SoK: The Design Paradigm of Safe and Secure Defaults

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Abstract

In security engineering, including software security engineering, there is a well-known design paradigm telling to prefer safe and secure defaults. The paper presents a systematization of knowledge (SoK) of this paradigm by the means of a systematic mapping study and a scoping review of relevant literature. According to the mapping and review, the paradigm has been extensively discussed, used, and developed further since the late 1990s. Partially driven by the insecurity of the Internet of things, the volume of publications has accelerated from the circa mid-2010s onward. The publications reviewed indicate that the paradigm has been adopted in numerous different contexts. It has also been expanded with security design principles not originally considered when the paradigm was initiated in the mid-1970s. Among the newer principles are an "off by default" principle, various overriding and fallback principles, as well as those related to the zero trust model. The review also indicates problems developers and others have faced with the paradigm.

Keywords: fail-safe defaults; security engineering; security design principles; scoping review; systematic mapping study

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1. Introduction

The design paradigm of safe and secure defaults traces
to the classical work by Saltzer and Schroeder who derived
eight general principles for computer, software, and cyber
security in general [1]. These are shown in Table 1. In
particular, the paradigm's roots originate from the principle of fail-safe defaults. This principle is about access
controls; a default should be a lack of access, and a design and its implementation should identify the particular
conditions upon which access can be permitted.

Upon replacing the noun access with some other suitable word, the principle generalizes to a broader notion
that defaults should be safe and secure. With this generalization, also many of the other design principles in Table 1
are related to the fail-safe defaults. For instance, it could
be argued that a system's or a software's defaults should
satisfy the principle of separation of privileges; in modern terms, it would mean that two-factor or multi-factor
authentication would be a default.

The Saltzer's and Schroeder's paper is a modern classic in computer science. Yet, thus far, no systematic reviews have been conducted about its use in academic re-

sic in computer science. Yet, thus far, no systematic reviews have been conducted about its use in academic research, although there are some existing reviews that come close [2]. The review presented fills the apparent knowledge gap. In addition, the review fulfills other common functions of literature reviews, including the identification of trends and patterns, clarification of complex concepts, and support for education through cataloging important or even foundational knowledge [3]. Regarding trends, as will be seen, the design paradigm has been continuously

discussed in the face of new technologies. It has also been extended and customized to meet requirements originating from new design problems. Furthermore, it has frequently been misused in practice. This misuse raises also the review's practical relevance. As will be pointed out later on in the concluding Section 4, secure defaults are mandated by recent cyber security regulations. Thus, the SoK is beneficial also for practitioners and regulators who both may find new insights from the knowledge cataloged.

A couple of terminological clarifications are needed before continuing. The first clarification is that the topic is about design *principles*, which are broader and more theoretical than design patterns. An analogy from programming suffices to elaborate the distinction; reusability is a common software design principle, whereas design patterns often allow to satisfy this principle through a customized use of recurring design solutions to common design problems [4]. Then, in the present context the overall problem is about insecurity, unsafety, or both. The second clarification follows; the distinction between safety and security is debated and blurry [5] . In what follows, unsafety is understood to refer to unintentional mistakes often originating from poor designs that have consequences particularly for the health and well-being of humans. In contrast, insecurity is taken to involve a potential of intentional attacks or other disturbances against a design and its implementation. Note that insecurity may cause unsafety, but the reverse relation is often less clear.

The focus on security design principles frames the paper toward security engineering. Alas, there is no single universally agreed definition for security engineering. In general, it can be seen to be about putting "security theory into security practice", meaning that "a security

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Table 1: The Eight Security Design Principles of Saltzer and Schroeder [1, quotations from pp. 1282–1283]

Principle	Quotation
Economy	"Keep the design as simple and small as possible."
Fail-safe defaults	"Base access decisions on permission rather than exclusion."
Complete mediation	"Every access to every object must be checked for author- ity."
Open design	"The design should not be secret."
Separation of privilege	"Where feasible, a protection mechanism that requires two keys to unlock it is more ro- bust and flexible than one that allows access to the pre- senter of only a single key."
Least privilege	"Every program and every user of the system should op- erate using the least set of privileges necessary to com- plete the job."
Least common mechanism	"Minimize the amount of mechanism common to more than one user and depend on by all users."
Psychological acceptability	"It is essential that the human interface be designed for ease of use, so that users routinely and automatically apply the protection mechanisms correctly."

engineer designs and makes systems that are protected against threats, i.e. forces to which systems may be subjected" [6, p. 59]. In the present context the notion about putting theory into practice is about adapting and applying the abstract design paradigm in more practical contexts. The framing toward security engineering is also important because it puts the paradigm into a context of engineering secure systems; hence, the research reviewed is also largely about defensive cyber security. Although there are papers about vulnerabilities in existing systems, whether hardware or software, the majority of papers reviewed are about building or improving systems, software, networks, protocols, or technologies in general with security and safety in mind.

As for the paper's remaining structure, the literature reviewing methodology is elaborated in the opening Section 2. The actual review is presented in the subsequent Section 3. A conclusion and an accompanying discussion are presented in the final Section 4.

