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Rationality for Engineers: Part I- Setting the scene

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ABSTRACT

The truly complex element of modern times is not the technology, but the engineers who develop, design, manufacture, and maintain it. An engineer's job is to change/improve existing situations into more desirable ones, as well as to respond to the demands or needs of society. Engineers cannot wait until all phenomena and their implications are well understood. Engineers have worked for centuries solving problems with limited information and knowledge and are presumed to be rational decision-makers. Then, how do engineers make their decisions with limited knowledge, time, and cognitive capacity in a variety of domains? Engineers require understanding what part of information can be ignored, and what situations require fast, and timely response, resulting hopefully in a better decision by freeing cognitive capacity to make it. A rational decision-maker should choose an option that maximizes the expected benefits (utilities), although there may be significant hurdles in achieving such goals, especially in emergencies where time pressure is acute. To overcome these hurdles, most engineers revert to "rules-of-thumb", also known as heuristics. Heuristics are experience-based methods of gut feelings that can be used as an aid to solve specific problems in a particular environment. Heuristics, however, are imperfect; thus, engineers must understand their limitations. Their applicability is also limited by the context under which they were derived as well as their fit with the environment of the problem at hand. The overall objective of these four-part papers is to discuss heuristics and how they can make decision-making easier and faster for engineers. These papers also remind them of their own cognitive biases and describe ways of avoiding them. This first part aims to set the scene by providing background information. These papers address the type of rationality that engineers need to be effective build on the existing literature and liberally draws from them. Engineers cannot march on the spot while thinking for a solution, they must think while moving forward, thus there is a danger not starting on the right foot.

1. Introduction

Engineering is an overarching profession that encompasses engineers working in various fields, such as aerospace, interplanetary exploration, offshore, chemical processing, civil structures, mining, and many more. In some disciplines, engineers use advanced numerical techniques, whilst in others, an engineer's job is to keep an operation running smoothly by preventing the breakdown of equipment. The common denominator of all such activities is engineers. Engineers are the thread that keeps beads of civilisation together. Their roles in their domain at the macro level are similar. This paper makes no distinction between various specialisations.

The term 'heuristic' is used as a label for procedures that are gained by experience and guides judgement in decision-making. Heuristics are commonly understood as rules of thumb procedures that may not lead to optimal or solutions but will generally produce outcomes that are 'good enough. It is also widely acknowledged that heuristics can result in systematic errors or biases. But all this is usually understood as a trade-off: heuristics forego optimal outcomes in favour of the economy. Systematic errors may result on some occasions, but they tend to produce satisfactory results.

A combination of both heuristic and numerical knowledge is used in the design and maintenance of engineering systems, as well as responding to emergencies such as oil spills, landslides, hurricanes, etc. Heuristics can also be used to decide on the layout of a system, then numerical knowledge is often used to conceptualize the complete system. Although experienced engineers know where to find information and how to make accurate computations, they also keep some amount of information in their brains for rapid recall, made up largely of shortcuts and heuristics.

Engineers are the prime tool of innovation of all ages. Thus, it is of interest to understand how engineers think, reason, and engage when using advanced analytical techniques and other tools to analyse and understand the demands of a situation. Engineers' roles are the prime influencer in all fields of human endeavour from aerospace to offshore to civil structure as well as just keeping an installation operational. To perform their tasks engineers, require more than analytical and numerical tools. They also rely on their intuition and learned experiences. The profession is not just to observe, collect and file data, but also to judge where the system is heading. For example, the job of an engineer in charge of a plant is not just to read dials and make a note of numbers, but to comprehend them and make a connection to the health of the system; and make a judgment if a runaway process is in progress. In such a context, expertise means how fast you can think on your feet.

An engineer in charge of preloading a jack-up in its new location does not model the operation using a powerful computer on the spot, even if he did, the results would be not very useful if the soil and weather conditions turn out to be different than predicted; the engineer must decide on what corrective action is required while the installation is still in progress. Similar uncertainty exists when a pilot tries to land a helicopter on an offshore platform when the weather is favourable. How do they do it?

This paper argues that the primary tools of engineering are heuristics, which are the experiences accumulated by many years of fieldwork, and possibly some by education. Koen [21] asserts: "*Engineering is the use of heuristics to cause the best change in a poorly understood situation within the available resources.*" This definition embodies two important concepts; first, engineers need heuristics, and second, problems requiring engineers' attention are generally too poorly defined to ignore heuristics. Though abstractions, analyses, and other cognitive tools may be used to obtain a better insight, the reality is too complex for full understanding. It is impossible to predict and assess every possible operational case and situation for a system over its life cycle. Koen [21] describes heuristics in this way: "*Although difficult to define, a heuristic has four definite signatures that make it easy to recognize: 1. A heuristic does not guarantee a solution, 2. It may contradict other heuristics, 3. It reduces the search time for solving a problem, and 4. Its acceptance depends on the immediate context instead of on an absolute standard*." Sometimes the rationale behind a heuristic is obvious e.g.: "Measure twice, cut once." Other times the rationale is more obscure such as "*Allocate resources so long as the cost of not knowing exceeds the cost of finding out.*" [21]

Experience shows that heuristic solutions work, but we do not have a mathematical proof for them. Heuristics are commonly defined as cognitive shortcuts or "rules-of-thumb" that simplify decisions, especially under time-limited conditions. However, heuristics can also lead to cognitive biases, which is discussed in Part IV. Simplify as the adage says, "you can't eat an elephant in one sitting". Simplifying is to strip out unnecessary so that you can see the necessary.

