EUROCONTROL

Patterns in How People Think and Work

Importance of Patterns Discovery for Understanding Complex Adaptive Systems

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Contents

INTRODUCTION

> *"The future seems implausible, the past incredible."*
>
> **(Woods & Cook, 2002)**

The first weak signals project in 2014 used the quote above as one of its core ideas. It refers to the situation that within complex socio-technical systems foresight is a key strength of an organisation. Yet, the capability of being prepared for future surprises is a very challenging one to acquire, and pro-active information about the organisational resilience level is not always easily available. This makes it difficult to formulate reasonable forecasts regarding the ability to respond to future challenges and hazards`(Woods 2020).

On the other hand, with the power of hindsight, the past very often seems incredible. "How could we have ended up with this situation?" is an all too often cited phrase after a tragic event has occurred. Formal accident or incident investigations regularly reveal that all the information that prefigures an unwanted event was available in time, but not properly connected. Therefore, no one within the organisation had complete knowledge at system level because sense-making and the transformation of data into knowledge did not happen adequately. "Fragmented problem solving" and "structural secrecy" are terms that have entered the academic vocabulary and describe the phenomena organisations are confronted with in the design of their safety management activities. Consequently, the ability to capture drift or perilous adaptations that are normal by-products of complex adaptive systems is an important asset of an organisation within a competitive, dynamic market. Especially in environments where safety is at stake, practical applications are needed to address these contemporary issues.

To overcome the limits of traditional safety approaches that rely too much on retrospective data or on taking past success as a guarantee for future safety, the weak signals II project develops proactive methods to constantly monitor the organisation's ability to monitor its current level of resilience as smaller and larger stresses challenge the edges of the system. Monitoring the level of resilience is important because systems as complex as air traffic management (ATM) are characterised by continuous change. Change in ATM refers to influences from the outside – such as the economy, airlines, noise abatement and regulations – and the inside – such as automation and procedures – which have an effect on the system's overall performance.

Adaptation and the ability to anticipate change are essential components of ultra-safe complex systems. The ability to anticipate and to adapt is a property and an asset of the human roles at all levels of the system. The ability to monitor, understand and learn is a critical property of a modern resilience management system.

To achieve this capability, it is important to acknowledge, understand, and monitor the difference between work-as-imagined and work-as-done. This includes the basic understanding that adaptations tailored to contingencies and context are always going on. The adaptations that make the system function also hide the systems weaknesses.

> *"Filling the gap is hiding the gap"*

Management often can't see the gaps so it seems that the system is functioning as designed. In the first weak signals project we used the metaphor of a snow-covered glacier, where from the outside the crevasse is not seen as it is covered by snow – but it's there.

The conclusions and necessary focus areas from the Weak Signals I project are:

1. Disconnected pieces of information
2. "Work-as-Done" vs. "Work-as-Imagined"
3. Identification of Patterns
4. Testing the system's resilience

This white paper addresses the third finding. It provides the basis for an inventory of patterns. This will lay the foundation for pattern identification work tailored on ATM systems as change continues. Patterns are used everywhere throughout aviation. Information about traffic, load, approaches, operations are all organized around patterns.

First, in the paper we illustrate:

- What is a pattern (a pattern is in the relationships and emergent properties),
- How people think in patterns, especially about disruptions and recovery,
- How visual patterns aid thinking,
- How engineering has long used visual patterns to bridge the gap between general principles and highly variable specific situations. The last point is expanded through examples of how visual pattern based displays have been able to assist operators in dynamic situations and to supervise automation.

Second, the paper explains the pattern approach pioneered by Christopher Alexander and its important role connecting research and practice in human-computer interfaces and in the design of human-machine and human-automation joint cognitive systems. It hence explains how *pattern finding* is important in proactive human and organisational aspects of operations.

Third, the paper illustrates three use case topics where pattern finding provides information about emerging risks and vulnerabilities that go beyond specific incidents in specific contexts. The first is patterns about how complex systems fail in the Columbia Space Shuttle Accident. These kinds of patterns helped NASA focus on systemic changes after the accident. The second case is automation surprises as a pattern in pilot interaction with cockpit automation. These findings highlight important issues for deployments of today's more autonomous capabilities. The third case is the topic of workarounds when standard plans and procedures do not fit the actual situation pilots, controllers, operators face in particular situations.

The three cases illustrate how pattern finding is important in proactively managing human and organisational aspects of operations. The goal is to find patterns (or how patterns are changing) before serious incidents or accidents occur (Case 1). Case 2 illustrates how to find generalized patterns from different studies and line experiences and how these generalized patterns can be used in design and training. Case 3 shows how to monitor for patterns where and when workarounds occur, and how this information provides proactive signals for monitoring the gap between work as imagined and work as done.

The paper ends by providing a general sketch of the pattern-finding process as a valuable and unique information source for human and organisational aspects of operations.

I. THE PATTERN APPROACH IN HUMAN SYSTEMS

A longstanding approach to understanding the role of people in high performance, high risk systems focuses on uncovering the recurring patterns of how sharp-end practice adapts to cope with the complexities of work (Hollnagel and Woods, 1983). The pattern approach to cognitive work systems is based on Christopher Alexander's Pattern Language (Alexander, Ishikawa and Silverstein, 1977). In this approach, observations of people at work reveal general patterns that play out across various specific situations. These patterns cut through the variations in the surface appearances to reveal underlying and recurring regularities. The stream of concrete situations in each specific domain of work appears infinitely variable and unique, and highly specialized for each work system, generation of technology, and organization. However, these variations spring from and express a small number of basic patterns about cognitive systems at work (Woods and Hollnagel, 2006).

I.1 What are Patterns?

A pattern captures a set of relationships. Specific elements are needed to represent the relationships, but the pattern is not about the elements themselves. The pattern emerges

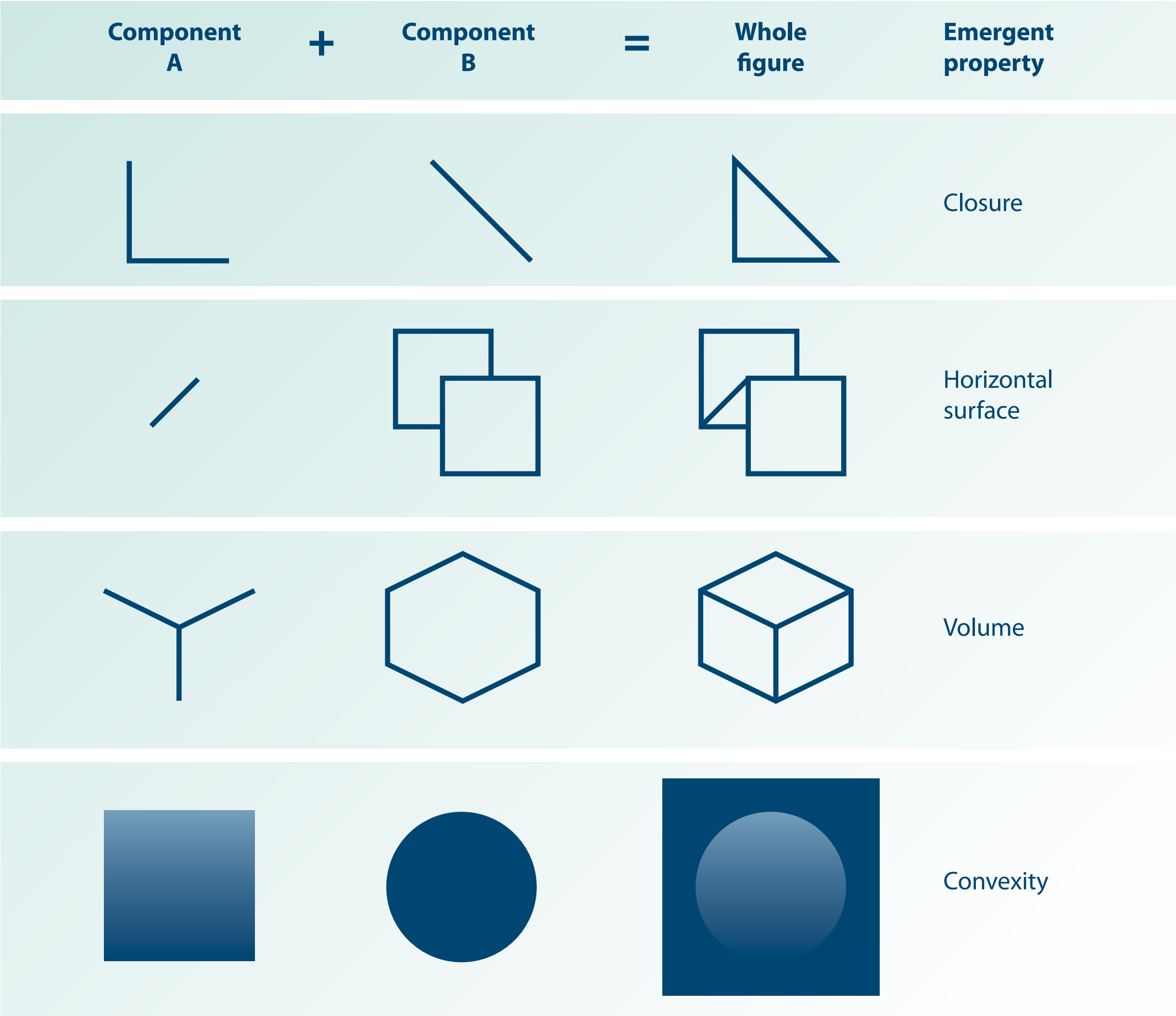

Figure 1.
Combining elements forms a pattern that specifies a higher order property. Volume, depth, closure, convex/concave are example of actual properties of objects that can only occur and be seen based on relationships between visual elements. See Wagemans et al. (2012).

