

Concepts and Models of Safety, Resilience, and Reliability

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Abstract	<p>Approaches to safety have often considered the “human” factor in an organisation or operation as a major contributor to unwanted outcomes. The view of “human” as a problem leads to responses that involve trying to exert more control over people. While these may make intuitive sense for some, research suggests that such a view may not be valid as there are an enormous number of other factors (many of which are beyond control of the human at the sharp end) that are behind the creation of success and the occasional failures. This chapter begins with a review of normal accident theory, before using complexity science to fill out the problematic nature of the notion of “human error”. It then discusses one of the prominent problems associated with complexity, safety drift. Lastly, this chapter looks at various proposed solutions (e.g. resilience engineering) by which a healthcare system can manage complexity and perhaps reduce the potential harm to patients.</p>	

Keywords (separated
by “ - ”)

Normal accident theory - Complexity - Drift - Resilience - High reliability -
Safety

Concepts and Models of Safety, Resilience, and Reliability

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3

Jonathan Gao and Sidney Dekker

"This place would be a lot safer if I could just get rid of the nurses who make mistakes"

—Nurse Manager

4 Introduction

5 Approaches to safety have often considered the
6 "human" factor in an organisation or operation as
7 a major contributor to unwanted outcomes. Most
8 responses to this "problem" involve trying to
9 exert more control over people [1]. This can hap-
10 pen through the generation of policies, guidelines,
11 and prescriptions, and of course the enforcement
12 of procedures. While these may make intuitive
13 sense for some, research suggests that such a view
14 may not be valid as an extensive focus on failures
15 creates the erroneous impression of humans as a
16 liability, and ignores the many other instances of
17 humans contributing to success and resilience [2].
18 Not only are people crucial in the creation of
19 safety in the messy details of everyday work,
20 there are also an enormous number of other fac-
21 tors (many of which are beyond control of the
22 human at the sharp end) that are behind the cre-
23 ation of success and the occasional failures.

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Normal Accident Theory

24

25 With the rapid advancement of technology, many
26 organisations today are complex systems, and
27 these systems interact with an equally (if not
28 more) complex environment [3, 4]. Complexity
29 has been argued to render these organisations
30 accident prone in two ways. First, minor failures
31 between multiple components within a system can
32 interact in incomprehensible or difficult-to-follow
33 ways to produce a larger failure. Second, the com-
34 plexity of these systems makes it difficult for any
35 one individual to fully comprehend every single
36 process involved in keeping the system functional
37 [4, 5]. Therefore, when an accident occurs, opera-
38 tors within the system may find it difficult to rem-
39 edy the situation. Most retrospective responses to
40 such issues rely on adding more components or
41 layers of defences, such as an extra alarm or
42 another backup power generator. However, this
43 only adds to the system's complexity and might
44 lead to even more unintended interactions and
45 consequences. Given that failures involving com-
46 plex component interactions are unusual and often
47 unforeseen, they are not considered when we
48 attempt to determine the probability of an accident
49 occurring. Therefore, it is likely that the actual
50 probability is much higher than we think.

51 Of course, not all organisations or surgical
52 operations may encounter accidents since they
53 are loosely coupled [3]. In such systems, the con-

54 tinued functioning of a component is rarely
55 dependent on the functioning of other compo-
56 nents [3, 6]. For instance, the performance of a
57 medical faculty in a university is rarely dependent
58 on the performance of the business faculty. This is
59 not the case for tightly coupled systems such as
60 the operating room, where the function of the sur-
61 geon depends greatly on the function of another
62 component such as the anaesthesiologist, and thus
63 an issue with one of them is likely to lead to an
64 issue with the other. In turn, other personnel (e.g.
65 nursing and the recovery room staff) who rely on
66 them will experience disruption to their work as
67 well. These disruptions and issues may interact
68 with one another in an unforeseeable manner,
69 causing an accident. In sum, organisations that
70 operate using systems that are both complex and
71 tightly coupled will likely experience an accident
72 and numerous near misses at some point in time
73 [3, 7]. These accidents are an expected by-pro-
74 duct of a complex and tightly coupled system, and
75 therefore seen as “normal”. Hence the term nor-
76 mal accident theory.

77 Complexity Science

78 Some might disagree with the above notion, and
79 will continue to argue that accidents are a result
80 of human error [8, 9]. This section discusses com-
81 plexity and explains why blaming accidents on
82 human error alone may be a simplistic approach
83 that misses the bigger picture. To do that, we will
84 look at the underlying assumptions of this view-
85 point, and argue for why these assumptions may
86 not be realistic, especially in a medical or surgical
87 setting.