2. Methodology

The paper is a systematic mapping study—or, alternatively, a scoping review. Both systematic mapping studies and scoping reviews share the same overall rationale. Their use is often justified when operating in a heterogenous context in which traditional empirical evidence may be lacking and multiple disciplines may operate. In addition, both literature reviewing techniques are often justified when feasibility is a concern; the techniques are useful for determining a value as well a potential scope and a cost of undertaking a full-blown systematic literature review [7, 8]. If systematic literature reviews are seen to align with confirmatory research—after all, they try to collate all evidence about a topic, systematic mapping studies and scoping reviews are more on the exploratory side of things. In general, they explore the nature and scope of existing literature, trying to inform future research, including further reviews, by identifying not necessarily evidence gaps but knowledge gaps in general [9]. These general characterizations justify also the paper's reviewing methodology; as will be seen, the topic is highly heterogenous without much traditional empirical evidence.

That said, both scoping reviews and systematic mapping studies have adopted from systematic literature reviews the good practice of using a structured and transparent protocol for searching literature. Thus, the literature search protocol used in the present review is:

(safe AND default) OR (secure AND default),

where AND and OR are Boolean operators. The two clauses separated by OR capture both security engineering design practices and more general design solutions involving safe defaults. They also capture common associated phrasings such as fail-safe defaults.

In addition to removing duplicates, four criteria were used to exclude less relevant or otherwise ill-suited literature. The first criterion was that only primary studies were included; hence, a paper merely citing in passing some other paper that discusses safe or secure defaults did not qualify. The second criterion was that a qualifying paper had to discuss safe or secure defaults by providing a definition, an example, a rationale, an explanation, or some related elaboration. Thus, those papers were excluded that simply pointed out that there is a design paradigm involving safe and secure defaults. The same applies to drive-by mentions of general design ideals, such as "secure by default", "privacy by default", and "security by design". Likewise, many papers discussing default values for algorithms were excluded. The third criterion imposed was that only peer reviewed journal articles and publications in conference proceedings were qualified; hence, book chapters, standards, editorials, and related content were excluded. The fourth criterion was simple: all papers addressing financial matters were excluded; therein, the word default has a different meaning.

Even with the criteria, preliminary queries indicated a vast amount of peer reviewed literature. To deal with this severe feasibility obstacle, the final searches were restricted only to the ACM's and IEEE's electronic libraries. This restriction underlines the paper's nature as a scoping review. Regarding the noted value contemplation before conducting a full systematic literature review, it can be tentatively concluded that not much additional value would be supposedly available because the n=148 reviewed papers (see Fig. 1) are already sufficient for conveying the relevant points raised and soon discussed. If further databases would be queried, it also remains unclear whether it would be possible to review the literature without resorting to natural language processing or bibliometrics.

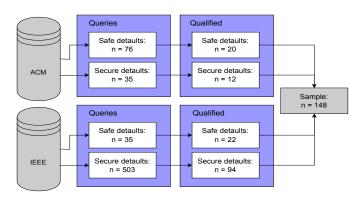


Figure 1: The Sample of Literature Reviewed

It can be also noted that the criteria were strictly followed in order to minimize subjectivity. Therefore, it is worth further remarking that there is a paper [10] that has likely used so-called tortured phrases [11] or something alike. To deal with such papers as well as the overall feasibility problem, it might be possible to evaluate the quality of papers [12], but the problem is that there is no universally agreed definition for paper quality [13]. This lack of a definition would presumably increase subjectivity. A potential solution would be to focus on national rankings of publication venues [14], journal impact factors, or related quantitative information, but also this choice would likely bias a literature sample because high-quality work is published also in low-prestige venues, and the other way around. These points notwithstanding, it can be remarked that the overall quality of the sample is good based on a subjective evaluation. This remark can be reinforced by taking a look at the publication venues; many, but not obviously all, papers were published in well-known or even top-ranked security conferences and journals.

Finally, the reviewing itself follows a thematic approach that is common in qualitative research [15, 16]. In other words, the goal is to capture and categorize the major themes present in the literature. The thematic approach is also necessary due to the large amount of literature sampled. The themes were constructed by first identifying a large number of distinct categories, which were then narrowed and sharpened by collating and merging of overlap-

ping, overcasting, or otherwise fuzzy categories [16, 17]. In practice, the identification of themes and the reviewing in general were started by reading each paper's abstract. The second step was about reading the portions in which defaults were discussed. If a more detailed reading was required to deduce about the defaults, a paper's introduction and conclusions were first read. If these were not sufficient, as was the case with a few papers, a full reading was conducted, from the first to the last sentence.

3. Review

In what follows, the review is presented in five subsections. The first subsection presents a few quantitative observations about the literature sample. The two subsequent subsections elaborate the computing domains in which the papers have operated together with their motivations. The design principles behind the paradigm are discussed in the next subsection. The final subsection briefly discusses some problems identified in the literature.

3.1. Quantitative Observations

The classical paper of Saltzer and Schroeder [1] was published in 1975. To this end, a good way to start the review is to look at the publication years of the papers sampled. These are shown in Fig. 2.

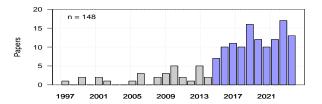


Figure 2: Publication Years

As can be seen, there has been a growing interest in the design paradigm. However, the earliest papers were published in the late 1990s, which marks an over twenty years gap between the classic and the initially following contributions. A further point is that the publication pace has accelerated from about mid-2010s onward. As soon discussed, there is a specific reason for the acceleration.

The classical paper has been explicitly cited only in two papers sampled, meaning that the full title of the paper appears in bibliographies. Implicitly, however, the surnames Saltzer and Schroeder appear together in about seven percent of the 148 papers sampled. Furthermore, either the character string fail-safe default or the character string fail safe default appears in about eight percent of the papers sampled; these strings were searched from anywhere in the lower-cased textual representations of the papers. Thus, it may be that the 1970s paper is not that well-known after all—or it may be that it already belongs to the common pool of computing knowledge, such that citing it is no longer necessary.

