High-Reliability Organizing (HRO) for the Color of Noise: Forcing Functions, Collaboration, and Safety

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Abstract:

The aviation industry operates in an environment where forcing functions and catastrophes can be deadly to the public and not easily explained away. The industry formed a safety improvement collaboration known as CAST, the Commercial Aviation Safety Team. Within ten years, the fatal accident rate decreased from the pre-CAST rate by more than 80% while also improving productivity. Signals carry information while noise interferes with information. This distinction is one of predictability versus unpredictability. Noise as a stochastic variation may represent unrecognized influences in the system. By existing in a world of stochastic variation, biological systems must maintain dynamic stability far from equilibrium. The meaning of the types of environmental stochastic noise comes from the characteristics of their fluctuations that cause unpredictable events and the energy of their 'forcing functions.' Frequencies with the power to force a system or population to respond to the environment are forcing functions. White noise environments follow the Gaussian distribution and are amenable to prediction, algorithms, rules, and protocols. Red and pink noise develop from autocorrelation, the feedback from the past influencing the present or a system interacting with other systems. Red noise environments with low frequency forcing events have a greater influence on the system than white noise. Red noise environments contain ill-structured problems requiring the use of heuristics and experience. Considered a response to reddened frequencies, we can discuss safety as information about long-period events and forcing functions or as the forcing function itself. The threat of punishment and litigation incentivized pilots, as it currently does healthcare professionals, to hide their errors and near misses and not report the errors and near misses of others.

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Introduction:

"We don't fight fires; we solve problems the public cannot or will not solve themselves." William J. Corr, Captain, LAFD, and WWII US Navy veteran, South Pacific, held an expanded view of the fire service. He uniquely presaged the ideas of red noise forcing functions, and pink noise 'flicker' catastrophes could arise from any mundane problem. Corr expected and modeled attending to and reporting relevant, contextual details. Karl Weick observed that managing details without context is micromanagement (personal communication). Corr and Weick indirectly articulated what the authors also learned through experience – that context can amplify details into forcing functions. We must remain vigilant, monitoring and responding as necessary. Today, we might describe this as residing in the white noise environment but mentally operating in the pink noise space.

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The aviation industry operates in an environment where forcing functions and catastrophes can be deadly to the public and cannot be easily explained away. In the early 1990s, despite many safety improvement efforts, the previously declining accident rate had stopped declining. The airline industry formed a voluntary government/industry safety improvement collaboration known as CAST, the Commercial Aviation Safety Team.

CAST focused not only on errors but also became proactive by focusing on upstream threats that make those errors more likely. This relationship is like the effect of contextual details interacting with an unexpected forcing function to cause extreme failure. Their collaborative approach ensured that all participants involved in or affected by the threats were involved in developing mitigations for the threats. The operational environment is large with many facets. Even the least experienced participant, when well trained, can offer valuable information. This flow of information included what was not going well and whether the remedies regarding what was not going well-improved safety without producing unintended consequences.

CAST faced a challenge from many safety experts who thought the pre-CAST fatal accident rate was exemplary and could not be substantially improved. However, within ten years, the fatal accident rate decreased from the pre-CAST rate by more than 80% *while also improving productivity*. The collaboration minimized unintended consequences. This enormous safety improvement occurred without CAST generating any new regulations.

Despite numerous longstanding efforts by the healthcare industry to reduce errors and injuries caused by errors, the error and injury rates have stubbornly resisted significant, sustained improvement.

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Information, Noise, and Collaboration

Signals carry information. Noise interferes with information. This distinction is one of predictability versus unpredictability (2). However, noise as a stochastic variation may represent unrecognized influences in or on the system (3). Stochastic properties follow a probability, but the probability is on a probability distribution that can change. Stochastic variation, then, appears random yet also appears to follow or contain deterministic processes.

Appreciating that noise contains information can contribute to the use of noise for prediction, alter our view of the environment (4-6), and change how we think and reason (7-10). Increased predictability can focus on our vigilance, reduce our exposure to vulnerability, and mitigate some of the effects on the system that arise from threats (5, 11, 12).