88 The perception of accidents as the simple
89 product of human error usually contains at least
90 four underlying assumptions. First, it assumes
91 that the system involved solely operates in a lin-
92 ear manner [10]. In other words, A only causes B,
93 B only causes C, and so on. Second, it assumes
94 that since the system operates in a linear manner,
95 it therefore follows that with sufficient knowl-
96 edge, an operator within the system can or should
97 be able to predict the outcome of their actions.
98 Therefore, when an adverse event occurs, such as

a wrong-sided surgery, the surgeon is often 99
blamed for not having anticipated the outcome. 100
Third, it assumes that the linear manner in which 101
the system operates means that it is possible for 102
one to reverse the linear process to discover the 103
cause of an accident. In other words, since C is 104
only caused by B and B is only caused by A, this 105
means that A is the source (or root cause) of the 106
problem. Fourth, it assumes that it is possible for 107
investigators to collect all the information neces- 108
sary to form a true story of what exactly happened 109
to give rise to the adverse event. 110

111 However, these assumptions may not be real-
112 istic, especially in the domain of healthcare and
113 especially in highly complex surgical microsyste-
114 ms [11]. There are many examples which indi-
115 cate that not all systems operate purely in a linear
116 manner. For instance, the performance of a nurse
117 in a hospital is potentially influenced by a pletho-
118 ra of factors like the nurse’s case load, whether
119 there is a staff shortage, the type of observation
120 charts used, the noise level and lighting within the
121 wards, and whether the nurse is interrupted [12–
122 16]. Likewise, the performance of a surgeon can
123 be affected by factors such as disruptions, fatigue,
124 and stress levels [17–19].

125 Since the healthcare system operates in a com-
126 plex manner, it stands to reason that the second
127 assumption of outcomes being predictable is
128 likely to be false. A complex system like health-
129 care is likely to experience a huge amount of
130 interactions, some of which are non-linear, among
131 all of its components [20–22]. These interactions
132 can take a range of forms, such as the interactions
133 between staffs across multiple disciplines or small
134 physiological changes within a patient interacting
135 to cause major disruptions in the patient’s health.
136 Systems of such complexity mean that it is impos-
137 sible for any one individual to fully comprehend
138 all the tasks necessary to keep it functional [4, 5].
139 Given the complexity and interactivity involved,
140 outcome prediction is near impossible.

141 Following from the above, the third assump-
142 tion is likely to be false as well. Since the health-
143 care system is immensely complex and highly
144 interactive, finding out the factors contributing to
145 an accident is not as easy as simply reconstructing
146 a linear process [20–22]. Moreover, not all acci-

147 dents have a cause, as discovered during the
 148 investigation into the accidental shooting of two
 149 US Black Hawk helicopters by two US fighter
 150 jets. This shooting is thought to have happened
 151 due to the many local units each developing their
 152 own procedures and routines to manage local
 153 demands. The development of local procedures
 154 and routines is a normal occurrence, as the origi-
 155 nal plans do not always suit the local situation.
 156 However, the differences in procedures and rou-
 157 tines among the various units made it difficult for
 158 these units to act smoothly and successfully in a
 159 tightly coupled situation, leading to the shooting
 160 [23, 24]. Lastly, this assumption also depends on
 161 the accident investigator being given full access
 162 and the ability to gather all the necessary informa-
 163 tion to reconstruct an accurate picture of the acci-
 164 dent. As will be argued below, it is highly unlikely
 165 for that to happen.

166 The fourth assumption regarding an investiga-
 167 tor being able to gather all the necessary informa-
 168 tion to reconstruct an accurate picture of the
 169 adverse event is likely to be an invalid assump-
 170 tion, for the following reasons. First, systems that
 171 are highly complex and interactive tend to con-
 172 tinuously evolve, thereby retarding any attempts
 173 at retrospective analysis especially for an outsider
 174 unfamiliar with the nuance changes in complex
 175 systems [25]. Second, a huge amount of informa-
 176 tion might be lost or difficult to obtain in the
 177 course of accident investigations since one's
 178 behaviour can be influenced by a multitude of fac-
 179 tors, such as unwritten routines or subtle oral or
 180 behaviour influences by other supervisors or staff
 181 members [26].

182 Third, research has shown that memory is unre-
 183 liable and highly context dependent [27–30]. The
 184 way in which a question is phrased has the capac-
 185 ity to alter answers and memories. Furthermore,
 186 people are also susceptible to incorporating misin-
 187 formation from various sources into their memory
 188 of an accident, and this altered memory can remain
 189 even if people are made aware of the misinformation.
 190 Thus, this might hinder or at least affect
 191 attempts at information gathering and increase the
 192 chance of hindsight bias [31].

193 Lastly, the process of reconstructing a repre-
 194 sentation of an accident is at risk of succumbing

195 to the hindsight bias [31]. Given that the outcome
 196 of an accident is already known, it is easy for acci-
 197 dent investigators to determine which behaviour
 198 or decision led to the accident and wonder why
 199 the people involved failed to notice the same
 200 things. In doing so, the challenges that these peo-
 201 ple faced are trivialised and the bigger picture,
 202 that such accidents are mostly the product of com-
 203 plex and interactive systems, is missed (Table 3.1).

204 In summary, attributing adverse events to
 205 human error hinges on the four assumptions being
 206 valid. However, these assumptions are unrealistic
 207 in complex and interactive systems like health-
 208 care. Rather than looking at accidents using a lin-
 209 ear approach, we should perhaps follow in the
 210 footsteps of high-reliability organisations (see
 211 section “Principles of High Reliability”) and adopt
 212 a systems approach instead, which is well suited
 213 for complex settings such as in surgical setting.
 214 Essentially, this approach takes the view that an
 215 individual failure is a symptom of a larger prob-
 216 lem within the system, which enables organisa-

Table 3.1 Summary of the four assumptions of attributing accidents to human error and reasons that these assumptions are invalid

