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Rationality for Engineers:
Part III: Content and Context of Heuristics

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ABSTRACT

The focus of heuristics is on the content of decisions; however, the contexts are equally important; that is, where and how heuristics are used will often have a great influence on the outcome. Engineers need a lot of specialized skills, hard as well as soft, to successfully apply heuristics, i.e., to identify the heuristic that best fits the environment. Heuristics can help to lessen (not eliminate) the cognitive burden. This part of the four-part paper discusses how heuristics are created, improved, and refuted, and describes what judgment errors they might cause. In using heuristics, engineers must be aware of biases, which is examined in this part. The context of decision-making is also considered, and finally, the paper shows how heuristics should be used.

In engineering, heuristics are experience-based methods used to reduce the need for calculations such as equipment size, performance, or operating conditions. Heuristics are fallible and do not guarantee an optimal solution. It is important to understand their limitations when applying them to a different context. Heuristics work well in a stable environment, but if the environment is complex and changing, heuristics may lose their relevance and require updating. Though the applicability of heuristics is conditional, they can be of value when used expertly.

1. Introduction

Imagine heuristics as tools in a toolbox. You need to choose the correct tool for the job. There might be several tools that could be used, and each may have some advantages and disadvantages. One may be too big for the tight space, another too short to provide enough leverage. Yet the third one is difficult to use. You can establish the connection and suitability of each tool to the task, but the task determines which tool is preferable. Tools wear out and become obsolete, and there is a need for a renewal or replacement process. Tools can be borrowed, rented, or bought, but nothing can compete with the ones that you own and have deep insight into their workings. Even poor heuristics used with great insight can be formidable tools.

Tools are the content, and the task is the context. Content is the material/matter/methods that are available to the engineer, and the context is where the engineer applies it, i.e., the environment. Context is created by the positioning of the content, storyline, or purpose that provides value. As Bate [2] said, "Context is everything."

The context, in heuristic literature, is also referred to as the environment or domain of application. A heuristic developed for one context may not work in a different environment; the portability of heuristics is uncertain.

Heuristics are just working hypotheses until proven wrong. They should not be considered as universally true or as relevant now as they were 20 years ago; due to the dynamic nature of the engineering profession. As ime passes some heuristics may become less relevant as technologies evolve, thus there is a need for practitioners to invest in continuous professional development. The ability to learn is a characteristic of humans. Learning is faster when it is supervised by a skilled guide. Take a foreign language, how much you can learn from a teach-yourself book compared to learning with a tutor, or even better, to be surrounded by native speakers. This shows the importance of learning on the job. Learning never stops, it comes as a series of lessons, with the last one being the most important. What an engineer learns after formal education is mostly heuristics and how to apply them. In this context mistake is a very effective teacher. Another skill that Engineers need, is employing mental mapping to design from the perspectives of the users of their creation, how users would interact with their creation.

Engineering at its core is a marriage of art and science. which requires both judgment and skill in execution. Skill is obtained in stable and regular environments, with the opportunity to learn from ordinary events through prolonged practice (exposure), while also perfecting judgment at the same time. Heuristics blend theory and pragmatism in equal measures. Excessive reliance on theory can lead to blind faith in manufactured numbers; too much emphasis on pragmatism may prevent engineers from moving forward with technology. Successful design requires both; but when in doubt, this author suggests that more emphasis on pragmatism will increase the odds of success.

The Hegelian model “Thesis, antithesis, synthesis” for the progression of ideas is also known as a dialectic. Hegel believed that A better understanding can be achieved by creating two diametrically opposed views or explanations of a situation (i.e., a thesis and antithesis). By clashing thesis and antithesis, something better would emerge. The result is a more complete, enhanced knowledge--what Hegel called a synthesis. Such a philosophy suggests that problems are solved not through conformity but through confrontation. Greater understanding is created by pitting present views against their most compelling counterarguments. Such controlled conflict has both positive and negative consequences. Among the advantages are: better ideas were produced; a new way of looking at a problem; hidden problems would surface; assumptions were clarified.

Analytical ability and experience would help engineers to decided which heuristic to use. The heuristic of “chop & change, integrate, simplify” is an example of a heuristic used for a conceptual design. For a development design concept, engineers break down a system nto several manageable modules, ommensurate with constructability, skill set, transportation, access roads, ability to analyse, etc. It seems likely that explicit training in developing the effective use of heuristics would enhance the creation of the idea generation skills for engineers, which are generally left to be learned on the job. Engineers are emigrants to the land of engineering. They can perfect their accent by associating with those who have a few more years over them. Every engineer speaks engineering with an accent, but gradually the rough edges of the accent get smoother, and they understand each other more easily without straining their wits.

People look for evidence to support their beliefs and objectives, not to refute them. They often do not use reasoning to correct their beliefs, but to advance them, and to defend them against others— I’m the best; I deserve the last sweet. Similarly, people use reasoning to tear apart other people’s arguments. When it dawns on them that they are defending the undefendable, they shift their focus from winning at all costs to wresting the most value.

