Seven Issues on Distributed Situation Awareness Measurement in Complex Socio-technical Systems

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Abstract. Distributed Situation Awareness is the modern perception of Situation Awareness that considers it as an emergent property of a complex socio-technical system rather than an individual endeavor. Although there are a plethora of Situation Awareness models and measurement techniques, it is doubtful whether they mirror the critical elements and behaviours of real collaborative and complex environments. This paper collects some of the most crucial issues surrounding the existing SA measurements techniques that arose under the complex socio-technical systems settings, and along these lines it addresses the need to change the paradigm in order to prepare the ground for a future Distributed Situation Awareness assessment technique, moving beyond the existing network-based approaches.

1 Introduction

In order to achieve their purposes, complex socio-technical systems involve various interactions between humans, machines, and other actors possibly coming from the outer environment of the system. Within the predefined boundaries of socio-technical systems, all elements and agents affect, and are affected by, the system's overall behaviour, thus they need to be looked at as an entity. There is therefore a shift from an analysis based on system decomposition, to an analysis that looks the system as a whole, when the objective is to examine the behaviour of a complex socio-technical system in terms of different inner or outer phenomena and/or stimuli. In such systems, Situation Awareness (SA) arises as a crucial requirement to achieve their higher goals.

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Endsley [1] defines SA as a state of knowledge of an individual; SA depicts how much, and how accurately, humans are aware of their current and/or systems situation and it concerns (a) the perception of the elements within a system, (b) the comprehension of their meaning, and (c) the projection of their future state.

In socio-technical systems, the complex links of responses and feedback between agents, elements, hierarchical levels, and (sub)systems, which all exhibit dynamic behaviour, are important for the formation and transformation of SA, since SA is not in a steady state. Hence, the Distributed SA (DSA) approach accounts for SA in collaborative environments [2, 3] and holds that the socio-technical system is the unit of analysis [4], because it treats SA as an emergent property of the complex socio-technical system.

In Figure 1, Salmon *et al.* [2] give a DSA example, where DSA is denoted by the big 'bubble' and integrates subsystems and a complex network of their in-between links. Within the big circle, each cluster is bounded by a smaller dashed circle, i.e. open boundaries that serve communication purposes, and represents individual SA affected by other's individual SA. Within these clusters, there are human-like figures representing human agents, there are document- and computer-like objects representing elements that convey information and data to the elements with which, and/or whom, they are affiliated. The technology-to-technology, human-to-human, and artifact-to-human links represent the communication channels that aid the efficient data and information acquisition to the required human and/or nonhuman system elements in real-time setting.

Naderpour *et al.* [5] state that any given system should be able to support the SA of its agents, i.e. the group of system elements that possesses

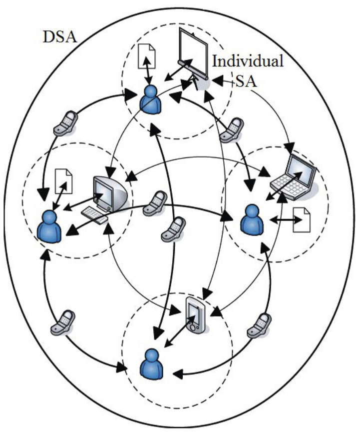

Fig. 1 Distributed Situation Awareness example [2]

reasoning mechanisms and demonstrates a capability to influence other agents, elements, and/or situations. Respectively, the ownership of information is initially at a system level [2], but it can be used, passed, and shared by agents to shape their own picture about the current situation of the system and, through this, support the emergence of DSA required for the system to function effectively. Furthermore, each information package held by one system element, e.g. agents, computers, documents, displays etc., serves to modify, and is modified by, other element's information. Therefore, DSA is held by the entire system since no one system agent has a complete picture of any situation, but just a facet of the situation at any point in time [2].