Our view can then move beyond situations within a specific space and time in ways that can increase the flow of information within the system (13), bring into better distinction the boundaries of our capabilities, make visible early heralds of failure, and give better clarity to the presence of covert, compensated states (1). We generate and update information, make more effective inferences from imperfect information, and process the evolving consequences of simultaneous acting and *not* acting (14). We begin to think by acting (15-18). A collaborative approach then emerges as a robust flow of safety improvement information consisting of, among other things, information about errors and near misses.

Widespread nonuse or misuse of safety procedures, such as hand hygiene, handoff procedures, and checklists, indicates that the procedures may not be entirely suitable for the operational circumstances. The lack of operational suitability is often an indication that the procedures were not collaboratively developed; that is, the end-users of the procedures were not adequately involved in identifying the reasons for the nonuse or misuse and developing appropriate remedies. The stigma of errors and the threat of punishment incentivize health care professionals to hide and/or not report errors and near misses. Understood as environmental forcing functions, errors and near misses identify and mitigate potential threats that lead to errors and injuries.

The collaborative approach discussed in this article derives from commercial aviation. Collaboration improved aviation safety while also improving productivity without an increase in regulations. Involving all who touch the system – not only pilots but also maintenance personnel and, if appropriate, air traffic control personnel – helped ensure that those who touch the system would be aware of, and know-how to, engage any residual 'error traps'

not adequately addressed. The tragic Boeing 737MAX accidents demonstrated that even after decades of development and improvement, the process for ensuring that airplane designs are adequately friendly and intuitive to the end-users – the pilots – has, and will always have, room for further improvement.

The difficulty lies in translating the knowledge and experience gained in new or dangerous contexts to routine operations with only the potential for serious harm. The risk lies in mistranslation by those inexperienced in dangerous contexts or those who lack a vocabulary that is familiar or readily accessible to spectators (1, 6). Missing is the salience and meaning spectators can use to expand their necessary cognitive, affective, and behavioral repertoires (19). Knowledge and experience reduce the effect of bravado, the influence of movies and television (12), the substitution of abstract for contextual (5, 20), or the understanding beyond the grasp of outsiders (1). The authors have organized a series of articles in *Neonatology Today* that combines the primary sciences, primary experience, and practical ways to overcome mistranslations while also bridging this gap.

This article describes the environment in a manner that applies to dangerous contexts, to environments with rare though severe disturbances, and to routine operations that are unlikely to experience such threats (21-23). Further, since everyone has the same brain structure, this material is given context within the neurosciences (6, 11, 19).

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The Environmental Color of Noise

In a world of stochastic variation, biological systems must maintain dynamic stability that is far from equilibrium (24, 25). Stochastic environmental variation as noise or a time series has the characteristics of a spectrum. When decomposed into constituent frequencies (by Fourier transforms), we can identify some frequencies with no temporal correlation. The values of a random signal at two instants in time are entirely independent of each other. This circumstance is "white" noise. In white noise, the variance is the same for all frequencies. There is no correlation variance, and time and space have constant variance (3, 26).

White noise is the variance incorporated into academic and scientific models (26). The randomness and independence of events in a white noise environment create a Gaussian distribution from which we can calculate statistics and probabilities (27). Independent, discrete-time intervals are amenable to applying classical logic and the formation of linear and deterministic processes (28). With independence, and discrete-time intervals comprising white

noise, we can create mathematically tractable models and more concise theories that possess greater conceptual clarity from the randomness (3, 29). While we may use white noise for mental representations of the environment, we must not mistake it for the actual world.

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White noise is not characteristic of the natural environment or the response of organisms to maintain homeostasis, the complex "coordinated physiological reactions which maintain most of the steady states in the body" (Walter B. Cannon (30)). A white noise environment, with white noise responses and the concomitant Gaussian distributions, supports Cannon's classic "homeostatic" approach of the organism maintaining constant output. However, the world, particularly the biological world, is noisy and experiences stochastic demands and threats. This random variation affects the physiological and behavioral dynamics of organisms.

The healthcare industry and commercial aviation community are populated with good people working to do the right thing under sometimes challenging circumstances. When they attempt to maintain homeostatic stability in a dynamic environment, they may do something inappropriate. The problem is probably not solely caused by the person, especially if a high percentage of people similarly situated might also do the same inappropriate thing. Instead, a significant contributor to the problem is probably the applicable procedures and equipment the person uses.