Assumption	Reason(s) for assumption being invalid	
System operates in a linear manner	Performance of healthcare practitioner is influenced by a plethora of factors	t1.6 t1.7 t1.8
Operator within the system can predict outcome of actions	Complexity and interactivity of healthcare system or surgical microsystem make outcome prediction near impossible	t1.9 t1.10 t1.11 t1.12 t1.13
Possible to reverse the linear process to discover the cause of an accident	Complexity and interactivity of the system make it difficult to reconstruct what happened	t1.14 t1.15 t1.16
	Not all accidents have a cause	t1.17
	Depends on investigator(s) having full access to all necessary information	t1.18 t1.19 t1.20
Possible to collect all the information necessary to form a true story	Systems that are complex and interactive tend to evolve over time	t1.21 t1.22 t1.23
	Information can be lost or difficult to obtain	t1.24 t1.25
	Memory can be unreliable and context dependent	t1.26 t1.27
	Risk of hindsight bias	t1.28

217 tions to learn from their mistakes and improve the
218 system [32–34].

219 It should be noted that such an approach does
220 not mean that humans are entirely blameless, as
221 there are scenarios in which pursuing individual
222 responsibility might be necessary [35]. However,
223 most errors are arguably committed by proficient
224 and well-meaning operators who possess a finite
225 capacity (as do all humans) and who face numer-
226 ous challenges when carrying out their duties
227 [31, 36]. Thus, the focus here should not be on
228 punishing them, but to examine the means of
229 improving the system in order to alleviate some
230 of their difficulties and attenuate future adverse
231 events [32, 36].

232 Safety Drift and Procedural 233 Violations

234 Safety Drift

235 Healthcare systems are vastly complex and set in
236 an environment that is equally (if not more) com-
237 plex [3, 4]. Besides consisting of a multitude of
238 individual components (e.g. doctors and nurses,
239 technological artefacts, regulatory pressures),
240 systems of such complexity also possess subsys-
241 tems (e.g. anaesthesiology team, general surgery
242 team) that are working to achieve their own goals
243 [25, 31]. These goals are not always compatible,
244 however, resulting in conflicts that need manag-
245 ing. Those involved would have to make deci-
246 sions based on the situation and some of these
247 decisions might require the sacrificing/trade-off
248 of safety to achieve a particular production goal
249 or to live up to other duties [37, 38]. Typically,
250 this trade-off does not yield any immediate nega-
251 tive consequences [39]. Therefore, those involved
252 would be misled into assuming that the trade-off
253 is acceptable and it becomes part of the normal
254 process. When another conflict emerges and
255 another trade-off is made with no adverse results,
256 this second trade-off might be once again be
257 assumed to be acceptable and becomes part of the
258 normal process. This process (known as normali-

259 sation of deviance) will repeat itself, slowly
260 nudging the system towards greater risks until an
261 adverse event takes place.

262 Despite the risks involved, those within the
263 system are unlikely to be aware of this drift to
264 failure as signs are typically only noticed by those
265 outside of the system (e.g. accident investigators)
266 after an accident has occurred [24]. To those
267 within the system, seemingly poor decisions in
268 hindsight are actually rational, given the contem-
269 poraneous circumstances [31]. While seemingly
270 a bad phenomenon, the drift away from safety is
271 not necessarily a negative indicator of an organ-
272 isation's performance [24]. Rather, it is simply a
273 by-product of a complex system adapting to the
274 challenges from both within itself and the envi-
275 ronment. The challenge is to ensure that the clini-
276 cians involved understand the role and importance
277 of these trade-offs (i.e. clinical sensemaking)
278 [40].

279 Features of Drift

280 So what are the elements that contribute to a sys-
281 tem drifting towards failure? At present, it is theo-
282 rised that at least five factors are involved, namely
283 (a) scarcity and competition, (b) decrementalism,
284 (c) sensitivity to initial conditions, (d) unruly tech-
285 nology, and (e) contribution of protective structure
286 [24].

287 Scarcity and competition refer to an organisa-
288 tion experiencing a lack of resources, and facing
289 intense competition [24]. Rasmussen suggested
290 that a typical organisation has to work within three
291 boundaries, the first being economic, the second
292 being safety, and the third being workload [41].
293 Working beyond the economic boundary means
294 that the organisation would not be able to maintain
295 itself financially, while crossing the safety bound-
296 ary means that the organisation's operation is
297 highly dangerous (e.g. patient's well-being may
298 be endangered). Lastly, exceeding the workload
299 boundary means that the people and/or the tech-
300 nologies within the organisation are no longer
301 capable of carrying out their work. As mentioned

302 earlier, organisations generally drift away from
 303 the safety boundary to satisfy production pressure
 304 since the loss of safety is rarely felt while the
 305 reaching (or not reaching) of production pressure
 306 is tangible [37].

307 Incrementalism means that an organisation
 308 moves to the edges of the safety boundary over a
 309 series of small steps (instead of instantaneously),
 310 as it attempts to meet production pressure, as
 311 explained earlier [24]. This should not be con-
 312 fused with normalisation of deviance, which refers
 313 to trade-offs made in response to abnormal situa-
 314 tions (e.g. high demands) being seen as the new
 315 norm.