The overabundance of SA models, e.g. individual, team SA etc, is the evidence that SA is one of the most discussed and complicated cognitive processes in the field of socio-technical systems. Accordingly, the need to measure SA in man-made systems has led scientists to introduce a number of SA measurement approaches. Despite the intense activity regarding SA-related matters, Salmon *et al.* [3], Stanton and Young [6], and Salmon *et al.* [7] claim that there is criticism associated with the existing SA measurement techniques and their accordance with the disciplines, i.e. hierarchy, emergence, communication etc [8], of complex socio-technical systems. In particular, they argue that there is little evidence that these measurement techniques actually work [7], and they also raise concerns about their reliability and validity in cases where the objective is to measure SA in complex socio-technical systems. Furthermore, Salmon *et al.* [3] and Salas *et al.* [9] have stated that the existing (and exhausted) individual and team SA models and measurement techniques are proven not to be adequate in the context of modern complex systems. The DSA concept, however, sets the foundations for a systemic framework for explaining the emergence of SA, contrary to individual and team SA models, which only partially explain the SA formation, missing the notion of the emergence of SA as a system property.

This paper argues that the existing SA measurement techniques are not capable of measuring DSA and identifies some of the most challenging issues that render the existing SA measurement techniques inadequate for the purpose of measuring DSA in a complex, multi-hierarchical, and multi-agent environment. Thus, in the Conclusion, this paper provides a vision for researchers to assess DSA in the context of complex socio-technical systems, as a possible solution to the DSA measurement problems, triggered by the issues of the existing SA measurement techniques, which consist the core of this paper, and they are thoroughly discussed in the next sections. As a result, we move towards the need for a change in the paradigm and a more holistic viewpoint that encompasses mental, physical, and environmental aspects, far beyond individual and team concepts.

2 Previous Work

Stanton *et al.* [4] identified three approaches to describe the different contexts, in which the SA concept was developed and measured over the years. These approaches can be categorised as: (a) physiological, (b) engineering, and (c) ergonomics, and they were developed in parallel to social, technical, and socio-technical systems accordingly. In practice, the different SA measurement techniques are rooted in these three approaches that correspond to researchers' different perceptions of SA: individual, technical, or systemic endeavour.

The first approach perceives SA as an individual psychological phenomenon. It has gained the interest of many researchers, such as Endsley, who consider SA as a cognitive in-the-head process, without taking into account that human reasoning is usually affected by outer stimuli, owing to their communication with their environment, whether it consists of human or nonhuman elements. The second approach, i.e. the engineering one, describes the "world view" of SA [4]. In this approach, SA is considered to be affected mostly by information possession and flow, as well as by technical infrastructure, e.g. computers, displays, information systems etc. The way in which information is presented by artifacts influences SA by determining how much information can be acquired, how accurately it can be acquired, and to what degree it is compatible with SA needs [10]. The third approach is based on the idea that SA is distributed and it emerges from the interactions between human and nonhuman system elements, because the system is viewed as a whole. All in all, the DSA aspect combines the view of SA in the mind and SA in the world [4].

2.1 Types of SA Models

To explain the different aspects of SA, scientists have introduced seven SA models. These are: (1) individual [11, 12], (2) team and (3) shared SA [2, 3, 9], (4) collective SA [13], (5) meta-SA [2], (6) compatible SA [3], and (7) distributed/emergent SA [13, 14].

Individual SA is an individual's dynamic understanding of "what is going on" [1] around him/her. Team SA is usually examined in combination with shared SA. The latter is the common understanding of the situation, whereas the former is composed by team members' individual SA [4], along with their shared SA. Collective SA, on the other hand, is the sum of the individual SA, i.e. the SA that each team member bears, without having necessarily a common understanding over the situation, in which their environment finds itself. DSA is initiated by distributed cognition theory [15], according to which cognition is achieved through the coordination among system elements. Researchers, who adopt the DSA model, embrace the notion of emergence, according to which a property is emergent when it cannot be detected on a single system element, but on the system in its wholeness. Compatible SA refers to elements that hold a distributed system together, and each element and agent in this system has his/her/its own awareness, related to personal goals and understanding over the situation. Compatible SA is not shared, since each team member's view on the situation is different, despite using the same information [16]. One can grasp the difference between compatible and shared SA, by keeping in mind that compatible SA is usually represented by puzzle pieces [3], while shared SA is the intersection between two or more sets. Moving a step forward, Salmon *et al.* [2] introduced the awareness of other agents' awareness, i.e. meta-SA stems from the fact that the knowledge of other agents' knowledge is contained in the system, such that each agent could potentially know where to go, when they need to find something out or manage a situation.