What we observe as a stochastic variation arises from instability due to environmental fluctuations, countered by non-equilibrium dynamical systems. Environmental fluctuations are caused by various factors correlated on different time and space scales (3). Non-equilibrium dynamical systems arise from internal fluctuations due to multiple degrees of freedom (31). Stochastic feedback from multiple degrees of freedom drives the system away from extreme values and toward stability. However, multiple degrees of freedom do not produce the constant output of classic homeostasis (24, 31).

Every inappropriate action made by a participant provides an opportunity to learn about what procedures and equipment should be improved to reduce the likelihood of stochastic error. In aviation, reports about errors and near-misses are one of the primary sources of information about the existence and potential remedies to mitigate stochastic threats. Convincing pilots to report their errors and near misses necessitated a change from their old way of doing business, which was to hide their mistakes as much as possible. This change, in turn, necessitated three other changes:

- a change from believing a mistake was an indication of a bad human to recognizing that all humans make mistakes, even on their best day
- a change by the employers (airlines) away from using reports of inadvertent error as a basis for punishment toward using reports of the inadvertent error to learn how to

make the system less likely to cause an error
- a change by the safety regulator away from using reports as a basis for punishment or enforcement toward using reports of the inadvertent error to improve the system safety

Collecting more data or data over a longer time series does not produce a better norm or better stochastic models. Increasing variance with time (or distance) creates 'redder' noise. Variance in red noise does not form a Gaussian curve. Instead, the variance increases with the time series, and we lose the norm in power distribution. More data only increases the measured variance, and in pink noise, the variance increases no matter how long the time series (32). "In comparisons of model predictions and real data, stochastic models often perform as poorly as deterministic ones, John M. Halley (32). We can better understand environmental stochastic noise and non-equilibrium dynamic stability by describing and understanding noise as a spectrum (3, 33).

Since noise is a spectrum within the environment, the errors created by noise form an environmental spectrum; treating errors as information (34) in aviation allowed the regulator – the Federal Aviation Administration – and the airlines to learn from inadvertent errors. Rather than punishing for error, error became an important step toward continuously improving safety because it enabled the free flow of information about aspects of the system that needed improvement. Punishing the people when the real problem is the procedures or the equipment undermines the labor-management relationship – because punishment develops an adversarial relationship between labor and management – and it incentivizes people to hide their mistakes rather than learn from them.

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Decomposing a time series by Fourier transforms and identifies white noise, described above, and distinguishes frequencies with long periods. Like the longer frequencies of red light, this is "red" noise. Because of the magnitude of measurements, frequencies are plotted against their power as a log:log plot. A log(frequency) to log(power) plot for colored (reddened) noise signals approximates straight lines. A specific line for $1/f$ or f^{-1} is called pink noise, midway between white noise (f^0) with constrained variance and "brown" noise (f^2) for randomness (named for Brownian motion).

Time dependence forms a power distribution describing a more significant influence on the system from uncommon low-frequency events. These red noise events are also poorly predictable. A special relationship occurs at the 'flicker' frequency, the $1/f$ oscillation, where increased power spectrum at low frequencies produces abrupt, rapid fluctuations and catastrophic failure. This concept is 'pink noise.'

Development of Reddened Noise:

This problem of more data clouding the conclusions develops when an event is influenced by what preceded the event. That is, the event is no longer independent of preceding events. Autocorrelation is when past observations or events have an impact on current ones. Autocorrelated events are more susceptible to feedback loops, allowing even minor or mundane noise signals to achieve resonance, becoming amplified and consequential.

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Spatial autocorrelation has a role in epidemiology as the degree of similarity between objects located near each other – everything is related to everything else, but near things are more related than distant things. Spatial autocorrelation identifies disease clustering as clustered, random, dispersed, and whether the disease is in a general or specific region. Spatial autocorrelation measures the degree of similarity between objects located near each other. If spatial autocorrelation confirms spatial dependency, then the

disease rates can be adjusted in adjacent areas (35).

Neighbors are features within a neighborhood used to characterize spatial relationships among objects. This relationship could be absolute distance based on the distance separating them, relative distance with the nearest feature considered a neighbor or topology-based with neighbors considered based on their relations or attributes.