316 Sensitivity to initial conditions (otherwise
 317 known as the butterfly effect) essentially argues
 318 that seemingly small factors in a system's starting
 319 conditions can lead to large failures, as these factors
 320 interact in novel ways to give birth to unintended
 321 consequences, pushing an organisation towards the
 322 edge of the safety boundary [24]. Unruly technol-
 323 ogy refers to the gap that exists between how
 324 designers of a technology think it will work, and
 325 how the technology actually works when exposed
 326 to the environment [24, 42]. For instance, the intro-
 327 duction of poorly designed health information
 328 technology in some hospitals has been argued to
 329 cause issues such as (a) making it difficult for phy-
 330 sicians to gain a proper understanding of a patient's
 331 condition, and (b) producing reports that lack infor-
 332 mation value, due to the technology's insistence of
 333 using standard phrases [43].

334 The last factor is the contribution of protec-
 335 tive structure, which suggests that the protec-
 336 tive structure that was deliberately created to
 337 keep the operation safe can end up contributing
 338 to a drift towards failure [24]. One example is
 339 a safety or governance department that, through
 340 its generation of many different layers of
 341 defence and guidelines, actually contributes to
 342 complexity, thereby rendering real sources of
 343 risk less visible to the sharp end users.

**Possible Means to Reduce Potential
 for Drift**

344
 345

346 Despite the potential for drift to result in unwanted
 347 consequences, a definitive solution to reduce an
 348 organisation's potential for drift does not appear
 349 to exist. Nonetheless, this section will be devoted
 350 to the exploration of some of the ideas in the
 351 hopes that some would find it useful.

352 As suggested earlier, signs of drift are not
 353 always obvious to those within the organisation
 354 [24]. Therefore, one plausible approach of reduc-
 355 ing an organisation's potential for drift is to study
 356 how decision makers make sense of the informa-
 357 tion environment (e.g. why they take in certain bits
 358 of information and ignore others) as well as how
 359 they make and rationalise their decisions [44].
 360 However, this may not be a fruitful endeavour
 361 since an organisation's drift into failure is usually
 362 only known after an accident has occurred and any
 363 knowledge gleaned might be specific to that acci-
 364 dent and have little applicability in other
 365 contexts.

366 Arguably, a decision maker must pay atten-
 367 tion to multiple sources of information and invite
 368 doubt to make the best possible decisions [45].
 369 But this may be an idealistic notion as decision
 370 makers may be bombarded with an enormous
 371 amount of information, which would require a
 372 long time to process, and immense cognitive
 373 resources [24]. Furthermore, tell-tale signs of
 374 drift may be weak or unbelievable, and hence go
 375 unnoticed [37].

376 Another potential approach would be to move
 377 the organisation away from the safety boundary,
 378 reducing the likelihood that it will be crossed and
 379 produce an accident [41]. Examples include reduc-
 380 ing production pressure or investing in proven
 381 safety methods. However as with the above,
 382 expecting an organisation to reduce production
 383 pressure might be wishful thinking. Even if an
 384 organisation chooses to invest in proven safety
 385 methods, it is highly likely that production
 386 pressure will follow this increase as staffs would
 387 be expected to produce a greater output with the
 388 same resources (i.e. be more efficient) [37].

389 In sum, while there has been several sugges- 434
 390 tions on ways to diminish an organisation’s poten- 435
 391 tial for drift, these suggestions each come with 436
 392 their own caveat. Nevertheless, this does not mean 437
 393 that it is impossible to reduce an organisation’s 438
 394 drift potential since there may be other solutions
 395 that have yet to be explored. For example, Rochlin
 396 and his colleagues have observed that the various
 397 subsystems on board a naval aircraft carrier were
 398 able to balance multiple constraints and pressures
 399 to consistently produce smooth performances [5].
 400 Perhaps an in-depth study on how these subsys-
 401 tems co-operate and negotiate with one another
 402 might yield some useful information.

403 **Procedural Violations**

404 As argued earlier, drift is not an indicator of an 448
 405 organisation’s failing, but a sign of it adapting 449
 406 [24]. It can appear in many forms, such as proce- 450
 407 dural violation (also known as workarounds). 451
 408 Workarounds appear to be frowned upon as it 452
 409 deviates from rules and regulations, which some 453
 410 consider sacred [46]. Such a viewpoint may have 454
 411 its merits, for deviations from rules and regula- 455
 412 tions have resulted in unwanted results. For 456
 413 instance, it was argued that non-compliance with 457
 414 rules and regulations contributed to an incident 458
 415 where the wrong patient was given an invasive 459
 416 procedure. 460

417 However, it might be a mistake to assume that 461
 418 all forms of procedural violations are bad. For 462
 419 example, one form of medical guidelines in the 463
 420 USA specified the use of levofloxacin for 464
 421 community-acquired pneumonia [47]. But others 465
 422 have suggested that a physician should not always 466
 423 follow these guidelines as levofloxacin is an 467
 424 expensive form of antibiotics that not all patients 468
 425 can afford, and not having antibiotics could lead 469
 426 to patients’ conditions worsening [48]. To avoid 470
 427 this outcome, physicians need to deviate from the 471
 428 rules and regulations and prescribe a different and 472
 429 more affordable form of antibiotics. Furthermore, 473
 430 each patient has their own unique co-morbidities 474
 431 and medical history, making it near impossible to 475
 432 create a set of guidelines to address each case. 476
 433 Under such circumstances, physicians should be 477
 478

allowed to act as they see fit instead of being 434
 penalised for not complying with procedures. In 435
 other words, procedural violation may not always 436
 be a bad thing as it captures the local wisdom of 437
 the providers. 438