An analysis is performed to understand the problem you are trying to solve, the problem's environment determines what behaviours should the solution exhibit. etc. Analyses help to decide which heuristic fits best to the problem at hand. The term Analysis is used in this paper to mean the *investigation* of a problem and requirements, rather than a solution. For example, if a new highway is desired, then an analysis must identify which communities it would serve, what other facilities needed to enable its functionality? Analyses are for gaining gain insight and to understand what is needed to get more out of a solution. Engineers mostly refer to analysis as the process of applying mathematical models and other tools to find the answer to a question.

The term *Conceptual Design* refers to a *conceptual solution* that fulfils the requirements, rather than its implementation. For example, a concept is a complete listing, description, and order of all equipment required for a subsea production facility to function, but not their physical properties e.g., weight, size, footprint, etc. Conceptual design is deciding how to organize a solution based on a concept of operation once the requirements are understood [31].

Ultimately, a conceptual design must be detailed. The true and complete realisation of a concept is termed detailed design. Thus, detailed design is the creation of something which meets the specification of the concept, that is recreating something whose purpose and functionality have already been specified in some detail [34].

These four papers are structured as follows. Part I sets the scene by providing a discussion of the background principles that are relevant to engineers' decision-making, i.e., fundamental ideas and principles of rationality, and rational and critical thinking [2]. In Part II [35] two major research programs regarding heuristics lead by Kahneman [16] and Gigerenzer [10] are described. The findings of programs led by Kahneman and Gigerenzer are discussed. Part III [36] primarily deals with misconceptions in reasoning and biases when using shortcuts. Then, in Part IV [37], we discuss the appropriateness of heuristics for use in engineering. A discussion in Part IV [37] ties all these papers together and provides some overall conclusions.

2. Meaning of Rationality

The term rationality is taken to mean 'to act reasonably' as judged by peers, which is different from being logical which can be proven to be right or wrong using mathematics. Thus, rationality requires (a) a coherent worldview and what you want to achieve. Human judgments often deviate from logic but still can be rational. The so-called rational approaches to decision-making, in literature, make extensive use of logic, with theories based on axioms using mathematical models. As formality carries a connotation of being scientific, viewed from this perspective, rational approaches are thought to yield the best results. However, in a complex situation, such an approach is difficult to optimize due to many reasons including cognitive ability, time pressure, and data availability; thus, intuition would triumph in such situations [10].

In this four-part paper, rationality is defined as 'the ability to make reasonable judgments and decisions in time,' (which is different from intelligence), and can be improved through education and training, but intelligence is what one is born with, i.e., it is innate. However, going through the educational system does not guarantee that you are rational, just like going to church does not make you a Christian.

The concept of rationality is much more than the concept of intelligence since it does not stop mastery of facts that are achieved as thoughts. It is the ability to comprehend, and the capacity to evaluate the principles and purposes in the light of reasons; it implies consistent behaviour. Making a rational decision [33] means continual questioning to eliminate inaccuracies, wrong assumptions, enhance understanding, and strive for intellectually honest results; such combinations are very difficult to optimize when under time pressure and the situation demands a fast reaction. Rational thinking emphasises the ability to draw reasonable conclusions from data, rules, and logic, thus education and practice can increase rational thinking. But, if the environment changes, then a rational thinker may require a different skill set for the new environment. The logic used for sense-making of scientific experiments cannot be applied when buying a car or picking groceries from a supermarket shelf, which demands a different skill set and is termed "Rationality" in this paper. Learning to act rationally requires both practice and theory. Reading a car driving manual will not make you a driver, also just practicing will not either. One needs a correct blend of both. You need a good understanding of physics. Engineers decide by combining rational analysis and gut feeling; the proportion depends on the task. Both decision-making tools are sound but are subject to errors in different ways. The primary emphasis of engineering education is on analytical ability, not much time is dedicated to scrutinizing the premises of the analytical method. When using these analytical tools an engineer needs to make a lot of subjective judgments (assumptions), such as properties, boundary conditions, loading, among others, i.e., relying on legs that can barely support the body. Dijksterhuis et al. [7] have studied the relative effectiveness of rational and intuitive decision processes, concluding that although rational procedures score better for simple decisions, the reverse is true where the situation is complex. Engineers have developed many methodologies based on experience to guide them in decision-making. Once engineers have experienced something, the mark will remain with them forever and shapes their next movie which will also be tempered with new experiences - this is the adaptive tool. They become adept at recognizing where each scheme yields the greatest benefit. Applying the correctly learned patterns provides a fast, efficient, and proven approach to problem-solving. Engineers as experts depend on their long-term memory, and their ability to analyse problems deductively, selecting and retrieving cues by recalling the appropriate patterns from memory, and correctly applying them to solve a problem. This paper calls such learned tools "heuristics", and engineers accumulate these in their decision-making toolbox. The use of heuristics by engineers is not limited to their professional life. "*At some (high) level of generality, there is considerable overlap in the way pretty much everyone interested in heuristics at all thinks about heuristics"* [20]. The issue is, where and how heuristics can be (and are) used in engineering, and whether there could be a set of heuristics that could be powerful aids in helping engineers to make good decisions in complex systems' context [8].