Red noise is dominated by low-frequency (or long-period) cycles producing an increased probability of long runs of above or below average conditions. Low-frequency events (reddened spectrum) have an inordinate influence on a system because prolonged decay continues dissipating energy and environmental disruption (3, 25).

Pink noise (also called fractal, flicker, $1/f$, or f -1 noise) is half the integral of white noise. Pink noise is the power function halfway between white noise's predictability and the randomness of brown noise. We can observe 'flickers' of power (abrupt increases in magnitude) (36, 37) at 'half' the integral of white noise processes. Flicker noise sums (calculus integration) *diverge toward zero or infinite frequencies*. Without a long-term mean or defined value at an instantaneous time, pink noise does not form a Gaussian curve. Because these divergences are logarithmic, extending time intervals in a time series may not capture the flicker (36). Rare events, acting as forcing functions, are more severe and sudden in the pink noise environment (32), forming a power distribution. Forcing functions are events to which the system must respond.

[The name flicker noise came from John B. Johnson's initial measurements of the white noise spectrum. He measured an unexplained flicker at low frequencies, halfway between white and brown noise (37).]

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Color	Structure	Variance	Distribution
White	No frequencies dominate Flattened spectrum Spectral density has equal amounts of all frequencies	Data *decreases* variance Forms Gaussian curve	Gaussian distribution - Elements fully independent - No autocorrelation
Red	Low frequencies dominate Long-period cycles	Data *increases* variance Forms power distribution	Power law distribution - Elements *not* independent - Mutual/ reciprocal relations
Pink	The midpoint of red noise Slope lies *exactly* midway between white noise and brown (random) noise	Data *continuously increases* variance Distinguishes pink noise from reddened spectra	Power law distribution - No well-defined long-term mean - No well-defined value at a single point

Table. Patterns and Characteristics of Noise (38)

Time Scales:

The effect of noise on a population as variance comes from the relative time scales between environmental and population-level processes. This effect is from the relative magnitudes of environmental stochastic autocorrelation times and population dynamics. Short environmental autocorrelation times act as white noise on populations. The contribution of environmental stochastic noise will dominate in large systems (39).

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Subsystems with short time scales may not be affected by noise frequencies with more prolonged periods. A more extensive system or one with a long time scale may have the capacity and experience to dampen long period disturbances that will damage smaller systems or those with short time scales (3). We see this with the difference in experience between a novice and a veteran. The danger to the system occurs from a reset baseline as those new to a program enter an established, well-controlled system (40). Knowledge is lost, and expectations of readily achieving stability become stronger as those new to the field replace veterans.

To capture the experience of novice and veteran alike, CAST brought in pilots with a wide variety of backgrounds and experience – not just the manufacturer's chief test pilot – to "fly" the design in engineering simulators as the design was developed. This array of experience helped identify possible additional human factors issues beyond those that the human factors experts included in the original design.

Problem Characteristics:

Despite their stochastic characteristics, white noise environments follow the Gaussian distribution and are amenable to algorithms, rules, and protocols associated with known success. These are the well-structured problems described by Herbert Simon (41). The environmental stochastic variance of white noise can appear daunting to the uninitiated, believing they have experienced a reddened environment.

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Red noise environments with low frequency forcing events have a greater influence on the system than white noise—reddened events within the normal variation of activity act as forcing functions on populations. Red noise environments contain ill-structured problems requiring the use of heuristics (41) and bias-correcting error (34), decision-making driven by feedback (John Boyd's OODA Loop) (8), and practical, common-sense problem-solving approaches (10).

"In the pink noise environment, catastrophes occur when the environment becomes a major aspect of the problem. Catastrophic events arising from the change in entropy due to environmental stochastic noise differ only in magnitude and timescale (32). The external and internal environments share feedback, embedding the problem into the external environment."