A primary tool of engineers is their imagination. This is as true now as it was in ancient times. The particular set of assumptions about the world that Engineers adopt guides their actions and directs them towards success or failure. The three primary characteristics of engineers are:

- concern about the future states of the world and the need to protect them.
- seeking to secure a preferred future state to achieve certain ends.
- Believing there is more than one choice of different qualities.

2. Some Common Heuristics

Following are a few examples of heuristics that may help people decide or solve a problem:

- "Consistency heuristic" is a heuristic that requires a person to respond to situations in a way that allows them to remain consistent.
- "Educated guess" is a heuristic that allows one to decide without exhaustive research. The educated guess is based on past observations and applies to a situation where a more definite solution has not been found.
- "Absurdity heuristic" is applied when a claim or a belief seems silly or defies common sense, i.e., an absurd or very atypical and unlikely situation.
- "Contagion heuristic" causes an individual to avoid something that is thought to be associated with contagion. In an epidemic, someone might apply this simple heuristic and decide to avoid social interaction altogether to avoid being infected.
- " Thinking forward and reasoning backward". Supposing to know the solution and working backward to see how such a solution can be obtained.
- "Familiarity heuristic” Assuming a familiar situation is like the situation under consideration, and thus taking the same decision as before. A military man only sees a military solution.
- "Scarcity heuristic" is used when a particular object becomes rare, which means if something is scarce, then it is more desirable.
- “Going with your gut” is when you make a snap judgment based on a quick impression. This heuristic looks at a situation quickly and decides without further check. It is worth remembering that instinct and emotion are the basis of all decisions, actions, values, and worldview.

- "Authority heuristic" refers to believing the opinion of a person of authority just because that person is in a position of authority. Engineers apply this heuristic all the time by referring authorities to authoritative texts or quoting. A variation of this heuristic is known as the "Halo effect", which states; if somebody is seen as infallible (such as a politician or a religious leader), then she/he cannot do wrong.
- "Less is more". Truth is lost when too many messy details are included.
- Not seeing the wood because of the trees.
- Everything happens for a reason; It is in God's hand.

By reviewing these heuristic examples one can get a general idea of techniques of decision-making and how to use them.

Individuals are constrained by limited resources, which applies to all engineers while making decisions, or formulating a question. Heuristics may be answering the wrong question, namely, the actual question is unknowingly replaced with a familiar question.

A love story is just one story, but whoever tells it you feel as if you have not heard it before. The word love evokes a different emotion, and each person has a different connotation and context. Some likened the word 'risk' to the word 'love'. It means different things to different people; you need to know the context to make sense of it.

Some common heuristics used by engineers are explained below.

#1: Considering more parameters will make a problem better defined but including too many parameters will make it intractable.

The idea is to select parameters that:

- have the best explanatory power, and
- are logically the most appropriate and have a high impact.

#2: Break the problem into smaller size problems. The engineer should decide on the right amount of granularity. Engineering education for problem-solving liberally uses the idea of deconstructing a problem, analysing it, and assembling the result. An important balance must be struck, i.e., the level of detail provided by the solution. Availability of data, analytical method, and time are all constraints when considering a problem that has too many details. Equally important is the need for enough detail, as the heuristic explains "problems must be simplified as much as possible but no more than that".

#3: Let available data drive the boundaries of the solution space.

#4: Do not lift a large stone that could fall on your feet; or do not bite more than you can chew.

#5: Be mindful of parameters and data you did not use or decided not to collect. Data collected by others may be irrelevant (not valid for the problem at hand) hence all data must be looked at with suspicion. Collecting more data may not be fruitful if one is entrenched in biases.

#6: Do not do more analysis than the data or the problem warrant. Torturing yourself will not yield better results. Do not labour at a problem, because it can be done; if it can be done, it does not mean that it should be done.

#7: Mental models are used to come up with a solution; A model is not reality, since it is an abstraction of what the participants think (and hope) the system and its environment will look like. The real world is messy, and reliance on a model that will solve all problems is risky.

#8: All models are wrong, but some of them are useful. This heuristic is due to George Box [18] entitled Robustness in the Strategy of Scientific Model Building. The message models have many limitations but at the same time provide useful information. Starting with the sceptical view that all models (heuristics) are wrong may sound negative but helps to be cautious.

#9: Begin with the end in mind. Think about what you would like to see when the dust has settled.

#10: Requirements are supreme. What you trying to achieve is the requirement; subject to verification; provided you know what you need.

#11: Not all requirements are equally important. Requirements have different levels of complexity and importance, and various level of difficulty associated with their implementation.

#12: Free is a special price that you or somebody must pay. Some solutions sound free but are accompanied by external costs to somebody else down the line. Routing of a railway through a floodwater runoff may look cheap/free, but when floods occur, somebody must pay for the flood damage.

#13: Remember that personnel capability or the budget is not infinite, when you are dealing with a large project or disaster, you must live within your means. When contemplating a large project that is being designed or constructed, it is reasonable to limit your expectation to your budget and skillset and other available resources. Thinking that you will cross the next bridge when you get there, could cause you to lose sight of what is achievable.

