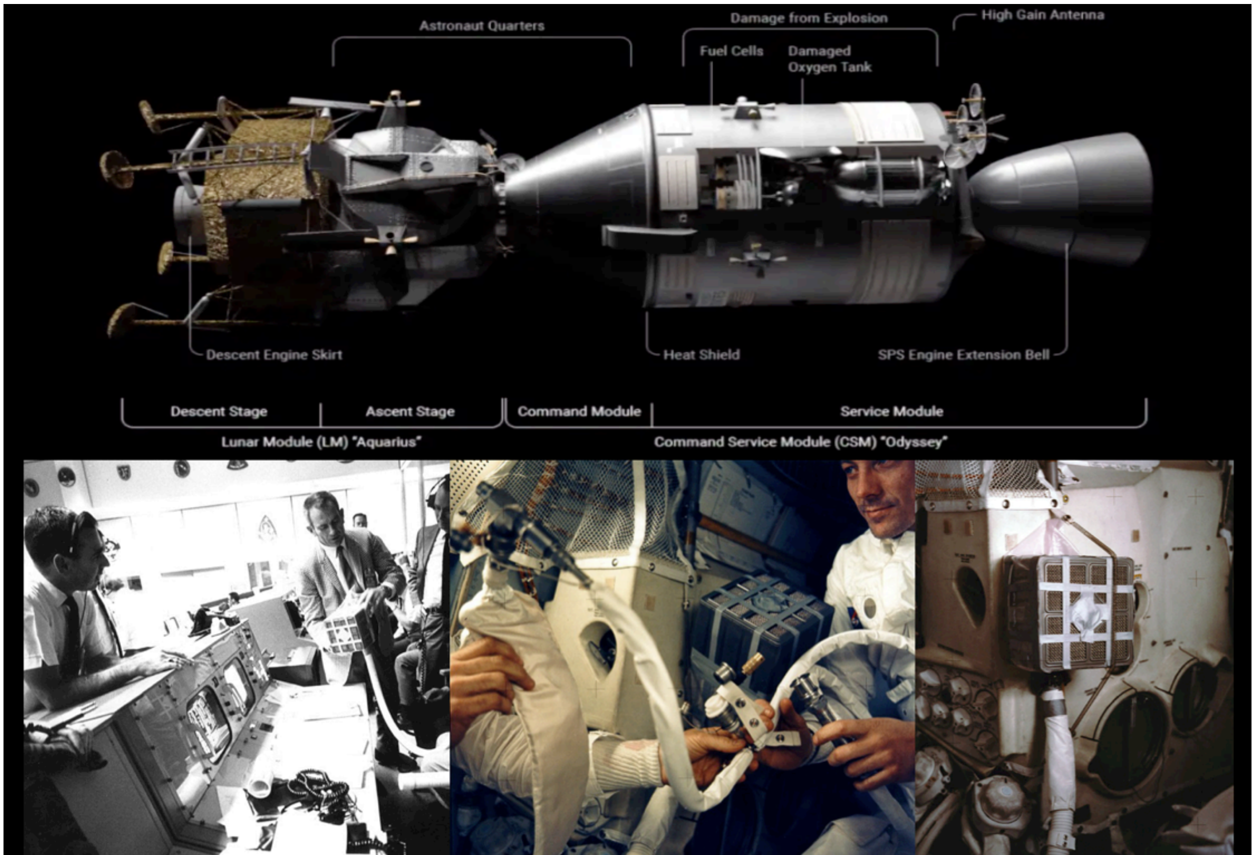
24 May 2023, How might warfighter use of fast and frugal heuristics work along with AI to better facilitate means for dealing with uncertainty and unforeseen events at the edge of warfare?



NASA Apollo 13 images. Upper diagram depicts Apollo 13 modules. Lower images depicts three photo snapshots of devised adapter to address CO2 buildup problem. From left to right: Slayton shows devised adapter to NASA managers, Lovell and Swigert (face showing) assembling the adapter, and its placement in Lunar Module (Aquarius).