2.2 Existing SA Measurement Techniques

Stanton *et al.* [17] have reviewed more than thirty different SA measurement techniques, eighteen of which have been used by many scholars. In their paper, Stanton *et al.* [17] have categorised these measurement techniques into six general categories in terms of individual SA: (1) freeze probe techniques, (2) real-time probe techniques, (3) self-rating techniques, (4) observer rating techniques, (5) performance measures, (6) process indices, as well as into three categories, and shared SA: (1) team probe-recall techniques, (2) observer rating team SA, and (3) team task performance-based SA measurement techniques.

Table 1 lists the ten most extensively researched categories of SA measurement techniques, together with a brief description of the experimental measurement settings, under which they are executed. The corresponding weaknesses of each category, as being detected in the context of socio-technical systems, are presented in column C. From row 1 until row 6 the individual SA measurement techniques are listed. The team SA measurement techniques are included in rows 7* to 9* (the '*' symbol indicates team SA measurement technique). Finally, the DSA measurement technique is listed in row 10.

Table 1. Categories of SA measurement techniques, description, and weaknesses

	A - category	*B* - description	*C* - weaknesses
1	freeze probe e.g. SAGAT, SALSA	random activity freeze and questionnaire answering, based on agents' knowledge and understanding of the situation	- they constitute interference in the normal course of events within the system - observers measure what agents know, not how knowledge is obtained or maintained
2	real-time probe e.g. SPAM, SASHA	on-line and real-time, observers take into account both the content of responses and the time to respond	- rushed intensity of the respondents attention - observers may neglect other work packages, not currently examined - the bigger the system the greater the volume of observers (e.g. different mental models, cost concerns etc.)
3	self-rating e.g. SART, SARS	post-trial subjective measurement of agents' SA [5]	- individuals subjectively rate the quality of their own SA - responses affected by agent's psychological background - individuals do not rate their SA in each operational sub-process, they generally rate themselves, in terms of their overall performance
4	observer-rating e.g. SABARS	SMEs observe participants in action and score their performance via predefined "benchmarking" behaviour	- observers judge what is going on in individuals' heads from their "outer" attitude, over- or underestimation of individual SA - acceptable behaviour and high performance do not (necessarily) entail high SA - individuals know they are observed for specific behaviours, i.e. feigned good behaviour to avoid low scoring
5	performance measures	measuring relevant aspects of participants performance, e.g. 'kills' and 'hits' imply the success or the failure of the mission [5]	- unclear how the measured characteristic is linked to SA - good performance of one part of the system does not mirror the SA of the entire system - satisfactory SA does not mean that a sub-process will definitely run smoothly
6	process indices e.g. eye trackers and software	measurement of cognitive processes employed by participants to develop and maintain their SA	- eye-tracking machines rate the concentration of the human eye by perceiving data from behaviours considered to be related to SA - "look-but-failed-to-see" (Brown 2001), i.e. the individual 'looks' or 'sees' (e.g. eye-tracking devices grasp the motion of the human eye, without, however, being able to decide whether the observed agent comprehends the stimulus or just looks at it)
7*	team probe-recall	SA related questions are posed to all team members, one-by-one, during freezes in task performance	- difficult to be applied during real world collaborative tasks, i.e. used in simulated environments (Bolstad *et al.* 2005)
8*	observer-rating team SA	observers observe team performance and rate each individual team member about his/her SA as well as the shared awareness	- observer's measurement is subjective - it is not clear if observers measure individual, team, and/or shared SA
9*	team task performance e.g. CAST	examines responses to changes in team processes and environment, i.e. how aware the entire team and each individual, within the team, are	- roadblock scenarios work like preparedness exercises - unclear relation between performance and SA
10	DSA network-based approach	connections are important to explain SA in terms of collaborative systems. DSA is a set of information elements [3]	- networks only allow the representation of information flow between the interacting human and nonhuman agents - depiction not a measurement technique

2.3 A Network-Based Approach for Measuring DSA

Up to now, there is only one reported technique which claims to measure DSA. Indeed, Salmon *et al.* [2] and Stanton *et al.* [16], guided by the notion that there is a shift from models accounting for SA "in-the-head" [3] to models accounting for SA held by systems [18], attempted to introduce a theoretical approach as a measure of DSA under the perspective of complex socio-technical systems. Salmon *et al.* [3] also point out that it is crucial to describe the current situation of the examined system by using the available information, as well as taking into account who has the 'ownership' of that information, and how the different agents interact with each other via numerous technical system elements in order for the awareness to emerge.