In the pink noise environment, catastrophes occur when the environment becomes a major aspect of the problem. Catastrophic events arising from the change in entropy due to environmental stochastic noise differ only in magnitude and timescale (32). The external and internal environments share feedback, embedding the problem into the external environment. We see this with neonatal care during abrupt and prolonged disasters when the environment intrudes into the NICU, effectively embedding the NICU into the environment (21, 23). This moment-to-moment feedback can create a "loss of cosmology," which can collapse sensemaking (42), or the individual allows 'abstractionism' to supersede contextualization of the problem (20)

While some search for or develop plans for the stochastic ill-structured or the embedded problem, another approach is to use what famed airline pilot Capt. Chesley "Sully" Sullenberger used for real-time error management (personal communication before the Hudson River landing). He recalled hearing of an error described as a ball rolling down a ramp, where speed bumps captured the error. The steeper the ramp, the taller the speed bumps need to be. This relationship is essentially like increasing capture frequencies as the error (the ball) increases its speed. "Another part of the idea is that it often requires more than a one-speed bump to trap the error finally. The ball may miss some bumps or roll over them if it is going fast enough. (So, the taller the bump, the more likely it will trap the ball.) Having many speed bumps represents 'defense in depth,' a military concept that we talked about that day. A multilayered defense system is less likely to be penetrated than a single layer." The "error ball and ramp" model that Sullenberger describes is a dynamic organizational design to reduce system failure that recognizes the operator's real-time efforts decrease the chance of failure.

Forcing Functions:

The meaning of the types of environmental stochastic noise comes from the characteristics of their fluctuations that cause unpredictable events and the energy of their 'forcing functions.' Frequencies with the power to force a system or population to respond to the environment are forcing functions.

The forcing functions become ubiquitous in reddened noise environments, not entirely random except by timing. The forcing function emerges from known processes within normal variation, differing only as a matter of time scale and magnitude.

Fluctuations with long frequencies, slow in onset, and that carry greater power to affect the environment are *red noise,* as in long-wavelength red light.

Fluctuations with long frequencies that can cause abrupt catastrophic events are *pink noise* because they are *exactly* between white noise and red noise or between white noise. The hallmark of pink noise, 1/*f*, is the presence of rapid fluctuations and a power spectrum that increases at lower frequencies. Pink noise represents long-timescale fluctuations without a well-defined long-term mean. Accuracy does not improve by averaging more measurements over time (36).

Red and pink noise disturbances occur on any timescale with any order of magnitude. There is no special distinction between normal environmental variation and ecological 'catastrophes': it is the same thing seen at different timescales (32).

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While possibly counterintuitive, this also describes human behavior – our past experiences influence our current behavior, and we constantly interact with those around us. All human behaviors are autocorrelated. Any system with *human behavior is a red noise environment that will generate forcing functions into the system.*

Birds entering the plane's engine are forcing functions. Captain Sullenberger's water landing would apply more strictly to engineers, pilots, flight crews, and passengers if framed as a normative incident. If framed as a forcing function, the water landing applies to all of us because forcing functions are a part of living.

Capt. Sullenberger was trying to increase the angle of attack as much as possible just before the landing before the aircraft stalled to maximize the flare and thus minimize the airplane's downward velocity when it impacted the water. His effort was frustrated because the phugoid damper* prevented him from getting the last 3 1/2 degrees of nose-up pitch that would otherwise have been available before stall. Consequently, the sink rate was higher than it otherwise would have been, and the rear fuselage structure was breached to the extent that a flight attendant seated in the rear was injured, and water entered the airplane. Automation intended to improve safety and comfort hindered the most adaptable part of the system, the human pilot. *Sully was unaware of this until we [the NTSB] discovered it in our investigation* [emphasis added]. In

other words, Sully solved a problem he did not know he had.

* "Phugoid" describes the aircraft pitching up and climbing, then pitching down and descending. The aircraft's speed changes between climbing and descending.

A convergent, deductive, analytic approach drives the search for facts and information which will guarantee our conclusions. The security offered by our actions and the structures we create will reinforce the normative frame, but the linearity impedes stochastic resonance (24). Rigid structure and linearity narrow and increasingly confine responses. As in Sullenberger's water landing, a pragmatic frame with stochastic resonance enhances our capability to solve problems linked to more profound, unidentifiable structures.

Safety:

Considered a response to reddened frequencies, we can discuss safety as information about long-period events and forcing functions or as the forcing function itself. We caution against a punitive approach to an error in reddened systems as we all become novices again at some level and situation. "For everyone, there is a first time," Kaldhen Sherpa, Sherpa Trekking Service.