On 11 April 1970 the Apollo 13 lunar mission was aborted, at about 56 hours into the mission, after a short circuit in a Command Service Module (CSM) oxygen tank caused combustion and tank rupture, resulting in extensive damage to CSM systems and the loss of both CSM oxygen tanks. This incident changed the mission objective from a lunar landing to crew survival and expeditious return to Earth. For the next four days the astronauts and NASA's mission control fought to bring the crew back to Earth safely. This required overcoming multiple and interdependent problems, many of which had not been foreseen.

Basically, the Apollo 13 crew faced a series of cascading problems from the combustion and resulting damage: the CSM was losing power and oxygen fast but reasons were initially unknown. After a quick assessment it was determined that the CSM was severely damaged and out of commission. Its' battery power had also been partially depleted and it was important to turn off systems in the CSM to conserve remaining battery power for use during reentry of the command module (CM) back to Earth. Since the crew had already docked to the lunar module (LM) before the explosion it was decided to use it as a lifeboat. Then it was noticed that there was a problem with carbon dioxide (CO_2) removal in the LM. Also, there was limited battery power and water inside the LM and it was not known whether there was enough to get the crew safely back to Earth. Since the crew had copied all mission data from the CSM to the LM it had to stay powered up to maintain knowledge of where it was in space for navigation around the moon and 'burns' to position properly for the trajectory back to Earth. After getting around the moon the crew had to power down to about 300 watts in the LM to conserve enough power for the return trip. That meant the crew had to figure out where they were and confirm what the guidance system was saying. On top of everything else the crew had to manage passive thermal control to make sure the spacecraft didn't get heated or cooled too much on one side. This proved very difficult to do with a minimal amount of energy expenditure and without a computer after the power down.

Systems can fail without explanation. In such cases, problem causes and solutions are not always obvious. This proved true for the Apollo 13 explosion in the service module that led to several problems some of which had not been foreseen from advanced planning and simulations conducted to address anticipated worst-case scenarios. For Apollo 13, survival of the crew required specific behaviors and collaborative troubleshooting processes largely dependent on human capabilities for sensemaking to mitigate multiple and interdependent problems by making the most of what was available at hand for timely good-enough solutions. This so-called MacGyver mindset, to make use of and recombine common items at hand for timely inventive solutions to perplexing problems, has often proven critical for successful human adaptability to uncertainty in the face of crisis involving limited information and time (see Barile, et.al., 2019). French anthropologist Claude Lévi-Strauss (1966) coined the term 'bricolage' to describe this fascinating feature of human problem solving involving means to successfully adapt in the face of uncertainty and unforeseen events. Humans make the best use of what is around for possible solutions by reexamining and repurposing original functions of objects to serve entirely new functions. Let's now take a closer look at the solution devised for the Apollo 13 CO_2 buildup problem to further illustrate this fascinating feature of human problem solving.

A bricolage solution to the problem of CO_2 buildup up in the Lunar Module involved the invention of a device by repurposing available resources under severe constraints. A NASA engineer named Robert E. 'Ed' Smylie played a key role in leading an effort to solve for the CO_2 buildup by devising a filter adapter to make use of Command Module (CM) lithium hydroxide canisters to remove excess CO_2 from the Lunar Module (LM), now serving as the 'lifeboat' for the Apollo 13 crew (note: the square-configured CM canisters would not fit into LM round-configured canister slots). Smylie was known among his NASA colleagues as 'Mr. Fix It' who could make 'stuff work' from whatever was at hand while keeping his cool and presence of mind under pressure. It is worth highlighting an excerpt from an oral history transcript of an interview of Smylie by Carol Butler that highlights his 'MacGyver-like mindset' (see NASA Johnson Space Center Oral History Project, Smylie, 17 April 1999):

> Butler: What were your roles and responsibilities during your work on the Apollo Program, or at least initially to start with?
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> Smylie: Well, initially it was environmental control system for the command module [CM] and, a little later, the lunar module [LM], and then very early on involved in what we ended up calling the extravehicular mobility unit, or EMU, which is a combination of the suit and the backpack. We started that program off to build a prototype. I don't

think we had any idea how large that program was going to become, because our first contract was just to build a single prototype, was under a million dollars.

