Engineers Shouldn't Think Too Fast

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ABSTRACT

Engineers, being human, have the same innate characteristics as all humans. One of these is that we have two thinking modes, intuition and analysis. The intuition mode, system 1, is automatic and acts with great confidence, while the analysis mode, system 2, requires conscious activation and would typically rather not be activated, because it is lazy. System 1 uses a range of heuristics that lead to certain biases in our thinking. Sometimes these heuristics and biases produce glaring errors. As engineers, we must be vigilant so that system 1 does not act alone in inappropriate situations, since the mistakes that it tends to make could produce serious errors in environments where we do not have significant experience. Encouraging an awareness of these dangers is the purpose of this paper.

INTRODUCTION

All engineers use intuition in engineering design, but intuition can lead us astray, particularly when we are working in a new design environment. Kahneman and Tversky (Kahneman 2011) have described how humans have two thinking modes: system 1, where we think fast, also called intuition; and system 2, where we think slowly, also called analysis. Since humans over history have often lived in dangerous environments, system 1 tends to take precedence if we do not consciously apply system 2. If the bushes move in the jungle, it is better to run than to stand and think about running. Those who ran often ran from nothing, but those who stopped to think about running eventually got eaten. Unless system 2 is consciously activated, system 1 will give an answer and that answer will be accepted. Furthermore, since system 1 has worked so well for so long, we often are overconfident of our system 1 answers and do not activate system 2.

One of the reasons why this behavior may occur even when making engineering decisions is that we as structural engineers get little feedback on our designs, in the sense that we experience few failures. As Petroski (2006) has pointed out, we learn very little from success. We learn that our structures have not failed so far. We thus can fall into the trap of thinking that everything we have done in the past was correct, and that our intuition is almost always right. Kahneman and Tversky (Kahnemann 2011) would call this What You See Is All There Is (WYSIATI). This way of thinking blinds us to errors that we might make by relying too much on system 1 alone and to unusual events to which our structures might be subjected. This type of thinking is referred to as a *confirmation* bias; the success of our structures seems to confirm that whatever we did in the design must have been right.

We as engineers are good at not depending too much on system 1, but in environments that are changing, humans will tend to fall back on it and—even worse—may be overconfident in the answers that it gives. This paper will describe systems 1 and 2, as well as how thinking fast can lead the engineer to make confident decisions that could be shown to be wrong upon closer examination.

SYSTEMS 1 AND 2

The following problem (Kahneman 2011 pg. 44) will allow you—or, at least, most of you—to see how system 1 works. Read the problem below and let system 1, your intuition, determine the answer. Then consciously shift to system 2 and solve it again.

> A bat and ball cost $1.10.
> The bat costs one dollar more than the ball.
> How much does the ball cost?

Most of you will have gotten a system 1 answer of 10 cents, but, of course, the actual answer is 5 cents, as system 2 determined. Those of you who got the correct answer the first time either have seen the problem (or a similar one) before or switched to system 2 automatically. After all, you were warned (implicitly) that there was something unusual about the problem.

When facing any decision, you cannot simply turn off system 1. It gives an answer whether you request it or not. The quality of the system 1 answer depends on the nature of the question. Is it related to an environment that you have seen many times before? Were those past answers adequate? Is the present event enough like the past events? Are appropriate heuristics being used by system 1? (Heuristics, basically rules of thumb, will be discussed in more detail below.) In order for system 1 to give good answers, you must be in a situation that is very familiar, and you must have received a significant amount of feedback about the quality of your past answers.

System 1 likes to jump to conclusions. As Kahneman (2011 pg. 79) says: "Jumping to conclusions is efficient if the conclusions are likely to be correct and costs of an occasional mistake acceptable, and if the jump saves much time and effort." System 1 makes its decisions using heuristics, and as engineers we also make decisions using heuristics—specifically, engineering heuristics. Let us consider these before we move on.