#14: If you are thinking to sin, be sure to sin consistently. This is the principle of consistent crudeness. The capability of engineering in an organization is determined by the skill set and its resources. If you are including or excluding something or someone, be consistent, although it may be difficult to be consistent. Consistency may not solve all your problems, but it will stop enough people from trying to find a hole in your argument and actions. Where there is a want of inconsistency, then there must be some error in reasoning.

#15: Whatever you do evaluate early, often, and correctly. The focus must be to catch problems early and arrest the drift from the original goals. This also provides an opportunity to revisit the original assumptions.

#16: Experts will disagree forever. If there is a situation where many experts are involved, they will usually disagree on the relative influence of certain parameters. Limit the expertise by defining the boundaries.

The above set of heuristics which are not mutually exclusive are a baseline that every engineer can build from by applying, validating, or refuting, based on their empirical work. They may be applied to individual tasks, large projects, or even organizations. Engineers must gather knowledge from all things in life. Where data and analytical capability are abundant and experience is reliable, then the use of heuristics should simply serve as sanity checks.

17: Similarity heuristic. This heuristic operates when we seek patterns and look for similar situations. We may notice in some way a situation is like another one and infer that what happened before will therefore be more likely to happen now. This heuristic works much like analogies and metaphors. When the similarity is relevant, it would make the inference more pertinent. For example, the boss fired your colleague for sleeping on the job, and you draw the reasonable conclusion that if you sleep on the job, you will be dismissed too. On the other hand, a similarity might be superficial or not connected with the outcome at all, which would make the inference incorrect. For example, you see a TV commercial showing a slim young person sporting an outfit and infer that it would look as good on you, even if you can shed 30 kg.

18: Doing the same thing again and again while expecting a different outcome is pointless. A once failed decision may be a mistake, a second failure you may call experience, but a third failure must be considered insanity.

19: Jumping to a conclusion, or think before you jump, is a heuristic warning against the hasty decision. Act in haste repents in leisure. It seems jumping to the conclusion was Einstein's favourite sport as the following quote attributed to him signifies "*If I had only one hour to save the world, I would spend fifty-five minutes defining the problem, and only five minutes finding the solution*.".

20: The indicator heuristics (used for methods, novel concepts, etc.). Novelty is categorized into five classes (1) new or unusual and never used; (2) used by others in a different region of the world or different industry; (3) used by others in our industry; (4) used by us in a different project; (5) it is commonly used by us. This use heuristic is useful for ranking risky situations or risk mitigation measures, when new material, a new concept, or a new approach.

#21 Credible bounds heuristics. How big or small something can be.

#22 "Think outside the box "(if dead, you have to think inside the box)". This a heuristic suggested for creative thinking [22].

3. Using, Improving, and Refuting Heuristics

A heuristic about heuristic:

"Do not assume that the original statement of the problem is necessarily the best or even the right one." [15]

Understanding that the problem requires a solution is the first step. In doing so one needs to ask questions. The effort to understand "what is the question" leads to pondering "what is the right question to ask". This is a trial-and-error process with many blind alleys.

The wrong question will divert you from the right path, but who knows what the right question is? Asking questions with different slants could help to find the right path. Colleagues can also help if you are in learning mode, not the convincing mode. Curious and enquiring minds feed upon themselves.

The following heuristics suggest the need to make sure that the right question is asked. Generally, engineers are faced with two primary questions.

- Am I solving the right problem? i.e., is the right problem being posed?
- Am I solving it correctly?

This is important when we know what we need (and want) and the solution is not out of reach, i.e., when some leap of imagination may bring the need closer to the solution, to make it attainable. In such a situation the desire for a solution may influence the question we ask, which consciously or not, we try to shape the problem so that we can solve it.

- There must be agreement among experts that the heuristic which is used is useful and correct.
- The applicability of the heuristic must be obvious.
- The heuristic must be resilient across different types of scenarios and environments, but not necessarily in different domains.

What Can We Do?

- Think Bayesian: Don't suspend your common sense because you are caught up in numbers.
- Think broadly and deeply: Look at any important problem from multiple perspectives. Do not bet on a particular model.
- Think critically: Question everything.
- Maintain a sense of proportion.
- Remember ABC: Assume nothing; Believe nothing and Check everything.
- The devil may be in the detail, but the sting is in the tail.

Emphasising 'assumes nothing' is all well and good, but we need assumptions to make a start; their validity is at stake. We cannot function without them, especially assumptions which help to suppress other assumptions. We also use assumptions (perhaps fallacies) to prove cherished pet theories or reject others. Creating a heuristic starts with conjecture. Most people will try to find reasons to validate their assumptions. You can always find reasons to believe something is true. Popper [14] believes we must find a reason to refute the conjecture. He said, two people, reading the same newspaper article can find reasons for and against a theory.

We are generally eager to build an explanatory narrative when the observed data is the effect of chance. There is a need for a backup plan (plan B) and a triggering mechanism to change course.

