working in each of these areas in the future will rely on different tools, methods and approaches to navigate these complex problems, such as sense-making, novel and adaptive thinking, social intelligence, trans-disciplinarity (Institute for the Future 2011).

This emerging future presents exciting opportunities for the broader application of SE, as well as great challenges. For today's PSE, we argue that learning the textbook detail of different flavours of traditional SE is less useful than developing a broad, intuitive understanding of systems approaches to engineering problem solving. Universities need to help PSEs to become bold in unravelling complex problems, adept at navigating the context, constraints, limitations and boundaries of problems, considerate of different perspectives free from their own biases, capable of managing the expectations of competing stakeholders, confident to make sound decisions with incomplete information and creative in order to resolve poorly defined problems into clearly defined opportunities (Bell *et al* 2015).

Instead, the habits, like any thinking paradigm, should be invisible—a natural way that people think about the world. In Barry Richmond's words, it should be "the water we swim in." (Draper 2010, p. 53). In this way, the habits are the broadest conceptual repertoire of approaches common to systems engineers, regardless of context, stage of the system lifecycle or specific technical activity. Although these aspects are great importance to the delivery of systems engineering projects, these details are considered outside of the scope of this discussion.

The systems habits

The proposed systems habits are a collection of habits that PSE should use intuitively to approach problems. These should not be viewed as competencies or capabilities, but rather the 'usual' way of behaving that is exercised routinely, or even unconsciously. For each 'habit' there is a corresponding mantra that accompanies the habit. These are listed in Table 1.

Table 1: The systems habits

ID	**Systems habit. "The PSE…"**	**Systems mantra**
H1	..creates the best solution using available resources	Always iterate
H2	..works on problems that cannot be solved by an individual	Situate the problem space
H3	..navigates the context of interconnected systems	Identify constraints and enablers
H4	..synthesizes multiple perspectives and disciplines	Consider stakeholders
H5	..learns from history and contributes to future knowledge	Look left, and right
H6	..considers the entire lifecycle of a solution at multiple scales	Plan ahead
H7	..understands the parts by understanding the whole	Change scales; define interactions
H8	..makes sound decisions when presented with imperfect information	Create choices
H9	..identifies feedback in a system and plans for unintended consequences	Locate response
H10	..reduces uncertainty through the application of engineering science	Embrace unknowns

The discussion that follows briefly introduces the habits, and a complementary mantra from the SE domain that can be applied to model the habit. These habits are deeply intertwined and should be considered as a collection, rather than a set of discrete axioms. Within the detail of each habit, there is little that should be unfamiliar to the practicing SE – these are a collection of activities on which much of SE practice is based. What is, perhaps, unfamiliar to the SE is only at this level, and does not seek to justify its effect through detailed application or analysis. In this sense, the habits remain generic and broadly applicable.

H1. The PSE creates the best solution using available resources

This habit brings in three ideas important for the PSE to solve problems. This habit clearly derives from Koen's (2003) discussion of the engineering problem solving method[1]:

Create: Engineers create things. SEs create the systems that create things. PSEs realise the purpose of the design activity through actual creation of artifacts that support the engineering effort.

Best: 'Best' is a contested value, and introduces the concept of optimization and multi-criteria analysis. Different stakeholders will have different requirements ranked in different priorities. The PSE must be able to optimize their solution to meet these competing priorities.

Available resources: Alongside optimising for a solution, the PSE is constrained by the resources at hand, beyond the defined requirements of a system. These limitations can constrain the creation of the best solution, but also presents an opportunity space for optimisation and creativity.

A mantra is to **always iterate**. A generic is the concept of iteration, shown in Figure 1. The principle of iteration towards a final solution and incremental improvement through a design cycle are fundamental to an SE mindset. There are dozens of instances of these loops (see Deming (2000), Martinez & Stager (2013), Kolb (1984)). At this generic stage, the labels on the steps are less important than the principle of iteration itself.

