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Building and revising adaptive capacity sharing for technical incident response: A case of resilience engineering

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ABSTRACT

We report an organization's method for recruiting additional, specialized human resources during anomaly handling. The method has been tailored to encourage sharing adaptive capacity across organizational units. As predicted by Woods' theory, this case shows that sharing adaptive capacity allows graceful extensibility that is particularly useful when a system is challenged by frequent but unpredictably severe events.

We propose that (1) the ability to borrow adaptive capacity from other units is a hallmark of resilient systems and (2) the deliberate adjustment adaptive capacity sharing is a feature of some forms of resilience engineering. Some features of this domain that may lead to discovery of resilience and promote resilience engineering in other settings, notably hospital emergency rooms.

1. Introduction

Despite more than a decade of discussion (Hollnagel et al., 2006) there remain few examples of resilience engineering in the published literature. This is perhaps to be expected when the term *resilience* has such varied use (see Table 1).

What is resilience *engineering*? What does a resilience engineer do? Are there principles of resilience engineering? If so, what are they? What makes it possible to engineer resilience? At present none of these questions have satisfactory answers, in part because of the paucity of examples of resilience engineering.

This paper offers a resilience engineering case report. The case is drawn from internet-facing business system operations (see Table 2). The case shows how engineers developed and refined a method for dealing with challenging events and, in the process, engineered the resilience of that system. The deliberate, iterative, empirically grounded production of a system with desired properties we take to be *engineering* (Petroski, 1982; Vincenti, 1990) and, because the goal of the activity was to share the organization's adaptive capacity, we regard this case as an example of *resilience* engineering. We rely on Woods' theory of graceful extensibility (Woods, 2018) along with the notion of sustained adaptive capacity (Woods, 2015) for resilience itself.

The increasingly high-stakes work of maintaining the health of internet-facing business systems poses a significant challenge. Disturbances in these systems are common and costly (see Table 2). Methods for detecting, mitigating, restoring, and repairing these systems rely on people with highly technical skills. Because challenge events may occur without warning and at any time, high availability entails continuous surveillance for new events and fast response when an anomaly appears. Although many anomalies that require attention are mundane, a new event may represent an entirely new phenomenon or a novel combination of phenomena. Although many anomalies have mild impact, even those that initially appear benign can escalate to cause severe damage or become existential threats for the firm (Woods, 2017; Cook, 2019).

This industry has grown enormously over the past two decades. E-commerce sales in the United States grew twenty fold between 2000 and 2019 (U.S. Dept. of Commerce, 2003; U.S. Census Bureau, 2020); the estimated value of the whole U.S. "digital economy" was US$ 1.35 trillion in 2017 (U.S. Bureau of Economic Analysis, 2020). Worldwide data flow grew from 0.1 terabytes per second (TB/s) in 2002 to 45 TB/s in 2017 and is expected to reach 150 TB/s by 2022 (United Nations, 2019). This growth has driven an efflorescence of invention and exploration as the organizations involved struggle to cope with new demands and seize new opportunities amidst increasing complexity.

Incidents pose substantial difficulties that are the subject of this paper. In particular, the frequent but irregular drumbeat of operational incidents stresses the organization's capacity to adapt. Over the past few

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Table 1
Four senses of resilience (from Woods, 2015).

	term	Describes how a system …
1	*rebound*	"… rebounds from disrupting or traumatic events and returns to previous or normal activities"
2	*robustness*	"… is able to manage increasing complexity, stressors, and challenge"
3	*graceful extensibility*	"… extends performance, or brings extra adaptive capacity to bear, when surprise events challenge its boundaries"
4	*sustained adaptability*	… is able "to adapt to future surprises as conditions continue to evolve"

Table 2
Examples of on-line systems anomalies.