ENGINEERING HEURISTICS

Engineers must use heuristics in the design process. Koen (2003, pg. 28) defines a heuristic as "anything that provides a plausible aid or direction in the solution of a problem but is in the final analysis unjustified, incapable of justification, and potentially fallible." Heuristics are techniques that we as structural engineers use to help solve problems and perform designs that would otherwise be intractable or too expensive.

As Koen (2003, pg. 28) says, "The *engineering method* is the use of heuristics to cause the best change in a poorly understood situation within the available resources" (italics in the original). Engineers are often forced to deal with problems where the underlying physics is not completely understood and the mathematical solution, such as the solution to a differential equation, cannot be practically solved point by point throughout, for instance flow problems. In many situations, exact solutions are not available, and even approximate theoretical solutions are too complicated to use in design. In those cases, engineers will resort to semi-empirical solutions, the combination of test data and basic theory. Semi-empirical solutions are heuristics. Koen (2003) argues, as stated above, that the engineering method is to use heuristics.

Heuristics as discussed above will be referred to as *engineering heuristics* in this paper to distinguish them from the more basic kinds of heuristics that system 1 employs. Engineers know that engineering heuristics have limits and that care needs to be taken when using them, particularly in new environments or at the limits of the state of the art. Similar care needs to be taken when system 1 uses its heuristics. Engineers are trained to understand engineering heuristics during their education. Training to use engineering heuristics is one of the traits of an engineering education that distinguishes it from education in other disciplines (Bulleit 2012). Although engineers are not trained to avoid system 1 errors, it would be professionally beneficial for us to think about how system 1 heuristics can lead to errors in a manner similar to how blindly using engineering heuristics can lead to significant design errors.

HEURISTICS AND BIASES

System 1 does its intuitive job in a number of ways. One, as stated above, is to use heuristics. An understanding of some of these heuristics will allow you to spot when system 1 may be making a decision that should be reassessed by system 2. To make matters worse, though, if system 2 is otherwise engaged, it will tend to believe what system 1 tells it, and system 1 is gullible and biased to believe. System 2 also tends to be lazy, so there is a predilection not to go to system 2, even when you should do so. Here lazy means that system 2 invests only as much effort as is strictly necessary. The easy thing to do is allow system 1 to make the decision, and system 2 will choose that path unless forced to act otherwise. The use of heuristics by system 1, even if you do not know that it is using them, causes *biases* in your thinking and the resulting decisions. So, the use of engineering heuristics is a much more conscious operation than is the use of system 1 heuristics. When you see an engineering heuristic, you can consciously examine it in light of the situation in which you plan to use it. That is not the case with system 1 heuristics. It is possible for a system 1 heuristic to be used without you being conscious of the heuristic. Thus, avoidance of system 1 errors requires an alertness to system 1 behaviors that is more watchful than that required to avoid errors related to engineering heuristics.

Confirmation bias was described briefly in the Introduction. This bias arises when limited information is available. Our structures have not failed; therefore, they must be good, safe designs, and everything that we have done in those designs must have been right. When stated that way, it sounds somewhat silly; we all know that there may be errors, hopefully small ones, in our designs. But that knowledge does not stop system 1 from telling you that the designs must be right, unless you take the time to bring system 2 to bear on the question. Each of us has a relatively small data set from which to work: a set that consists of all the structural designs that we have performed. The number of failures in that data set is small, probably very small, and possibly zero. Thus, we are prone to the confirmation bias. Petroski (2006) refers to this data limitation as the *paradox of design.* To quote Petroski (2006, pg. 114): "Things that succeed teach us little beyond the fact that they have been successful; things that fail provide incontrovertible evidence that the limits of design have been exceeded."