3. Critical Thinking and Emotion

Historically, critical thinking is limited to a subset of rationality which deals with identifying and avoiding fallacies, argument analysis, and evaluation, as well as on reasoned judgment. "*Rationality and critical thinking include things about deciding what to believe and what to do*" [2]. Critical thinking is the ability to think clearly and coherently, understanding the logical connection between ideas. In Siegel's [26] view, critical thinking is the same mental and psychological activity as rational thinking. He [26] defines a critical thinker as "*one who is appropriately moved by reasons, and he argues that this characterization can be used as that of a rational thinker without any modifications*." Hence, the notion of reason conceptually binds together critical thinkers and rational thinkers. This paper is not about critical thinking, but engineers should be critical thinkers to use heuristics correctly and in the right domain. Rationality engineering means taking a measured decision, which is not risk-free but aimed at achieving the desired goal while attempting to maximize gains.

The reason is rarely carried out without emotional influence. Emotion makes it difficult to objectively evaluate the situation [39]. Humans depend on "feeling" for their survival, which is as true as it now as it was for the first humans on earth. In this way, feelings are heuristics that have evolved by evolutionary processes and are not exclusive to humans. Simply by being aware of your tendency to be swayed by your feelings and emotions, you will be better able to make more objective and balanced decisions. We feel something "in our bones" or feel this is the correct outcome based on our emotions. Feeling leads to attachment which influences decision-making. Feeling gives the final push in decision-making, though the degree of its influence may differ. Learning through emotional fear is quick and sometimes effective, but "expertise" is a collection of micro-skills that are acquired through time, involving numerous encounters with fear.

Lehrer [22] relates the story of a patient he calls Elliott who lost the ability to decide, due to part of his brain removed to excise a tumour. The surgery eliminated his ability to "feel," leaving him completely rational but utterly unable to decide. Lehrer [22] notes that Elliott's inability to decide came down to a lack of emotion. "*It seems to make good decisions; one must learn to combine rational thought with emotional awareness*."

A celebrated case is *Phineas Gage*, age 25, the foreman of a crew who was cutting a railroad bed in Cavendish, Vermont USA, in 1848 [15[. On September 13, as he was using a tamping iron to pack the explosive powder into a hole, the powder detonated. The tamping iron shot skyward, penetrated Gage's left cheek, ripped into his brain, and exited through his skull, landing several meters away. Dr. John Martyn Harlow, who treated Gage for a few months, wrote "*Gage's friends found him no longer 'Gage'*; he *could not make decisions or plans*." Loss of the frontal lobes, which is associated with planning and intellectual strategies, has also an important role in emotion, which pushes one towards or away from a decision.

Human thoughts and actions extend beyond the narrowly defined notion of perfect rationality and are shaped by factors such as contextual cues, social norms, decision anchors, and selectively recalled feelings and experiences. These systematic patterns of deviation from classical notions of rationality are called 'cognitive biases' which influence what people view as rational. If overlooked, these processes can lead to erroneous decisions. Engineers as rational thinkers are also subject to cognitive biases (See Part II, 35). It worth remembering that instinct and emotion are at the basis of all decisions, actions, values, and world outlook. Reason and rationality are used to justify.

4.Engineering Rationality

There are limitations on people's ability to make 'Rational' decisions in every situation for a variety of reasons, including cognitive capacity and time pressure. One such limitation is understanding probabilities and frequencies (see part IV, 37). Humans can have a reasonable understanding of the frequency of an event (how often an earthquake with a certain magnitude would occur), but not as good an understanding of probabilities (the likelihood of an earthquake in their locality). Another issue is that humans fear a loss more than relish an equivalent or greater gain. For instance, most people would refuse a gamble in which they could earn $11 if a coin lands on heads but lose $10 if it settles on tails. People will often choose to avoid such a bet because the potential pain of losing often outweighs the pleasure of winning. Playing this game just once is a gamble, but if it is repeated then it becomes less of a gamble. Rejecting such a gamble is not a sign of humans' inability to think rationally. Becoming a more rational thinker in every domain is not feasible, thus humans settle on the best results by focusing on the things they value most [27]. Rational decisions are based on verifiable facts, reproducible data, and principles of logic, however when the emotional content of a situation is high, then emotions have their say. Herbert Simon in 'Reason in Human Affairs' book [28] wrote: "*To have anything like a complete theory of human rationality, we have to understand what role emotions play in it*," Emotions are needed to make a decision. When we are thinking about thinking, we are thinking about feeling [38].

Engineering rationality is the reasoning that leads not to abstract knowledge, but to knowledge-enhanced know-how, which is employed to solve problems. Thus, engineering reasoning is explicitly based on values, which are intrinsic to what will constitute an acceptable solution. Human values influence which issue is important, and hence affect their decisions. However, values are just one among several influencing factors, but they may be the dominant factor that will define the boundaries of involvement and the facts that humans consider relevant. We need to ask ourselves a set of exhaustive questions to make it transparent which elements should or should not be considered as relevant to the situation encountered. The rationality of engineering reasoning is measured by how the results of that reasoning 'work', are judged relative to a set of subjective value judgments [3] By asking questions you can turn data into information.