However, the same authors acknowledge that there is an oxymoron in their technique, which is based on propositional networks. On the one hand, they introduce this technique as a network-based approach for measuring DSA, while on the other hand, they characterise this technique as a qualitative depiction of SA. According to Salmon *et al.* [3] (p.71) *"The propositional networks approach therefore differs from existing SA measurement approaches propositional networks do not attempt to quantitatively score each agent's SA quality they describe the content of the system's DSA during task performance and the usage of this information by the different agents involved."* Indeed, their propositional network approach to measure DSA is, in practice, a stepwise description and guidance for studying and depicting agents and networks of agents involved in the acquisition and maintenance of SA through information processing and assessment. The outcome of this method is qualitative and it mostly bears a resemblance to semantic networks.

3 Why It Is Not Worthy to Combine the Existing SA Measurement Techniques

To overcome the limitations of the existing SA measurement techniques, one might consider combining them. That would have probably been an acceptable strategy, if the examined system did not contain numerous elements and agents distributed at different hierarchical levels. However, in terms of measuring DSA in complex socio-technical systems, there seems to be some aspects of incompatibility. The first incompatibility refers to the measured objects. For instance, the real time probe techniques (Table 1 - row 2) measure individual's knowledge and understanding regarding what they see happening around them, whereas observers, in observer-rating techniques (Table 1 - row 4), identify and 'collect' benchmarking behaviours that are supposed to convey a positive SA-related conclusion. The second incompatibility refers to the experimental conditions of the measurements. Specifically, the existing measurement techniques are governed by mutually exclusive constraints regarding the processes and tools they integrate. An example of mutually exclusive constraints exists between freeze (Table 1 - row 1) and real-time probe techniques (Table 1 - row 2). Typically, in freeze probe techniques, a task is randomly 'frozen' in a simulation of the task under analysis, all displays and screens are blanked, and a set of SA queries regarding the current situation at the time of the freeze is administered [7]. On the contrary, real-time techniques perform measurements on a real-time base while the participant is performing the task under analysis [7].

An example that combines both aspects of incompatibility includes the freeze probe, e.g. SAGAT, and self-rating, e.g. SART, SA measurement techniques. For Salmon*et al.* [7] specifically, SAGAT and SART techniques are entirely different, because the former queries participants for their knowledge of task-specific elements, whilst the latter does not refer to the specific elements related to the task, rather it focuses on generic, overall task characteristics. Generally, in freeze probe techniques on the one hand, experts interview agents [7] about their own view in relation to their understanding about the current situation of the system, whilst in self-rating techniques users make use of rating scales, which are more structured and somehow 'quantitative' compared to open-answer questions. This entails that one needs to modify the measurements, at least of one of the two techniques, to combine the results of the two measurement techniques in order for them to be comparable and to be able to 'draw' a joint conclusion about SA. Any kind of intervention in values may harm the genuineness of raw data, be time consuming, and/or lead to additional costs.

4 Issues on DSA Measurement

Among the literature of SA measurement techniques, there are reviews which identify most of the profound defects of the aforementioned techniques, e.g. time-consuming processes, training is presupposed, huge amount of resources is required etc [3, 18]. However, they fail to detect the deeper problems that underlie the lack of proper SA measurement techniques in complex socio-technical systems. In this section we group the most crucial points that render the given SA measurement techniques quite insufficient.

1. Unclear context and definition of system boundaries: SA measurement techniques were at first developed to measure individual SA in the field of aviation, e.g. freeze probe, real-time probe techniques etc. Researchers, who developed these measurement techniques, made their assumptions according to the conditions that exist in cockpits or in air traffic control towers, which are confined control rooms, under the notion that they do not keep up with the idea of extended and multi-agent socio-technical systems. What is more, researchers, such as Boy [19], insist that traditional SA-related army models are not enough to illustrate and/or comprehend the design and management of complex socio-technical systems, seeing that authority sharing is crucial for the distribution of awareness between system agents. Unfortunately, the conceptualization of SA in confined systems, within which agents act in their own 'microclimate' in isolation, does not provide a realistic model of what is happening in complex socio-technical systems. Thus, the conclusion to be drawn from this claim is that, researchers need to set the system's boundaries and determine the level and depth to which they are going to investigate its operations, before adopting any kind of SA measurement technique. However, to do so, it is important to clearly define the roles, duties, and tasks of all agents who take part in the operation within a system. If for example, the observer is about to measure shared SA, he/she should consider both individual and team roles. Hence, the decision concerning the selection of the appropriate SA measurement technique depends on the assumptions that a scholar makes when determining the boundaries and the elements of the system.