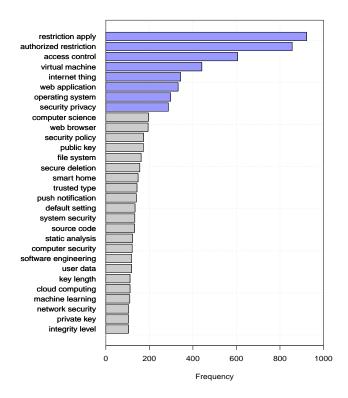


Figure 3: Top-30 Bigrams

Further basic quantitative information can be provided in the form of the top-ranked bigrams shown in Fig. 3. These were constructed from the lower-cased textual representations of the papers with a conventional pre-processing strategy: the texts were tokenized according to white space and punctuation characters; only alphabetical tokens recognized as English words were included; the tokens were lemmatized into their basic dictionary forms; only lemmatized tokens longer than three characters and shorter than twenty characters were included; and stopwords were excluded. Then, as can be seen from the figure, already the most frequent bigrams indicate a presence of numerous distinct contextual domains. These are disseminated next.

3.2. Domains

A good way to continue with the review is to present the particular computing domains in which the studies reviewed operated. These are enumerated in Table 2. As the review mixes also a few papers that do not belong to the sample formally gathered, the table serves also as a bookkeeping material about the literature explicitly reviewed. In what follows, a term non-sampled literature is used to distinguish papers referenced that are not part of the actual sample.

As can be seen from the table, safe and secure defaults have been discussed in a number of distinct domains, ranging from traditional computer science and software engineering domains, such as cryptography, databases, operating systems, and programming languages to newer domains and technologies, such as smarthomes and blockchains, and from there to a little more unconventional domains, such as psychology and even work safety. Regarding the unconventional domains, a couple of concrete examples can be given. The first is a paper investigating secure deletion of files; it is noteworthy because data is not generally deleted securely by default [19]. Thus, the paper demonstrates how fundamental the paradigm's violations can be. The same point applies to the couple of papers dealing with hardware. The second outlying example is a paper investigating the use of A/B testing for experimenting how users react to new designs, features, or bug fixes. It is noteworthy because it demonstrates how the design paradigm can emerge as a side-product; among the paper's conclusions is a recommendation that developers should be educated to conduct experiments in such a way that a safe default state is always maintained and all leftovers are cleaned afterwards [20]. Although not captured by the literature search protocol, the clean-up recommendation is also known as a remnant removal design principle; a terminating system should clear past traces that are not required for later use [21]. As may be common to design principles in general, the remnant removal design principle might be also known with some other term in some other context.

Although a thematic analysis is not well-suited for quantitative insights, it can be still concluded that embedded devices, including particularly the Internet of things (IoT) devices, have been the leading force behind the design paradigm—or, rather, its abuses. In fact, the bigram internet thing takes the fifth place in Fig. 3. This domain is also referred to as the Internet of vulnerable things in the literature [54]. Alternatively, the insecurity of "thingernets" is related to the vulnerabilities in the "thingabilities" and "thingertivity" of things [72]. To put the paper's humor aside, the "thingernets" concept is illuminating in a sense that it has been estimated that it was around the early 2010s when more "thingabilities" than humans were connected to the Internet according to the non-sampled materials [166]. Thus, the IoT domain largely explains also the acceleration of papers discussing the design paradigm (cf. Fig. 2). The reason is the domain's overall insecurity. In this regard, it is worth continuing the historical narrative by pointing out a couple of papers discussing the Mirai botnet built around compromised IoT devices [70, 74]. It was first discovered in 2016, and rang the alarm bells throughout the computing world.

As will be soon discussed, the various vulnerabilities and insecurities plaguing IoT devices are also a good example about software's role in the design paradigm and

¹ This pre-processing strategy follows existing research from which further details can be found [18]. In the present context it is only relevant listing the custom stopwords used: article, available, conference, downloaded, fig, figure, future, international, licensed, limitation, online, related, restriction, shown, southern, university, use, vol, and work. All are related to boilerplate text that appears in publications, some of which is added by publishers

Table 2: Contextual Domains

Domain	Papers
A/B testing	[20]
Artificial intelligence	[10]
Blockchains	[22]
Configuration management	[23, 24]
Cyber-physical systems	[25, 26, 27, 28, 29, 30, 31]
Cryptography	[32, 33, 34, 35, 36, 37, 38, 39, 40]
Databases	[41, 42]
Data deletion	[19]
Distributed systems	[43, 44]
Education	[45]
Emails	[46, 47]
Embedded devices (including IoT)	[48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66,
	67, 68, 69, 70, 71, 72, 73, 74, 75
Governmental systems	[76]
Hardware	[77, 78]
Healthcare	[79, 80]
Honeypots	[81]
Networks (excluding IoT and web)	[82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100,
	101, 102, 103, 104]
Operating systems (including virtualization)	[105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118,
	119, 120, 121, 122]
Passwords	[123, 124, 125, 126]
Programming and programming languages	[127, 128, 129, 130, 131]
Psychology	[132]
Security engineering	[133, 134, 135, 136, 137, 138]
Smarthomes	[139, 140, 141]
Smartphones	[142, 143, 144, 145, 146]
Social networks	[147, 148]
Trusted computing	[149]
Web	[150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163]
Work safety	[164, 165]

its abuses. Regarding computer networks more generally, new paradigms, such as software-defined networks (SDNs), further underline software's importance also in domains not explicitly associated with software engineering. In any case, the design principle has frequently been discussed and applied also in other computer networking domains, including obviously the Internet but also the world wide web and many other networking areas. Also operating systems have been a frequent context in which the design principle has been discussed. In this regard, it is worth pointing out that many of the early publications discussed and used the paradigm in a context of access controls. Later on, the operating system domain gained traction vis-à-vis the paradigm through the emergence of virtualization and related techniques. These points can be drawn also from Fig. 3 within which the bigrams authorized restriction, access control, virtual machine, and operating system rank high. Of the newer contextual domains, it is worth mentioning cyber-physical systems, including robotics, within which the paradigm has often been discussed in relation to the safety of humans, machines, and their interactions.