Area	Example
Airline systems	*"British Airways computer glitch causes big delays at multiple airports."* September 6, 2016 Mullen J (2016). CNN Business, https://money.cnn.com/2016/09/05/news/companies/british-airways-computer-system-delays/, accessed July 2, 2020.
Stock exchanges	"*NYSE shut down for nearly 4 h by technical glitch*", July 7, 2015 McCrank J (2015). Reuters, https://www.reuters.com/article/us-nyse-trading-idUSKCN0PI25A20150709, accessed July 2, 2020
Hospitals	*"Software issue fixed, UK HealthCare no longer diverting patients"* September 23, 2019 WKYT News Staff (2019). WKYT, https://www.wkyt.com/content/news/UK-HealthCare-diverting-patients-to-other-hospitals-citing-computer-issues-561140481.html, accessed July 2, 2020.
"Cloud" computing	*"Multifactor authentication issue hitting North American Azure, Office 365 users"*, October 18, 2019. Foley MJ (2019).. ZDNet, https://www.zdnet.com/article/multifactor-authentication-issue-hitting-north-american-azure-office-365-users/, accessed July 2, 2020.
Entertainment	*"Hulu's World Series Stream Crashed in the Middle of Game 4"*, October 29, 2017. Robert JJ (2017). Fortune, https://fortune.com/2017/10/29/world-series-hulu-crash-problems/accessed July 2, 2020.
Retail	*"Target says cash registers back online and customers can make purchases again after systems outage"*, June 15, 2019. Connley C, Kimball S (2019). CNBC, https://www.cnbc.com/2019/06/15/targets-in-store-payment-is-system-down-impacting-stores-nationwide.html accessed July 2, 2020

years we have had the opportunity to follow a variety of incidents and to observe how the organizations have adapted to their changing character and chosen to use the always limited resources available to them. Together the incidents and the organizational response constitute a case of what we believe is resilience engineering.

2. The case

For the past few years an academic-industrial collaboration has focused on exploring disruptive events in internet-facing operating environments. Participating firms share experience and insights about recent incidents in a framework that encourages hypothesis generation and investigation using a variety of methods and approaches. The opportunity to examine, compare, and contrast events and responses is intended to allow individuals in organizations to reflect on and improve practice (Woods, 2017).

The consortium members come from different business sectors and vary in size, organization, and computing technology. They have in common the need to develop, maintain, operate, and repair large, complex technological assemblies. All the members have to cope with a continuous stream of disruptive events that range in consequence from minor annoyances to substantial threats.

Each consortium member routinely reviews and assesses its response to significant events. The purpose of this practice is to understand the event's sources, the way the event was handled, and to identify technological or organizational changes that could reduce the likelihood of future events or improve the quality of future event response.

A site visit with one consortium member prompted discussion of a recent salvo of significant events. The salvo had taxed the organization's capacity to respond, leading to near exhaustion of the responders. The discussion revealed that the organization had adapted its response approach over the prior year, partly in response to a prior event salvo.

Within the company, normal work is done by small teams. Teams maintain an on-call rotation and are responsible for handling events that affect their assigned components. While this approach produces efficient response to many anomalies the event salvo contained events that were difficult to troubleshoot. In response, a group established a support cadre to assist in response to high severity or difficult to resolve events. This group would provide a deep technical resource that could be called on to support incident response.

The support group was composed of eight engineers and engineer managers from the different technical units. The group organized an on-call rotation to provide a reserve of engineering and operational expertise. One member of that group would participate in incident response when specific thresholds (e.g. consequences for customers, incident duration) were reached. This approach was taken without altering the workload of the support group members' teams.

The support group met weekly to review recent experience and adjust the approach. It was clear early on that the approach was useful in several ways. It allowed some incidents to be terminated more easily. It relieved some of the stress that came with managing high consequence incidents. It also eliminated the "fire alarm" effect. Previously a serious incident could easily capture the attention and efforts of many senior engineers, disrupting work across many teams. The new approach allowed these people to pay less attention to the stream of incidents knowing that one of the group was on-call and would engage if needed.

The approach was modified substantially over the next year. For example, incident first responders sometimes did not call for support during long-lasting or severe incidents. Some were caught up in problem solving; others overconfident in their ability to resolve the incident without help. A support group member wrote software that tracked incidents in progress and sent a message to the on-call expert under certain conditions (eg. duration, registered severity). This offloaded the request-for-help burden for first responders and, in some cases allowed the support experts to learn about incidents independently.

The success of the support function became a burden for the group members and a few left the group. The company needed a pipeline to replenish the group. The group began to recruit new members, offered training, and established an apprenticeship program. Recognizing that this resource had become an important part of incident response, the organization sought to raise the status of the role, provide financial incentives, and make inclusion in the group an explicit part of career advancement. The company imposed a requirement that group members be exempted from their home teams' on-call rotations. Similarly, term limits were established for incident response group members so that turnover in the expert group would better distribute the additional work.

3. Observations

3.1. Adaptations in context

Responding to challenge events is an intrinsic requirement of internet-facing business operations. All firms have individuals and groups assigned to detect, identify, characterize, and remedy events in real time. These activities are tightly integrated in the technical and organizational structures of the firm. Because all the consortium members are "open for business" continuously, the responsibility for initial event recognition and handling usually rotates among individuals or crews. The large majority of operational anomalies are routine and their immediate consequences are handled by the front line person or persons. The distributed nature of modern software systems makes them relatively robust to many faults. This has the paradoxical effect of making impactful events more difficult to diagnose and repair.