The world is too chaotic to understand without a coherent story (some may call it a theory). We create a narrative of our lives to make sense of it. We tend to dismiss new information that does not fit with our narrative of how the world works. This is known as “Confirmation Bias,” which reinforces our belief. Unexpected events sometimes surprise us, to make sense of them in our world, we make more stories. Thus, we believe in correlation and causation from insignificant observed samples when there is none. Another effect is an inability to consider the "regression" effect whereby, in any series of observations, any extreme value is likely to be followed by another which is closer to the mean of the ensemble. For example, the variation of the learning performance of a person is a “noise" around a slow learning curve, where each outstanding performance would naturally be followed by a poorer one. Lack of understanding of regression has led to widespread beliefs in the value of punishment towards improving people's performance [5].

We observe that certain heuristics applied in a specific situation may cause side effects. We conjecture that the use of heuristics may make it more likely to lead to that side effect. This conjecture is legitimate, but to become a respectable theory it would need either a causal explanation, or an analysis of a sample of many similar cases where different approaches are pursued, and the side effects of that heuristic were not observed but a significant correlation was detected. New evidence would cause a heuristic to be reinforced, modified, or refuted. Heuristics are based on past data, i.e., what you know. Using old heuristics and dusting them down has a certain appeal, but the change is to look for new data to assure they are still usable.

Emergencies demand a different mental framework. Responders need to think on their feet. An emergency is not a lab environment in which you can devise experiments, produce, and analyse data and then decide. In an emergency, data, come slowly (one at a time) and there may not be time to update your prior belief. On such occasions, the subjective probability is all you must act on. Humans are better to discover connections between bits of information. Whatever comes to your senses (attention) influences your decision. The quality of the decision is not equal to the quality of the decision. In the short run, chance elements may not be favourable, thus do not confuse luck with skill. In an uncertain environment, it is better to focus on improving the process of decision-making rather than the outcome alone without accounting for the element of luck. In an emergency, data comes in simultaneously from different sources, creating an incomplete picture of an evolving situation. You need to use each piece of information to update your prior belief as to what is going on. It is not a laboratory condition where you can undertake 10,000 experiments to update and reduce uncertainties.

4. Situation Appreciation

Real-life situations are not like a museum where every exhibition is fake, or a carefully constructed fiction, because the context is not really replicated. Or like an advert that leaves out reality or dismisses causal relationships and falls into the abyss of irrationality. Engineers cannot ignore the environment and how it influences the likely solutions. Engineers need the practice to see the relationship of the problem and its environment and how any problem interaction would affect solutions can be employed. Moreover, the environment changes as time goes on. This requires constant practice; One cannot leave the profession and come back later expecting everything to be preserved in a time capsule.

You need to understand how we perceive your environment and interpret information within it. Perception is defined as the way we gather information from our environment and interpret what it means. Thus, *Perception* is the multiple ways in which we receive information from our surroundings, help us to understand our environment and what is going on. On the other hand, cognition i.e., *the* way we comprehend our environment, is through immediate sensory experience coupled with memories and experiences from the past. Psychological studies of perception and cognition look at how we organise, identify and interpret information through our senses. Acquired knowledge and experience are situated at the interface between us and the environment. Specific places and moments shape understandings and lead us to recognize things or respond in particular ways. To some *extent, Seeing is believing* is true, as eyes allow us to see our environment, but what we perceive in any given moment is not only determined by sensory input, but also by our physical abilities, feelings, our memory, and experience, and more. Things that seem true and universal are often just our own unique experiences of the world. This is useful to know—we understand what irrelevant factors manipulate what we see and think, we can perhaps find ways to overcome these influences and make better sense of information to make better decisions.

Understanding how engineers perceive and make decisions enhances their ability to be better decision-makers. Appreciation of the situation and planning to resolve the problem (posed by a situation in an environment) is one of the engineer's key functions. A five-step planning process is suggested for engineers to approach a situation to determine tasks that must be carried out for achieving the desired outcome. The objectives are to understand the problem, find a solution and ways and means of implementing the chosen solution as well as to allocate resources to achieve the set objectives. This planning process has the following five steps [4].

1. Characterise the situation and identify goals to be achieved (the desirable end state).
2. Decide on what must be achieved to obtain the desired end-state;
3. Order the sequence of actions that lead to the achievement of goals;
4. Allocate resources and develop the concept of operation;
5. Identify how to monitor and continually improve- what data must be collected and how to judge if the goals are obtained; suggest modification is deemed necessary.

In a similar vein, Australian Military has developed the concept of **situation Appreciation** to help commanders to gain an understanding of the situation**.** According to the Australian Army Manual [1] "*An appreciation is a logical process of reasoning, the object of which is to determine, from facts known or assumed, the best or better course of action to take in any given circumstance."* This describes a logical process to identify a course of action which fits the circumstance. This is, in essence, a process of clear thinking and logical reasoning. Arthur Conan Doyle said through Sherlock Holmes, "*Appreciation is problems solving by logical assessment of all known facts."*

Australian Army appreciation process consists of six distinct steps, the first two steps are to understand what must be done and the rest for deciding how it should be done. The parts or steps to be taken are as follows:

1. what are we confronted with? **-** the situation.
2. What goals to be achieved
3. What course of action to take?
4. Consider all **factors** but select the most relevant ones and make a **deduction.**
5. What are the options? Possible ways to attain the goals.
6. Decide on the best **course of action** – what to be done

Each step includes several sub-steps that break down the overall process into manageable chunks for more granularity.