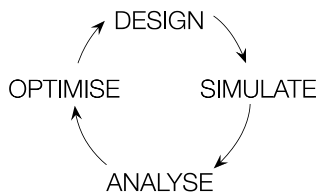

Figure 1: a generic diagram of iteration

H2. The PSE works on problems that cannot be solved by an individual

This habit situates SE as a large-scale activity that requires interdisciplinary teamwork, and integration of multiple technical and non-technical perspectives. In fact, these are the interesting problems. In contrast, problems that can be conceptualised and solved by a single way of thinking are trivial and uninteresting.

[1] Koen's fourth concept, uncertainty, is picked up in H10.

This habit is based on Schön's (1983) topography of professional practice: the manageable problems that can be solved through technical solutions reside on the high ground, and the interesting, 'messy' problems of greatest human concern reside in the swampy lowland.

A corresponding mantra is the ability to **situate the problem space** in the bigger picture, as shown in Figure 2. The principle of situating the problem is based on frameworks such as the triple-bottom line (Slaper and Hall 2011). The ideal location of the problem and/or solution should balance the needs of the different context spheres of interest. Here, the labels and numbers of the spheres that are represented in the Venn diagram are less important than the need to balance the needs of these spheres.

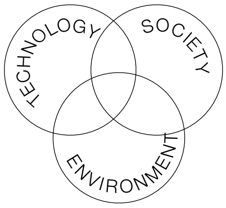

Figure 2: a concept diagram of situating the problem space

H3. The PSE navigates the context of interconnected systems

Navigating the context of a problem is an essential way of thinking for an PSE. This recognises that problems are rarely isolated, as they are often presented in engineering science textbooks. PSEs must be able to draw the boundary around their system of interest and understand both how the connections that cross this boundary effect their system of interest and how decisions made within their system of interest effect other problems.

Further, this can be extended to being able to understand one problem in terms of another. An example of this generalisation is the transferability of the system archetypes used in systems thinking. These small models can have a powerful effect on thinking (Newell 2012). For example, the Fixes that Fail archetype recognises that the solution to addressing a problem symptom can often lead to making the problem worse – such as building freeways to alleviate traffic congestion can lead to increased travel times as populations grow around the new freeways (Sterman 2000).

A corresponding mantra is to **identify constraints and enablers**: understanding the inputs and outputs of a process is based on input-process-output models, shown in Figure 3. This concept encourages an PSE to recognize that the output of an activity is a product of the input, constraints and enablers, and to recognize the context that could be applied to multiple project instances.

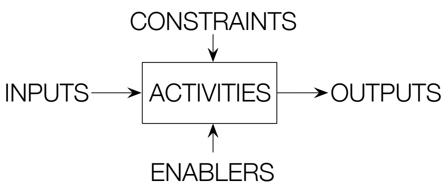

Figure 3: generic input-process-output model with constraints and enablers

H4. The PSE synthesizes multiple perspectives and disciplines

PSEs must be able to put their own biases aside, and be able to understand, empathise and synthesize multiple perspectives. As the divergence of stakeholder perspectives decreases, the complexity of a problem decreases (Head & Alford 2013). Empathy is a key idea in design thinking and human-centred approaches to engineering (IDEO 2015), and is essential to generating good design requirements.

The PSE should also be able to recognise that different disciplines—not just different engineering specialisations—approach problems differently. PSEs are required to be more than just a representative of a discipline in a multidisciplinary team, but require an interdisciplinary or trans-disciplinary mindset to operate successfully. Key to the habit is the idea that PSEs should be working on problems that enable the fusion and cross-fertilisation of knowledge from multiple contributors, generating new visions, explanations, theories and an enriched understanding of the problem (Brown et al 2010).

The corresponding mantra is to **consider stakeholders**. The observation that problems move from 'tame' to 'wicked' as both the uncertainty of the problem and the divergence of the stakeholders increase (Head & Alford 2013), shown in Figure 4. Divergence is represented both by the number of stakeholders, and the number of viewpoints the stakeholders have.

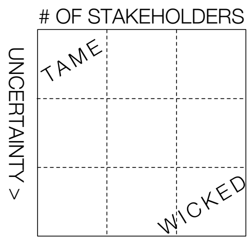

Figure 4: problems increase in complexity as the number of stakeholders increase.