439 **Stretching the Limits of Adaptive**
 440 **Capacity**

441 As argued above, healthcare organisations have to 441
 442 adapt to multiple constraints both within itself and 442
 443 the environment [24, 25, 31]. One way of doing so 443
 444 would be to stretch its adaptive capacity. Adaptive 444
 445 capacity refers to a system’s ability to adjust its 445
 446 actions in response to high production pressure, 446
 447 such as a hospital temporarily using stretchers or 447
 448 chairs in the hallways when there are insufficient 448
 449 beds to accommodate a sudden spike in demand 449
 450 [49, 50]. When a system attempts to adapt itself to 450
 451 handle a particular type of disruption, it will inevi- 451
 452 tably become less adept at handling other types of 452
 453 disruptions [51]. When these other disruptions 453
 454 actually happen, the system’s adaptive capacity 454
 455 will be tested and failure is a real possibility. Since 455
 456 failure is an unwelcome result, it is therefore 456
 457 important for a system to know where it stands in 457
 458 terms of its adaptive capacity, the type of prob- 458
 459 lems that can arise in an adaptive system, and the 459
 460 means of stretching this finite resource if neces- 460
 461 sary [52]. For a system to figure out where it 461
 462 stands in terms of adaptive capacity, it should pos- 462
 463 sess at least the following *three characteristics*: 463
 464 (a) capacity to reflect on how well it has adapted, 464
 465 (b) awareness to know what it is adapting to, and 465
 466 (c) changes within its environment [51]. 466

467 There are three potential ways by which an 467
 468 adaptive system can break down [51]. The first is 468
 469 decompensation, which essentially refers to a 469
 470 system’s adaptive capacity being unable to keep 470
 471 up with a disruption that has occurred. In the 471
 472 initial phases of decompensation, the system 472
 473 automatically attempts to compensate when a 473
 474 disruption takes place and is somewhat successful 474
 475 in doing so, hence masking the problem as it 475
 476 continues to fester. Eventually, the system’s 476
 477 adaptive capacity would be drained, causing a 477
 478 sudden collapse and failure. 478

479 The second issue is one that has been dis- 524
 480 cussed earlier, namely the possibility of various 525
 481 subsystems having conflicting goals with one 526
 482 another, leading to each subsystem taking actions 527
 483 that may benefit them individually but limits the 528
 484 system's adaptive capacity [51]. The final possi- 529
 485 bility is that the system may persist in using out- 530
 486 dated practices even though the environment has 531
 487 changed and despite the introduction of new 532
 488 practices. 533

489 Given the importance of adaptive capacity in 534
 490 ensuring that a surgical system remains func- 535
 491 tional, it is therefore necessary to figure out the 536
 492 means of stretching this finite resource to avoid a 537
 493 system failure [52]. One plausible way might be 538
 494 to stay sensitive to indicators that the system is 539
 495 silently compensating for disruptions and to take 540
 496 remedial actions immediately when these indica- 541
 497 tors display abnormal signs [51]. However, this 542
 498 might not be an easy task since it requires one to 543
 499 be able to successfully differentiate between 544
 500 good adaptive behaviours (e.g. workarounds to 545
 501 increase efficiency) and bad adaptive behaviours 546
 502 (disruptive behaviours that indicate that the sys- 547
 503 tem is on the path to failure). 548

504 **Resilience**

505 A second means of dealing with constraints and 549
 506 complexities would be to apply the principles of 550
 507 resilience engineering. Resilience is defined as 551
 508 the ability of a system to adapt its functioning 552
 509 prior to, during, or following any changes or dis- 553
 510 ruptions to sustain regular operations under all 554
 511 conditions [53]. The key term in the definition is 555
 512 adapt, meaning that resilience is about the sys- 556
 513 tem's ability to adjust its functioning to meet 557
 514 challenges. A system that is able to sustain regu- 558
 515 lar operations under all conditions is not necessar- 559
 516 ily resilient, since this can be easily achieved via 560
 517 inefficient means such as stockpiling an absurdly 561
 518 large amount of resources (e.g. having multiple 562
 519 empty wards in a hospital in case of an emer- 563
 520 gency). Hence, adaptation is important. 564

521 However, some form of excess resources may 565
 522 still be necessary for the system to draw upon in 566
 523 times of need, meaning that not all excess 567

resources should be removed under the pretext of 524
 efficiency [52]. Therefore, one possible problem 525
 with resilience engineering would be the difficulty 526
 in determining whether a set of spare resources 527
 should be removed for efficiency or retained to 528
 achieve resilience. Whether a system can success- 529
 fully manage this is likely to depend on how it 530
 implements and sustains the four pillars of resil- 531
 ience. For example, if a system is proficient in pre- 532
 dicting future threats (one of the four essential 533
 pillars of resilience), it should be able to deter- 534
 mine if the extra resources available would be use- 535
 ful in helping it achieve resilience by allowing it to 536
 better meet challenges, or if the extra resources 537
 are a hindrance as it prevents the system from 538
 operating efficiently. 539

540 **Four Pillars of Resilience**

541 Given the apparent benefits of resilience (i.e. able 541
 542 to handle disruptions), healthcare systems might 542
 consider adopting at least some of its principles. 543
 Currently, it is argued that a resilient system 544
 should possess four key abilities, namely (a) the 545
 ability to respond to disruptions, (b) the ability to 546
 monitor ongoing developments, (c) the ability to 547
 predict potential threats and opportunities, and 548
 (d) being able to learn from both failures and suc- 549
 cess [54]. 550