The rational engineering method may be defined as the use of heuristics to obtain the best results in an inadequately defined situation using the available resources. The term heuristic, in this definition, refers to anything helpful, useful, and based on experience, but it can be unjustifiable, and potentially fallible. Engineering heuristics involves graphs, mathematical equations, and empirical correlations used by the engineer while exercising their profession. They also include strategies used to reduce risk, allocate resources, and establish the approach required for problem-solving. A single heuristic is seldom used in isolation, but most often several heuristics are used in groups. The term "Best Engineering Practice" refers to the best collection of heuristics in the engineering community, which also includes analytical procedures.

A young recently trained analyst may be adept at solving well-defined technical problems but may not find a path through an ill-defined problem with multiple dimensions and issues, compared with a seasoned supervisor. The supervisor, in turn, understands the questions that need answering but does not understand the quantitative techniques required to find an answer, and so must take on faith, and approve, that the quantitative approach chosen by a junior is technically correct and that the young engineer's results are sensible. In such a situation a supervisor devises heuristics that make sense and what should be considered suspicious. Such heuristics maybe "Back of an Envelope Calculations" for sense-making to gain confidence in the technical ability of a junior colleague.

The thing that is called engineering judgment [32] has an important role in the engineering profession. Engineering judgment is learned and used as an experience-based yardstick, which is acquired by integrating diverse evidence into making a sound decision. In many situations, this form of engineering judgment, which is inferred from complex evidence, is an important resource for the decision-maker, especially when there is not much objective evidence. This dependence on judgment is especially evident in an emergency where a situation evolves fast, and a decision must be made under a time constraint. Evidence-based decision-making is not about prediction but for understanding and explanation as to why you came up with a certain conclusion. Only inquiring mind solves problems. The "Just do it" mantra most likely would lead you to a mess that you cannot climb out of. You need to think about which mess to jump in (*think before you jump*)- choose your own mess. Engineering judgment is a heuristic that has an essential role in the assessment. Experimental research about the way humans think, and how humans integrate evidence, as well as the performance of experts in tasks requiring engineering judgment, supports the belief that the ability of 'experts' to judge accurately may be overrated.

5. Heuristics

Engineers' decision-making is not entirely based on analytical fact, but intuition and employing methods that have worked before. Every engineering decision is essentially a problem-solving process. A civil engineer provides tangible, technical solutions to situations that demand answers to satisfy an identified need, for example, a building or a bridge. Engineers can be defined as problem solvers, from the viewpoint that engineers are responders to human technical needs.

The common major steps in decision making are [25]; "

- *Stating the problem (what is the right question)*
- *Developing a plan, i.e., the strategy (How to solve it)*
- *Implementing the plan i.e., idea generation; (What are viable solutions)*
- *Comparing solutions and pick the most promising one; (Why is this the right solution)"*

The emphasis of the process, as detailed above, is on applying rigorous and logical deductions to complex and ill-defined situations to obtain sound solutions. However, there are many situations where it is difficult to follow this process fully, for example, situations where a decision must be made in a limited time. Proficient engineers make decisions by using their experiences to recognize patterns and recall actions for situations that worked in the past.

George Polya in his book, *How to Solve It* [25], revived the heuristics concept to help students develop their thinking abilities to enhance problem-solving abilities. He defined the concepts and strategies of heuristics as:

"*Heuristic reasoning is reasoning not regarded as final and strict but as provisional and plausible only, whose purpose is to discover the solution of the present problem ... We shall attain complete certainty when we shall have obtained the complete solution, but before obtaining certainty we must often be satisfied with a plausible guess. We may need the provisional before we attain the final. We need heuristic reasoning when we construct a strict proof as we need scaffolding when we erect a building*." [25]. People reason from a set of premises and only consider possibilities that they believe to be compatible. Several possibilities are generally considered and among them pick the one which fits best with the situation.

In some cases, problem-solving may end up in complete certainty. However, problems often require a large mental effort commensurate with their complexity. Although, heuristic reasoning may be sufficient, but for problems requiring certainty, heuristics may only be a means to an end. Polya's [25] heuristics view complements the ideas of Simon's [29] which he called "Satisficing". Simon considers that " *the real-world solutions are often not reached by rationality, probabilistically, or recursive optimization, instead the decision-maker deems a solution as sufficient since the decision-maker has neither the time nor the wits to discover an 'optimal path', and the primary concern of a decision-maker is only to find a choice mechanism that would lead to a 'satisficing' path, a path that will permit satisfaction at some specified level of needs*" [27]

Simon [29] incorporated Polya's [25] heuristic concepts into a framework where problem-solving includes both the decision-maker and the environment where the decision is made. Gigerenzer and Todd [11] build upon Simon's work and contrasts the concepts of "Unbounded Rationality" and "Ecological Rationality". Unbounded rationality, as described by Todd and Gigerenzer [30] assumes a completely logical solution exists and that a solution can be found, or as Polya [25] said, "*a solution of complete certainty.*" However, often there are insufficient resources to find a solution of complete certainty. Furthermore, the environment in which one operates may not permit a solution with certainty. The environment may limit the number of outcomes that are discoverable with heuristic thinking. This is a bounded solution, which Gigerenzer and Todd [11] called "Ecological Rationality" and Simon termed as "Satisficing". Engineers often work in an environment with limited resources and in several dimensions, including time and information. In this environment, it is not always possible to attain a theoretically certain solution, but only a plausible solution is possible, based on a bounded view of rationality [1]. Bounded rationality, satisficing, ecological rationality, and heuristics can be defined by Naturalistic Decision Making (NDM) [19]. Klein [17,18] defines NDM as *"the study of how people use their experience to make decisions in field settings. We try to understand how people handle all of the typical confusions and pressures of their environments, such as missing information, time constraints, vague goals, and changing conditions*".

