Creating Safety by Engineering Resilience

or

On Being Resilient in the Age of Complexity

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Walls of Complexity
Complex Adaptive Systems / Resilience Engineering

- new sciences (measures, models, findings) on how adaptive system work and breakdown

- new techniques to
  ~ enhance resilience in face of potential surprise
  ~ monitor for increasingly brittle systems
  ~ assess how change expands or constricts adaptive capacities

Progress in Adaptive System Sciences
NASA failure history captures cumulative complexity circa 2000

Creating Safety Under Pressure

NASA in a changing environment under performance demands and resource pressures:

• Drive down the cost of launch
• Shorter, aggressive mission schedules
• New partners and relationships
• New roles
• Skill erosion
• Heightened public interest

“Risk, therefore, becomes the “fourth dimension” of project management—treated equally as important as cost and schedule.”
NASA failure history captures cumulative complexity circa 2000

Design for Safety
The Challenge

- Safety is a System Property
  - Components, subsystems, software, interactions, organizations, human behavior
  - Continuous throughout the entire life-cycle
- Traditional Methods do not address complex system issues
  - System de-coupled => only components and subsystems addressed
  - Static, rule-based, deterministic process
  - Risk not explicit in trade space: entirely external to the main processes
  - Knowledge resides in people
- Today’s Challenge
  - Increased mission complexity to meet ambitious goals
  - Increased resource constraints
  - Increased expectations: the safety bar raises every year

C/S/E/L :2010 Fundamental Tradeoffs

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NASA failure history captures creeping complexity

1999: 3 space exploration failures

Report on Project Management in NASA

by the Mars Climate Orbiter Mishap Investigation Board

March 13, 2000

increasingly brittle systems under faster, better, cheaper (FBC) pressure

2003: Run up to Columbia accident

C/S/E/L :2010 Fundamental Tradeoffs
The Law of Stretched Systems: every system is continuously stretched to operate at its capacity. People as problem holders exploit ‘improvements’ to better achieve goals by pushing the system out to operate near the edge of its new capacity boundaries. The process of adapting to exploit the improvement results in a new intensity, complexity, and tempo of activity.

Patterns of Reverberations

Much of the equipment deployed ... was designed to ease the burden on the operator, reduce fatigue, and simplify the tasks involved in operations. Instead, these advances were used to demand more from the operator. Almost without exception, technology did not meet the goal of unencumbering the personnel operating the equipment

... systems often required exceptional human expertise, commitment, and endurance.

... there is a natural synergy between tactics, technology, and human factors ... effective leaders will exploit every new advance to the limit. As a result, virtually every advance in ergonomics was exploited to ask personnel to do more, do it faster and do it in more complex ways.

... one very real lesson is that new tactics and technology simply result in altering the pattern of human stress to achieve a new intensity and tempo of operations.
Sample 1: Resilience

Shortly before surgery, an attending anaesthesiologist comes to understand that the surgical plan expects a relatively short procedure with little blood loss. However, the attending recognizes that given this patient’s other problems, it will be difficult to establish access quickly if significant fluid replacement is needed to manage cardiovascular physiology. Furthermore, the anaesthesiologist recognizes that, while the surgical plan represents a typical surgical course, in this context the procedure could go much longer and blood loss could be much greater than expected. As a result, the attending instructs the resident to place more lines than normal when the patient is being prepped for surgery. This will allow the attending to respond quickly with fluid replacement should any challenges to cardiovascular physiology occur during surgery.
Sample 2: Resilience

Anaesthesiology has become much safer over the last 15 years. In addition, there have been changes in medical practice that allow for/encourage surgeries to occur in outpatient settings (e.g., cosmetic surgery). As a result, anaesthesia practice has migrated away from the traditional operating room setting where there are a variety of technological and human resources that can be called on should a crisis occur. The safety manager for the health care network recognizes that moving more anaesthesia practice to outpatient settings increases brittleness, that is, should an unexpected event trigger a crisis, less expertise, experience, and equipment is available to manage the situation. The safety manager initiates a new crisis management training program for outpatient surgery teams that allows personnel to practice how to respond to a crisis including how to find and bring additional expert resources into the different locations where a crisis could occur.
easy to see a person or a piece of technology
easy to see components, rules
easy to see things

hard to see expertise

harder to see interactions, coordination, synchronization

harder yet to see adaptation, complexity, brittleness, resilience

easy to mistakenly—
  juxtapose people versus machines,
  see erratic human behavior,
  regulate components
when the *dynamics of complex adaptive systems* are the underlying drivers
Fundamentals of complex adaptive systems drive systems