from the relationships and can represent properties that are not present in the elements. Figure 1 captures simple emergent properties that arise from combining elements: a figure which encloses an area emerges from lines, a volume emerges from a combination of flat lines, convex or concave property emerges from combining a shading gradient over a shape. A very strong example of emergence is subjective contours (Figure 2).

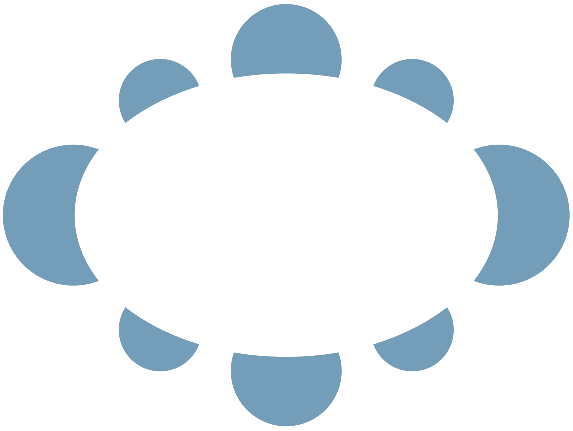

Figure 2.
Subjective contours are emergent properties that require elements but the property has nothing to do with the elements themselves. In this case, an oval is perceived from the configuration of surrounding elements. See Wagemans et al. (2012).

Adding more elements can make a pattern emerge, as in the well-studied configuration superiority effect or popout effect (an example is in Figure 3). This points out how patterns effectively integrate data converting a large number of low level elements into a few higher order properties or events (Woods et al., 2002).

I.2 People Think in Patterns

Visualizations like the figures in this White Paper work because people perceive the world around them in terms of patterns. People also utilize patterns to make sense of the world, constructing explanations of real-world phenomena and making predictions about the future. Figure 4 shows an event pattern that plays out over time as physicians monitor vital signs data (from Christoffersen et al., 2007). The time dependent behavior of heart rate and blood pressure signals a specific condition (the Cushing effect) that modifies the actions that should be taken as compared to treating just low heart rate or just high blood pressure. The event is characterized by a relationship over time (a relationship relative to change — another relationship).

This case demonstrates how the human brain is sensitive to events and how changing events match or deviate from expectations very early in the brain's neurological processing of incoming data. The Cushing pattern is specific to cardiovascular malfunction and, simultaneously, the pattern is an instantiation of a larger more generic event pattern that plays out across all dynamic systems: the deteriorate/recovery event pattern (Figure 5). The deteriorate/recovery event pattern applies as readily for monitoring space systems on a vehicle or orbiting station as it does to critical care medicine and physiology. It can be seen in other settings as well such as business critical software infrastructure and energy systems.

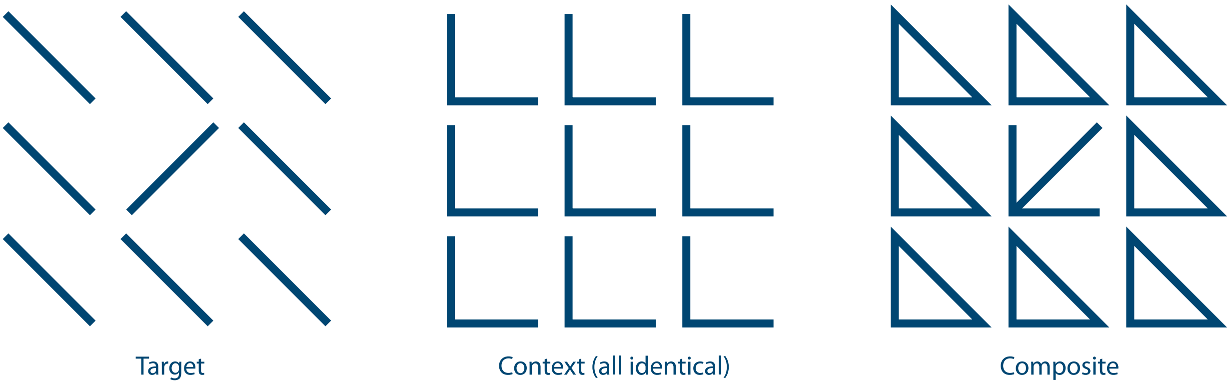

Figure 3.
A classic pattern advantage is called configural superiority or the 'popout' effect. The target in a search task is to detect the odd line out of a set of distractors (left panel). Adding more identical elements would seem to just add noise and reduce speed and accuracy (middle panel). However, the target pops out in fast, accurate performance despite all of the extra elements, when those extra elements combine with the original display to form different patterns that distinguish the target from distractors (right panel). See Wagemans et al. (2012).

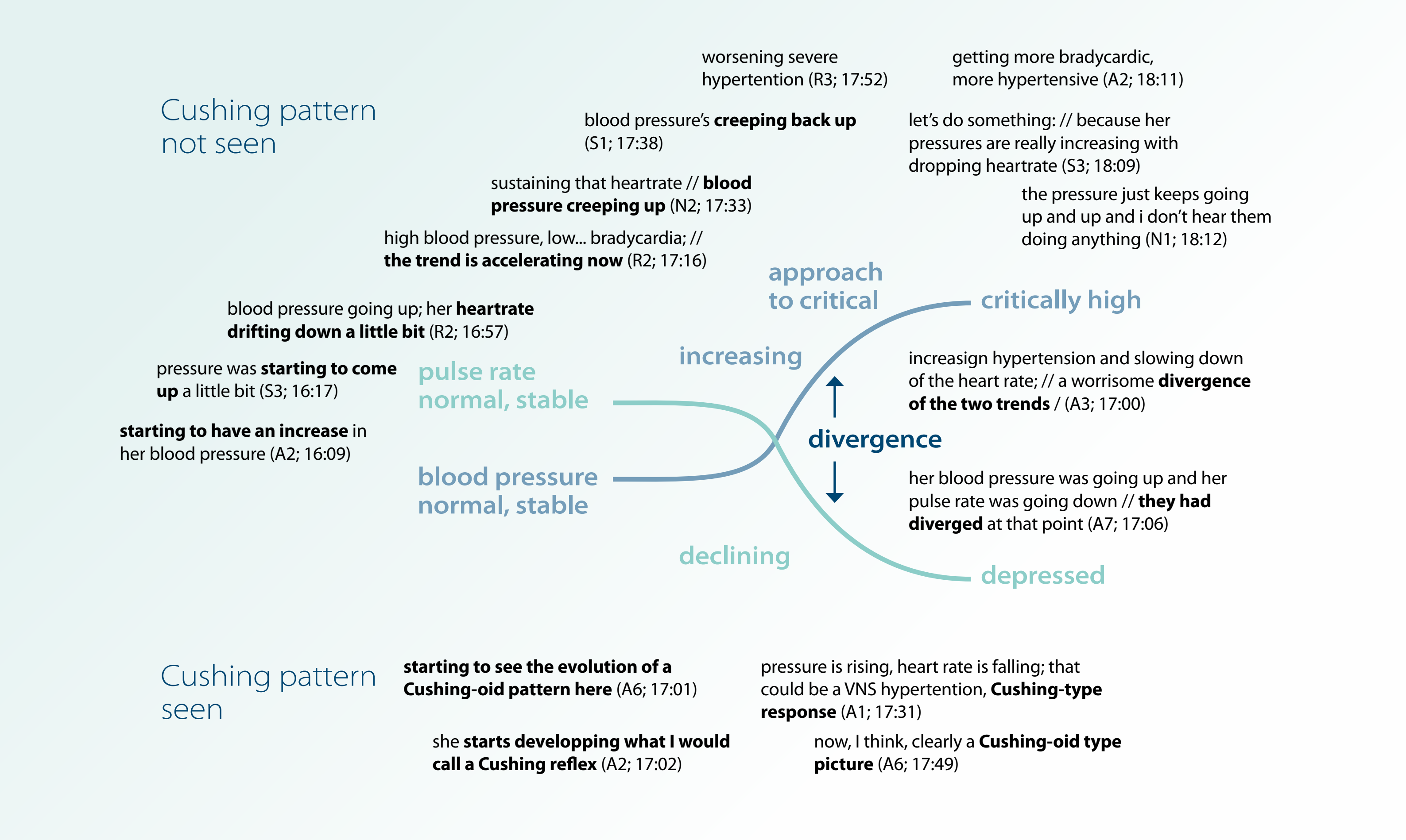

Figure 4.
An event pattern from a study of how physicians recognize events from data telemetry streams (Christoffersen et al., 2002). The change over time and the relationship between the two key parameters are needed for physicians to recognize the patient's problem. Recognizing this 'Cushing reflex' pattern improves with experience.