We had no specification. The only spec we had was Kennedy saying, "Go to the moon and come back." I remember us trying to evaluate proposals. Me and Dick and Matt [Matthew I.] Radnofsky and Walt [W.] Guy and Jim Correale and Ted Hayes sitting around saying, "What are we supposed to do with this system? Does it get out on the moon, look up at the Earth and get back in? Does he walk around? Does he have to walk? Does he have to pick up any samples?" Nobody had told us. We didn't have any specification of what to do on the moon, and we were off developing a system. So we made it all up.

Butler: Worked pretty well.

[skipping to point in interview addressing Apollo 13 crisis…]

Butler: It must have been quite a challenge to develop procedures that you could just read up to the crew and have them understand what to do.

Smylie: It was pretty straightforward, even though we got a lot of publicity for it and [President Richard M.] Nixon even mentioned our names. I always argued that that was because that was one you could understand nobody really understood the hard things they were doing. Everybody could understand a filter. I said a mechanical engineering sophomore in college could have come up with it. It was pretty straightforward. But it was important.

Butler: Very.

Smylie: And we were pretty proud to have been able to do it. If you read the book and look at the movie, it sounds like I did all of that. I went back and looked at the list of people that I identified were involved, and there was probably sixty people involved in one way or another. A lot of contractors. There were probably thirty or forty contractors that set up that test to run it. So it takes a lot of people to do something like that.

Butler: Absolutely.

Smylie: And make it work.

Butler: You mentioned that you were working at 1 AM at one point on this. Can you tell us about the atmosphere at the time and how you ran things? Did you just grab sleep on the fly? Were you at the Center the whole time?

Smylie: First I heard about it on the radio at home and went out to the Center. Don [Donald D.] Arabian—Don's sort of a wild man, but also very smart and able to generate a lot of activity—had set up a war room, and we all gathered there and were going through what all the things were that we had to worry about, what the problems were, and what had to happen and so forth. Don was sort of running that and was handing out action items. I don't really recall whether we decided the CO2 was a problem or we just looked at expendables in general at that point, but that's what we did probably from the time I got there around 10:30 until I went back to the division around 1 AM, and began to look at the problem in detail.

[skipping to point in interview addressing his greatest challenge…]

Butler: Looking back over your career with NASA, what was your greatest challenge?

Smylie: Well, I guess the challenge of making it to the moon in the time period we made it and having to invent things that didn't exist because there had never been a requirement for it within that time frame, and put together both the contractor and the

> government team to pull that off was the biggest challenge. It was both a technical and a management challenge, and I think we made significant progress in both.
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> The technical challenge was the most fun to be able to accomplish that and to maintain the discipline to be sure that we did enough to be able to accomplish the mission and not overreach and try to do too much. It was the old cliche that better is the enemy of the good. We had to know when we had it good enough and stick with it and have the discipline to stick with it, and not have somebody talk us into taking the next leap. That was part of the management challenge, and the rest of the management challenge was just the size of that team and the geographic dispersion of it and trying to bring it all together.

What can be gathered from the interview with Smylie, beyond his humility about his own contribution, is his acknowledgement of the importance served by collaborative effort to benefit from the synergy of multiple perspectives about the problem. What is also fascinating about Smylie's approach to unforeseen problems was his ability to employ his reasoning in a fast and frugal way that was 'good enough' for the task at hand. The problem solving goal for when something goes wrong without explanation and there is little time for a solution was not to make the perfect choice, or the choice that has no defects or is without risk but what is good enough (see Francis & Tsekouras, 2020).