It is also worth noting a generic security engineering domain in Table 2. The papers in this domain have addressed the security, usability, documentation, and other related aspects of APIs, that is, application programming interfaces [133], developer-oriented software security engineering [134], using experiments to support security designing [138], the design paradigm under review [135], design of access controls [136], and the practical use of the design principles behind the paradigm [137]. Particularly the two papers explicitly dealing with and discussing the paradigm are worth emphasizing already because they also signify the review's relevance. That is, there is an interest around the design paradigm that goes beyond technical implementation work.

3.3. Motivations

By and large, the whole paradigm has been motivated in the literature though a negation. In other words, as can be also concluded from Fig. 4, which visualizes the motivating themes used in the papers, the starting point

and motivation have usually been unsafe and insecure defaults. The motivations through a negation are expectedly particularly pronounced in the IoT domain. Some publications talk about an insecure default configuration problem, meaning that IoT devices are routinely shipped with extremely poor configurations with respect to best—or even elementary—cyber security practices [49]. As has been pointed out in numerous publications, these configuration mistakes include, but are not limited to, default or weak passwords. Regarding the other issues, the IoT domain is shaped by "extreme heterogeneity, mostly plug-and-play nature, computational limitations, improper patch management, unnecessary open ports, default or no security credentials, and extensive use of reusable open-source software" [73, p. 11224]. On one hand: as with the Mirai botnet, it is also worth emphasizing that the insecurity problems can escalate into larger, even society-wide problems. Although many of the publications analyzed, discussed, and elaborated the IoT domain with conventional consumer-grade devices, such as routers and modems, the same issues seem to plague even smart grid devices [71]. On the other hand: although IoT devices have likely exacerbated the problem, it is worth noting a publication from 2010 that discussed the same issues with default passwords [65]. Another publication from 2012 analyzed the insecure default settings in Windows and Linux operating systems at that time [103]. Thus, like with the design paradigm itself, the antonyms of unsafe and insecure defaults are nothing new as such in the computing world.

The security issues in the IoT domain translate also into network protocols. In particular, numerous publications have analyzed and tried to improve the so-called MQTT protocol, which does not encrypt traffic by default. In this regard, the QUIC protocol has been seen as a promising alternative [122]. However, it should be noted that the issues with protocols go beyond the IoT and related domains; among other things, the same-origin policy for the world wide web has been seen to violate the design paradigm too [161]. In any case, cryptography is also a good example otherwise; among other things, some publications have analyzed insecure use of cryptographic libraries; hence, secure defaults should be provided in these.

Insecure defaults are indirectly reflected also in observations that some cryptographic libraries are prone to side-channel attacks [38]. Regarding other common protocols: while the transport layer protocol (TLS) is the *de facto* one for the today's world wide web, electronic mail is still unencrypted by default, which has motivated some to try to improve the situation [10]. Another example would be nowadays popular end-to-end encryption; people seem to lack knowledge about it and do not trust it [39]. As always with cryptography, a point has also been raised that encryption of IoT and other devices may cause obstacles for forensics and law enforcement investigations [69]. A further point is that the antonyms have not motivated only research on IoT, protocols, and cryptography. A good example would be the operating system domain; therein,

some virtualization solutions have been seen to unnecessarily expose too many system calls [121]. Another example would be possibly insecure push notifications used in smartphones by default [146]. All these examples can be seen to belong to the domain of insecure and unsafe defaults, the antonyms of the design paradigm.

As can be also seen from Fig. 4, there have been also other technology-oriented motivations. Problems with existing access control implementations are among these. Among other things, some mandatory access control (MAC) implementations have been seen to violate the paradigm because programs without a security policy run unconfined by default [105]. Misuse of access authorizations has also been seen as a more general problem in otherwise secure systems due to imprudent choice of default privileges [119]. At the same time, some publications have designed and argued for a middle-ground between a totally open and a strictly closed system [120]. This point serves to underline that there are often trade-offs involved, as will be also elaborated later on in a different context.

Three publications used system monitoring, dynamic behavior of networks, and a risk of a single point of failure as motivations. Remotely conducted monitoring was seen to provide means to detect misconfigured security settings [108], traffic locality and dynamics exhibited were argued to contradict often coarse-grained and static default network configurations [86], and a dynamic conflict arbiter was designed to prevent single points of failure [30]. It can be noted that in the non-sampled literature single points of failure are related to the classical security design principle of defense in depth [21]. There was also an odd category labeled as opt-in. For instance, an argument was raised against the C language in that its use "rely too much on disciplined opt-in; there is still no safe default" [127, p. 243]. The category is closely related to the nontechnical motivations labeled as human factors in Fig. 4.

On the human side of things, one of the primary problems—if not the primary problem—is seen to originate from human behavior and incentives of humans, whether end-users or developers. The incentives are often perceived as non-rational in the literature; people allegedly tend to stick with unsafe or insecure default settings due to various cognitive biases and other psychological reasons.