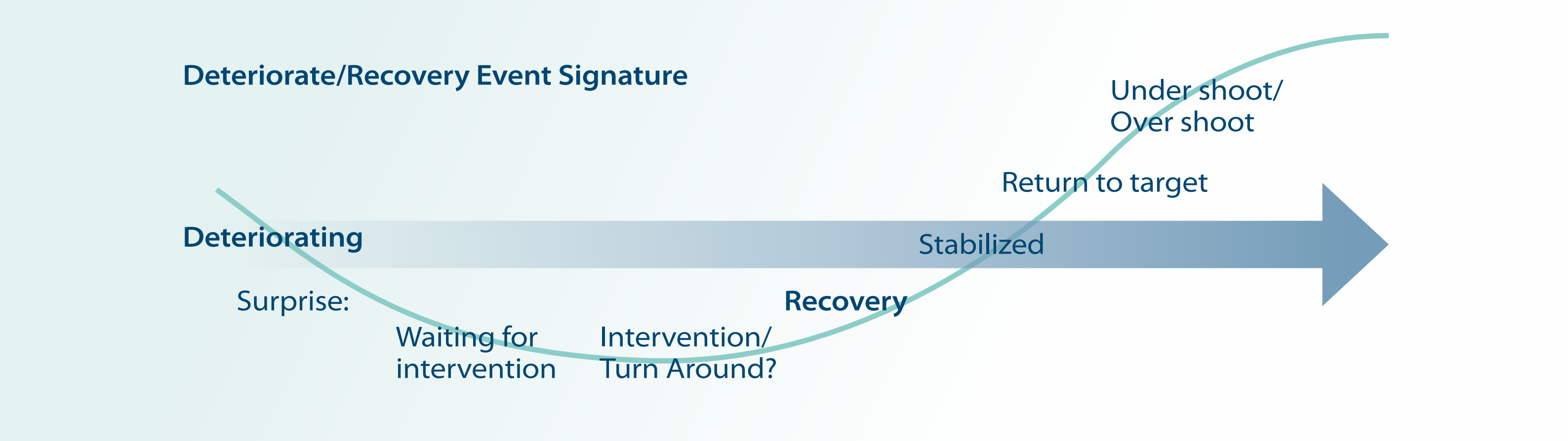

Figure 5.
The basic template of the deteriorate/recovery event pattern for monitoring and controlling dynamic systems. This high level pattern consists of a set of relationships over time and can appear in a wide range of dynamic situations.

Pattern recognition facilitates sense-making by permitting operators to integrate new information into an existing pattern-based mental model (Weick et al., 2005; Klein et al., 2006; Hoffman and Fiore, 2007). A key aspect of sense-making is how individuals assimilate new information through their existing knowledge and experience. Mental models, previously developed through experience with a wide range of cases, continually help the sense-maker select and organize the specific phenomena they experience. Pattern recognition connects data relationships over time to actions allowing accelerated responses to keep systems operating within bounds or to resolve anomalous behaviours. Patterns as an aid to action are especially valuable in situations where the time available for response is limited. When confronted with such challenges, the ability to generalize based on motifs abstracted from past experience permits operators with the ability to anticipate the next phases of an unfolding event. While the specifics of each situation will be unique to that context, experienced operators can recognize more general patterns to respond appropriately and quickly. Recognizing patterns allows one to use knowledge generalized from other situations to act advantageously in a new specific situation despite the variation in details.

I.3 Patterns as Cognitive Aids

An example of using patterns as cognitive aids in engineering is the history of nomographs. Nomographs are graphical computing devices or diagrams (their development and use dates to late 19th century, though use declined rapidly with accessibility to digital computing). Ranging from the generic slide rule to nomographs for specific engineering fields and tasks, nomographs capture multiple relationships via the relative movement and visible alignment across multiple variables, given appropriate scaling, limits, and gradations. Historically, nomographs were often developed to provide graphical representation of the equations that modeled the physics of mechanical or electromechanical systems. The nomograph provided a way to map the basic mathematical relationships into a tangible form using visual relationships across multiple scales (Glasser and Doerfler, 2019). By manipulating the relationships embodied in the nomograph, users under practical pressure could quickly get an answer for a specific situation that could vary over a range of important factors. Doerfler (2009) covers a broad set of examples of nomographs in engineering.

Good nomographs provide a visual model of a system that captures inter-relationships across variables in an easy to manipulate representation. This analog device is manipulable to allow one to explore sensitivities and order of magnitude effects in specific problems. Good nomographs capture constraints that apply in any problem that would benefit from the computations captured in the nomograph. The constraints encoded in the relationships built into the nomograph support and guide the user when they confront specific versions of a general problem, reducing risks of some classes of mistakes. For example, digital systems, though they provide high precision results, easily fall prey to the fallacy of misplaced precision where results look more accurate and confident than the data and analytic assumptions warrant. Analog computations using tools like nomographs provide good checks to detect order of magnitude errors in digital systems because digital results are hypersensitive to input, data entry or specification errors.

Using a good nomograph requires, but also stimulates, an understanding of the key concepts/connections and how they can apply to a diverse range of situations. Skill and understanding grow with the use of the nomograph across a variety of particular cases (Hoffman and Fiore, 2007). The visual/physical model provides quick answers for real tasks especially where overload pressure and time pressure occur.

Because nomographs are tools designed to permit the user to benefit from the existing relationships in the world, sailors were able to make use of the relationship between Earth's horizon and specific astronomical bodies via a sextant. Critically, the nomograph does not create the relationships between the variables or scales, it encodes or manifests the general relationships to simplify a particular class of applied problems.

I.4 The Pattern Approach in Visualization and Representation

Aiding thinking through visual representations dates back to the mid-1880's in the work of Minard (Rendgen, 2018). In visualization, the pattern approach manifests in two lines of work. In one path, designers note the recurrence of patterns in visual form (Lima, 2011). For example, there are various subclasses for tree-like structures for visualization of data sets such as fields of knowledge, kinship, or biological connections across species. Circles are another recurring visual form (Lima, 2017). The second line of work focuses on techniques designers can use to visualize patterns of relationships that convey meaning to users. For instance, representations via circular forms utilize the power of the center to organize visual search, make compact use of limited space to encode a large amount of data, and depict multiple layers of relationships in parallel. Not surprisingly in ATM the sectors are centered in the middle of the radar screen and air traffic controllers develop scanning techniques to capture the conflicts at the entry of the sectors and at the crossing points within the sectors.

Figure 6 from Hedges et al. (2015) illustrates many aspects of pattern finding (see also Lima, 2017 for a discussion of circular pattern visualizations). The graphic is called a Timetree of life which integrates data from thousands of studies to capture and reveal emergent properties of speciation and diversification in the history of life on earth.

Figure 6.
Timetree of life as a circular visualization integrates data from thousands of studies and reveals emergent properties of speciation and diversification in the history of life on earth. From Hedges et al. (2015). See also, Lima (2017) who explores circular visual forms across a variety of cases in multiple fields.

The graphic uses a circular visual form to capture a very long time scale. First, it captures events over time. Second, it captures multiple layers of relationships (multiple time scales and sub-patterns within larger patterns). Third, it uses a pattern visual form that supports mapping multiple relationships. Fourth, some of the relationships in the pattern visualization are emergent. Fifth, the designers planned some of the representation mapping properties of speciation and diversification onto properties and relationships in the visual form. Sixth, as a good pattern-based representation, many interesting relationships are captured without being explicitly designed into the representation.