The problem with this model is that it does not consider the cognitive and emotive effects that influence decision-making. However, the foundation on which the Australian army situation appreciation has been designed is the assumption that decision-makers are rational in neu classical economic sense.

The above Discussion sketched the situation appreciation. Another important awareness issue especially for those who are on the scene responder is situational awareness.

Awareness of what is happening around you is required for making a decision to fit the situation. Understanding the environment, judging the consequence of one's actions and the potential risks are necessary components for sound decision-making. The method of understanding a situation is known as Situation Awareness (SA) SA is covered in some detail in [23] with some details.

5. Context and Content of a Decision

Klein [10,11] suggests that the chances of getting intuitive decisions right are much improved by good situational awareness, which in turn depends at least in part on effective pattern recognition; it is the way we organize, make sense of and use our experience. So, memory and recall are fundamental to recognition primed analysis. Situational awareness differentiates between luck and skill. The brain looks for information from experience. Pattern recognition is emotional tagging Emotional tags help us to act fast. Most of the time pattern recognition works well, especially when past patterns are appropriate for the current situation. Pattern recognition in driving, when negotiating a sharp bend, may turn out wrong. The brain fills in data by pattern recognition. Deep-seated desires look for a pattern when there is none.

In our decision making, it is necessary to obtain an understanding of what are we trying to achieve (goals), how to achieve it (plans), the impact on others or their impact on us, and where we think we will end up in the system's domain once the dust has settled. This requires forward projection (imagining the future state) and backward reasoning; looking from the outside in and vice versa; seeing things from the eyes of the system's element and their demands and constraints. As Kierkegaard suggests "life must be understood backward but lived forward".

Engineers' first task in any situation is to comprehend what the problem is and understand the lay of the land (the context of the problem). There is always more than what you can see. Nothing stands in isolation; the problem must be understood in its environment (context) [2]. There are many elements in that environment, and everything is connected to everything else, making a system of things with varying degrees of relationship. We are all part of the system in which we function, and we each influence those systems, even though we are also influenced by them. Controlling nature is not easy but understanding how it works enhances the effectiveness of the knowledge we have for decision-making. We are part of a system; hence we must learn to work with it. Generally, content is less important than context.

Seeing everything as a system means that one can deconstruct (breaking down a larger system into its modules) and reconstruct (putting it back together). The gains are:

- The ability to see relationships (dependencies)
- Accounting for constraints
- Understanding Trade-offs

The word 'system' is used to describe something that comprises more than one element. In other words, a system is a collection of individual elements that together produce results not achievable by a single element alone; hence the adage "a system is larger than the sum of its elements (parts?)". However, assembling elements does not necessarily create a system. Elements must be arranged and related to each other in a particular way to achieve the system's goals. The elements may represent people, facilities, software, hardware, procedures, policies, and infrastructures. The relationship between the elements and how they are interconnected creates value. Within a system, there are likely to be multiple agents. An agent is defined by its role within the system and may be an individual, an organization, or a collective entity that gets value from the system in some way (i.e., the public). For example, a country's transportation system consists of road, air, railway, and underground systems, which must be connected in a meaningful way to be effective. Moreover, the transportation system must be connected to the energy system to function, since in a system everything is connected to everything else, and dysfunction of one part could bring down a larger part of a system. The same fact is true for implementing a change to a system that could propagate through the system and result in unforeseen consequences. Engineers need coordinated strategies that consider the consequence of treating a single issue in isolation and remember key causal relationships, leverage points, and gaining foresight across a system by whatever means, including using data-driven methods. The world is dynamic, not static, there is always a second step, and many more steps after that. Thus, engineers should think in terms of the system when trying to influence an element of it. Senge [16] in his book "The Fifth Discipline" states that: "*Systems Thinking is a framework for seeing interrelationships rather than separate things, for seeing patterns rather than static snapshots. It is a set of general principles, spanning fields as diverse as physical and social sciences, engineering, and management."*

Systems Thinking is a conceptual framework for understanding how and why systems behave as they do. A complete understanding of a complex open system may elude us, because of the number of entities within them, and the infinite interconnections and relationships between infinite parts, leading to nonlinear and unpredictable behaviour. Engineering systems are not often open, except the ones that include social systems. However, it may require stripping out weak relationships to reduce their complexity for simplification. People tend to focus on the short-term consequences and believe that long-term behaviour is inconsequential. We tend to see one part of a system and ignore the rest and are surprised when we have unintended consequences. The challenge is to identify all elements and their relationships and to consider the problem overall, not just a selection of fragmented parts.