In the book, '*Power to the Edge: Command, Control in the Information Age'* that had been written for military planners, the authors, Alberts & Hayes, (2003) state that: "during the undertaking of the mission, those involved need to make sense of the situation and orchestrate the means to respond in a timely manner. These functions are performed iteratively with the means being adjusted dynamically in response to changes in the situation and/or command intent. Making sense of the situation is inherently dynamic" (pp.16-17; note: see also Alberts, 2014, 2015). This describes how NASA reacted to the crisis on Apollo 13 but, importantly, the technologies and processes were not only in place, they were up-and-running enabling the entire support system to become aware of the situation and monitor changes (see Francis & Tsekouras, 2020).

Means to employ a form of reasoning using fast and frugal heuristics is tied to neural processes highly involved in the control of sensory-motor responses to solve specific tasks by active manipulation of objects at hand. This kind of reasoning makes use of what is known as 'embodied rationality' to assess and respond given limited information, time, and cognitive capabilities to apply a solution that works good enough. A common way of discussing rapid and frugal human problem solving driven largely by sensory-motor processes makes use of the concept known as 'heuristics' (see Newell & Simon, 1972). There is much debate about whether heuristic responses made under limited information and time constraints can be considered adaptively rational (think: logical) for the task at hand. One debated viewpoint taken by Tversky and Kahneman (1974) is that although heuristics employed in judgment under uncertainty are 'highly economical and usually effective' often tend to be automatically triggered and tend not to fit specific task environments, violate specific rules of logic and probability so as to produce biased judgments and lead to systematic and predictable errors (Kahneman, et.al., 1982; Kahneman, et.al., 2021). While another viewpoint offered by Gigerenzer (1991) is that 'fast and frugal heuristics' can and often do generate satisficing (good enough) solutions when dealing with uncertainty. This viewpoint takes the position that early formed sensory-motor responses to specific task environments employed for survival in highly uncertain situations can be co-opted, via exaptation, to shape (via tinkering) in service to higher-level cognitive functions useful for rapid and frugal problem solving in the modern world. An exaptation is defined as any adaptation that performs a function different from the function that it originally held for a better response fit to evolving environments/situations. Under this viewpoint, the human mind is conceived as a modular system that is largely composed of heuristics, their building blocks, and evolved exaptated capacities that have served human survival very well under challenging life-threatening conditions (see Mastrogiorgio, et.al., 2022).

It is important to point out that Kahneman and his colleagues are not arguing against the utility and benefits of human usage of heuristics. This point often goes unmentioned by their critics. Rather their research is focused on highlighting flaws in human judgment that can arise when multiple people are involved in making decisions in complex problems that introduces individual differences arising from a variety of backgrounds, personalities, and experiences leading to what is referred to as 'noise' (think: variation) and biases (e.g., availability and salience of factors due to recency, loss aversion) in judgments. It is worth highlighting Kahneman's perspective on this (Kahneman, et.al., 2021, p. 371):

> 'To be clear, personal values, individuality, and creativity are needed, even essential, in many phases of thinking and decision making, including the choice of goals, the formulation of novel ways to approach a problem, and the generation of options. But when it comes to making a judgment about these options, expressions of individuality are a source of noise. When the goal is accuracy and you expect others to agree with you, you should also consider what other competent judges would think if they were in your place. A radical application of this principle is the replacement of judgment with rules or algorithms. Algorithmic evaluation is guaranteed to eliminate noise--indeed, it is the only approach that can eliminate noise completely. Algorithms are already in use in many important domains, and their role is increasing. But it is unlikely that algorithms will replace human judgment in the final stage of important decisions--and we consider this good news. However, judgment can be improved, by both the appropriate use of algorithms and the adoption of approaches that make decisions less dependent on the idiosyncrasies of one professional. We have seen, for instance, how decision guidelines can help constrain the discretion of judges or promote homogeneity in the diagnosis of physicians and thus reduce noise and improve decisions.'