This type of thinking is also an example of the *availability heuristic* (Kahneman 2011, Tversky and Kahneman 1974). You are inclined to believe that which is most available in your memory. If I had asked you three years ago, what is the probability of a tsunami hitting a nuclear power plant, the answer would have been smaller than if I asked you today. The incident at Fukashima was not a data point available to you three years ago, but today it would be right up front in your mind. If you engage system 2, you will realize that the probability of a tsunami event of that kind is no different today than it was three years ago, anymore than the probability of the 100-year flood is different just because a large flood occurred last year. When thinking about your designs, you will have a tendency to do the same thing. The design decisions that are most available to you are the most recent ones. If they all have been successful, as is likely the case, you will tend to believe that what you did in the designs was correct and place a low probability on a failure occurring. But, if you have had a failure in the recent past, we hope small, then you will likely estimate too high a probability of a similar failure occurring again. In neither case do you know whether your estimates are correct since you have no other data available to judge your estimate.

System 1 will reach its conclusions using only what it knows from experience, thus Kahneman's acronym, WYSIATI: What You See Is All There Is. As Kahneman (2011, pg. 86) says, "System 1 is radically insensitive to both the quality and the quantity of the information that gives rise to impressions and intuitions." The only way to avoid system 1 errors is consciously to use system 2, but system 2 is lazy and would prefer simply to accept the conclusions of system 1. One way to begin to consciously activate system 2 is to become a reflective practitioner (Schon 1983). This approach requires that you take time to reflect on your designs and the thought processes that you used to justify your designs. Reflection can be used at points during the design to influence what you are presently designing and after the design is complete to influence future design processes.

Knowing when system 2 needs to be activated can be difficult, since we tend to be very confident in system 1 answers. One of the worst structural failures in terms of loss of life was the Kansas City Hyatt Regency walkway collapse (Delatte 2009). We all are familiar with the failure and know that the effect of a change made during construction was overlooked. A single nut on one threaded rod was changed to two threaded rods with a nut on each. The change increased the pull-through load on a nut in the connection by a factor of two. A fairly brief examination of the change using basic statics shows the problem. To make matters worse, the design change exacerbated a problem with the original design which itself was somewhat inadequate.

So how was the danger missed? No one will ever know for sure, but it is a fair bet that whoever reviewed the plans allowed system 1 to decide quickly that the change was acceptable. He had probably had significant experience with rods and nuts and connections, so his system 1 decided that this case must also be acceptable. He was also likely using system 2 for other work and thus was easily convinced by the system 1 decision. Whether or not this scenario is right on all counts, it is certainly possible and indicates how mistakes could easily be made by allowing system 1 to jump to conclusions.

Engineering heuristics as described here are different than the heuristics used by system 1, but both can lead to mistakes. We know that the engineering heuristics given in structural building codes and other engineering documents are not valid over the entire range of engineering problems to which they seem to apply. It is not always obvious where the limits lie, but we know to be cautious when we attempt to use engineering heuristics to solve engineering problems which are new to us or push the state of the art.

The failure of the Tacoma Narrows Bridge was a result of applying the existing suspension bridge engineering heuristics beyond their applicable range (Delatte, 2009). This example is a fairly extreme case, but it does show the dangers involved with the use of engineering heuristics. Prior to Tacoma Narrows, there was not a lot of experience with the relevant heuristics; after all, only several bridges of that size had been built previously. So, the use of engineering heuristics becomes problematic when experience is limited and the range of applicability is not well known.

The heuristics used by system 1 are also most questionable when it has not had a lot of experience in situations where the heuristic is being used. Intuition is most dependable when it is grounded in a long history of making similar decisions and receiving feedback on those decisions, both positive and negative. Changing environments are particularly problematic. As Kahneman (2011, pg. 241) says, "Remember this rule: Intuition cannot be trusted in the absence of stable regularities in the environment." This rule also applies to the use of engineering heuristics.

RISK

As should be evident from the above discussion, your confidence in an answer may not accurately reflect reality. Kahneman says (2011, pg. 212), "Subjective confidence in a judgment is not a reasoned evaluation of the probability that this judgment is correct. Confidence is a feeling, which reflects the coherence of the information and the cognitive ease of processing it." System 1 searches for a clear pattern of what you know (coherence) and measures the ease with which the information was processed (cognitive ease). Using this pattern of easily processed information, system 1 makes its decision. At this point, you will have a decision in which you have confidence, and lazy system 2 will be quiet unless you consciously activate it.