Solution generation is the stage where engineers consider multiple options. It occurs throughout the decision-making process as solutions are developed and refined. For the initial idea generation, the goal is to explore, in both depth and breadth, the solution space. As the engineer explores solutions, heuristics are used to help generate solutions. Multiple heuristics may be employed within a single solution, and each heuristic can be applied repeatedly to transform the existing solution. Heuristics can focus on the form or the execution of an idea. The form tells us how a solution looks like, and the execution explores how to implement it.

A problem is defined as a situation that needs mental effort to create and/or select a transformation to a goal situation while observing a specific set of constraints. There may be some problem over how engineers use and select heuristics and their relevance for the situation at hand. This should be expected as heuristics are the result of experience and how they evolved. Thus, heuristics are context-dependent, intuitive, learned knowledge, or experiential understanding, which provides directions to enhance the chance of reaching a satisfactory solution, but not necessarily the optimal one. Experience leads to new truths that knowledge has not been able to reach. "*Knowledge is knowing a tomato is a fruit; experience tells you not to put it in a fruit salad"* (*Miles Kington, British journalist 1941-2008*). This quote means, a wise fool gains knowledge but has not yet acquired the wisdom, to apply it correctly. He/she knows enough to sound smart, but not enough to be wise. Charles Spurgeon (1834 –1982), was an English Particular Baptist preacher) once said, "*Wisdom is the right use of knowledge. To know is not to be wise. Many men know a great deal and are all the greater fools for it. There is no fool so great a fool as a knowing fool. But to know how to use knowledge is to have wisdom*."

Heuristics are both window and mirror; a window to look outside and a mirror to see yourself. If you think the concept of the window too restrictive, then think of it as a sliding door through which you can get out to enrich your experience or invite others in to draw on their experiences.

"**Common sense**" is a **heuristic** that is used for decision-making based on one's observation of a situation, as well as in the sense of being right and fair. This is a practical and prudent method that can be applied where the right and wrong answers are relatively distinct. Common sense is inborn rational thinking that is passed down by generations either genetically or by learning. Common sense incorporates thinking skills developed from logic, intuition, and the human capability to observe events and absorb lessons and information. Intuition is nothing more than recognition and hence most useful in repetitive tasks.

Proverbs, as suggested by Polya [25], works like heuristics but should be used with caution. He wrote: "*It would be foolish to regard proverbs as an authoritative source of universally applicable wisdom, but it would be a pity to disregard the graphic description of heuristic procedures provided by proverbs" (1985, p. 113).* Numerous proverbs are remembered by engineers. "Measure it twice and cut once". " It is not things you don't know that kills you, it is the things you know but it ain't so"; "You can't chew with somebody else's teeth": "no one would scratch your back except your fingernail"; "can't see the wood for the trees."

The analogy is another heuristic that is commonly used to draw inferences between similar events. The understanding of analogy is important since, " *... people often use vague, ambiguous, incomplete, or incompletely clarified analogies*" [25]' Like other cognitive models, overt awareness of usage helps to avoid misuse and capitalizes on strengths, "*It would be foolish to regard the plausibility of such conjectures [analogy] as a certainty, but it would be just as foolish, or even more foolish, to disregard such plausible conjectures*" [25]. Analogies are used in science to gain insights into phenomena that are usually unobservable. "*In science, two systems are analogous if they agree in the relations between their respective parts. Analogies are fundamental to the development of new ideas and the lifeblood of human thinking*" [4]. However, taking an analogy literally can be misleading.

The problem is how to be sure that our analogies are a good "fit" for the current situation. Thus, we need to bring rigor to our intuitions and mitigate the impact of flawed memory, heuristics, and cognitive biases?

Neustadt and May [24] suggest the following approach:"

- *Write down a list of not only the similarities in a situation that are considered analogous to your experience but also the differences.*

- *List what is known, unknown, and presumed about the situation.*

- *Share this appreciation with others and invite them to challenge it."*

Axillary elements were introduced by Polya [25] is "*An element that we introduce in the hope that it will further the solution is an auxiliary element"*. An example of adding an auxiliary element is superimposing of directions on the map in satellite navigation, which is further enhanced by verbal descriptions.

Mnemonic is a memory aide for information retention or retrieval. Numerous mnemonics are devised for different professions. For example, the mnemonic CURVES: (Choose and Communicate, Understand, Reason, Value, Emergency, Surrogate) addresses the abilities that a patient must possess to have decision-making capacity, as well as the essentials of emergency treatment. Table 1 [5]. This may be used, albeit with some modification in providing emergency relief to victims of a disaster.

Table 1 A Mnemonic Suggested for Providing Emergency Treatment in an Acute Setting [5]

C: Choose and communicate. Can the patient communicate a choice?

U: Understand. Does the patient understand the risks, benefits, alternatives, and consequences of the decision?

R: Reason. Is the patient able to reason and provide logical explanations for the decision?

V: Value. Is the decision in compliance with the patient's value system?

E: Emergency. Is there a serious and imminent risk to the patient's well-being?