Arnheim (1969) emphasizes the role of visual form and design as an aid to thinking. This can be seen in the history of nomographs. Nomographs in engineering have used circular visual patterns to capture layers of relationships and support manipulation of the relationships to graphically and rapidly compute answers to specific problems (the Smith Chart in electrical engineering and transmission lines, for example; https://en.wikipedia.org/wiki/Smith_chart). Other examples of nomographs use circular or geometric frame of reference in combination with linear frames of reference depending on the mathematical properties being depicted.

One of the first uses of pattern visualization based on circular representation is a nuclear power plant display depicting the dynamic "safety state" of the plant during upsets (Woods et al., 1981; Woods et al., 1987). The design had to develop a way to represent the abstract property of safety state from multiple key parameters, limits, normalization, and dynamics of how failures disturb the state of a nuclear reactor. The representation was designed to take advantage of human pattern recognition capabilities. There are an infinite variety of ways that faults appear, grow, and are resolved depending on initial conditions, combinations of failures, and the pace of automatic and operator actions. Yet with experience (Hoffman and Fiore, 2007), operators can learn to see patterns to:

- Recognize different patterns that discriminate between different classes of failures (e.g., a loss of cooling accident versus a control system failure).
- Recognize a general pattern while retaining high sensitivity to the variety, scale and timing of the particular failure underway (e.g., is it slowly developing loss of cooling? is it early or later in the progression of this class of event? are responses to the event going well or poorly to mitigate the failure?).
- Recognize patterns of conflicts of aircraft in an Air Traffic Control sector, or on an aerodrome traffic circuit or on the maneuvering area of an airport.
- Recognize a general pattern helps operators step back from details of the situation to track the big picture of the threat and failure response (is the situation deteriorating or recovering — i.e., the generic pattern in Figure 5).

The octagon display also illustrates the power of circular forms for visual thinking as articulated by Arnheim (1969; 1982). Arnheim's emphasis on the power of the center is illustrated in Figure 8. Well-designed circular forms allow users to see in parallel larger scale patterns (is the situation continuing to deteriorate?) and more detailed patterns (did an intervention stabilize pressure?). Well-designed circular forms allow designers to integrate large amounts of information in a navigable form given the limited space available (Figure 6). Users' ability to find or discover patterns can grow as users gain experience at monitoring the system through the lens of the representation (Hoffman and Fiore, 2007). Well-designed circular forms also provide a longshot perspective that helps users navigate the large space of potential views of data in modern systems reducing the risk of getting lost in massive data spaces (Woods and Watts, 1997).

Figure 7.
The "octagon" display of how failures disturb the state of a nuclear reactor based on human pattern recognition capabilities. There are an infinite variety of ways that faults appear, grow, and are resolved depending on the specific conditions. The octagon is the expected normal state of the reactor across all plant contexts; deviations from the octagon highlight patterns of disturbances and how the situation is deteriorating, stabilizing or recovering (Figure 5). This was developed as one part of the post-Three Mile Island accident control room fixes to help operators keep track of the big picture during an emergency. See Woods et al. (1987). Photo: D. D. Woods, personal collection, with permission.

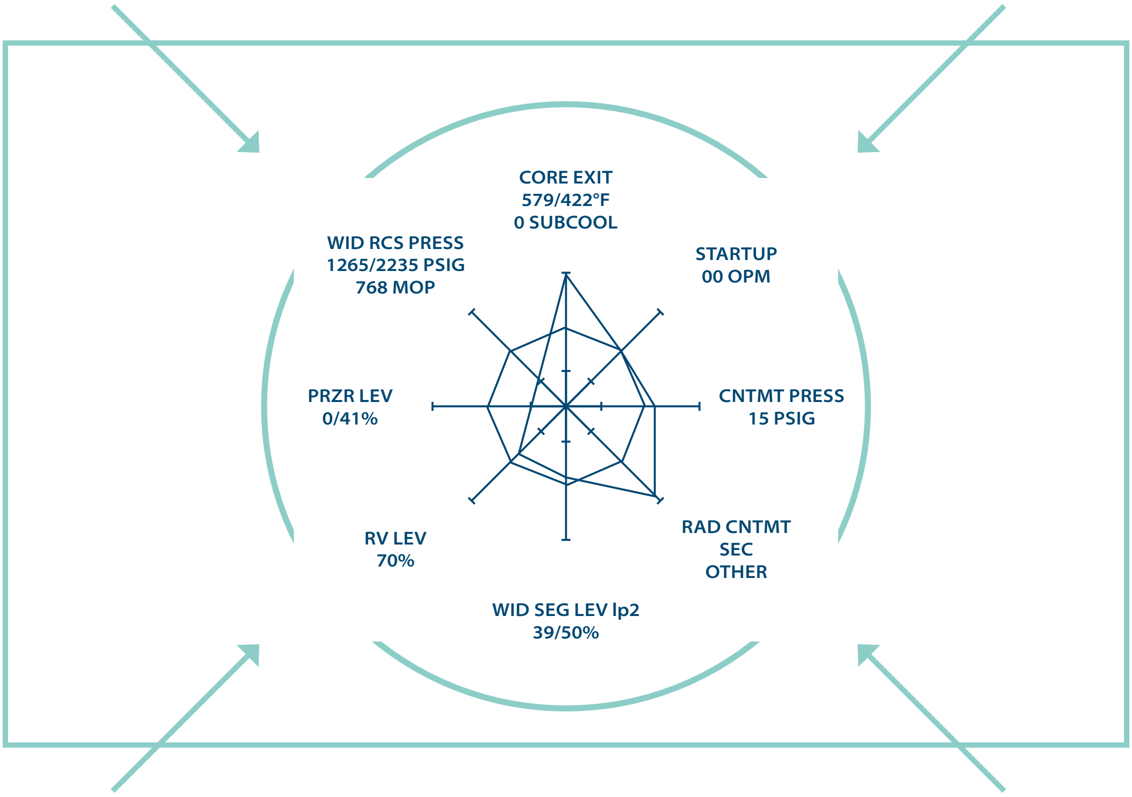

Figure 8.
The power of the center to organize visual search based on Arnheim (1982). A user's focus of attention and visual scan tend to be anchored around the center of the display whether a physical drawing or a computer display. The rectangle marks the border of a visual display. A circular representation occupies the center region as marked by the circle (the content is a drawing of the 'octagon' display from Figure 6 which represents the safety state of a nuclear reactor during an upset condition, i.e., the deviation from a regular octagon normalized for context). The four arrows represent the tendency for user's attention to flow toward the center area. D. D. Woods, with permission.

Many algorithms used in sensor processing and computer vision are based on geometric frames of reference (trigonometry). Morison and Woods (2016) took advantage of this to create an interactive visual representation for human supervisors who utilize the sensor/algorithm's outputs despite weaknesses such as uncertainty from sensor limitations, non-targets that can be confused for targets, and masking from environmental conditions in Intelligence, Surveillance, Reconnaissance imaging applications. Figure 8 shows the circular form mapped to represent the class of algorithms' properties to provide a visual model that can tap into human pattern recognition capabilities. Figure 9 highlights several high level patterns that can emerge in the visualization and that correspond to important aspects of the sensor/algorithm's discrimination power: panel (a) strong signal match, (b) strong background, (c) weak signal match, (d) weak background, (e) unknown sample, (f) strong confusor match, (g) ambiguous.

In representation design the goal is to tap into the human power for visual thinking and turn what would be slow deliberative inference processes into fast accurate perceptual recognitions. There is a long history of representation design of this type in Cognitive Science and Engineering. This work provides both the empirical and formal basis for why representations make a difference (Norman, 1987; Woods, 1991), and helps avoid common ways visualizations confuse, mislead, and hide meaning (Tufte, 1990). Techniques have been developed to aid designers on how to develop innovative visual representations for many different design challenges (Flach, 2019).

I.5 Patterns about Patterns

The illustrations in this paper are visualizations that capture *patterns* about patterns. On one hand, the illustrations quickly show readers what are patterns. Visual forms are good for depicting relationships, and relationships are central to the value of patterns. On the other hand, the illustrations demonstrate aspects of how people think in patterns so that visual patterns can become an aid to thinking and thus to cognitive work.

What is important looking over the illustrations is how they support key points about patterns that Alexander identified and sought to take advantage of when he proposed pattern-centered inquiry.