Clearly the true quality of your decision will depend on how much you know and how easily it was taken from memory. In many cases, the less you know, the easier it is to get coherence. The feeling of coherence and cognitive ease represents a danger. If you have worked in an engineering area for a long time and with frequent, appropriate feedback, you will have a large amount of relevant information that will be easy to access. Thus, the system 1 decision may be fully adequate; i.e., it may represent good engineering judgment. But if you have limited knowledge, or worse, you apply your knowledge to a problem to which it does not apply, and accept your system 1 decision, you may significantly increase your chance of making a mistake and the risk of a failure. It is when system 1 makes decisions in which system 2 should have been involved that the risk increases.

All of this discussion should seem like common sense; if you do not have the engineering knowledge for the job, or if you are working in an area where what you know might not apply, then you should be careful. The problem is that system 1 has confidence in its fast answers and system 2 is happy to accept those answers. So, in a nutshell, you should not trust intuitive judgment, but you should not dismiss it either. It works, and it does not work.

Humans seem to be innately poor performers in probability and statistics. This statement applies both to system 1 and system 2. System 1 must be over-ridden by system 2, and system 2 must be trained to think probabilistically. There are a few ways that we as humans are poor at statistical thinking, but a primary one is basing our judgments on too small a data set, without recognizing that our data set is too small. People who forecast the weather are fairly good at giving a probability of tomorrow's weather and giving their confidence in that prediction (Evans 2012). The primary reason for this ability is that they have made many forecasts and received feedback, both negative and positive, on all of them. Since humans tend to use WYSIATI to estimate probabilities, we typically do not do a very good job making probability estimates, particularly when we have little experience and limited feedback in the subject in which we are estimating probabilities.

Structural engineers, who get very little negative feedback on their designs, except during design reviews, tend to underestimate the probability of errors and the likelihood of failure. As Ferguson (1992, pg. 193) has said, "If we are to avoid calamitous design errors as well as those that are merely irritating or expensive, it is necessary that engineers understand that such errors are not errors of mathematics or calculation but errors of engineering judgment—judgment that is not reducible to engineering science or to mathematics."

ENGINEERING JUDGMENT

It should be apparent from the preceding discussion that engineering judgment is affected by more than just engineering heuristics and engineering experience. Innate human thinking processes influence the way engineers think in ways that may not be obvious. System 1 will jump to conclusions that may not be warranted by the amount of experience available, WYSIATI, and will be confident in the correctness of the conclusion. As the title of the paper says, engineers shouldn't think too fast. We should always be consciously examining the amount and quality of information and experience that we are bringing to bear on our intuitive decisions, and when in doubt, consciously shift to system 2. It is good to remember that system 1 will be confident in its decisions, and it often will be more confident with a small amount of experience. If we think of the design process as a system that includes the people involved in the process, then the impact of system 1 and 2 on design must be considered. To quote Ferguson (1992, pg. 193) again, "Human abilities and limitations need to be designed into systems, not designed out."

As we gain more experience in engineering, we gain intuition, most of it the system 1 variety. The quality of the data set that your intuition works from is directly related to both the amount of information available and how much feedback you have had related to the accuracy of the information. But, as was discussed previously, the availability of the information is also important. Recent feedback and more frequent feedback will be most available to you. Unlike weather forecasters, structural engineers do not get regular feedback on their decisions, and the feedback that they get does not give them the full range of information, both successes and failures, necessary for system 1 to make adequate intuitive decisions. Your system 1 information consists primarily of successful engineering decisions, often made over a fairly small range of structural types, under fairly limited environmental and loading conditions. Much like an engineering heuristic that has a specific range of applicability, your intuition is useful only when the design situation under consideration is like the ones that are part of your experience. As Kahneman (2011, pg. 243) says: "If the environment is sufficiently regular and the judge has had a chance to learn its regularities, the associative machinery will recognize situations and generate quick and accurate predictions and decisions. You can trust someone's intuitions if these conditions are met."