551 For a system to be able to respond to disrup- 551
 552 tions, it should come up with a list of potentially 552
 disruptive events and develop a set of possible 553
 responses to these events, so that it may react 554
 appropriately in a timely manner when the dis- 555
 ruption occurs [53]. For the list to be effective, 556
 the disruptive events that are being included should 557
 be rigorously examined on a frequent basis to 558
 ensure their relevance and timeliness. 559

560 In terms of developing a set of responses, the 560
 561 system needs to be able to verify its effectiveness 561
 as well as consider appropriate means of main- 562
 taining such responses [53]. As mentioned above, 563
 having an absurdly large amount of excess 564
 resources (e.g. dozens of empty beds) might be 565
 an effective response, but it is certainly not effi- 566
 cient and is costly to maintain in the long run. 567

568 For a system to have the capacity to monitor
 569 ongoing developments, a list of valid and reli-
 570 able indicators needs to be developed and con-
 571 tinuously monitored [53], in other words, an
 572 organisational dashboard of indicators that can
 573 consistently yield useful information. An exam-
 574 ple of a poor indicator would be the number of
 575 human errors committed, since it depends on
 576 unrealistic assumptions and misses the bigger
 577 picture, as argued earlier.

578 Additionally, these indicators are unlikely to
 579 always remain relevant, and thus should be con-
 580 stantly revised and updated [53]. A clear set of
 581 guidelines is necessary to guide this revision pro-
 582 cess as the typical approach is to simply revise the
 583 indicators after an accident has occurred. Such an
 584 approach is inadvisable because of two reasons,
 585 namely (a) it holds the unrealistic expectation that
 586 indicators should be able to predict all adverse
 587 events, which is unlikely to happen due to com-
 588 plexity, and (b) revisions based on this approach
 589 usually do not yield effective solutions due to a
 590 heavy focus on face validity. Aside from the above,
 591 the development of suitable monitoring indicators
 592 requires the consideration of other factors as well,
 593 such as the predictive value of the indicators, the
 594 means by which the indicators are measured, and
 595 whether the information provided by the indica-
 596 tors refer to temporary or permanent events.

597 To determine if a system is capable of predict-
 598 ing both potential threats and opportunities, the
 599 assumptions that it holds about the future should
 600 be examined [53]. If a system perceives the future
 601 to be a replication of the past, or that past events
 602 can be used to deduce future events, then the sys-
 603 tem is unlikely to possess the ability to predict
 604 potential threats or opportunities as the past may
 605 not always be a good indicator of the future [33,
 606 53, 55]. If a system perceives future events to be
 607 a phenomenon caused by the complexity and
 608 interactions both within itself and the environ-
 609 ment, then it might be able to successfully predict
 610 potential threats and opportunities.

611 Lastly, a resilient system might display the
 612 willingness to learn from both failures and suc-
 613 cesses, since both types of events arguably share
 614 the same underlying processes save for the recov-
 615 ery from failure [53]. Academics studying resil-
 616 ience have argued for the importance of studying

617 success as it provides useful information for the
 618 occurrence of failures, the rationale being that
 619 there are no magical processes that only mani-
 620 fest themselves when an accident happens, but
 621 otherwise remain dormant [54, 56]. Instead, if an
 622 accident happens, it is likely that the underlying
 623 causes have been around for a while and are only
 624 made obvious by the accident. Furthermore,
 625 understanding how success happens and investing
 626 in it can not only reduce the possibility of things
 627 going wrong, but can potentially increase produc-
 628 tivity as well. For a system to truly be resilient, all
 629 four components are thought to be essential.
 630 However, the importance of each component in a
 631 particular system generally depends on the sys-
 632 tem in question and is highly context dependent.

Limitations of Resilience 633

634 Despite the positive sides to resilience engineer-
 635 ing, it still possesses some limitations which
 636 could mitigate its effectiveness. Many of its rec-
 637 ommendations are vague and thus hinder attempts
 638 at implementing them. For example, it recom-
 639 mends that a resilient system should develop both
 640 a list of plausible disruptive events and a set of
 641 responses to these disruptions [53]. However, it
 642 may not always be clear as to which events should
 643 be included on the list, and which events should
 644 be excluded.

645 Moreover, as a system seeks to improve its per-
 646 formance in dealing with a particular set of disrup-
 647 tive events, it will inevitably experience some form
 648 of setback in dealing with other types of events
 649 [51]. Therefore, when these other types of events
 650 do happen, failure becomes a real possibility.

Principles of High Reliability 651

Concept and Characteristics of High Reliability 652

653 Despite the problems mentioned above, some
 654 complex and tightly coupled organisations have
 655 been able to defy the odds and limit failures, yet
 656 consistently produce high performance [5]. Such
 657 organisations are said to possess high reliability.
 658

659 In an attempt to understand how these organisa- 705
 660 tions managed such a feat, different groups of 706
 661 researchers have studied these organisations and 707
 662 identified different sets of characteristics which
 663 they believe might be the key. The lists that these
 664 researchers came up with share several similari-
 665 ties, but possess some differences as well. There-
 666 fore, this section will first discuss the common
 667 characteristics before looking at the differences
 668 observed.