Among other things, they may lack knowledge, they may defer changes to settings due to cognitive biases, including a bias that a default setting conveys information about what is reasonable, or they may lack technical skills to make changes [76]. There is also a so-called status quo bias; people allegedly fear that changing security configurations break existing functionality [23, 76]. Though, the incentives or biases may also be rational in a sense; people allegedly stick to default security features in operating systems because they are provided free of charge [111]. Whatever the actual reasons might be, some [139] or most [147] people never modify default configurations. Passwords are a good example. For instance, one study found that "an outstanding 83.2% of the students have not changed their

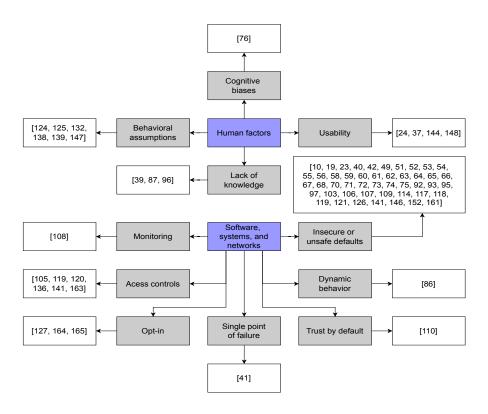


Figure 4: Thematic Motivations for the Design Paradigm

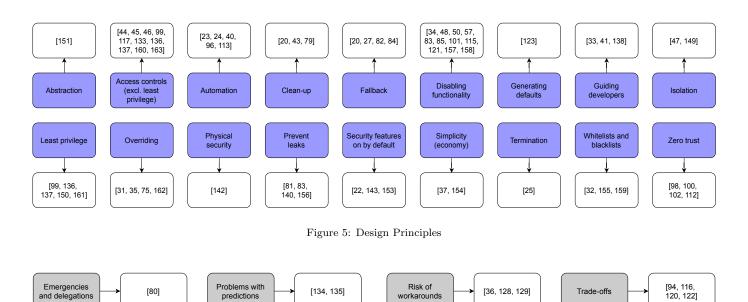


Figure 6: Problems

passwords" [124, p. 1431]. However, similar claims do not affect only end-users. Also software developers tend to use default security features offered by a given provider [145]. Furthermore, there is a phishing-related angle to this reasoning; even users who follow good security practices may opt for insecure solutions when presented a choice during their work flows [138]. There are a couple of problems in

these claims and the associated reasoning about human factors related to default settings.

The first problem is that the literature sampled contains also contrary claims. For instance, one study found that default configurations for local area wireless networks are frequently altered, hinting about a proactive stance to security [88]. The second reason follows: with a couple

of surveys and experiments notwithstanding, much of the reasoning has been speculative. In other words, most of the claims raised in the literature about human behavior are not backed by robust and systematized empirical evidence. Despite these problems, the human factors have expectedly motivated also usability and user interface research—after all, also Saltzer and Schroeder perceived ease of use as essential, connecting it to the psychological acceptability of security mechanisms (see Table 1). For instance, secure default settings were seen in one paper as being particularly important for the elderly [144]. However, the literature sampled contains also critical perspectives; among other things, limited customization was seen as a problem [24]. Indeed, in case the defaults are insecure, a lack of customization options may even imply that it is impossibly to remedy the insecurity by default.

3.4. Design Principles

The literature has presented numerous security design principles, some of which are relatively straightforward security design principles and some others more general ideas about good security practices to adopt. All of these are on the technical side; none of the papers sampled provided feasible and plausible ideas on how the problems with human factors could be resolved, provided that generic points raised about improved education and security awareness are not counted. On these notes, the design principles are summarized in Fig. 5.

A few papers have operated with high-level design principles. These include the Saltzer's and Schroeder's economy principle. For instance, "the recent emphasis on simplifying APIs (and choosing secure defaults) has provided improvement; we endorse continuing in this direction" [37, p. 168. The economy principle has also been correlated with the psychological acceptability principle in the literature; "designs should be as simple as possible and provide users with a secure default path-of-least-resistance to complete authentication" [154, p. 203]. The notion about path-of-least-resistance is also known as a user-buy-in security design principle in the non-sampled literature [21]. In addition to the economy principle, a general abstraction design principle and a principle of isolation can be seen to belong to the category of high-level design principles. In terms of the former, abstracting security features has been argued to reduce a likelihood that developers will misuse the features, possibly introducing vulnerabilities along the way [151]. Then, isolation has been used to restrict computer communication between entities [149], and more generally, "an isolation-by-default policy results in a significant increase in user security" [47, p. 1342]. It should be remarked that isolation as a default is again nothing new as such; in the non-sampled security literature it is essentially also behind the compartmentalization design principle [21]. Regardless of a terminology, in the literature reviewed isolation has gained a newfound interest due to the emergence of virtualization, cloud computing, and associated technologies and services.

As already noted, quite a few publications have operated with access controls and the least privilege principle considered already by Saltzer and Schroeder. The works in this domain often use apt slogans to motivate their designs. "Deny by default" [45, p. 509] is a good example. Although the basic idea remains the same, the slogans vary from a context to another. For instance, publications dealing with input and output operations have justified their designs by security policy notions such as a "fail-safe default of no write access" [44, p. 119] or a default "to automatically deny the read-write" [46, p. 260]. These access control slogans and security policy dictates align with a principle of blacklists and whitelists. Before continuing, it should be noted that the former violates the Saltzer's and Schroeder's original fail-safe default principle, whereas the latter conforms with it. Among other things, whitelists have been used to restrict parameters supplied to cryptographic libraries [32], whereas "billions of devices benefit from the blacklist enabled by default" [155, p. 4345] in web browsers. This quotation demonstrates that it is not always possible to fulfill the ideal of denying by default; there are billions (or more) of legitimate websites, and thus no one can curate a whitelist in practice.