A result is that the next incident is likely to be easily dealt with but may be challenging or even pose an existential threat. Being able to modulate the response to match the need is important. 'Ordinary' events can be handled by the regular responders but the response to larger events benefits from additional expertise. To respond effectively *and efficiently* to the variable, unpredictable challenge pattern requires the capacity to adapt.

3.2. Characteristics of the incidents

The example suggests that sharing adaptive capacity depends on specific characteristics of the environment. Among these are the tempo, duration and magnitude of challenges from the environment.

Tempo: There is probably a narrow range of incident tempo that makes this sort of support approach viable. Here the rate is a dozen events per week. If the rate were very low it would be difficult to accumulate experience and refine the processes around sharing. In contrast, if the rate were very high, incessant demand for expertise would exhaust the available supply and, perhaps, create pathologies (e.g. hoarding expertise, substitution of low quality for high quality expertise).

Duration: Incidents need to last long enough for the sharing process to take effect but not so long that the sharing leads to damage for the donor team. Incidents in this environment are typically minutes to hours long; exceptionally few last for more than a day.

Magnitude: There is enough variation in severity across incidents such that sharing remains a feasible approach. If all incidents were minor there would be no advantage to sharing resources. Having only major incidents would encourage provision of highly capable units. The variability of incident intensity makes sharing expertise useful.

3.3. The organization and distribution of expertise

Mobilizing and applying the adaptive capacity in this example depends on the nature of local expertise and the ability to bring that expertise to bear without significant delay. Sharing expertise is possible because relevant expertise is distributed across the work teams. The individual experts have similar general skills and knowledge and also sufficient experience with the local environment that each can be expected to make a significant contribution to most incidents. If the individuals were markedly different in their abilities the broad sharing program would not work. Thus the group has to have some requisite homogeneity.

The situations where sharing capacity is useful must also be familiar enough to the group members that each is able to "get up to speed" quickly enough to make that individual's contribution useful. The example suggests that familiarity with local conditions will make sharing efficient. Sharing is efficacious because the individuals are in more or less constant contact with the problem space, are up to date with the state of the system, and are well suited to engagements with the other people working on the problem. It is likely that smooth sharing of adaptive capacity will be more difficult for people who lack local knowledge and possess only general expertise.

Given the unpredictable timing of challenges, the expertise resource should also be available for mobilization. The work tasks of the group members in the example case are relatively interruptible so that a sudden demand for sharing can be met. If their tasks were very difficult to interrupt it would be practically impossible to share their expertise. Consider, for example, the situation in a hospital with several operating rooms. If all the surgeons are in the midst of procedures sharing expertise will be difficult. In contrast, in the same hospital the internal medicine staff might well be able to interrupt tasks.

Communications plays a role in requesting and supplying support. Many internet-facing business operations are physically dispersed – in this case, around the world – but tightly connected by communications links that provide, among other things, opportunities for shared views of system processes and states. This technological framework allows those engaged in coping with an incident to call for and provide help and coordinate complex efforts. It also suggests that resilience itself is highly dependent on communications.

3.4. Continued engineering to sustain adaptive capacity

In this example it quickly became apparent that simply sharing existing adaptive capacity would consume it and that sustaining the ability to share adaptive capacity requires resources and attention. The individuals and their expertise need to be replenished. Indeed the cadre of experts from which the group was drawn is itself continually changing. Given the rapid pace of change in this domain what constitutes useful expertise will continue to evolve. Whether the approach is durable is very much an open question.

These features suggest that successful resilience engineering may – at least at present – depend on identifying and exploiting situations and resources that are already well configured (Table 3).

4. Discussion

Woods' theory of graceful extensibility predicts that resilience will appear as individual "units of adaptive behavior" exhaust their own adaptive capacity and obtain additional capacity from other units in their network. Resilience is not fortitude but the moment-by-moment sharing of adaptive capacity within a network of units of adaptive behavior. Fig. 1 shows this schematically.

The example demonstrates graceful extensibility. The unit here is a team of people that, from time to time, is required to cope with an incident. When an incident threatens to exhaust that group's capacity it can obtain support from those in surrounding units.

Graceful extension of the group's capacity to respond is an *expression* of resilience (Eksted and Cook, 2015). What makes the example a case of resilience *engineering* is the deliberate, iterative, and empirically based creation and modification of a method to make that makes the expression of resilience – the sharing of adaptive capacity (Woods, 2018) – efficient, effective, and – most of all – sustainable.