669 **Common Characteristics of High**
 670 **Reliability**

671 The first characteristic of high-reliability organ- 717
 672 isation is their proactive approach towards risk 718
 673 management. Rather than aiming to prevent fail- 719
 674 ures, which would be an impossible enterprise, 720
 675 these organisations choose to make allowances 721
 676 within their systems for them [33, 34, 57]. 722
 677 Additionally, they obsess over failures and regard 723
 678 them as symptoms of a larger problem within the 724
 679 organisation. As such, personnel are encouraged 725
 680 to (a) report errors (and are rewarded for doing 726
 681 so), (b) learn from near misses, (c) avoid being 727
 682 overconfident, and (d) be aware of the potential 728
 683 for small failures to interact and produce an expo- 729
 684 nentially larger failure. 730

685 The second characteristic of high-reliability 731
 686 organisation is their appreciation of the complex- 732
 687 ity involved in the daily operations of the organ- 733
 688 isation, and knowing that they can never fully 734
 689 comprehend it [33, 34]. Therefore, they do not 735
 690 become overconfident but instead continue to 736
 691 remain hyper-vigilant for possible disruptions. 737
 692 Furthermore, they understand that the system's 738
 693 complexity means that it is impossible for a sin- 739
 694 gle individual to fully master every single task 740
 695 needed to keep the organisation operational [5]. 741
 696 Therefore, tasks are broken down into smaller 742
 697 tasks, with a specific group attending to each 743
 698 smaller task. 744

699 The third characteristic of high-reliability 745
 700 organisation is their deference to experts instead 746
 701 of authority [5, 34]. In this case, experts do not 747
 702 refer to those with the most experience, as experi- 748
 703 ence may not always be the best indicator of 749
 704 expertise. Instead, expert here refers to the person

who has the specific set of knowledge needed to 705
 respond appropriately to the situation at hand, 706
 regardless of the person's authority [58]. 707

Different Characteristics 708

As mentioned in the introduction to this section, 709
 some differences exist between the two lists of 710
 characteristics of a high-reliability organisation. 711
 By differences, we mean that one group of aca- 712
 demics have proposed a particular characteristic 713
 (e.g. continuous learning) as a contributing factor 714
 to high reliability, while another group of aca- 715
 demics have not. 716

The first characteristic is the habit of continu- 717
 ous learning. While on board an aircraft carrier, 718
 Rochlin and colleagues observed that personnel 719
 of high-reliability organisations are continuously 720
 learning, with new methods of work constantly 721
 being introduced, and conventional means always 722
 being scrutinised for flaws [5]. However, this 723
 does not mean that procedures are always chang- 724
 ing. Rather, new methods are only accepted after 725
 its benefits are proven. 726

The second characteristic is constant commu- 727
 nication among personnel, even when there is a 728
 lull in activities [33]. Such behaviours not only 729
 keep communication channels open and help 730
 everyone to stay updated, but they also permit trust 731
 to grow and experienced members of the team to 732
 spot signs that might indicate potential trouble. 733

The third and final characteristic is the display 734
 of sensitivity to the needs and requirements of those 735
 working at the front line [34]. As stated above, 736
 healthcare organisations today operate under incre- 737
 dibly complex and regulatory situations, meaning 738
 those at the front line of the organisation are 739
 required to adapt to changing circumstances on a 740
 frequent basis in order for the organisation to oper- 741
 ate safely. Conversely, those who work at the back 742
 end are typically temporally and spatially removed 743
 from the front line and hence have a limited under- 744
 standing of what is actually happening at the sharp 745
 end [4]. High-reliability organisations are aware of 746
 this and therefore attempt to be sensitive to the 747
 needs of the front line to close this gap. 748

749 **Limitations**

750 While the works on high-reliability organisations
 751 have produced fascinating and useful information
 752 that all organisations can apply, they are not with-
 753 out flaws. A common criticism of studies on
 754 high-reliability organisations is that they have
 755 been focusing mainly on unique organisations
 756 like the Navy or air traffic control, and hence the
 757 applicability of principles gleaned from these
 758 organisations to other settings remains to be seen
 759 [59, 60]. Furthermore, these unique organisations
 760 often do not face production pressure unlike other
 761 organisations in domains like healthcare, where
 762 medical staff have to attend to a large number of
 763 patients in a small amount of time and where
 764 technology continues to curb their autonomy
 765 [61]. Hence, it may be unrealistic to expect organ-
 766 isations with these constraints to achieve high
 767 reliability [62].

768 Such concerns are certainly valid, and while a
 769 few studies have displayed some level of success in
 770 applying high-reliability principles in a healthcare
 771 setting, many questions remain unanswered and
 772 hence additional empirical research is necessary
 773 [63–65]. For example, Madsen and his colleagues
 774 found that although their implementation of high-
 775 reliability principles improved the performance of
 776 a paediatric intensive care unit, medical staff from
 777 other departments resisted the change. Furthermore,
 778 these improvements were abandoned when the
 779 implementers left the unit. Therefore, further
 780 research could examine the optimal means of
 781 introducing high-reliability principles with mini-
 782 mal resistance, as well as looking at ways of ensur-
 783 ing that these principles are sustained in the long
 784 run. This means addressing the barriers to culture
 785 and organisational change that can get in the way
 786 of moving towards higher reliability of care [66].