A principle of disabling functionality is prominent in the literature. The explanation is partially related to the overall insecurity in the IoT domain. A few illuminating quotations help to again elaborate this principle. "Making communication default-off has tangible security benefits" [50, p. 117]. This "off-by-default approach" [85, p. 197] is commonly endorsed in the computer network research domain; all communication is denied by default [90, p. 321] and computer networks have been designed so that they "only admit the expected traffic, by default treating the rest as unwanted traffic" [101, p. 1]. In fact, recent "proposals for capabilities-based networks have provided some ideas on the fundamental shift in the design philosophy of networks by moving from the Internets 'on-by-default' principle to an 'off-by-default' assumption" [91, p. 1931]. However, the principle generalizes to other domains as well. For instance, web security has been argued to improve from "disabling the behavior by default in web browsers" [157, p. 673, including with respect to browser plugins [158]. Furthermore, the off-by-default dictum has been adopted as a general argument about delivering software products; they "should really be distributed with access disabled until administrators explicitly customize the access control policy and mechanisms for their organization" [152, p. 10]. Finally, the principle also aligns in the literature with the economy principle; a design "aims for true minimality in the sense that nothing should be included by default that the service does not explicitly need" [115, p. 251]. It is not difficult to come up with other slogans aligning with the principle—it could be described also with phrasing such as "disable by default, then enable", "close by default, then open", and so forth and so on.

The off-by-default dictum should not be generalized to everything; the literature also emphasizes a principle of turning security features on by default. In addition to technical designs and their implementations, including those mandating an execution of specific instructions [22] and those related to enabling sanitization routines in web applications [153], the principle aligns with the human factor side. The incentives discussed earlier are visible in observations that study participants "were happy to use two-factor authentication as a secure default that is set up at registration, while they would not go through the steps to set it up afterwards" [143, p. 12]. Thus, also this principle aligns with the psychological acceptability principle; people should be encouraged to adopt good security practices, whether via education or user interface designs.

There is also a principle related to overriding functionality enabled by default. For instance, a design hooked calls to existing APIs in order to enforce validation of host names and certificates [35]. Another good example involves computer networking; a study designed a system via which "the default credential is exchanged for a credential that is suitable for the service in question" [162, p. 150]. Though, an argument can also be raised that overriding things should not be necessary in the ideal world because it indicates that something is non-optimal in a design that is being overridden.

To some extent, the already noted clean-up design principle aligns with a principle to prevent leaks of different kinds. Such information or data leaks vary from a context to another. A good example would be enforcing "best practices when enabling logs, ensuring the server administrator really intended to expose this information" [83, p. 4]. Another example would be plugging leaks in honeypots in order to improve deception and prevent detection by adversaries [81]. In the general, non-sampled literature the detection techniques are known as anti-honeypot and anti-introspection methods [167]. As could be expected, the leak prevention principle has also been adopted to protect the privacy of users by default [140, 156]. Thus, leaks are a good example on how security design principles sometimes extend to other domains as well.

Then, there are design principles related to automation and generating defaults. Regarding the former, examples include automation of network security configurations [96], providing personalized security settings [24], automation of virtual machine configurations [113], and automatic provision of certificates to end-users [40]. Regarding the default generating principle, a paper presented a technique to ensure a secure default option by generating strong passwords automatically for users [123]. While a full automation of security configurations may be challenging and thus also risky, the latter idea would seem sensible for also fixing some of the basic issues with IoT devices; user names and strong passwords could be generated at a factory and perhaps printed to stickers placed at the bottoms of all IoT devices manufactured and shipped.

There is a further design principle related to explicitly guiding developers about security. For instance, a paper designed a fail-safe default that forces developers to check

and validate their configurations [33]. Another paper dealing with databases designed a solution "forcing security modellers to think about any cycles in a schema, and add explicit constraints to weaken the schema only where they believe this is safe" [41, p. 113]. This principle aligns with the earlier points about secure defaults for cryptographic libraries, further strengthening the defaults with explicit constraints.

Furthermore, there are design principles about robust fallback and termination. Some of these principles are on the safety side and the domain of cyber-physical systems. For instance, a custom solution for unmanned aerial vehicles (UAVs) was compared against a "default mitigation strategy" involving opening a "parachute when a failure is detected" [28]. Another paper operating in the UAV domain discussed a fail-safe default of either landing or returning to home [29]. That said, sometimes there is no other option but to gracefully terminate an execution; "stopping locomotion when an error is detected is a safe default action" [25, p. 150] in some robotics applications. Closer to the domain of software and systems, the fallback design principle often involves reverting to a last known good or valid state in case of a malfunction [84]. Some of the fallback designs also correlate with the other principles outlined. Among these is isolation; "monitor the system and rapidly adapt when conditions change, falling back to strict isolation as the safe default" [82, p. 351]. Analogously, a "system responded by disabling all network ports and defaulted to the safe-operation mode established previously" [26, p. 1]. While these and other fallback and termination designs were not considered by Saltzer and Schroeder, they too can be seen to belong to the principle of fail-safe defaults.