H5. The PSE learns from history and contributes to future knowledge

The creation of knowledge is incremental, and a habit of an PSE must be that mistakes from the past are avoided, lessons are heeded, and successes are shared and repeated. A common experience here is the decision to buy an off-the-shelf system element, or design and build a customised system element. The PSE must first look to the past before embarking on the process of design. This is a broad undertaking, but is an important habit to develop. Exploring the nature of things is more important than repeating the formulaic answer.

The PSE must also recognise that the knowledge they are creating today will be the historical knowledge of the future. This emphasises the importance of making decisions based on sound evidence and processes, important to the success of an SE project. Work undertaken must by repeatable, with transparent methodology and open access to data and processes that led to design outcomes.

The corresponding mantra is to **look left, and right** on the timeline: **do not reinvent the wheel**. Understand how the context for the problem at hand has changed over time, described by the time-series graph shown in Figure 5.

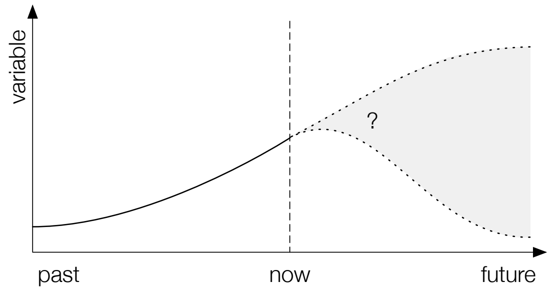

Figure 5: a time-series graph of a variable of interest

H6. The PSE considers the entire lifecycle of a solution at multiple scales

The PSE considers the whole project lifecycle, from the concept stages through to retirement. Planning for the entire lifecycle allows the PSE to plan ahead for future design stages, and encourages PSEs to learn from the previous projects and lifecycle stages. Considering how the lifecycle stages interact at different scales is also an essential habit to form; for example, how one sub-project life-cycle feeds into another. These scales move at different speeds, as described by the concept of 'pace layers' (Brand 2000), where different levels of a project move at different speeds.

Here, the generic lifecycle stages (ISO/IEC/IEEE 15288:2015) is shown in Figure 6, with additional connections to incorporate ideas considered in the habits. The corresponding mantra is to **plan ahead** through the entire project lifecycle; that a SE plans ahead for future phases of the project or system lifecycle, and embraces the learnings from previous projects and phases.

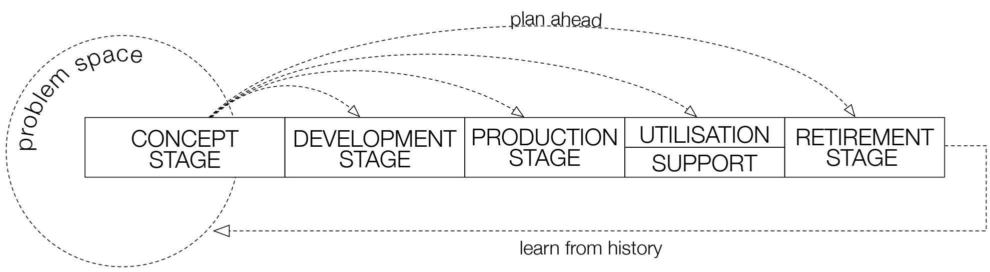

Figure 6: Planning and learning from the whole project lifecycle

H7. The PSE understands the parts by understanding the whole

The PSE must develop the habit of understanding the parts and the whole. Understood broadly as a knowledge of the physical and functional hierarchy of a system, a complementary philosophical view is provided by the hermeneutical circle: that the parts of a system can only be understood in the context of the whole, and that the whole of the system can only be understood in the context of the parts.

This circular understanding of the relationship between the parts and the whole ensures that PSEs do not become reductionist in their thinking about systems, nor do they become overwhelmed by the whole. This habit highlights the concept of modularity and integration, such that the replacement of a single part must be considered not only in the context of the immediate inputs and outputs, but also in the context of the whole system.

The corresponding mantras are to **change scales** and **defining interactions**, shown in Figure 7. These mantras apply equally to the level of detail within the system hierarchy, and the processes that enable a design to be completed[2].