787 Besides facing different challenges (e.g. pro-
 788 duction pressure), high-reliability organisations
 789 and normal organisations may also differ in other
 790 ways, which could make the application of high-
 791 reliability principles difficult. One instance would
 792 be personnel selection. Given the stringent nature
 793 of the recruitment practices used by air traffic
 794 control and the Navy, it is plausible that the per-
 795 sonnel within these organisations are not repre-

796 sentative of the personnel that one might find in a 796
 797 typical organisation [67, 68]. 797

798 Also, a study in Germany discovered that indi- 798
 799 viduals low in agreeableness, neuroticism, and 799
 800 openness to experiences were more likely to 800
 801 choose military service over community service 801
 802 [69]. This might mean that individuals with par- 802
 803 ticular personality traits are more likely to join the 803
 804 Navy, and these traits in turn make it easier for the 804
 805 Navy to achieve high reliability. This is purely 805
 806 conjecture, given that the study was conducted in 806
 807 Germany, whereas the studies on high reliability 807
 808 in the Navy were carried out in the USA. Extensive 808
 809 empirical studies are needed to determine if there 809
 810 is any truth to the speculation. 810

Surgical Microsystems

811
 812 Aside from the teachings of high reliability, the 812
 813 idea of surgical microsystems has been touted as 813
 814 another possible contender for those seeking to 814
 815 manage the various constraints in the domain of 815
 816 healthcare while maintaining a high level of per- 816
 817 formance [65, 70]. According to Sanchez and 817
 818 Barach, the concept of microsystems originated 818
 819 from Quinn’s works regarding intelligent enter- 819
 820 prises [65, 71]. In the domain of healthcare, a 820
 821 microsystem refers to a small group of individu- 821
 822 als delivering a service to a particular group of 822
 823 patients for a certain purpose. For example, a sur- 823
 824 gical ICU can be considered as a microsystem as 824
 825 it is made up of a group of people (e.g. healthcare 825
 826 practitioners and the patients’ family) working 826
 827 together to care for the patient with the goal of 827
 828 helping the patient recuperate. It is proposed that 828
 829 the microsystems are the building blocks of a sys- 829
 830 tem and thus any attempts at improving the 830
 831 healthcare system to cope with the multitude of 831
 832 constraints should begin at this micro level [70]. 832

Characteristics of Surgical Microsystems

833
 834 Sanchez and Barach suggest that a good surgical 834
 835 microsystem should possess the following prin- 835
 836 ciples, some of which are similar to the principles 836
 837

838 of high reliability [65]. First, there should be an
 839 acknowledgement of the fallibility of humans,
 840 and the acceptance of accident (or errors) as normal.
 841 Instead of pursuing individual responsibility
 842 when something goes wrong, it should focus on
 843 the complex systemic factors behind the incident.

844 Second, a good microsystem needs to possess
 845 chronic unease, a state where an individual (or in
 846 this case, a microsystem) is concerned that potential
 847 risks are not being properly managed [65,
 848 72]. It has been suggested that such an unease is
 849 useful as it keeps people alert to possible dangers
 850 and reduces the potential for complacency. Third,
 851 it is essential that communication channels remain
 852 open and dissenting views are not swept aside.
 853 Additionally, workers should be provided with
 854 proven tools that can help reduce the potential for
 855 errors. One example might be the redesign and
 856 usage of clinical charts that were specially designed
 857 to be user friendly using applied human factor
 858 principles [73, 74].

859 Fourth, the reporting of errors and near misses
 860 should be encouraged, and the learning value of
 861 near misses needs to be appreciated [65]. Fifth,
 862 patients should not be excluded from communi-
 863 cation channels and in face communication needs
 864 to be designed around the needs of the patient
 865 care with the focus on co-producing exceptional
 866 outcomes with the patients [7, 65, 75]. In other
 867 words, when a patient is erroneously exposed to
 868 danger, a good surgical microsystem should pay
 869 attention to the patient's side of the story in order
 870 to gain a better understanding and learn from this
 871 safety breach. Lastly, effective microsystems
 872 need to base their system on proven human factor
 873 principles to optimise performance, support staff
 874 engagement, and attenuate impact of errors and
 875 other constraints such as providing nurses with
 876 user-friendly clinical charts [65, 73, 76].

Conclusions

877
 878 Rapid technological advancement has led to
 879 organisations becoming complex systems and
 880 dealing with a complex environment, making acci-
 881 dents a normal part of operations [3, 4]. Arguments
 882 that these accidents are caused by human errors

883 hinge on several unrealistic assumptions being
 884 valid, and do not address the complexity in today's
 885 surgical world [10]. Such complexity creates mul-
 886 tiple challenges and constraints for both the sys-
 887 tem and its subsystems, which forces them to
 888 adapt in ways that could cause a drift towards fail-
 889 ure [24, 25, 31, 37]. To manage these issues, sys-
 890 tems can learn to stretch their adaptive capacity,
 891 attempt to become more resilient, apply the same
 892 principles as high-reliability organisations, and/or
 893 learn from clinical microsystem wisdom [5, 33,
 894 34, 51–54, 65]. While each of these ideas come
 895 with their own limitations, they are nevertheless
 896 an excellent starting point for anyone seeking to
 897 improve performance and safety in the surgical
 898 care of patients across the perioperative continuum.

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