S: Surrogate. Is there a surrogate decision-maker available?

Source: CURVES: A Mnemonic for Determining Medical Decision-Making Capacity and Providing Emergency Treatment in the Acute Setting. Chest. 2010;137:421-7.

Another example is DESIDE (Detect, Estimate, Set safety objectives, Identify, Do, Evaluate) [23], which has been demonstrated to significantly improve military pilots' in-flight decision-making performance'; Table 2. There are numerous mnemonics for decision-making in fast-moving situations. Decision-making requires sense-making i.e., how to size up a situation, which is the result of many years of learned experiences.

Table 2 DESIDE Mnemonic to Improve In-flight Decision-making Performance.

Detect: The decision-maker may or may not detect that a change in the expected outcome has occurred.

Estimate: The decision-maker may or may not estimate the need to react to the change

Choose: The decision-maker may or may not choose a desirable outcome, in term of success for the flight

Identify: The decision-maker may or may not try to identify actions that could be successfully counter the change

Do: The decision-maker may or may not do something positive to adapt to the change.

Evaluate: The decision-maker may or may not evaluate the effect of the action in the previous step.

Decomposing and recombing: Engineers generally break down a complex problem into smaller chunks, whose solutions are either known or may be readily found; this is known as the "Reductionist Approach". In designing complex structures or ideas, engineers will often break these down into smaller, simpler parts, find a solution for each part, and assemble these solutions to obtain a solution for the whole. This may not be possible when time is at a premium. The real challenge is when "*Too many or too minute parts are a burden on the mind. They may prevent you from giving sufficient attention to the main point, or even seeing the main point at all*" [25].

Enrico Fermi used to challenge his students with problems that seemed impossible. One such problem was that of estimating the number of piano tuners in Chicago given only the population of the city.

A typical solution involves breaking down this problem into simpler problems that would involve multiplying together a series of estimates that would yield the correct answer if the estimates were correct.

For example, we might

make the following assumptions:

1. approximately 5,000,000 people are living in Chicago.

2. On average, there are two persons in each household in Chicago.

3. Roughly one household in twenty has a piano that is tuned regularly.

4. Pianos that are tuned regularly are tuned on average about once per year.

5. It takes a piano tuner about two hours to tune a piano, including travel time.

6. Each piano tuner works eight hours a day, five days a week, and 50 weeks a year.

From these assumptions, we can compute that the number of piano tunings in a single year.

in Chicago is: (5,000,000 persons in Chicago) / (2 persons/household) × (1 piano/20

households) × (1 piano tuning per piano per year) = 125,000 piano tunings per year in

Chicago.

And we can similarly calculate that the average piano tuner performs: (50 weeks/year) × (5

days/week) × (8 hours/day)×(1 piano tuning per 2 hours per piano tuner) = 1000 piano

tunings per year per piano tuner.

Dividing gives: (125,000 piano tuning per year in Chicago) / (1000 piano tunings per year

per piano tuner) = 125 piano tuners in Chicago.

This method does not guarantee correct results; but it does establish a first estimate which might be off by no more than a factor of 2 or 3--certainly well within a factor of, say, 10. We know, for example, that we should not expect 15 piano tuners or 1,500 piano tuners.

6. Mental Model for Reasoning

A mental model is our perception of reality. Once it takes hold, we may believe it is a good match of reality. There are many ways to form flawed models of reality. We see the world much more coherently than relay is. Engineers conceptualize something which does not yet exist, which requires intuitive leaps. For such a leap of imagination, engineers need Mental Models to make better decisions. Heuristics are part of many Mental Models. However, sometimes the answer you are seeking requires knowledge beyond what you know, or heuristics can tell you. Heuristics that come from a wide range of disciplines such as psychology, physics, statistics, and behavioural economics, are useful to analyse problems from different perspectives.

A Mental Model is a representation of a domain to understand how something works and or how someone reasons. Mental Models allow reasoning about a situation without having direct experience of it. They are based on generalizations and analogies which may or may not be accurate; while heuristics are a set of rules-of-thumb, methods, or strategies used for decision making. A heuristic to open a door could be to push against the door, while another could be to add your body weight as well. Another example is when you exit a room that has a handle on it, do you push it or pull it? Heuristics tell us that handles are made for pulling.

Humans do not think in mathematical terms but create a simple narrative for everything that requires making sense of it; call it a Mental Model. If the constructed narratives deviate too much from reality, realism gets lost in the decision-making process, and when you venture too much beyond the borders of reality, your perception of the world is flawed, while you may still believe in your narrative. Humans in constructing their stories need causation and they see a causal relationship where there might be none. Engineers must find lots of information and weave it together to come up with a coherent narrative.

Human reasoning does not work like proving a logical problem; it is unstructured and sometimes goes around the houses. Mental Models have roots in attitudes, such as beliefs, ethics, expectations, and values that allow individuals to function as they do. You exploit what you know and do not differentiate between deduction, induction, and abduction, namely you conclude things based on what you think you know. Mental Models are constructed using all possibilities and conclusions are drawn from these models. Looking at it this way, the reasoning is a simulation of the world constructed with what you know and believe to be true, without using a formal logical argument. The two elements of the above definition are:

1. Mental Models are based on belief, not facts. A Mental Model is what we think how a system works.

2. Individuals have their Mental Models, which are internal to their mind, and.

3. Different people will possibly construct different Mental Models of the same system’s working.

Mental models are the framework of human reasoning. They simplify complexities to a level that the brain can cope with. People use Mental Models for decision-making without the need to know everything about that system. Mental Models are influenced by the brain's dual processes. System 1 (Type 1 Thinking) does not give time for Mental Models to be checked for biases. However, it is possible to escape the attraction of Type 1 Thinking, by keeping impulses in check, listening to System 2, and reading between the lines. It is not the maximum intelligence one must strive for but avoiding repeating the same mistake.