2. SA models depict the individual's in-the-mind process, i.e. emphasis has been placed on individual level: The majority of SA approaches is based either on individual SA models, e.g. [1], or on team SA models, e.g. [3, 9]. Most of the widely known SA models, e.g. the three level model [1], the perceptual cycle [20] etc, only illustrate what is going on within one's own head, without taking into account his/her responses to events that possibly stem from interactions with other humans, artifacts, and/or environments, and it is inevitable to affect the inner operations within an individual's head. But the fact that a person can actually have high levels of awareness, relative to the current system's situation, does not entail the same levels of team SA. While trying to measure the SA on a system level, it is problematic to partially focus on the awareness of individuals, because this may lead to an incorrect evaluation, e.g. in case of team probe-recall techniques (Table 1 - row 7*). For example, some agents and/or elements may have low SA even when they have an efficient level of SA acting as team members. Things are getting more dubious when a researcher strives to depict and/or measure more complex types of SA, such as DSA. Hence, it is not sufficient to examine the individual focus of attention, but the system's focus as an entity.

3. 'Blurred' perception of what is going to be measured: None of the existing SA measurement techniques clarifies what characteristic and/or behaviour is about to be measured. Even when the theory behind the technique exemplifies what is going to be measured, the output of the measurement is different from the pursued objective, like it happens in the case of performance measures (Table 1 - cell 5B) owing to the unclear relationship between SA and performance [3]. In freeze probe techniques, as another example, human agents describe what they see happening around them, however, this does not entail that what they see is consistent to what really happens in the system. For instance, when a person's attention is captured by a situation, this is not necessarily equivalent to being (fully) aware of that situation. Process indices, where body actions are those observed (Table 1 - row 6), imply that when someone acts in an acceptable way, then he/she is aware of the situation. Researchers have developed this group of techniques making the assumption that SA is what happening within one's head. It is thus an oxymoron to monitor body reactions, which may be biased, deliberate, or even a "by-the-book" attitude [3], and do not necessarily mirror the "in-the-head" cognitive, SA-related, operations (Table 1 - cell 6C). The incomplete problem statement may possibly lead to the disorientation of the solution. In a nutshell, the crucial deduction, on which researchers should put all their efforts, is the accurate and elaborate statement of the problem before making any attempt to solve it.

4. Information as the only factor that determines SA levels: Information flow is considered as the most significant factor that affects the SA formation [21]. The given models and measurement techniques focus on information flows and they are motivated by the notion that the more the information that enters the system, the more awareness the system will obtain. Researchers, for instance, make the assumption that individuals who possess much information perform better, and are aware of more elements in their environment, however, in complex collaborative systems, this is by far simplistic. What is needed in order to measure SA is not memory but comprehension, which is not necessarily proportional to available information. The linear connection between information and awareness is quite simplistic, since information requires, at first, filtering and further processing in order to be usable by the system. In complex socio-technical systems, information is not the only component that contributes to SA; that is, information triggers awareness, but does not entirely shape it. Thus, existing measurement techniques neglect to investigate the interactions between system agents and elements, and although this gap has already been detected by researchers, e.g. Salmon *et al.* [3], it is not bridged yet. Team probe-recall techniques (Table 1 - row 7*) is an illustrative example of disregarding such interactions. Considering that this technique serves to measure team SA, it seems incomplete to pose the same questions to all team members, individually, omitting to acquire information about the shared, collective, and/or compatible understanding of the situation.