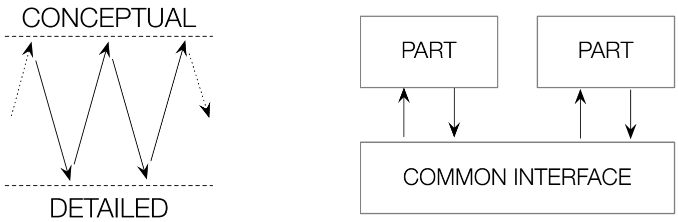

Figure 7: Left) changing scales; Right) defining interactions

H8. The PSE makes sound decisions when presented with imperfect information

The PSE must be able to exercise sound judgement and decision-making in the real world, and recognise that information is rarely perfect. The PSE needs to be able to be critical of data used to make decisions. Decisions need to be justified on the balance of probabilities. This habit does not ignore the fact that PSEs should be striving for better data collection, fidelity and access; rather, it is a recognition decisions are based on a broad range of assumptions, and that these assumptions are a source of risk. In this way, the humble approach of an 'all models are wrong' precautionary mindset can allow PSEs to see beyond the often-bounded rationality that detailed data analytics requires.

Engineering heuristics, informed estimation, and rules of thumb are practical and important ways of making decisions with imperfect information. For example, TRIZ is a structured way of heuristic problem solving for idea generation (Harlim & Belski 2011). Building up a model of the problem based on iterations of sound decision making—that is, solving problems with an authentic double-loop learning mindset (see Argyris & Schön 1974)—is an essential skill for all PSEs.

The corresponding mantra is to **create choices**, shown in Figure 8. This builds on the concept of diverging and converging seen in many processes, such as concept generation (Ulrich and Eppinger 2008) and double-diamond design process model (Design Council n.d.). In order to progress through a project, a project team should think broadly and creatively before converging on a solution to take forward into the next phase.

[2] This combination is similar to the assumed axes in the V-model (see Frosberg *et al* 2005), where time is implicitly represented by the x-axis, and system decomposition represented by the y-axis.

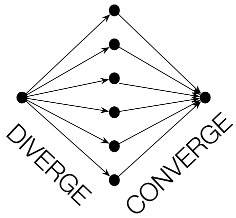

Figure 8: Create choices through divergence and convergence

H9. The PSE identifies feedback in a system and plans for unintended consequences

PSEs must recognise that systems are often dynamic and non-linear. PSEs need to be comfortable with counterintuitive responses because of the feedback structures within the system, and how the stakeholders may interact with the system. Not recognising this can be dangerous (Forrester 1969). Simple systems thinking approaches can open an PSE to the insights that come from identifying feedback systems, such as the sensitivity of stocks to reinforcing loops, balancing loops and delays. Being able to identify places to intervene in a system, such as the numbers, rules, information flows, goals, and paradigms is an important skill for the PSE.

Planning (such as in H6) is not sufficient to overcome the unintended consequences of problems and solution, and the bounded rationality that comes from traditional disciplinary thinking. PSEs need to develop the skill of black swan-thinking (Taleb 2007); that is, the plasticity of mind to encounter and deal with completely unexpected events. Being able to identify feedback in a system is a key method of preparing PSEs for the inevitability that their actions will, of course, have unintended consequences.

The corresponding mantra is to **locate the appropriate response**, based on the ideas in the Cynefin framework (Kurtz and Snowden 2003) shown in Figure 9. In an SE project, the required effort to solve a problem increases the further away from obvious it is. For the PSE, this is neither good nor bad; rather, understanding where the problem at hand is situated in the fields of obvious through to chaotic is of most value. There is a temporal aspect to this – over time, problems that were complex become complicated and then obvious through advances in technology and understanding.

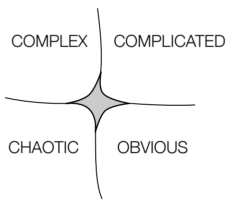

Figure 9: Locating the appropriate response using the Cynefin framework

H10. The PSE reduces uncertainty through the application of engineering science

The final habit, as presented here, connects the concepts of systems engineering to the traditional engineering sciences. Uncertainty in this sense is reducing the number of unknowns to an acceptable level, and using engineering science to do that; such as calculating the mechanical stress on a beam, or the potential energy losses in process. This concept fits neatly with the iterations and design loops presented earlier: the processes of prototyping, simulating, analysing before reaching a final design reduces uncertainty with each iteration.