Safety information

Safety information as long period frequencies reveal what the problems are, inform a determination of priorities regarding which problems should be addressed first, inform decisions regarding how best to remedy the problems, and provide quick and proactive feedback – i.e., "weak signals" that can help avoid having to wait for the next actual mishap to spot a problem – about whether the remedies are working. In a system populated by good people trying to do the right thing, the most valuable safety information is information about errors and near misses.

More specifically, good people trying to do the right thing make a mistake or have a close call. Information about errors and near misses reveals where there are error traps and weaknesses in the system and often suggests remedies for those traps and weaknesses.

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Did the person who made a mistake have all the necessary information at the moment, and if not, what additional information was needed, and how could it be made available? Was the process or equipment inappropriate for the situation? If so, how could that be addressed? Did the person understand the process or equipment? If not, should the remedy be in training, the design of the process or equipment, or both? Did the person know whether the process or equipment was working as intended? If not, how can that be remedied? Information about errors and near-misses helps to answer these and other questions that arise when undesired outcomes occur or almost occur.

Safety and Forcing Functions

Forcing functions that affect the working processes are productivity issues, those that affect the product or service are quality issues, and those that harm a person are safety issues. Viewed as the consequence, we inadvertently divide them among distinct review programs and can arrive at diverse solutions, missing the true incidence of the forcing function.

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Forcing function as a neutral term can drive investigation into the various reddened frequencies and stochastic interactions that make them so troublesome. Focus on error and safety as persuasion implies telling someone what they are not – mistaken and unsafe. Focus on early identification and dampening a forcing function tells people what they are – vigilant and trusted (43).

The idea of forcing functions makes visible safety lapses and the breach of duty in liability. In acting as outside influences rather than interactive forcing functions, liability and safety can cause decision errors. C. Northcote Parkinson (44) is known for his eponymic Parkinson's Law "work expands to fill the time available for its completion." Identified another contribution to economic inefficiency during WWII – any criticism would likely be met with, "Don't you know there's a war on?" (45) (Stevenson 1993). For example, healthcare executives, resistant to a patient safety study out of concern for liability to the hospital, queried a committee about liability. One member asked, "What duty are we breaching?" The executives could not articulate any duty the study would breach. Queries about liability and safety will easily terminate or endanger extension of operations into ambiguity, adversity, or threat. The hospital did not conduct the study.

William Haddon argued for an ecological approach to injury prevention, much like treating injuries as ecological forcing functions. Haddon applied this ecological model to injuries (46) using the same human-as-host concept. He described the "infectious" agent as energy and the vector as a carrier of that energy. A host (human) is injured by an agent (a form of energy) carried by a vector (automobile, chemical release, fire, and the like). With the addition of the phases, pre-event, event, and post-event as distinct time elements (47), the science of epidemiology could now identify more effective interventions to prevent or reduce injuries.

Error as Residuals

Any response to the environment has a deterministic component that is predetermined and predictable. There is another stochastic component, therefore not predictable, that we can associate with forcing functions. The difference between the observed value and the expected value (for example, the sample mean or expected outcome) is the measure of error as a 'residual.' Residuals can be random or non-random.

A non-random pattern of residuals indicates that the deterministic component has not captured explanatory information. That is, the data is not explaining all that is possible. The better the model

is, the fewer non-random residuals will appear. The deterministic component should not contribute to error. The random component is the stochastic portion from forcing functions.

Autocorrelation occurs when adjacent residuals are correlated. One residual can predict the next residual, revealing that predictive information has not been captured. This usually occurs with time series, called 'serial correlation,' as the degree of correlation of the same variables between two successive time intervals.

As autocorrelation of residuals, red noise becomes the stochastic component of error measures between the expected and observed. For example, error management too quickly becomes focused on subordinates and line staff (34). Identification of the forcing functions that contribute to error and then harm develops a full spectrum analysis (48) of noise internal to the system. Error management can expand to review information flow (13), leadership and management styles (49), and continuing education focus on competency rather than proficiency (50). A broader approach would be to compare forcing functions that changed the air transportation industry with efforts for patient safety.

Stochastic Feedback and Resonance

Healthy systems display highly irregular dynamics to generate non-equilibrium dynamic stability. This stability arises from internal fluctuations due to multiple degrees of freedom from stochastic feedback that interacts over time or space scales (31).