Framing complex engineering problems with many agents using a Systems Thinking framework allows us to gain valuable insights. What may seem haphazard behaviour to others, maybe rational and perhaps predictable, to a decision-maker who thinks in terms of systems. As we become familiar with Systems Thinking, we realize that our systems are not erratic but behaving exactly as they should give the capabilities and the relationships of its parts, the goals of its agents, the effects of various policies and rules, and the complex interactions that produce reactions and future actions.

Systems Thinking can also be defined as a process of looking at a problem in its entirety and focusing on the relationship between its parts, rather than considering the parts individually. For example, one can study each part of a car independently, or one can study cars, and see where each distinct element plays a relationship role in the function of the system. Reductionism only allows the study of individual parts, while Systems Thinking enables the study of the whole car. We need both; by reducing a problem to its constituent elements we may be able to solve it but ignoring the position of each element in the system might result in unpredictable behaviours. The current approach, as taught in dominant engineering schools, calls for a combination of both. Some people like to think of the systems approach as "seeing the world through the eyes of others and how your decision affects them". Not seeing a problem, is not a sign of everything is all right, but you might not see the problem.

To acquire System Thinking [3], engineers must understand their system by studying the underlying cause and effect interactions that produce the observable behaviours. Whether the system is a hospital with its access roads, safety system, or ecosystem, there exists a small set of common principles that help us to understand its dynamics and behaviours, and why often things do not go the way we assumed. The message is changing one element of a system may have unforeseen consequences; "walk before you run".

Also, you need a plan and be ready to revise it considering new information. You cannot say where a boat is going until you know the ocean, it is like setting sail without a map. In the language of Yogi Berra "if *you don't know where you are going you won't get there."*

6. Engineering and risk

Heuristics are not a recipe that turns engineering into a cookbook. A brain is needed to sit between heuristics and the real world. Engineering judgment is needed to turn ideas into reality. It also does not require engineers to be all-knowing, but optimistically cautious in their ability to deliver. For these engineers need practice to enhance their skills and be more effective. It is a container that can lose its usefulness. If foods frequently go bad in your fridge, do you suspect the food or the fridge?

Heuristics are likened to a *hammer*. It can help a blacksmith shape a piece of metal, but it does not guarantee the solution. A hammer may be critical to a skilled blacksmith while being of little use to an unskilled person who does not know what to pound, how hard to pound, or when to stop pounding. Heuristics do not replace skill, but they can make skilled people more productive. Heuristics can be considered as the best practice, but they need a skilled engineer to apply them. Skills that are needed are both social and mathematical.

Learning where a heuristic will work, how to apply it, how it can go wrong, when to stop, and finally when to use an alternative heuristic to change tack.

Hammurabi, the sixth king of Babylon, ruled from 1792 BC to 1750 BC. The Code of Hammurabi contains 282 laws which were inscribed on twelve stone tablets and placed on public view. "*The code also includes the earliest known construction laws that are designed to align the incentives of builder and occupant to ensure that builders created safe homes:*

229. If a builder builds a house for a man and does not make its construction firm, and the house which he has built collapses and causes the death of the owner of the house, that builder shall be put to death.

230. If it causes the death of the son of the owner of the house, they shall put to death a son of that builder.

231. If it causes the death of a slave of the owner of the house, he shall give to the owner of the house a slave of equal value.

232. If it destroys property, he shall restore whatever it destroyed, and because he did not make the house which he builds firm and it collapsed, he shall rebuild the house which collapsed at his own expense.

233. If a builder builds a house for a man and does not make its construction meet the requirements and a wall falls in, that builder shall strengthen the wall at his own expense."

The suggested reparations are harsh, and there is no suggestion of any compensation, and it appears that any financial loss would be borne alone by the homeowner. Hammurabi thought life mattered not property. Perhaps he was not wrong since if a seed does not perish it can grow again. Hammurabi's memory is still haunting researchers as they feel there is a need to add a disclaimer at the end of the technical paper to warn against its use.

This rule makes several assumptions including perfect knowledge, materials last forever, and no budgetary constraints. Hammurabi's tablets have lasted a long time and are kept in the Louvre Museum. You know that there is a risk that any house you build might collapse due to a variety of reasons. So, what do you do? You allow for the widest possible margin of safety. You plan for any possible risk you can imagine. You try to detect any flaw that could lead to a disaster. Cutting corners is not worth the risk. You want to walk away unhurt yourself.

Every engineering decision is an economic decision. You can tie up a substantial part of a nation's wealth in one edifice, or you can provide shelter for many, albeit with some risk of injury or loss of property. Who decides what level of risk is tolerable? In Europe, the state decides what is tolerable, explicitly, or implicitly, through codes. In the US, the tolerable risk is indirectly decided by the Codes of Practice.