The resilience engineering described in the example is the deliberate adjustment of adaptive capacity sharing. The organization engineered a way for sharing to take place. This was originally driven by an economic concern – the need to keep the operational cost of managing incidents in check. Over time, the engineering has refined the sharing to make it

Table 3
Conditions likely to promote resilience engineering.

Characteristic	Conditions conducive to resilience engineering
Tempo and magnitude of challenges	• The rate of challenge is high enough to allow accumulation of empirical evidence about the effects of engineered change. • The challenges include enough of these events to reinforce the value of resource sharing.
Duration and character of challenges	• Challenges arise and evolve slowly enough that there is time for shared adaptive capacity to be brought to bear. • Challenges resolve quickly enough that capacity sharing is temporary.
Local resources	• Resources to be shared are close enough to be useful in responding to the challenge. • Resources to be shared have or can easily obtain the situational context needed to be effective.
Communication between units	The communications across units are conducive to sharing resources.
Interruptible task milieu	Resources to be shared can undergo task interruption without unacceptable loss.

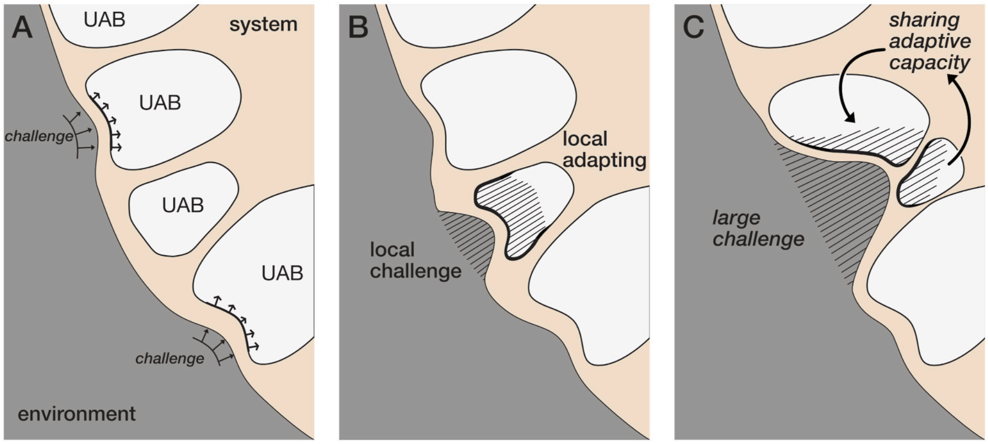

Fig. 1. Schematic of resilience as sharing of adaptive capacity

better and more efficient. The engineering also set up the conditions needed to replace and grow the adaptive capacity.

We hypothesize that this approach is successful because of the domain of practice and the stream of incidents make resilience engineering productive. In particular, the incident characteristics, tempo and variability make *ad hoc* sharing useful. If the incidents were monotonous with a fixed frequency and constant severity there would few challenges to the adaptive capacity of the response unit and no need for acquiring adaptive capacity from a neighboring unit. If all the units possessing useful expertise were engaged in uninterruptible tasks, no sharing would be possible. If the incidents themselves required long term commitments of resources sharing would damage the capacity of the contributing unit. The willingness of a unit to forego the services of so valuable an expert depends to a degree on the assurance of future reciprocal sharing.

This hypothesis seems testable. Situations where these conditions are present are likely to reward resilience engineering efforts. There are at least two situations where similar conditions obtain: intra-hospital rapid response teams (RRTs) and rural firefighting. The published experience with RRTs (Lighthall et al., 2017) can be interpreted as supporting the hypothesis and the factors noted in Table 3 may explain some of the variations in results there. The unique problems of rural firefighting (Verzoni, 2017) suggest that it is a naturally occurring laboratory for further resilience engineering study.

In contrast, situations with dissimilar conditions may prove resistant. Ironically these may be settings that have received comparatively more attention, e.g. air traffic control. Although resilience may be valuable across a wide variety of situations, resilience *engineering* is likely to be discovered where the conditions are conducive to that work.

5. Conclusion

There are likely to be a set of domain features and organizational conditions that are conducive to resilience engineering. The present paper describes some candidate features and conditions that have been observed in a specific case of resilience engineering. The analysis suggests that resilience engineering is underway in this setting and, by extension, in other settings with similar conditions. Because our understanding of resilience and of resilience engineering is admittedly at an early stage, efforts to discover opportunities for applications of resilience engineering are likely to bear fruit where the configurations are conducive to that effort.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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