Finally, in addition to an outlying paper implicitly dealing with a principle of physical security, three papers built upon the emerging zero trust principle. Its motivation can be located also from Fig. 4, which includes a paper discussing the many problems that emerged from an illconveyed historical principle of trusting by default. In general, the zero trust principle of never trusting and always verifying is often taken to imply rigorous monitoring and fine-grained access controls because an underlying assumption is that a part of a larger computing infrastructure has already been compromised. To this end, all "requests are not trusted to access the system networks by default unless passing the anomaly detection" [98, p. 4020]. Analogously, a paper's design stated that "no user or system can be trusted by default" [102, p. 79]. In fact, by "default, our allocation policy considers all legitimate users as attackers" [112, p. 440]. These and other related characterizations of the zero trust principle further strengthen the classical principles of fail-safe defaults and complete mediation initiated by Saltzer and Schroeder.

3.5. Problems

The literature reviewed has also discussed some notable problems, obstacles, and limitations in adopting the design paradigm. Four such problems were identified during the literature review (see Fig. 6). Thus, to begin with, first, a paper operating in the healthcare domain noted that sometimes access controls must be circumvented in order to save lives of patients, further emphasizing that fully locked systems may prevent necessary delegations to some trusted parties in emergency situations [80]. In the non-sampled literature this problem is sometimes known as breaking the glass [168]. The second important problem is related to predictions about the future.

In particular, it was argued that design "principles are based on tacit assumptions that were true in the past but possibly false now" [135, p. 92]. Analogously, "today's secure default becomes tomorrow's vulnerability" and "we question whether it is possible to design, before use, a secure default that can anticipate every possible use" [134, p. 54]. These arguments signify the earlier point about a need of empirical research. Further research is particularly needed to better understand whether and how the design paradigm adapts when systems, software, and networks evolve through time. In addition, the quotations underline a need to study how threat modeling could be improved, such that anticipation could be better—even in case perfect anticipation is reasonably taken as an impossible task to fulfill in practice.

The third area of problems was seen to originate from a risk of workarounds developed by software developers in particular. For instance, a paper operating in the domain of programming languages noted that "programmers will often choose a 'safe' default data type, often double floating-point precision, whether or not it is appropriate" [128, p. 8:2]. The problems were seen to also relate to the economy design principle. Among other things, the efforts to simplify often "remove choices available to developers, which leads to additional mistakes when programmers develop workarounds" [36, p. 182]. Regarding the mistakes involved, which can be severe, a paper found that developers introduced vulnerabilities by disabling security measures imposed and even broke cryptography [129]. Against such results, it might be contemplated whether the guiding developers design principle should involve softer motivating forms, such as those known with a term nudging.

Fourth, the literature also discussed different trade-offs behind the design paradigm. As could be expected, particularly a trade-off between security, including particularly in terms of encryption, and performance was raised in the literature [94, 116]. The trade-off context could be extended to cover also the human factors; the relation between usability and security has been debated ever since the work of Saltzer, Schroeder, and other early titans. Having said that, the trade-offs as well as the workaround problem could be argued to involve implementations and not the design paradigm in itself. If the paradigm would be properly implemented to begin with, it could be argued the problems would not be present.

4. Discussion

In what follows, a summary of the review is first presented after which a couple of limitations are noted. The final subsection points out four areas for further research.

4.1. Conclusion

This systematic mapping study and a scoping review addressed the security design paradigm of secure and safe defaults. In total, n=148 mostly high-quality peer reviewed papers were reviewed. The primary conclusions can be summarized with six concise points.

First, it is evident that the domains in which the paradigm has been discussed and applied have considerably expanded over the years. The Saltzer's and Schroeder's original context of access controls and operating systems is still present, but the paradigm has been applied, discussed, and extended in numerous other domains as well. Regarding the original context, virtualization, cloud computing, and related technologies and infrastructures have brought a revitalized interest in the paradigm and the associated security design principles, including the isolation design principle discussed in a couple of papers.

Second, the computer networking domain, including IoT devices, has discussed the paradigm particularly actively. The reason is simple: IoT devices are widely seen to violate the paradigm. Whether it is default or otherwise insecure passwords or a lack of update mechanisms, the IoT domain has been seen to operate with the paradigm's antonyms, insecure and unsafe defaults. The point is important because the majority of papers reviewed have motivated themselves through a negation of the paradigm. The computer networking and IoT domains are further important to emphasize because it seems a new "off by default" design principle seems to be emerging—or has already emerged—therein. It is also related to a principle about disabling unneeded or unnecessary functionality. It remains to be seen whether these principles help at remedying some of the notable issues plaguing IoT devices.

Third, regarding the contextual domains, it is important to emphasize that the paradigm is not only about security but also about safety. Cyber-physical systems are a good example in this regard. The questions about how to fail safely and what are safe defaults are quite different in this contextual domain compared to the other, more traditional computing domains.

Fourth, the motivations behind the papers reviewed can be reasonably well categorized into technical problems and those dealing with human behavior. This categorization aligns with existing argumentative reviews [169] with an exception that organizational aspects are entirely missing from the literature sample gathered and reviewed. Thus, without further reviews, nothing can be said about safe and secure defaults in terms organizational security, among other things. However, with respect to the noted argumentative review, it is important to emphasize that the literature has considered human behavior both in

terms of end-users and developers or professionals. Having said that, there are also some notable problems in this regard, as soon discussed. It is also worth pointing out that the absence of organizational security might well be due to the sampling from the ACM's and IEEE's electronic libraries alone. In other words, particularly social sciences are missing—as again soon pointed out, they too have interesting things to say about secure and safe defaults.