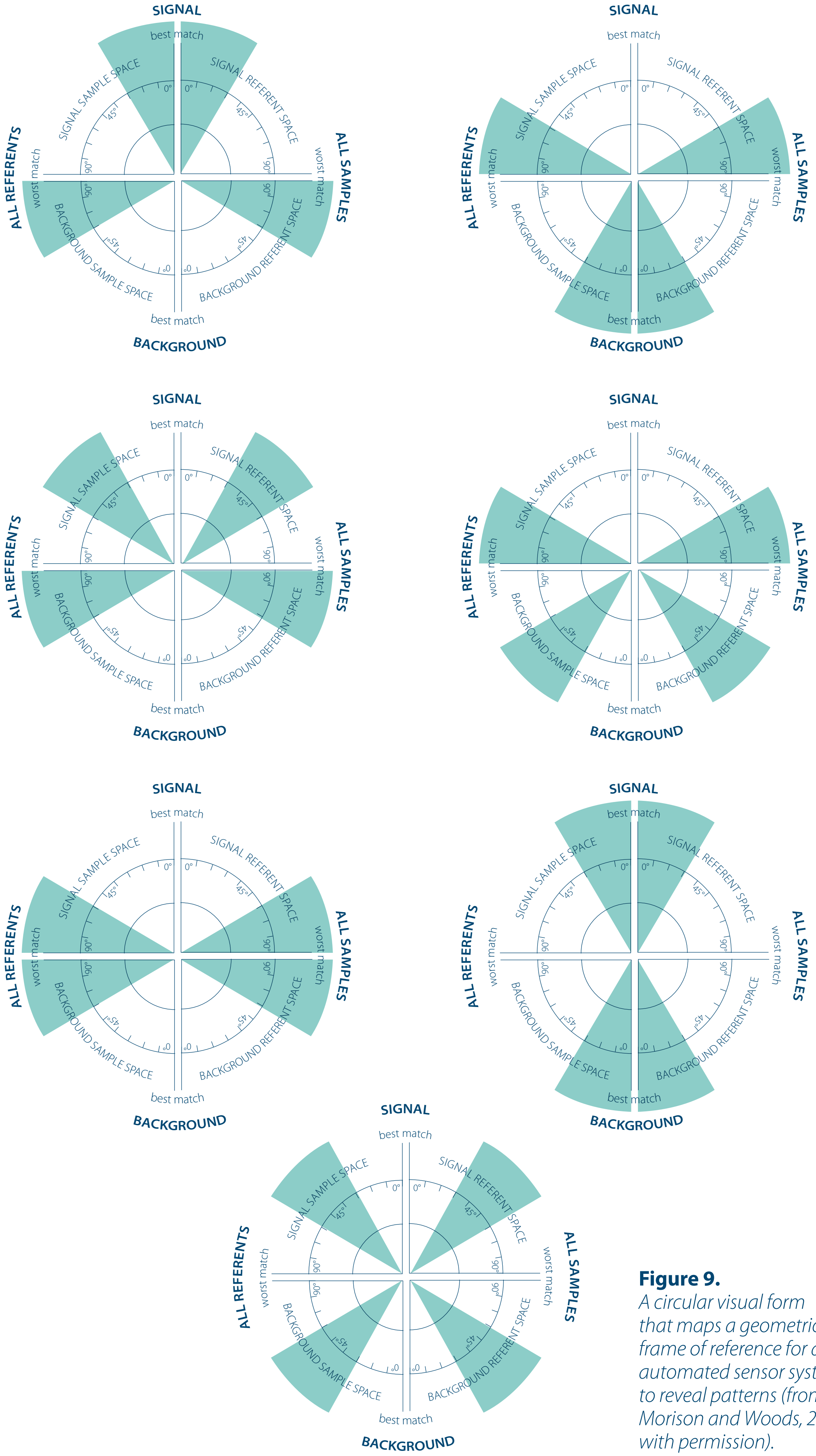

Figure 9.
A circular visual form that maps a geometric frame of reference for an automated sensor system to reveal patterns (from Morison and Woods, 2016, with permission).

II. PATTERN-CENTERED INQUIRY

Christopher Alexander pioneered Pattern-Centered Inquiry in the 1970's. While his intent was to address architecture and design, his work has been influential well beyond this starting point. It has been very important in human-computer interaction and especially in research and the pragmatic uses of those research results in Cognitive Systems and Resilience Engineering.

The underlying insight is — the relationships captured in a pattern can recur even as the elements that specify the pattern change. The pattern is general but is expressed in many different situations and settings. This means a pattern is a way to generalize and transfer findings from one situation to others. The general pattern can be illustrated or is instantiated in multiple different specific situations or places. Thus a pattern is sensitive to the details of specific settings and to different contextual factors while still allowing for generalization that would help explain or direct pragmatic action in other settings.

> *"Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice."*
>
> **(Alexander et al., 1977, p. x)**

Alexander took advantage of this property of patterns to synthesize general designs rather than see each design case as unique. If each case is unique, then only method, technique, or style generalizes across cases. He and his colleagues saw that underneath the variety of cases, there were common sets of constraints and general ways to adapt to or balance those constraints that reappeared across specific settings, people, and technology. Understanding these patterns then expanded, and yet grounded, the search for a broad set of potential design possibilities. This process stimulated innovation while being sensitive to the unique contexts of particular settings and the opportunities available at points of technology change.

Alexander's approach was particularly influential in how to do field research on human-machine systems in risk-critical settings because these situations include:

- too many variables,
- too many temporal contingencies as events occur and trigger responses (pacing and tempo),
- context matters (a lot),
- risk which places a premium on anticipating and defusing risks before serious incidents or accidents occur (being proactive),
- technology change which produces a combinatorial explosion of potential design features.
- operators' ability to adapt to technological, organizational and environmental changes.

These factors mean experimental methods and standard reliability statistics are inadequate and ill-matched to make progress, practically or scientifically. Studies of human-machine cognitive systems at work have utilized Alexander's approach to be successful at pattern finding — building a large repertoire of patterns in cognitive work systems that recur across the details of different settings and technologies (e.g., the patterns about reactions to failure in *Behind Human Error*, Woods et al., 1994).

The empirical work in Resilience Engineering to support and sustain highly adaptive systems that can produce foresight safety also is based on Alexander's pattern approach (Woods, 2006). The key is to identify how people, across human roles and levels of organizations, *adapt to make systems work* and to identify the constraints and opportunities that drive processes of adaptation (Hollnagel et al., 2006). Resilience Engineering builds a set of empirical patterns about adaptive behavior at multiple human and organizational scales. These include patterns about reciprocity, initiative, as well as trade-offs and how adaptive systems fail (Woods and Branlat, 2011; Woods, 2019a).

III. RESULTS FROM PATTERN-CENTERED INQUIRY

This section provides three examples of patterns that emerged from observing and monitoring operations in a few settings that continue to apply across multiple settings. These are examples of patterns about cognitive work systems, safety, and resilience/brittleness of complex systems.

1. Columbia Accident is a case of complex system failure where "weak" signals were abundant but discounted.
2. Automation Surprise is a pattern in flight crew interaction with cockpit automation. The pattern about human-automation interaction identified new vulnerabilities (e.g., mode awareness) that apply broadly, have been corroborated with findings from other industries, and still apply even as autonomous capabilities grow (Woods, 2019b).
3. Workarounds are a very basic pattern about how operators bridge gaps, overcome bottlenecks, and work around impasses. The general pattern links to many sub-patterns. Patterns about workarounds are important today in the difference between WAD-WAI in safety. It is one of the drivers for monitoring adaptations, conflicts & pressures that produce the WAD-WAI gaps (Shorrock, 2020).

In each of these cases the patterns can be expressed in template formats.

III.1 Columbia Accident as a Case of Complex System Failure

One example of the pattern-based inquiry is found in results of the Columbia Space Shuttle Accident Independent Board (CAIB) report which pointed to classic patterns in latent multiple contributors to accidents in complex systems (CAIB, 2003; Woods, 2005).

Table 1. Patterns about Complex System Failures that Recurred in the Columbia Accident

1.	Drift toward failure over time as defenses erode in the face of production pressure
2.	An organization that takes past success as a reason for confidence instead of investing in anticipating the changing potential for failure.
3.	Fragmented distributed problem-solving process that clouds the big picture.
4.	Failure to revise assessments as new evidence accumulates.
5.	Breakdowns at the boundaries of organizational units that impedes communication and coordination.

All of these contributed to the organisation discounting "weak" signals that the recurrence of debris (insulating foam) strikes on launch were a new risk that fell well outside of the boundaries for NASA's analyses and mitigation tactics for the safety of the space shuttle program.