Mental Models are like conceptual drawings of a system, which is an abstraction of reality; it looks like reality, but it is not a replica. Details are left out so that they do not obscure the underlying idea, hence consequently can be useful. They are simplifications of what they are supposed to represent. A drawing can also be a snapshot of a concept at a point in time, which subsequently has been changed. Mental Models help to perform mental stimulation, or thought experiments, to examine what can be known or when to investigate the nature of things and answer "what-if" questions.

Kenneth Craik [6] suggested that the mind constructs "*small-scale models of reality that it uses to anticipate events.*" That is, a Mental Model is a kind of internal representation of external reality, hypothesized to use in reasoning, and decision-making. Jay Wright Forrester's [9] definition of a Mental Model is: "*The image of the world around us, which we carry in our head, is just a model. Nobody in his head imagines all the world, government, or country. He has only selected concepts, and relationships between them, and uses those to represent the real system.*"

According to Johnson-Laird [12] "Mental Models can be constructed from perception, imagination, or the comprehension of discourse", which is like engineering drawings of structures, which are like the structure that they represent.

Mental Models are based on a few axioms (assumptions). Each Mental Model is a representation of a possibility of capturing what is common to all the different ways in which the possibility may occur [14]. They typically represent only those situations that are possible. However, they also can represent what is assumed to be true. According to Johnson-Laird [13], everyday reasoning depends on the simulation of events in Mental Models The principal assumptions of this theory are:

- Each model represents a possibility.
- Models are iconic insofar as possible.
- Models explain deduction, induction, and abduction.
- The Mental Model theory gives a 'dual process' account of reasoning.
- The greater the need for more alternative models the more is the likelihood of error.
- Mental Models represent only what is possible.
- The meanings of terms such as 'if' can be modulated by content and knowledge.

As discussed previously, the world is a patchwork of systems; large and small. Each of these systems consists of multiple inter-dependent parts which are organized in a particular way to achieve the required function. Systems Thinking is the lighthouse when navigating through a stormy sea; it forces you to consider different disciplines. Paraphrasing Ackoff:

"Disciplines do not constitute different parts of reality; they are different aspects of reality, different points of view. Any part of reality can be viewed from any of these aspects. The whole can be understood only by viewing it from all perspectives simultaneously.

Considering again the car, which is a system. It has many parts that depend on each other to enable the car to function. You wish to understand how it works and which part you can remove without affecting its functioning. You may jump into this decision-making process and remove a part that you believe is superfluous and see where your decision takes you. Alternatively, you may use your intuition shaped by past experiences, and perhaps other advice that is available to you. This is a better approach than blindly jumping in, but not by a large margin. The answer to what is the correct decision lies in Mental Models, and a disciplined approach to their use. You need a Mental Model to appreciate the role of each part and how they hang together to deliver a function. To create a Mental Model for the task, start with asking:

- What is the function that the system delivers?
- How are components arranged and relate to each other within the system?
- What are the underlying principles behind the functioning of the system?
- Can the same function be delivered differently?
- Can the identified principles be used differently?
- Is this system efficient yet?

Russell Ackoff asserted that "*The performance of a system depends on how the parts fit together, not how they act when taken separately.*"

In most cases, it is just one of a system's parameters that are constraining the system from achieving a greater total output. Therefore, identifying the controlling constraints by trial and error would increase a system's output by identifying and addressing the constraining parameter. In an iterative improvement, you may not be able to bring the system to your desired level of efficiency, or you may hit an impasse. It is then time to abandon and change direction. Use nothing but the proven, underlying principles.

When we make decisions, we rely more on intuition than on deliberation (Part II). In Type I reasoning, our intuitions make no use of working memory and create a single model. But intuition is not always enough for rationality, thus a single Mental Model may be the wrong one.

The more models you have—the larger is your toolbox—the more likely you are to find a suitable model to fit your decision-making requirement. Awareness of cognitive biases in thinking could assure fewer systemic errors in thinking. Most engineers carry more mental models in their heads than a scientist, who is a specialist. This patchwork of Mental Models enables engineers to see things from different angles. A typical engineer will think in systems by default.

Not all decisions are worth agonizing over. Are we improving the colour of the upholstery or the fuel efficiency of a car? The amount of effort must be on par with its return. You can improve on your effort and consider the car itself. Working hard when there is something with more value to work on, is the dictate of Type 1 Thinking. Enjoying the flow of the puzzle but avoiding addition. The objective of continual use of Mental Models is constantly adjusting the decision trajectory. You form an opinion by considering outputs only, but you can also form a strategy if you look at the world as a patchwork of systems. Optimizing systems to get more out of them, and making good decisions are two pillars of Mental Models. Good decision-making may occasionally require silencing System 1 Thinking and switching to System 2, which is about Mental Models.