Indeed, the hope with AI going into the future rests upon prospects for improving human judgment by offering computational means to apply algorithmic evaluation of big data collected for understanding and operating effectively with complex phenomenon. But, just as importantly, AI also should be able to help augment human use of beneficial fast and frugal heuristics. AI augmentation of human sense- and decision-making ought to be designed for application across a range of problems to include situations requiring 'fast and frugal' heuristics often needed at the 'edge' of professional practice in the face of highly uncertain situations involving resource scarcity and urgency for timely decisionmaking and action. This is particularly true in the domains of warfighting at the edge. That said, AI assistance can bring along its' own idiosyncrasies too since human biases can be 'baked' into AI systems from data used in its’ initial training. And, simply put: even the most advanced forms of AI systems do not offer 'bricolage-like' capabilities at this point in time sufficient to operate autonomously with means to problem solve for dealing with unforeseen events, uncertainty, and instability expected at the edge of war. There is also the challenge of how to even offer augmented assistance to warfighters at the edge with AI since considerable power is necessary (often involving high-performance computing infrastructure support for high-band transmission, storage, and algorithmic processing of data).

On the good news side with edge assistance to warfighters there are prospects with means to embed AI capabilities on portable devices whether the device is connected wirelessly or not to tactical networks. In some cases, local devices can also be paired on-demand (to include drones collecting overhead video) for collecting and sending data to an AI-enabled portable device. There are practical advantages with having embedded AI capabilities on portable devices. For example, AI-enabled portable devices can offer rapid analysis and present data visualizations of situations/ environments overlayed with intelligence insights. Such assistance offers considerable prospects to augment situational awareness and decisionmaking of a warfighter. Paired together, AI augmentation in support of a warfighters' fast and frugal heuristic responses can not only make a critical difference for survival but ensure adaptation for mission success.

There are, however, challenges to overcome. Attempts to feed raw sensor data to portable devices for AI processing typically involve too much volume for tactical networks to handle not to mention data storage limits associated with hand-held devices. So, data needs to be compressed/encoded in such a way to make it possible for secure and rapid transmission, processing, temporary storage, and uploading to other platforms as needed without exceeding the capabilities of the device (e.g., storage, battery); to include minimum fidelity of compressed data required for interpretable visualizations needed by the warfighter to be useful. And, since electronic jamming can be expected at the edge, there will be the need for AI-enabled portable devices to operate offline, as necessary, from ad-hoc local or tactical network connections.

Obviously, offering AI deep learning and natural language processing that can operate on a portable device offline from a local or tactical network, using very limited compute and battery power, presents daunting obstacles to overcome. It takes megawatts to run a deep learning or natural-language AI capability relying on digital values stored on physical components that makes use of millions of words. For example, a typical GPT processing request makes use of around 175 billion values; very large data-center systems can barely handle this level of processing. Compare that to the human brain that runs on about 20 watts (about the same as a light bulb)!

Given the considerable challenge of running AI on portable devices due to their limited compute and battery power AI engineers are now reimagining what might be possible with repurposing analog computing for offering AI capabilities on portable devices at the edge. One 'bricolage' solution they've come up with is to do analog computing on a chip for AI simply because such a chip would use very little power (Haensch, et.al., 2018; Ahiqvist & Ahigren, 2022). That's because using an analog chip would not require constant power to retain data (see Ulmann, 2022, 2020). Whereas, digital AI systems use a type of data random access memory (RAM) memory (named SRAM) that requires constant power to retain data bits in its memory as long as power is being supplied. Thus, AI systems must remain switched on even when it is not performing a task. Whereas, an analog chip can store neural weights (values) in flash memory (which doesn't require power to retain its state). Even with advantages offered by an analog chip there would still be the need to do bit-based precision calculations using digital components but now using considerable less power. Basically, AI precision calculations would then be able to co-process with an analog chip using very little power. There are other advantages offered by analog chips too. For example, factors in differential equations can be expressed in the analog chip and converted into machine language for bit-based precision calculations thus also reducing power consumption when computing for nonlinear phenomena (see Nasyrov, 2022). Thus far, analog co-processing prototypes have been made making use of an analog chip etched onto a silicon wafer (Tsividis, 2018). The analog co-processing chips worked good enough with the added advantage of dramatically reducing power consumption and putting AI-enabled portable devices within reach for use by warfighters at the edge.