This example of pattern finding arises by building on previous work that observed and studied how complex systems fail including the emergence of Resilience Engineering. The patterns surfaced in this previous work provided a frame to look at this particular event and see the operation of some (but not all) of these patterns about how complex and adaptive systems break down.

III.2 Automation Surprise as a Pattern in Cockpit Automation and Across Sectors

Wiener (1989) observed flight crews during actual operations as the new "glass cockpits" came into use in the 80's. Observing actual operations he noted common expressions pilots used, even though they occurred in many different circumstances. Referring to "the" automation, pilots asked each other:

- What is it doing now?
- Why did it do this?
- What will it do next?

Woods and Sarter saw these questions as representing automation surprises, i.e., situations where crews are surprised by actions taken (or not taken) by the auto-flight system, and they started a research program to examine these events in line operations and in full scope simulators (e.g., Sarter Woods Billings, 1997; Woods and Sarter, 2000). They charted the basic automation surprise pattern (Table 2).

Table 2. The Template for the automation surprise pattern

1. Automation surprises begin with mis-communication and mis-assessments between the automation and users which lead to a gap between the user's understanding of what the automated systems are set up to do, what they are doing, and what they are going to do.
2. The initial trigger for such a mismatch can arise from a variety of sources, for example, erroneous inputs such as mode errors or indirect mode changes where the system autonomously changes its status and behaviour based on its interpretation of pilot inputs, its internal logic and sensed environmental conditions.
3. The gap results in the crew being surprised later when the aircraft's behaviour does not match the crew's expectations. This is where questions arise like, "Why won't it do what I want?" "How did I get into this mode?".
4. Generally, the crew does not notice their mis-assessment from displays of data about the state or activities of the automated systems. The mis-assessment only is detected, and thus the point of surprise is reached, based on observations of unexpected and sometimes undesirable aircraft behaviour.
5. Once the crew has detected the gap between expected and actual aircraft behaviour, they can begin to respond to or recover from the situation. The problem is that this detection generally occurs when the aircraft behaves in an unexpected manner. e.g., flying past the top of descent point without initiating the descent or flying through a target altitude without levelling off. If the detection of a problem is based on actual aircraft behaviour, it may not leave a sufficient recovery interval before an undesired result occurs.

Unfortunately, there have been accidents where the misunderstanding persisted too long to avoid disaster. This means it is important to understand what factors contribute to the potential for automation surprises as captured in the pattern template in Table 3.

Table 3. The potential for automation surprises is greatest when three factors converge.

1. Automated systems act on their own without immediately preceding directions from their human partner,
2. Gaps in users' mental models of how their machine partners work in different situations
3. Weak feedback about the activities and future behaviour of the agent relative to the state of the world.

This case of pattern finding began when Wiener found the initial pattern of automation surprise and this then led to observations of human-automation coordination, or lack thereof, across a wide range of operational experiences and situations. The observations were then expanded to lay out the automation surprise pattern more carefully. Automation surprise patterns also are observed and occur in other settings such as space operations and critical care medicine.

Understanding the automation surprise pattern creates an opportunity to notice the occurrence of poor human-automation interaction without waiting for serious incidents to occur. When one notices signs of the automation surprise pattern, the pattern points to directions to intervene, most notably to provide better feedback about what the automation will do next. This leads to a variety of innovations in specific cases that support the ability to anticipate. However, aviation has also tended to ignore the results on the automation surprise pattern and has missed new vulnerabilities that produce difficult automation surprises such as sensor failures leading to misbehaving automation (Woods, 2019b). As a result, new systems have been introduced that produce automation surprises with fatal results (e.g., Boeing 737 MAX/MCAS). The role of the pattern approach is to anticipate changing risks and to identify potential interventions without waiting for accidents.

III.3 Patterns Related to Workarounds

The third example begin with a very basic and classic pattern — workarounds. Operators will confront situations where standard plans, procedures, contingencies, forms of interaction, policies, and automation are insufficient to handle the constraints, conflicts, uncertainties that arise in the flow of work. The result is a mismatch or gap between demands of the situation and the standard ways of working — as Rasmussen commented in 1981: "The operator's job is to make up for holes in designers' work", or as a software engineer commented in 2019: "people do, can, and have to adapt around normal operating approaches when things are not operating within the bounds of those norms, and you have to provide some latitude for them to do so." As Human Factors has noted repeatedly, much of human practitioners' expertise in action revolves around recognizing and bridging gaps when situations have gone awry relative to the scope of plans, automated processes, and procedures (Cook, Woods and Render, 2000; Perry and Wears, 2012).

Table 4. Workaround Pattern Template

1. Begins with a mismatch or gap between aspects of a situation relative to the normal plans for handling this kind of situation.
2. The mismatch often involves the potential for a bottleneck or crunch to arise as workload exceeds the resources available given time pressures or tempo of operations
3. The pattern is a manifestation of the fundamental result that procedures are underspecified relative to the variability of the world (Suchman,1987).
4. Adaptation is required to bridge the gap or mitigate the bottleneck or crunch. Gaps are regularly anticipated, identified, and bridged and their consequences nullified by the work of operators at the sharp end of systems.
5. Bridging gaps is so intimately woven into the fabric of sharp end work that this activity becomes invisible to outsiders and helps create the gap between 'work as done' and 'work as imagined.'
6. Operators' adaptations to bridge gaps become part of 'work as done', and it can be difficult for experienced personnel to explicitly reflect on how gaps arise and are resolved.
7. Gaps change. Gaps change because organizational, technological, and environmental changes continue in all worlds. Unintended side effects of changes may generate entirely new gaps or undermine the effectiveness of established bridges, especially since the fluency of adaptations hides the presence of the gaps
8. As the complexity of systems increases, often as a result of steps that increase productivity and efficiency, the prevalence of gaps increases, the ability to see gaps decrease, the ability of local adaptations to adequately compensate for gaps decreases, and the difficulty of tackling gaps strategically increases.
9. The pace of adaptations to bridge changing gaps can lag the changes underway resulting in reactive, narrow, weak compensatory efforts (Woods, 2019).

Workload Management Patterns

The Workaround Pattern is connected to another set of patterns on workload management processes. Workload management is concerned with the potential for workload peaks or spikes to occur which threaten to overload operators. Classically, the threat of being trapped in a workload bottleneck leads to four patterns of adaptation as captured in Table 5 (Woods and Hollnagel, 2006).

Table 5. Pattern template for the four basic adaptive responses to overload.

Tactical responses	Strategic responses / anticipating potential upcoming bottlenecks
1. shed load	3. shift work in time to lower workload periods
2. do all task components but do each less thoroughly, thereby, consuming less resources	4. recruit more resources

The first two are tactical responses to emerging bottlenecks. When facing a bottleneck, one can prioritize across tasks and activities, dropping out any but the essential ones. But shedding load is a narrowing process that has vulnerabilities if the re-prioritization goes off-track. Similarly, in a bottleneck, one can take energy/time from every task, though now each task becomes more fragile. The paradox in tactical responses to workload bottlenecks is that, if there are tasks which really are lower priority, why not always drop them, or if task performance does not degrade when one cuts the normal investment of energy/time, why would one ever make the larger investment?

The third and fourth adaptive responses are strategic and depend on anticipation of potential upcoming bottleneck points. With anticipation one can recruit more resources such as extra staff, special equipment, additional expertise, or additional time. But note that this strategy consumes organizational resources that are always under some degree of pressure. The other strategic response is more directly under the control of practitioners—shift workload in time. For example, Cook et al. (2000) refer to observations of operating room teams where anesthesiology residents performed extra work during the set-up of the operating room before the patient entered, in order to avoid potential workload bottlenecks should certain contingencies arise later. When anesthesiologists needed some type of capacity to respond to acute physiological changes in a patient, they rarely had enough time or attentional resources available to carry out the tasks required to create the needed capability. Hence, expertise in anesthesiology, as in many high performance settings, consists of being able to anticipate potential bottlenecks and high tempo periods and to invest in certain tasks which prepare the practitioner to be highly responsive should the need to intervene arise.

IV. PATTERN-CENTERED INQUIRY

How to link Pattern Finding and Pattern Priming

General patterns can be illustrated or instantiated in multiple different specific situations or places. And specific situations can be seen as cases that instantiate general patterns. Put the two together as a cyclic process and the result is the process of pattern finding through pattern priming (Figure 10).

In *pattern priming,* the availability of general patterns jump start monitoring in a specific setting to recognize when instances of this pattern occur (Figure 10). In *pattern finding*, monitoring local adaptations to make the system work (WAD) in a specific setting lead to identification of more general patterns about work (Shorrock, 2020). For example, noticing specific workarounds triggers a search of the different patterns about adaptations to cope with one or another kind of bottleneck. The mapping of specific adaptations to more general findings about patterns of adaptations is an iterative process that goes back and forth between priming and finding.