Tradeoffs
• optimality - brittleness tradeoff (Doyle)
  ~ acute-chronic
  ~ specialist-generalist
  ~ efficiency-thoroughness (Hollnagel)

Patterns in being Maladaptive

Anticipation of shortfalls - regulate Margin of Maneuver

Fitness Spaces and graceful degradation

Agent based Modeling

Polycentric or Resilient Control Architectures
First Principles:

• distinguish *first* and *second* order adaptive capacity
  ~ potential for action in the future when conditions change or
  new events challenge old models, ...

• optimality - brittleness and other tradeoffs are
  unavoidable (Doyle)
  ~ Even if the world were perfect, it wouldn’t be. Yogi Berra
  ~ Anomalies are what happens when something else was planned;
    whatever the plan, something else always happens.
  ~ Adaptive behavior consumes success.

• cross-level interactions
  ~ polycentric

• multiple perspectives
  ~ reflective
  ~ calibration
Patterns of Adaptive Breakdown - Mal-Adapted

Complexities in time --> **Decompensation**: exhausting capacity to adapt as disturbances/challenges cascade. Breakdown occurs when challenges grow and cascade faster than responses can be decided on and deployed to effect.

Complexities over scales --> **Working at cross-purposes**: behavior that is locally adaptive, but globally maladaptive inability to coordinate different groups at different echelons as goals conflict.
  - Fragmentation (stuck in silos)
  - Missing side effects of change (temporal)

Complexities in learning --> **Getting stuck** in outdated behaviors: the world changes but the system remains stuck in what were previously adaptive strategies.
  - Oversimplifications
  - Fixation

*C/S/E/L* :2010
Urban Firefighting

- distributed roles
- multiple echelons
- disrupting factors
- multiple goals
- interdependencies
Maladaptive Patterns and Critical Incidents in Urban Firefighting (Branlat et al., 2009)

Decompensation

• If request resources when need is definitive, it is already too late
• Regulate additional adaptive capacity (tactical reserves)
  ~ maintain margins of maneuver (ability to handle next surprise)
  ~ “avoid all hands situations” (incident command)
• Bumpy transfers of control

Working at cross-purposes (both horizontal and vertical)

• Actions of one group increase threats to other groups (opposing fire hoses; rendering escape routes or protected areas unaccessible)
• Failure to resynchronize
• Goal priorities/conflicts in response to distressed firefighter
• Tradeoff between information sharing versus data bottlenecks

Getting stuck in outdated behaviors

• Failures to modify plan in progress as situation changes
1. Decompensation breakdown occurs when challenges grow and cascade faster than responses can be decided on and deployed to effect.

- Starling curve cardiology
- Cardiovascular anesthesiology (Cook)
- Asymmetric lift, aviation automation, bumpy transfer of control (Sarter & Woods)
- ‘Surge’ capacity in ER (Wears)
- ICU bed crunches (Cook)
- Tempo of operations

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Box 1 Example of a case of “going solid”

**Setting**
A large tertiary care facility in a major metropolitan area in the United States.

**Event**
Near the end of a routine scheduled surgical procedure on patient A, the circulating nurse called the recovery room in anticipation of bringing the patient to it. The recovery room placed the transfer from the operating room “on hold” because all the recovery room locations were filled by patients. Among these was patient B who should have been transferred from the operating room directly to an intensive care unit (ICU) bed. Patient B was in the recovery room because there was no ICU bed available. Investigation of the circumstances revealed that the ICU bed was occupied by patient C whose condition would allow transfer to the regular ward but the regular ward bed was occupied by patient D who was ready for discharge but was awaiting arrival of a family member to transport him to his home. Bed occupancy within the hospital had been at saturation for both ICU and regular ward beds for several weeks.