Interestingly, an important ingredient in the success of the Apollo missions and their predecessors were analog and hybrid (analog-digital) computers, which NASA used for simulations and in some cases even flight control (Ibid, 2018). Today, bricoleurs involved in the design of AI systems are reimagining the use of analog computing for portable augmenting possibilities to support future warfighters at the edge and give them the advantage using heuristics for dealing with uncertainty and unforeseen events.

From the AI S&C Bibliography

Ahlqvist, C. O., & Ahlgren, M. (2022). *Analog computer prototyping for the future*. Thesis. Malmö University.

Alberts, D. S. et. al. (2014). *SAS-085 Final Report on C2 Agility*.

Alberts, D. S. (2015). *C2 Agility: Related Hypotheses and Experimental Findings*. Institute for Defense Analyses.

Alberts, D. S., & Hayes, R. E. (2003). Power to the edge: Command... control... in the information age. Office of the Assistant Secretary of Defense Washington DC Command and Control Research Program (CCRP).

Barile, S., Saviano, M., Di Nauta, P., Caputo, F., Lettieri, M., & others. (2019). A systems based interpretative framework for approaching exaptation and bricolage in decision making and value co-creation. Paper presented at The 10 years *Naples Forum on Service. Service Dominant Logic, Network and Systems Theory and Service Science: Integrating three Perspectives for a New Service Agenda*.

Francis, D. L., & Tsekouras, G. (2020). Apollo 13-crisis, innovation and sensemaking. Paper presented at *XXXI ISPIM Innovation Conference: Innovating in times of Crisis*.

Gigerenzer, G. (1991). How to make cognitive illusions disappear: Beyond “heuristics and biases”. *European Review of Social Psychology*, 2(1), 83–115.

Haensch, W., Gokmen, T., & Puri, R. (2018). The next generation of deep learning hardware: Analog computing. Proceedings of the IEEE, 107(1), 108–122.

Kahneman, D., Slovic, S. P., Slovic, P., Tversky, A. (1982). *Judgment under uncertainty: Heuristics and biases*. Cambridge University Press.

Lévi-Strauss, C. (1966). *The savage mind.* Trans. G. Weidenfeld, Nicolson Ltd.

Mastrogiorgio, A., Felin, T., Kauffman, S., & Mastrogiorgio, M. (2022). More thumbs than rules: Is rationality an exaptation? *Frontiers in Psychology*, 13, 6.

Nasyrov, R. (2021). Numerical simulation of continuous-time systems based on the analog computing paradigm. Paper presented at 2021 3rd International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency (SUMMA).

Newell, A., Simon, H. A., & others. (1972). *Human problem solving*. Vol. 104. Prentice-hall Englewood Cliffs, NJ.

Tsividis, Y. (2018). Not your father's analog computer. *IEEE Spectrum*, 55(2), 38–43.

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases: biases in judgments reveal some heuristics of thinking under uncertainty. *Science*, 185(4157), 1124–1131.

Ulmann, B. (2020). Analog and hybrid computer programming. In A*nalog and Hybrid Computer Programming*. De Gruyter Oldenbourg.

Ulmann, B. (2022). Analog-and hybrid computing. Lecture slides.

Willey, Scott A. (2014). NASM Mission AS-508 Apollo 13 1970 (including Saturn V, CM-109, SM-109, LM-7) Owners' Workshop Manual: An Engineering Insight into How NASA Saved the Crew of the Failed Moon Mission. *Air Power History*, 61(2), pp. 43+.