Hammurabi's approach to establishing the probability of guilt was practiced until 800 years ago when the jury system was introduced in Britain, 'Trial by ordeal' was used to establish guilt or innocence of the accused. Fire and water were the two main forms of the ordeal, with God being used as the jurors to establish guilt or innocence as revealed by the result. The accused would then be bounded and thrown into the water. Like trial by combat, trial by ordeal was based on the belief that God would intervene on behalf of the innocent by performing a miracle. A betting person should have a good idea of guilt or innocence before betting.

Engineering involves risk, albeit calculated ones. It is impossible to construct a project or an operation without accounting for the inherent uncertainty. However, the risk is difficult to comprehend. Countless behavioural and neurobiological studies show that human beings tend to avoid risk whenever possible and misconstrue it otherwise [7]. The trouble is further exacerbated by imprecise data. A natural reaction to this is to add more parameters or constraints or decimal places, hoping these would enhance the accuracy. Specified probabilities are approximate and it is dangerous to pretend otherwise. We hedge our bets towards the middle of our uncertainties; thus, we may not be as biased as we think.

In modern engineering, it is recognized that it is not possible, or practical, to eliminate risk but it can be reduced to a tolerable level. In the UK, the practice is to reduce risk as to the "As Low as Reasonably Practicable" (ALARP) principle [30].

7. How Heuristics Ought to be Used

Trial and Error is the most basic heuristic that can be utilized for everything, from matching nuts and bolts to solving numerical problems. By examining initial results, one may decide to go through another trial to close the gap even further. Engineers use the same concept to improve their decision-making process with each project they execute. This is achieved through "Lessons Learnt" by understanding the root cause of mistakes and exploring the ways and means for improvement. The ubiquitous design errors and their cumulative decremental effect upon the structural integrity of infrastructure are costly. Such costs are significantly higher in the event of an engineering failure leading to loss of life [13]. Most of these failures can be avoided by not forgetting the simple heuristic of "Lessons Learnt". It is illuminating sometimes to ask ourselves; how did we get into this mess?

However, we do not always get a second chance to learn and improve i.e., no time for rehearsal. Thus, every decision you make should be considered as your last chance and as if your life depends on it. Builders in Hammurabi time were faced with the same dilemma, of course, they can do better next time, but there might not be the next time, as their previous works could be a dead weight around their necks, causing them to sink for good. Natural phenomena can unleash their destructive powers in ever-increasing ferocity. Though the required knowledge in Hammurabi time was non-existence, buildings were not spectacular and those who desired a prestigious monument had the money to pay for their oversizing.

It has been recognized that in complex situations decision-makers often deviate from the normative prescriptions of logic and probability theory, and resort to simple, non-optimal strategies that have been variously termed as intuitive, muddling through, heuristic, fuzzy, boundedly rational, or recognition-primed. Klein et al [8,9] examined how decisions are made by military personnel under extreme time pressure, and in environments where the consequences of the decisions are high. They concluded that recognition primed, rather than calculation or analysis, is used for rapid decision making.

Rationality for engineers is generally the avoidance of disasters. When dealing with natural phenomena, there is a need for conscious decisions as to how much money you can lock into one building, just to avoid the rarer events. According to Hammurabi law, if an engineer gives an opinion, and someone takes it, the engineer is morally obligated to be exposed to its consequences, which is not very different now. The client does not want to know what you "think," but does want to be assured that you are taking potential risks into account. This is about rational (and ethical) behaviour and that the design will stand the test of time, not just a one-year limited warranty. Rational behaviour in the real world is something vastly deeper and evidence-based and is linked to the engineer's survival; liars and outliers are the exceptions to this rule. Real-life situations are not science fiction, adverse situations could happen at any given time. This puts a lot of emphasis on using correct methods and materials.

Engineering ethics require the mitigation of suffering and risk, as well as safeguarding society's well-being. Engineers do not share possible harms with victims, only their reputations are at stake. An old engineer who is enjoying fame is a sign that she has considered all possible harms with her client.

Consider a situation where engineers are engaged to design for extreme events that are by any measure ill-defined problems. They generally use two well-known heuristic strategies:

(i) A Common Event Heuristic - design for a more frequent event with no damage.

(ii) A Worst-Case Heuristic - design for a less frequent event and try to avoid loss of life, not property.

The consequences of an event happening are more important than its probability. Some events may break your back and you cannot stand up and dust yourself down. Thus, one should consider all events and see which has the worst consequence and which is difficult to recover from. Consider living to see another day.

The Common Event Heuristic aligns well with classical Bayesian probability [12]. The assumption that guides a decision considers what is the most likely event based on prior probabilities (i.e., something experienced before) and current requirements (i.e., what is adequate given the situation and regional history i.e., if there are codes of practice or regulations in place; good practice; engineering judgment, etc.). This heuristic directs engineers toward a 'Confirmatory' looking for something like their beliefs, the beliefs of their peers, and what might be accepted by the engineering community. Then the engineer would seek evidence confirming the most likely event.