Whether the process begins with patterns or begins with specific adaptations, identifying more general patterns allows for integrations of data about specific situations and behaviours.

Central to the interplay of pattern finding and priming is the key insight of Alexander's approach — the pattern is general but is expressed in many different situations & settings. The balance of the two directions guards against vague over-generalizations on the one hand and guards against getting lost in the details of a particular setting, task, and technology on the other hand. Thus a pattern is sensitive to the details of specific settings and to different contextual factors while still allowing generalization that characterizes the state of the system and can direct pragmatic action based on that assessment.

Summarizing the patterns or sub-patterns provides a different path to develop dashboards for management that contain leading signals. The goals is to develop dashboards that capture how patterns of adaptation are changing as challenges change.

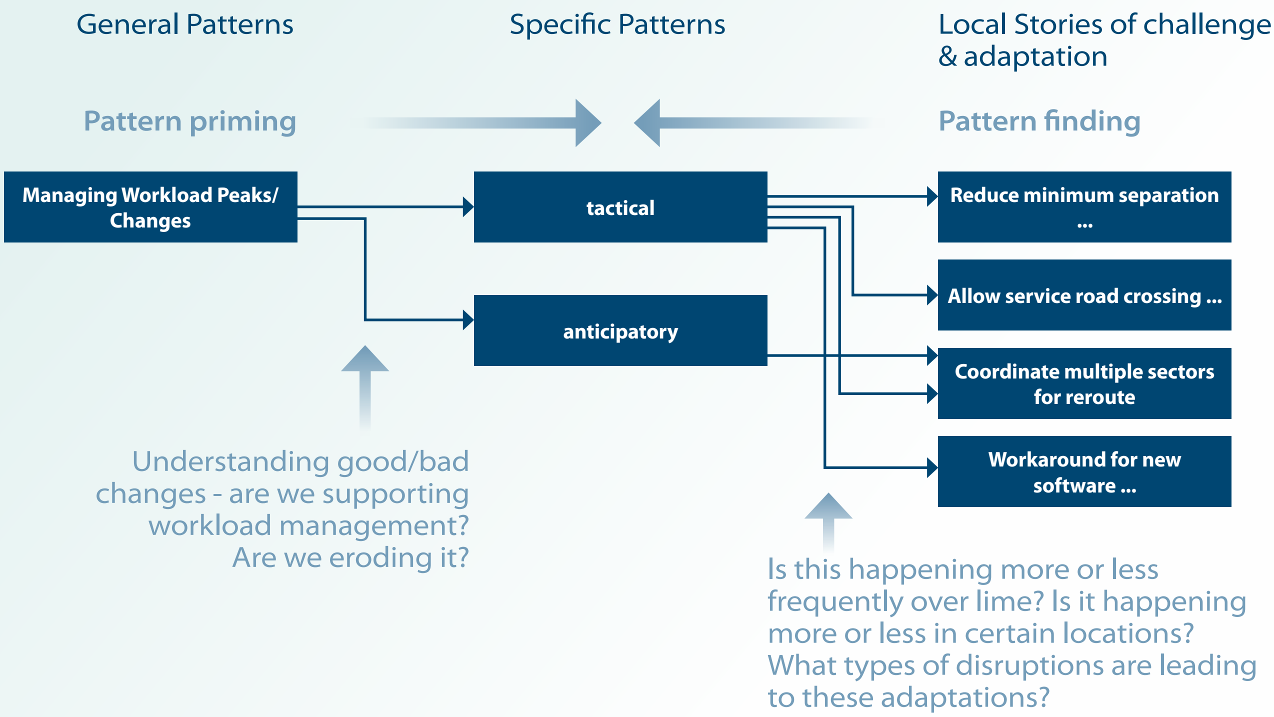

Figure 10.
Pattern-centered inquiry connects general patterns to specific contexts to help see patterns in action through pattern finding and pattern priming.

IV.1 The Value of Pattern Finding

As referenced earlier, the ability to detect and recognize patterns is crucial in monitoring and designing any joint cognitive system in any setting as change occurs. The stream of concrete situations in each specific domain of work appears infinitely variable, unique, and specialized for each work system, generation of technology, and organization. It is easy to just see the unique and particular. We also need a means to see the regularly recurring relationships and patterns underneath. An example is the longstanding approach to understanding the role of people in high performance, high risk systems — focus on uncovering the recurring patterns of how sharp-end practice adapts to cope with the complexities of work (Hollnagel and Woods, 1983; Woods and Hollnagel, 2006).

Patterns act as a form of diagnosis that captures the essence of a specific problem and points to promising directions for potential new solutions. As a form of diagnosis, pattern finding requires corroboration and may lead to revision or elaboration of the pattern. Pattern finding benefits from perspectives which can add detail or expand a pattern. The patterns about work systems are multi-level where a specific pattern serves as a sub-part in a broader level pattern and a context for lower level patterns. Patterns become guides to understanding new specific situations, yet investigators can judge for themselves how each pattern covers the situation at hand or what revisions are necessary.

When general patterns are recognized, the pattern also provides a guide for exploring practical possibilities for intervention that can be adjusted to fit current constraints that limit the range of modifications. Patterns are open-ended as they point to solution directions, yet allow participants to solve each problem for themselves by adapting the general pattern to fit the unique combination of conditions in the context at hand.

This white paper has covered and illustrated the valuable characteristics of patterns, how people think in patterns, how visual patterns are a cognitive aid, and how the processes of pattern finding has built a repertoire of patterns or generalizable findings about cognitive work in the face of complexities.

Pattern finding depends on having a set of patterns to guide observing a work setting and on mechanisms to monitor work in a particular setting regularly. Monitoring uses techniques to help see the adaptations that make systems work (Work as done) and to contrast these adaptations against different models of how work is thought to occur (Work as imagined). From this base one can start to extract the constraints, bottlenecks, conflicts, trade-offs and other factors that drive the adaptations that make systems work.

This white paper highlighted three groups of patterns on human-machine cognitive systems related to aviation. These three samples show pattern-centered inquiry already works. The patterns concern different forms of adaptation as systems improve, new anomalies appear, and new challenges arise. These general patterns show that monitoring for 'weak signals' consists of implementing a sustainable process of pattern finding/priming to keep track of cycles of change and adaptation at multiple time scales — in specific situations, regularly over a season of operations, and as a systemic response to major industry-wide changes. The patterns found become a current assessment of how a system stretches at what edges under a variety of stressors.

Air Traffic Management is a classical field where operators need to adjust their work to a constantly changing environment. Foresight, adaptations, adjustments and workarounds are necessary to get the work done. Consequently, work as described in procedures and protocols can only cover real world experiences to a certain point.

As the aviation business is not static it is not comparable with a production line following clearly defined and repeated processes. Aviation needs operators who are able to adapt and adjust when necessary, doing this they create safety and efficiency at the same time. Adjusting to changes create an environment where work as described is different than work actually performed.

The work as done versus work as imagined gap can be small or large depending on the effects of a planned change. Important for an organization is to understand this and find ways to recognize the gap. The Weak Signals project aims at providing ideas, methods and analytical tools where work as done and work as imagined can be explored.

This white paper provides the history of the pattern approach but also gives insights on how patterns emerge from the accident analysis following large events like the Columbia disaster. The data available and the wisdom of hindsight after the event makes it easier to identify underlying patterns. Learning from them and understanding patterns in normal work is harder and requires effort, motivation and financial support to develop practical methods to be deployed in the future.

The ultimate aim is to move from hindsight to foresight, identifying brittleness patterns from daily operations before before mishaps occur. Understanding work should be a daily activity with a systems thinking overview to be able to anticipate, react, monitor and learn in order to keep our organisations resilient.

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APPENDIX

This appendix offers a diverse selection of particularly interesting examples of thinking on patterns. These works cover areas including the philosophy of patterns, the utility of patterns, and pattern recognition and sense-making. While each areas of inquiry represented by these selections holds extensive bodies of literature in theory own right, only those pieces more useful in proving board coverage and background information were included.

Each example is accompanied by with a brief description of its usefulness to this particular project. The selection in the appendix includes important works not citied directly in the main report. Some, such as the works by Arnheim, already appear in the body of the report and therefore, are not included in the appendix.

Benner, and Christine Tanner (1987), Clinical Judgment: How Expert Nurses Use Intuition. The American Journal of Nursing, 87(1), 23-31.