In the ideal system, noise is the enemy. Stochastic resonance occurs in noise-added systems such as reddened noise environments. Through unpredictable fluctuations, stochastic resonance can increase the reliability of a signal and the system's performance through system nonlinearities. We can think of stochastic resonance as "noise-enhanced signal processing." We can consider stochastic resonance to be "noise-induced" (51).

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Stochastic resonance is nonlinear and cannot be beneficial in a linear system. The benefits of stochastic resonance come from the greater degrees of freedom and more complex interactions between nonlinearities and randomness rather than a particular frequency (51).

Criminalization of Safety Breaches

The threat of punishment and litigation incentivized pilots, as it currently does healthcare professionals, to hide their errors and near misses and not report the errors and near misses of others. Consequently, the air industry did not, and healthcare does not learn from those errors and near misses to identify and mitigate potential threats that can injure or kill.

The airline industry, both employers and regulators, shifted away from using reports of inadvertent error as a basis for punishment. The industry moved toward using reports of inadvertent error to

learn how to make *the system* less likely to cause an error. Error, as we discuss, is not the error in the elements of malpractice, negligence, or a crime. This process must be continually clarified to avoid confusing inadvertent errors due to environmental noise with an error that may comprise a torte.

The Federal Aviation Administration supported an important step toward continuously improving safety by not punishing. The change in position enabled the free flow of information about aspects of the system that needed improvement. Whether doing something inappropriate should result in punishment, or is there a better way to produce the desired outcome next time. Punishing the people when the real problem is the procedures or the equipment undermines the labor-management relationship.

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The line worker and pilot can too easily become a target. They have less immediate support than ancillary staff or those higher in the echelon, and their actions are more easily connected directly to a failure. Criminal prosecution does not address system issues such as:

– Robustness of connection for the part that fell off

– Mechanics fatigued, distracted, impaired

– Training of mechanics adequate

– Work environment suitable

– Necessary tools available

– Parts inventory adequate

– Adequacy of airport Foreign Object Debris (FOD) procedures

Pilots have faced criminal prosecution for actions encountering a problem that they have never seen before, even in training:

- Turkish Airlines, Amsterdam (2009)

- Rio to Paris (2009)

- Asiana, San Francisco (2013)

- 737MAX (2018-9)

There have been exceptions to the assumption of a criminal act:

- Hydraulic failure, Sioux City, IA (1989)

- Landing in the Hudson River (2009)

Overzealous criminalization, however, may adversely affect safety improvement efforts. Following the TWA 800 (1996) crash, the US NTSB successfully gained primacy of safety investigation over criminal enforcement unless there was evidence of intent to harm. From an MOU between the NTSB and FBI, the presumption that an accident was caused by inadvertent error rather than criminal wrongdoing, then the NTSB will lead an investigation. The FBI leads the investigation if the accident is clearly a criminal act (e.g.,

9/11). If the NTSB investigation uncovers criminal activity, the NTSB will ask the FBI to lead, and the NTSB will provide technical assistance as requested.

A Registered Nurse now faces a prison term after being convicted of criminally negligent homicide and impaired adult abuse after mistakenly administering the wrong medication (52). The criminal justice system seeks justice through an adversarial approach, one that "substitutes an abstract conceptual order for the current [experienced] perceptual order" (Karl Weick (20)).

Such an approach disintegrates contextual details critical for safety and reliability while modeling an abstract conceptual order that is impractical and endangers those who operate in dangerous contexts. Weick captures this in his discussion of the sinking of the 790-foot container ship, the *El Faro* – "A thread among many discussions of sensemaking is that the process boils down to managing interruptions and recoveries, discontinuity and continuity, differences and sameness across situations" (20).

Healthcare' routines' are replete with interruptions that healthcare professionals must recover from in a collaborative, supportive way. When we believe we have achieved continuity, a complicating element creates discontinuity. We do not have the option of starting afresh; we must change some things and keep others – but what to change or keep, we cannot know until much later. Across situations, we see the same thing, a headache attributed to COVID-19 is a stroke, acute gastroenteritis in the evening is a pediatric brain tumor, and abdominal pain while making jump shots playing basketball is appendicitis.