The high occupancy situation was managed by nurses and administrators by pairing new postoperative admissions with anticipated patient discharges, matching expected discharge and expected end of surgery times. Senior hospital management became involved in moment to moment decision making about bed allocation, surgical procedures starts, and intra-hospital patient transfers. Managers also sought increased efficiency of resource use, mainly through direct inquiries about patient status. A new administrative nursing position was established to centralize and rationalize bed resources. The system remained solid for approximately 5 weeks.
Patterns of Adaptive Breakdown

new disturbances arise
the system’s capacity to compensate is exhausted

Target

Disturbance

Control

compensation
decompensation

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A. Adaptive capacity exists before disrupting events call upon that capacity (it is a potential for future adaptive action)

B. One assesses (observes/models/measures) adaptive capacity through its exercise in the anticipation and reaction to past disruptions.

(A) means that the resources that support the potential, prior to visible disrupting events, may not be seen at all since they are not used; or if seen, they will be seen as excess capacity since it is not in use.

Under FBC pressures, systems tend to move back to the edge of their performance envelopes (law of stretched systems)

Monitor/Regulate Margin for Maneuver
Emergency Medicine

Figure 1. Schematic layout of the two units involved in these events.

Patterns of Adaptive Breakdown

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Characteristics of Resilient Control

1. Resilient systems are able to recognize the signs that adaptive capacity is falling or inadequate to the contingencies and squeezes or bottlenecks ahead.

2. Resilient systems are able to recognize the threat of exhausting buffers or reserves.
   
   Active version: resilient systems are able to assess how **margins of maneuver** are expanding or contracting relative to the potential for surprise.

3. Resilient systems are able to recognize when to shift priorities across goal tradeoffs.

4. Resilient systems are able to make perspective shifts and contrast diverse perspectives that go beyond their nominal system position.

5. Resilient systems are able to navigate interdependencies across roles, activities, levels.

6. Resilient systems are able to recognize the need to learn new ways to adapt.

C/S/E/L :2010 Resilient Control Architectures

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Complex Adaptive Systems: how change triggers adaptations across three levels

- Expanding Adaptive Capacities
  (*emergent system perspective*)
  
  Synchronizing Activities over Wider Scopes and Ranges
  (*distributed work perspective*)
  
  Growing Expertise in a Role
  (*learning and experience perspective*)
Changes in progress:
- Surgery
  - laparoscopic
  - 3-D
  - work hours
  - handoffs
  - robots
  - HIT (EMRs, ...)
  ...
“Systems”

Running into Walls of Complexity:
cumulative, creeping, inadvertent, due partly to successes
~ increasingly brittle systems
~ surprising failures

Fundamentals of Complex Adaptive Systems
~ new tools to model and measure the adaptive capacity of human systems

Resilience Engineering
~ provides ways to enhance resilience in face of surprise
~ predict how change expands or constricts adaptive capacities
~ Resilient or Polycentric Control Architectures for managing interdependencies at scale
Voir clairement qu’il était nécessaire de périr pour ne pas périr; et de s’exposer à des dangers de toutes sortes, afin d’éviter tous les dangers.

Jesuit Relations (1656-57)

- Optimality-Resilience
  Gaps in Fitness/Bounded Ecology

- Efficiency-Thoroughness
  Gaps in Plans/Bounded Rationality

- Acute-Chronic
  Gaps in Perspectives/Bounded Perspicuity

- Specialist-Generalist
  Gaps across Roles/Bounded Responsibility

- Distributed-Concentrated
  Gaps in Progress/Bounded Effectivity
Simultaneously, all human adaptive systems are

- **well-adapted**
  - fluency law: Well-adapted activity occurs with a facility that belies the difficulty of the demands resolved and the dilemmas balanced

- **mal-adapted**
  - tradeoffs
  - reflective
  - calibration

- **under-adapted**
  - pressures from stakeholders
    - (e.g. Faster, Better, Cheaper pressure)
  - law of stretched systems

*Struggle for fitness* is ongoing

In adaptive systems, yesterday’s solutions produce today’s surprises that become tomorrow’s challenges.