Fifth, the design paradigm has been discussed and developed with many security design principles, some of which can be traced to the work of Saltzer and Schroeder, but some of which are relatively new. Regarding the newer principles, it is worth noting that the "off by default" design principle is matched by an "on by default" principle in terms of some or all security features available. In addition, principles related to security configuration automation, clean-up routines, overriding existing functionality, and leak prevention can be mentioned as new design principles. Many papers have also designed different fallback solutions. The emerging zero trust design principle is also visible in the literature sample reviewed.

Sixth and last, the literature reviewed has also discussed different problems developers and others have faced when trying to apply the design paradigm. These problems include traditional concerns, such as a relation between security and performance, but also interesting points have been raised about human behavior. Among other things, some have argued that providing secure defaults increase a likelihood that developers will adopt potentially dangerous workarounds. Another important point raised in the literature is about predicting the future. In particular, an argument has been raised in the literature that today's defaults may be tomorrow's vulnerabilities. The point is related to the "unhelpful assumptions" discussed recently [169]. However, a critical argument can be raised that argumentation with such assumptions may be prone to the classical false balance bias—it seems counterproductive to wholesale abandon the paradigm just because there may be some unintended consequences.

4.2. Limitations

A couple of notable limitations should be acknowledged. The first limitation is that the review was conducted by a single author. This limitation affects both the literature sampling protocol and the qualitative thematic analysis discussed in Section 2. Therefore, it is also impossible to provide inter-rater reliability measures commonly used for systematic literature reviews and mapping studies [12]. However, it remains unclear and debatable how the limitation should be addressed in practice. The reason for this claim originates from the second limitation; it also remains unclear how the n = 148 papers reviewed generalize toward an unknown theoretical population of all papers discussing the paradigm. The two limitations are linked together due to the feasibility constraint noted earlier. Covering even more papers would quickly face the constraint, which would be also encountered by involving

multiple authors assessing the papers and the thematic constructs. This point is not unique to the review at hand.

As has recently been argued, systematic literature reviews and systematic mapping studies have become increasingly bloated and increasingly infeasible to conduct [170]. To some extent, the reason is simple: the volume of academic literature grows year by year, making the feasibility problem more severe step by step. To this end, alternative reviewing techniques, such as scoping reviews, have been proposed. There is also a discussion about using artificial intelligence tools for literature reviews [3, 171]. The review presented supports this line of reasoning—feasibility is a constraint also in the cyber security domain, and further discussion is needed on whether and how it could be addressed in the future.

4.3. Further Research

What about knowledge gaps and further research? Four points can be raised in this regard. The first point is that empirical research has mostly been absent. Although empirical research may be difficult to initiate in the domains of systems and network engineering, particularly the assumptions about human behavior would need rigorous empirical assessments. As it stands, many of the assumptions and theorizations presented in the literature more or less fall into a category of folklore—a criticism that is hardly unique to the literature reviewed [172]. This folklore category is related to the unhelpful assumptions noted.

The second point is that the security engineering domain would benefit from a systematic catalog of security design principles. Such a catalog might be designed by following the existing summaries on the bodies of existing knowledge in some computing disciplines [173]. It would be also useful for both researchers and practitioners to continue with the work initiated for translating security design principles into more concrete security design patterns [2, 6]. These points are important because the review also indicated that many security design principles are discussed with different, often overlapping concepts. The Saltzer's and Schroeder's principle of psychological acceptability is a good example; in more recent usability and user interface engineering research it aligns with the principle of least surprise [174]. As was discussed, the same point applies to other security design principles. For instance, the high-level software design principle of "building security in [175] did not appear in the literature reviewed, although it too can be seen to be a part of the paradigm.

The third point is that a full coverage of insecure default configurations has not been covered in the context of the design paradigm. Although the IoT domain has justifiably raised alarm bells in this regard, and there are works discussing configuration vulnerabilities already in the early 2010s—if not earlier, some notable recent domains are absent in the literature sampled. A good example would be vulnerabilities involving cloud computing and related configurations [176, 177]. This example serves to underline that configuration vulnerabilities may affect practically all

computing domains. Secure defaults serve as a starting point for mitigating such vulnerabilities.

The fourth and last point is that research on regulations is lacking behind. In this regard, a paper reviewed raised an argument that "policymakers should ensure the default setting be set to enable security" [76, p. 270]. Although regulations constitute a large and complex research domain of their own, the Cyber Resilience Act (CRA) recently agreed upon in the European Union (EU) is a good example with respect to the design paradigm.² It imposes many new security requirements for most information technology products, whether software or hardware based. Among other things, obligations are placed upon both commercial vendors and open source software projects in terms of vulnerability disclosure and supplychain security management [16, 178]. For the present purposes, it is important to emphasize that the so-called essential cyber security requirements upon which compliant products can be placed in the future to the EU's internal market include a clause that the products should be distributed "with a secure by default configuration". This point serves to emphasize that the design paradigm is wellrecognized also on the side of policy-makers and regulators, either explicitly or implicitly. The point can be also connected to the earlier remark that social science research is missing from the review. Without trying to delve deeper into the probably large amount of research on these sciences about default settings, an example can be mentioned about a relation between the currently prevailing opt-out defaults and privacy, misinformation, manipulation, and related online phenomena [15, 179]. Such a relation between default settings and online phenomena serves well to end the mapping and scoping review with a remark that the design paradigm extends well-beyond technical work related to security and safety by default.

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- ³ Paragraph 2(b) in Annex I.

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