It is important to realise that uncertainty itself is neither good nor bad. It is the management of uncertainty that is important—to be prepared for the unexpected—so that the uncertainties are understood, represented, communicated, reduced, accepted, tolerated, controlled, harnessed or exploited (Smithson 2008). The corresponding mantra here is to **embrace unknowns** – do not avoid them.

Discussion and Further Work

The list of 10 habits as presented is undoubtedly incomplete. Competing habits and mantras abound in the management and systems engineering literature, such as balancing depth and breadth in the notion 'T'-shaped people, and concepts from lean engineering, such as eliminating waste and avoiding rework. However, this paper aimed to provoke a discussion of the ways of thinking, or habits, essential to the development of all engineers prior to the Awareness stage in the Systems Thinking competency of the INCOSE competencies. The power of this idea is not necessarily in the any one of the habits, but instead <u>in the fact that such a list could exist</u>, however large or small. This idea has the potential to help explain the value of taking a systems approach to engineering in new and emerging domains, or indeed different professions: abstracted to the appropriate level, these habits—with few amendments—could be applied to other professional activities, such as decision-makers at all levels of government, professional services and industry.

There are many areas of further work that could be done building from this concept of the 'primed' student engineer. These questions could be a part of the focussed discussion around the emerging Systems Engineering for All Undergraduate Engineering Students (SE4AUES) initiative within INCOSE, but also more broadly in how we envisage "tomorrow's systems engineer" in an already fragmented global education system. To, this a number of research questions that we, the SE community, could follow on from this paper to help students develop these systems habits:

- **Better questions.** How can we emphasise the importance of navigating the plurality of systems engineering process to help ask the right questions in an educational system that simplifies ideas around the right answer? (H1, H3)
- **Better integration.** Many engineering programs teach practical elements of systems engineering in the silos of semester-based courses. How can we influence a meta-framing of these practical elements within the broader systems engineering context, over the duration of engineering studies? (H6, H7)
- **Better framing.** Many engineering science-based activities (such as hardware labs in various disciplines) benefit from the implied value of traditional engineering practice. How can we help instructors leverage these experiences in a systems engineering frame? For example, framing the lab as a design-review artefact against a specification. (H8, H10)
- **Better planning.** Many engineering student project are focussed around the earlier aspects of the design process, such as conceptual design and early development. How can we set up learning experiences that help students to improve their designs through learning that occurs in the later life-cycle stages? For example, the insights gained about the system in the support and retirement stages. (H5, H9)
- **Better teamwork.** Many engineering students are forced into a teamwork as a practical skill to learn without the benefit of learning processes relevant to the realisation of engineering

systems. How can we elevate team projects into the ‘real-world’ so that students can develop a broader skillset? (H2, H4)

Conclusion

10 underlying habits of ‘primed’ systems engineers were presented in this paper. The habits are intertwined, and one cannot be considered without a deep understanding of the other. Individually, these are principles common to any SE textbook. However, as a collection, they are a foundation for the pre-Awareness stage of the Systems Thinking competency within the INCOSE Competency Framework, and therefore are broadly applicable to other engineering domains. A foundation in these habits is important for the future workforce to be able to manage the complex and wicked engineering problems that will arise at the intersection of technology, society and the environment.

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Biography

Dr. Chris A. Browne's research and teaching focus is on building literacy in systems in the Colleges of Science, Health & Medicine at The Australian National University. This includes investigating conceptual models of complex systems, methodology of problem-solving processes, strategies for developing intuition of dynamic systems, and processes for constructing shared conceptual models of systems. Chris holds a PhD, Bachelor of Asian Studies and Bachelor of Engineering from The Australian National University, is a Senior Fellow of the Higher Education Academy, and Tomorrow's Systems Engineer lead in the Systems Engineering Society of Australia.