5. Researchers apply SA measurement techniques when the system is already operating: None of the already known measurement techniques is applicable to the design phase of the system, as a precautionary measure for enhancing and preserving the awareness of system's possible future states. Some of them, for instance, require the freeze of operations, e.g. freeze probe, whilst others are performed in real time conditions, e.g. real-time probe, whether they comprise self- or hetero-measurement. Unfortunately, in none of the cases was awareness investigated from the design phase of the system. Engineers however, should be able, right from the early design phase, to design the system in such a way that it could operate in an efficient, effective, and safe way in respect to the scope and higher goals of the system, and carry at the same time those properties that are desirable and may empower awareness.

6. All SA measurement techniques arrive at qualitative conclusions: The existing SA measurement techniques give qualitative results, and because of this, they are subject to subjective collection and interpretation of data and information. In case of SART (Table 1 - row 3) self-rating technique, for example, respondents rate themselves on a scale from 1 to 7 when answering a typical question like this one: *"How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?"* [7]. Nevertheless, this does not mean that the result is quantitative just because the answer has a numerical designation (e.g. from 1 to 7), but it is practically a numerical interpretation and an estimation of qualitative, e.g. cognitive, mental, emotional, characteristics that contribute to the shaping of SA under specific circumstances.

7. The means to implement measurement techniques: This issue is in close relation with the previous one, since it refers to the means of executing the existing SA measurement techniques. Namely, questions, e.g. questionnaires, rating scales etc, posed to individuals, limit the scope of SA and focus the interest on an individual's opinion and awareness. A direct consequence is the underestimation of the technical parts of the system and the loss of the related information. When using questioning, it is also crucial to choose the appropriate and understandable, according to mental models and experiences, wording and question formulation to avoid misunderstandings or divergence from the core inquiry, i.e. what does the question tries to elicit from the respondents. In addition, techniques where observes 'draw' the picture of the system, judging by what they see other people do, bear the risk of differently understanding the same situation. Specifically, observers, pursuant to their mental models, guess what other agents perceive and have in mind about the current system setting, regardless of the possible chasm between their mental models. A method structured in such a way, that is possible for the examiner and/or the examinee to misunderstand its initial goal or differently interpret its qualitative result, is not considered ideal for comparative analyses in engineering systems.

5 Conclusion

Judging from the literature, researchers contented themselves with sweeping generalities about the weaknesses of the existing SA measurement techniques, failing to think 'outside the box', i.e. they did not question the context of the SA approaches and measurement techniques. However, complex socio-technical systems require more holistic reasoning and targeted approaches. This, in fact, justifies why neither traditional SA measurement techniques, i.e. individual and team ones, nor the DSA network-based approach [3] are entirely adequate and/or valid for the measurement of DSA in complex socio-technical systems settings. For this reason, and by looking deeper into the fragility of the existing SA measurement techniques, we concluded to the seven issues that emerge from the underlying need to change the paradigm. Hence, in order for researchers to avoid a dead-end technique for the measurement of DSA, they first need to explore the possibilities of resolving the above issues in the context of complex socio-technical systems.

Within the existing context (i.e. using the existing SA measurement techniques alone is not sufficient enough to obtain an estimate of DSA in complex socio-technical systems) and the current technological basis (i.e. we cannot constantly monitor human brain functions and reactions to stimuli), it is the cognitive and distributed 'character' of DSA that possibly renders its direct measurement quite a challenging task. Thus, we incline to conclude that the development of a DSA assessment approach, based on palpable and measurable system elements and behaviours, seems to be a feasible and realistic solution to the problem explained above. The word 'assessment' was intentionally chosen, since Oxford dictionary defines it as an opinion or a judgment about somebody/something that has been thought about very carefully, in contradiction to 'measurement', which is the act or the process of finding the size, quantity, or degree of something and seems to be extremely difficult, if not impossible, for DSA in the context of complex socio-technical systems. But, to deal with the challenge, whether it is possible to effectively assess DSA or not, this may probably presuppose a shift in the perception over DSA. Perhaps there is no sufficient solution so far, not because of researchers' inability to see, notice, or demonstrate the system's 'mechanisms' that lead to the emergence of DSA, but owing to the fact that they need to shift their viewpoint and 'update' their mental models in terms of SA and DSA, specifically. This, in turn, may be advantageous to take some preliminary steps to resolve issues surrounding a DSA assessment approach, and, as a previous step, to determine the impact of system elements on the DSA formation process, so as to redesign the existing system or to choose a more advantageous one, judging by the degree of DSA that emerges from it.

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