Here the authors explore how expert nurses use intuitive judgement (understanding without explicit rationale) in their decision making and pattern recognition. It claims that intuitive judgement is what distinguishes expert human judgement from the decisions or computations that might be made by a beginner or by a machine. In regards to pattern recognition, the article claims that novices and experts differ in their capacity to recognize whole patterns - a novice might require a list of features in order to identify a pattern, whereas an expert can rely on intuitive judgement which can guide her ability to see some aspects as more important than others (sense of salience) and can help her interpret patterns in light of her expectations (and deviations from those expectations).

Gill, S. (1986). The paradox of prediction. Daedalus, 115(3), 17-48.

Gill acknowledges that explanations (reconstruction of the past) and predictions (construction of the future) are both dependent on pattern recognition, but focuses on prediction as a form of human invention. Gill then argues that the process of invention is fundamentally different in a closed system versus an open system. While a closed system contains a pre-existing pattern that must be discovered, prediction in an open system is subject to irreducible uncertainty. Gill's "paradox of prediction" is that a prediction made in an open system is simply a representation of our current understanding, and therefore influenced, shaped, and revised with the observation of new, unexpected, and contradictory patterns in a process which Gill compares to abduction.

McAllister, The Ontology of Pattern in Empirical Data (2010), Philosophy of Science, 77 (5), 804-814.

This article offers a very straightforward proof for finding real patterns and what to do with them. It starts by contending that philosophers typically decompose empirical data sets into that which they can explain (patterns) and that which they cannot (which they ignore).

1. In empirical data, no criteria exists to definitively demarcate distinct patterns that are physically significant and those that are not. Physically significant means that the pattern in the empirical data corresponds to as structure in the real world. The fact that a structure already does/not exist in the world is not admissible criteria to demarcate physically in/significant patterns. We cannot arbitrarily assign error tolerances of pattern existence in the data, as that would be imposing our own biases on this effort.
2. All patterns should be physically significant; what meaning does a pattern have if it doesn't withstand real world criticism
3. Distinct patterns, once denoted, must be regarded as providing evidence for distinct structures in the world.
4. "The world" as we know it must include all possible (i.e. demarcated, denoted, identified) structures (and by extension, all possible patterns); having withstood the rigor of this proof, we cannot exclude said patterns or structures from our worldview; it is our worldview that must change to include patterns newly elucidated (and thus the structures newly illuminated).

Projectability: pattern detected in one dataset is found later to be reproduced in another.

Consilience: patterns exhibited in datasets of different kinds provide evidence of the same structure in the world. Consilience emerges among datasets; it is not a property of a pattern nor can it be used as evidence that a pattern is physically significant.

In one way, this is a rigorous argument underpinning why a significant p-value means nothing if the hypothesis doesn't hold water* in the real world.

Bod, R. (2018). Modelling in the Humanities: Linking Patterns to Principles. Historical Social Research / Historische Sozialforschung. Supplement, (31), 78-95.

Focuses on commonalities between modeling in the sciences and humanities, differentiating between patterns as empirical and principles to theoretical. Traces how patterns and principles connect to form models throughout major historical periods in the way the humanities and sciences are modeled, with a focus on an epistemological approach to modeling humanities.

Puccetti, R. (1974). Pattern recognition in computers and the human brain: With special application to chess playing machines. The British Journal for the Philosophy of Science, 25(2), 137-154.

Puccetti argues that: feature-analysis is not recognition but identification; computers only operate on analytic principles, and thus are only suited for identification / fundamentally ill-suited for recognition; computers can only work with what we give them as decoding procedures, and we can only give them information-processing strategies modelled on the human brain's quite inadequate ones. However: it doesn't matter what you call it if the outcome is that the machine identifies as fast as humans recognize.

Background: this article is primarily relating to visual perception of patterns. Two opposing approaches to computer simulation (I think they mean modeling): 1) clarity about the nature of human [pattern recognition] behavior is required for successful simulation (Sayre 1965), 2) trying to program a machine will improve our understanding of the concept of human pattern recognition (Gunderson, 1971). Two main theoretical approaches to pattern recognition: 1) template-matching, wherein a new figure is identified by noting its coincidence, or congruence, with a basic model, as long as the match is reasonably good and better than any other (Neisser, 1967), 2) feature-analysis, wherein any pattern can be recognized simply by including enough feature analyzers in various weighted combinations (Neisser, 1967). Computer simulations involve passive perception of form, while organisms actively perceive form. Computer pattern recognition is limited at best because humans cannot totally comprehend their actions, let alone explain it in words [to program a computer]. We have no clear indication that the situation will ever significantly improve. (Bellman, 1968). Puccetti has two additional sections on modes of perception in the left and right cerebral hemispheres, and on chess playing machines.

Krausser, P. (1976). Kant's Schematism of the categories and the problem of pattern recognition. Synthese 33, 175–192.

Krausser argues that: Emmanual Kant's description of "schemata" is recognizable as a pattern recognition problem. His overarching theory is as follows: All concepts are essentially RULES of the productive and reproductive synthetic processing of "given" sensible manifolds -- major layers: empirical concepts, pure geometrical concepts, pure concepts of understanding

- Productive = new encounter
- Reproductive = from memory
- "Given" = things not originally produced in ones mind
- idealism (metaphysical philosophy) and Rationalism

Kant was right in recognizing that he (and we) did not understand how human brains recognize these concepts. His solutions to the problem are vastly insufficient. Cites "homogeneity" of a concept as a weak point in theory because it leads to indefensible point that a schema of a category must be homogeneous on one side with the category and on the other with the appearance.

Krausser thinks this unreasonable because he agrees with critical arguments made by Kemp Smith and R.P. Wolff (Rationalists). Despite this we can learn valuable lessons from studying one of his Schemata formulations Any free moving organism to be able to orient itself in its environment and regulate out or compensate by external activity and/or internal adaptation disturbances coming from that environment must be able to establish and to learn to make use of stable (reliable) correlations between: Every schema for every category (not only causality) must refer in some special way to the task of establishing correlations of appearances (and their changes) with certain kinds (and changes) of spontaneously emitted activities of the perceiver.

Connecting to machine pattern recognition: 1.) Existing programs do not seem to be very good at pattern recognition 2.) Suggests that our research for developing them may be fundamentally handicapped because computers using the programs do not satisfy the principle implied in Kant's schema of causality: They are neither free moving nor actively manipulating their environments so as to produce their own stimuli to which they can react (and learn).

Swan, L. (2013). Deep Naturalism: Patterns in Art and Mind. The Journal of Mind and Behavior, 34(2), 105-120.

This paper is about the metaphysical basis of the aesthetic experience from a theory of mind perspective. It claims that pattern recognition is an integral part of the way we appreciate art. A speculative hypothesis that art can appeal to our evolved pattern recognition capabilities, and that aesthetic experience in part can be attributed to this deeply ingrained evolutionary path.

Knight, T. (1998). Infinite patterns and their symmetries. Leonardo, 31(4), 305-312.

Knight works from the definition that patterns, in the geometrical sense, are defined by a motif and a transformation, where the motif is transformed by rotation or translation in a finite or infinite sequence. Knight then uses frieze patterns of simple repeating two-dimensional shapes to discuss how some specific transformations of motifs can create emergent symmetry or even emergent motifs. Knight concludes that the presence of an emergent symmetry with a perceived emergent motif different from the underlying motif transformation is dependent on whether or not the motif is continuous and whether or not copies of the motif are connected.

Whitehand, D. (2009). Patterns that connect. Leonardo, 42(1), 10-15.

Whitehand, an artist, reviews the history of different theories that contribute to the creation of art. She suggests that throughout history and amongst different cultures, artists have used similar neither random nor predictable patterns to those scientists use in their laboratories and researchers study to understand non-linear dynamic systems. Patterns can be found anywhere in the world, from processes to systems to organisms. Ultimately, she concludes that the find and use of similarities and patterns between art and science can be a useful approach to either of the disciplines.

Washburn, D., & Humphrey, D. (2001). Symmetries in the mind: Production, perception, and preference for seven one-dimensional patterns. Visual Arts Research, 27(2), 57-68.

Washburn and Humphrey conducted a mixed-methods study of how art students and non-art students produced, preferred, and perceived different symmetry combinations of seven one-dimensional band patterns. Their findings support that mirror reflection is a more salient symmetry than other patterns across art and non-art groups, and that there are differences in the patterns of symmetry produced and preferred by art students and non-art students. The authors suggest that much more research needs to be done to understand how the art and non-art cultures impact their production of and preference for different symmetries.

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ACKNOWLEDGEMENTS

The authors would like to thank all the members of Weak Signals II project for their valuable input in the realisation of this White Paper.

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