"Spectators such as lawyers and expert witnesses must reduce red forcing functions or pink catastrophic events into a white noise format – elements interchangeable in time and space. These elements create a right and wrong way, a defense versus a prosecution. Multiple interacting elements, some readily visible but irrelevant and some covert or occult, have temporal and spatial autocorrelations that may not be salient in the time scale of bedside treatment."

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Protection of oneself by not acting is not uncommon. One author (DvS) served in a pediatric ICU covering a large rural area. Management of epiglottitis, by the standard of care and medical staff policies, required endotracheal intubation in the operating room

by a pediatric ENT surgeon with the participation of an anesthesiologist. The medical center with the PICU had the only pediatric ENT surgeons on staff. About 0200h during the Fall, an emergency physician at a rural ED requested transport for a child with epiglottitis. To provide airway management, including intubation, the author traveled by surface ambulance because high desert winds precluded helicopter transport. Later in the morning, the Chief of Staff (an ENT surgeon) and chairman of anesthesia counseled the author about staff privileges and whether any subsequent intubation would result in loss of staff privileges. A prolonged discussion included the admission that no medical center anesthesiologist or ENT surgeon would travel 45 minutes to a referring hospital in the middle of the night, and no local anesthesiologist or ENT surgeon would intubate a child with epiglottitis. Several years later, a surgical resident staffing a distant rural ED with no other physician available requested the transfer of a child with epiglottitis. None of the four receiving PICUs would accept the child without intubation by the surgical resident. The author sent the PICU fellow to treat and transport the child. The following morning, one of the receiving PICUs chastised the author for taking a child in their catchment area and pointing out the dangers of intubating a child with epiglottitis. The author discussed these cases with his colleague. They decide that any physician transporting a child who dies in transit from airway obstruction would be a hero and consoled for the emotional pain. However, the same physician acquiring and protecting the airway to ensure safe transportation would lose his career.

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Criminalizing this environment drives critical information out of view, but it also becomes inaccessible for learning and knowledge creation. Insidious and more common, it drives actors to act by 'not acting' to create invisible errors that quickly become incorporated into organizational knowledge. Like safety, the injury from hiding experiences is today but only becomes visible tomorrow when the harm is irreversible. Like occult cancer, the criminalization of inadvertent errors can kill silently at a distance from its origin.

The Business Case:

When the US commercial aviation industry began its systematic collaboration with CAST (Commercial Aviation Safety Team), the primary objective was to improve safety. Moreover, given the widespread fear of flying, improving safety was so important that there was little or no initial concern about whether CAST would also improve the bottom line. Much to the pleasant surprise of CAST participants, CAST improved safety and productivity. This result was significant because, although safety improvement experts are reluctant to admit it, safety improvements that reduce productivity and hurt the bottom line are not generally sustainable. CAST has been sustainable and is still going strong after more than two decades because it improved productivity while improving safety. One of the major successes of CAST has been that it has not only improved safety, but it has also done so effectively and efficiently. Just as collaboration enables safety improve-

ments, as noted above, the collaboration also enables simultaneous productivity improvements.

Because all the key industry participants are involved in the collaboration, concepts that undermine productivity for any participants are rarely approved by the collaborative process. Significantly, the bottom-line improvements that resulted from CAST were not related to costs that were avoided because the safety improvements helped prevent accidents and incidents – a result that would not be provable. On the contrary, the bottom-line improvements were immediate and measurable reductions in operations and maintenance costs. Precedents in the healthcare industry have demonstrated the capability of collaborative programs to improve safety and generate immediate and measurable improvements in the bottom line (53-57).

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Conclusion:

John H. Steele (2) identified three essential features for conceptual or numerical models of natural systems: (1) a high order of nonlinearity, (2) large variability in the forcing functions, and (3) a wide range of space and time scales. The choice of model and level of analysis has implications in:

- Education, training, and planning (50)
- Categorization and standards (58)
- Developing approaches for allostasis

Despite integrating across multiple levels of analysis, such as degree of nonlinearity, forcing functions, time scales, spatial autocorrelation, and a topological space, ultimate and proximate causes cannot be accomplished in a single model. Arguing across levels of analysis creates false debate (59).

"Never use malice if ignorance will fully explain the member's behavior," William J. Corr.

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