At a certain point, the incremental benefits you get from analysing a decision will get increasingly smaller. When you are hungry the first sandwich gives you satisfaction, but the satisfaction from the second sandwich will not be as much. This concept applies to engineers in several ways. First, make sure you are focusing on the most critical demand. As crucial as detailed data collection is, knowing when to call it complete is more important. The outcome would probably not be doubled by spending twice as much time on data gathering, and as details get more trivial, the less those details will impact the outcome. There are diminishing returns to gathering obscure details, and the sooner you notice them, the sooner you can concentrate on what matters.

The concept of "Safety Margins" is to leave room for errors and to avoid a total loss. It is better to be pleasantly surprised than proven wrong.

We design systems with redundancy, to protect against failure. This drastically reduces the chances of total loss. The system may sustain some loss, but if it does not break you back, you can stand up again.

Mental Models are a decision-makers toolbox. You need to pick the right tool to suit the problem at hand. You need more tools to solve a wider variety of problems. On the other hand, using more Mental Models to solve a problem enhances certainty, since a theory may turn out to be wrong one day.

Upon taking up a problem your understanding keeps enhancing. With this newly gained knowledge update your Mental Models and see if they still suggest you are moving in the right direction and answering the right question. As the world around us moves forward, there is a need to revisit some past decisions. If you do not change your mind occasionally, you end up spinning on the spot.

There are many types of Mental Models, and each takes a unique approach to reduce complexity. We need simplification to make sense of the world around us and to make good decisions. Each Mental Model provides a kind of framework for looking at problems. To improve your problem-solving ability, you need a larger toolbox of Mental Models, giving you more options to come up with the right answer.

A patchwork of Mental Models allows us to adjust our views of a challenge if we need to. After all, not every dilemma is presented to us in the same way or can be decided on from the same vantage point. The more Mental Models you experiment with, the more adaptable you will become to the challenges coming your way. Where do you begin to build your patchwork of Mental Models? A few of the most common Mental Models are listed below, you might be using them without knowing.

Pareto Principle is a good Mental Model. This principle says 80% of your output will come from 20% of your inputs. Substitute different words for output and input. For example, 80% of your income will come from 20% of your efforts. Looking at outputs only (the result of a decision), you can form an opinion as to where your decision-making is taking you. Thus, by looking only for the output you can not only strategize, but you can also form an opinion.

Regret Minimization, namely choosing an option that you would most regret not adopting when looking back after the dust has settled.

Inversion Perspective, that is instead of thinking about the desired outcome, consider outcomes that you should avoid. For example, in a decision-making situation, instated asking yourself "what action should I take to get a favourable outcome", ask yourself "what are the top 5 things which would impact my decision negatively", then make sure to avoid them. Avoiding stupid decisions is easier than getting a brilliant outcome. You may not always make a good decision by inverting the problem, but surely you will improve it.

Reverse-Engineering is disassembling a system to understand how its elements relate to each other, and what function they deliver. This is to enhance the system, copy it, or re-engineer it. In decision-making, untangling threads of thought leading to a decision helps to clarify and separate the underlying ideas or facts from assumptions. After stripping out all the add-ons, what remains are the essentials. Aldus Huxley said, "fact *doesn't cease to exist if we ignore it*."

Algorithms are a sequence of steps, that one needs to follow, to get to an answer or set of actions resulting in the desired outcome. This is stated in the form of a series of "If-Then" statements.

Chain of Events: In risk analysis models, the chain events are constructed (known as Fault Trees and Event Trees) to study which events would lead to what accident, and then to erect barriers along the path to prevent it. Chain of Events modelling is intrinsic to forensic engineering and accident investigations, where failures are analysed for the root cause or causes. Only when failures have been investigated with conclusive results can remedial action be taken with confidence. There are several chains of events models and among them, Reason's Swiss cheese model is the most popular one.

Remembering isolated facts and heuristics and trying to fit them into a decision-making situation will not work if the facts are not woven into the fabric of a plausible theory, or those facts are not in a usable form. The fabric of Mental Models permits us to adjust our view of a situation if we need to. Not every dilemma presents itself in the same way or can be decided on from the same frame of mind. The more Mental Models you experiment with, the more adaptable you become to the challenges that come your way.

Mental Models are not a replacement for evidence-based engineering. Their biggest potential lies in how they help us navigate the world by creating meaningful and repeatable abstractions, so we can make better choices without reaching decision fatigue. Mental Models should be evaluated based on how useful they are, not by being right. The effectiveness of Mental Models requires scepticism, not cynicism, to succeed.

7. Conclusions

The objective of this series of papers is to advance knowledge of heuristics for engineers. The focus of this part is to provide background information and definitions of the terms used.

In a dynamic and uncertain environment, seeking an optimized solution is often difficult if not impossible. Confronted with this, engineers use heuristics to make decisions within reasonable time and effort. Heuristics can also help engineers to save time and mental energy, by freeing up cognitive resources for more complex planning and problem-solving endeavours.

Many commonly used heuristics are defined in this paper. Since heuristics are experienced-based (self or others) they are primarily valid only for a specific environment. Engineers may unwittingly commit an error, known as bias when using heuristics. Several biases, along with how to avoid them, are discussed in Parts II and IV. In literature, heuristics are identified by the errors (biases) they cause, thus the terms *heuristic* and *bias* became almost synonymous and sometimes are used interchangeably.

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