A structural engineer's design experience is based on designs that have been checked against structural building code criteria and against other engineers' judgment. This feedback implicitly includes failures since structural building codes have failure information incorporated into them. Structural building codes evolve under a number of pressures, one of which is structural failures. When a failure occurs, e.g., the steel moment connection failures during the Northridge earthquake, the design procedures for the structural element are modified. Thus, the knowledge gained because of the failure becomes embedded into the design specification. Furthermore, feedback on failures of the engineer's judgment has been received through interactions with other engineers during design reviews. So even though actual structural failures are not generally a part of an engineer's experience, successes and failures are implicit in the experience. So, the key questions to ask are: Does your range of experience cover the design on which you are working? Is it a regular structure or is it unusual with respect to your experience? Is your design experience applicable to the present structure? These questions are important because system 1 will give you answers no matter what your experience. To quote Kahneman (2011, pg. 243): "In a less regular, or low-validity, environment, the heuristics of judgment are invoked. System 1 is often able to produce quick answers to difficult questions by substitution, creating coherence where there is none. The question answered is not the one that was intended, but the answer is produced quickly and may be sufficiently plausible to pass the lax and lenient review of system 2." For instance, you may have a lot of experience with steel structures so system 1 might be perfectly willing to answer a question about a timber structure that seems to be very close to a steel structure with which you are familiar. It quickly substitutes steel structures for timber and offers a quick and plausible answer. Whether it is accurate or not depends on the specific situation. Certainly, common sense would tell you not to make this substitution, but intuition is not always constrained by common sense. The worst part of an intuitive judgment such as this one is that you will be confident in your system 1 answer. To once again quote Kahneman (2011, pg. 243): "This is why subjective confidence is not a good diagnostic of accuracy: judgments that answer the wrong question can also be made with high confidence."

CONCLUSION

Engineers are human and have innate abilities and limitations. These characteristics need to be considered in the design process. One significant limitation is related to the two thinking modes that humans use: system 1, which thinks fast and is confident in its decisions; and system 2, which thinks slowly and analytically but is lazy and would rather let system 1 do the work. We as engineers use design processes that help reduce the chance of design errors, e.g., design reviews, but the reduction of system 1 errors requires constant vigilance against the tendency of system 1 to jump to conclusions and run from the moving bushes, rather than stopping to think. The awareness of this particular human trait is the first step in minimizing the potential problems that can arise from its actualization.

REFERENCES

Bulleit, W. M. (2012) "What Makes an Engineering Education an Engineering Education?" 2012 SEI/ASCE Structures Congress, March 29-31, Chicago IL. Available at: http://ascelibrary.org/doi/abs/10.1061/9780784412367.102

Delatte, Jr., N. J. (2009) *Beyond Failure: Forensic Case Studies for Civil Engineers,* ASCE Press, Reston, VA.

Evans, D. (2012) *Risk Intelligence: How to Live with Uncertainty,* Free Press, New York, NY.

Ferguson, E. S. (1992) *Engineering and the Mind's Eye,* MIT Press, Cambridge, MA.

Kahneman, D. (2011) *Thinking, Fast and Slow,* Farrar, Strauss, and Giroux, New York, NY.

Koen, B. V. (2003) *Discussion of the Method: Conducting the Engineer's Approach to Problem Solving,* Oxford University Press, Oxford, UK.

Petroski, H. (2006) *Success Through Failure: The Paradox of Design,* Princeton University Press, Princeton, NJ.

Schon, D. (1983) *The Reflective Practitioner,* Temple Smith, London, UK.

Tversky, A. and Kahneman, D. (1974) "Judgment under uncertainty: Heuristics and biases." *Science,* 185: 1124-1131. Available at: http://psiexp.ss.uci.edu/research/teaching/Tversky_Kahneman_1974.pdf