The worst-case heuristic shifts the focus from mitigation against likely future events to mitigation against potential consequences from extreme events. For example, the design for the defence of a nuclear facility is based on a plausible scenario of intrusion. Of course, the plausibility of a theory is not proof of its validity. The system is designed to guard against total loss, or at least to keep the disaster within the facility's boundaries. If you let your imagination loose, there is no upper bound on possible events. As technology improves, the ability of intruders will improve with it. There may emerge a serious likelihood of missing or overlooking some condition that might ultimately lead to serious harm (i.e., unpredicted, or unpredictable Worst Cases). The Worst-Case heuristic directs engineers toward a disconfirming search to rule out possible Worst Cases, often when simultaneously contemplating the more likely event. Each heuristic on its own may reflect bounded rationality but combining them forms the basis for a type of rationality that differentiates between Worst Cases and Common Events.

To address the question of a satisfactory criterion for discriminating between Common Events and Worst Cases, it is necessary to consider the domain-specific values associated with the potential consequences of an error, or something which has been discounted. Thus, the decision is not simply a function of logic and discerning the 'truth', rather, it is a value-driven trade-off that could involve ethical issues. What costs are associated with the protection measures that would be required to conclusively rule out all Worst Cases? How severe would the accident consequences be of ignoring/missing a potential Worst-Case be? Governments around the world have taken this decision to some extent out of engineer's hands via codes of practice, rules, and regulations. However, those dealing with high-risk installations still face this dilemma in their work.

"Technological solutions to the problem of coping with hazards have typically been justified by a computation of benefits and costs that assume the people involved will behave in what the policymaker considers to be an economically rational way. However, it has slowly become evident that technological solutions, by themselves, are inadequate without knowledge of how they will affect decision making" [17]. The debate of engineering rationality and the way an engineer decides how to formulate rules for reflecting on the social and ethical issues in engineering requires consideration. Ethics and rules of moral behaviour are needed for large-scale engineering projects such as dams.

In normal situations, engineers engage in planning and mitigation efforts to reduce the damage caused by disasters. They are supposed to identify all hazards threatening a community including fires, floods, and industrial accidents, and then develop a plan to address those hazards. In the case of floods, engineers develop plans to mitigate the effects of heavy rainfall and overflow before they happen. Biases and heuristics may shape these decisions. For example, engineers might follow the lead of neighbouring provinces without taking the time to consider all relevant facts. They also might allocate more resources when an action to prevent damage is framed as potentially preventing a loss, rather than when it is framed as potentially securing a g benefit. Both options would be consistent with Kahneman & Tversky [6], and Tversky & Kahneman [19], research. There is nothing wrong with being extra cautious, but engineers in emergencies are charged with using collective resources prudently and fairly. We pay more attention when a clear threat exists.

Resilience is a heuristic used in design against natural disasters. Resilience in the context of the natural disaster means systems can maintain their integrity and remain stable when subject to a disturbance; that is, the system's ability to make a smooth transition to a new stable state in response to the disturbance, say, from an earthquake. There is no clear definition for resilience and as such, it is a design heuristic. It implies your best efforts to mitigate the effect of a disaster without throwing money at it. What is acceptable resilience depending on the acceptable risk, which means that engineers are dealing with two fuzzy concepts. Despite this fuzziness, this heuristic works very well by encouraging engineers to look for ways and means of mitigation without extra cost. These heuristics do not tell you what to do but require you to search if you can improve it for multi-hazard. The level of limitation gives you a clue if a system is resilient enough within your constraints. resilience is the product of many decisions among competing options and actions.

In system design, another concept frequently referred to is robustness. Robustness is the property of a system and is defined as "the ability of a system to resist change without losing its initial stable configuration".

8. Conclusions

If heuristics did not exist, we would need to invent them. This part of the four-part series is about how heuristics are constructed and used. There is no guarantee that heuristics will not lead to errors, but mistakes are 'fast and unforgiving teachers.'

According to an adage: 'the brain is like a parachute, and it works better if it is open'. Having an open mind is a prerequisite of being a good decision-maker, but you must be alert and keep a guard at the gate. A dose of scepticism will act as a guard against being tripped up by baseless beliefs. You need facts when your gut talks to you.

A heuristic may not become obsolete, but it may become worn out. With each use, its relevance can be perfected. The job is not only to determine which heuristic is the best fit but also how to implement it. There are mental traps, or biases, in using heuristics and there is evidence that indicates it is not possible to get rid of biases.

What makes a person an engineer? Is it a lot of common sense combined with an open mind and a pinch of scepticism. As Theodor von Karmann said, "*if science aims at revealing what is, engineering aims at introducing into the world what never was, for the sake of acting on the world in new ways*." Engineering is overwhelmingly a matter of projecting imagined possibilities onto a world that lacks them and then making those possibilities actual. Thus, engineers are required to act when there is no clarity or certainty. Heuristics are tools that help in such situations. Engineers shape their environment, which in turn shapes us. What engineers know may be important, but things that they do not know are even more important. We need System 1 Thinking to free some mental space for other activities. Suppressing System 1 is not possible nor desirable. However, we can train System 2 to kick in faster.

engineers may choose whichever approach seems to promise the desired results, often blending different heuristics. the art of engineering is the ability to blend many things to achieve the best possible solution.

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