On Cybersecurity Science and Engineering*

Francesco Beltramini[1], Marco Rocchetto[1], and Luca Viganò[2]

[1] *V-Research, Verona, Italy*
[2] *King's College London, UK*

Abstract

The objective of this research is to develop of a theory that defines (all and only) the possible insecurity and security configurations of any abstract system. The theory is structured upon other theories that defines how a component of a system can be abstracted into an agent, defining how agents can be formalized (both syntactically and semantically) to describe an abstract system, such as a graph. Some of these theories (e.g. used for the semantic definition of the abstract system) are the epistemological definition of knowledge, the Belief-Desire-Intent and the Assertion-Belief-Fact framework of reference, mereology, and topological structure. We argue that a mereology is the most appropriate abstract underlying structure, do to its generality, for defining the expressiveness of the system abstraction. Furthermore, a mereology allows us to define an ontology rather than a taxonomy. We also correlate different abstractions of the system to the TRL and the engineering V-model.

We implemented a formal theory (of axioms) of a mereotopology, and of the region connection calculus (RCC3 and RCC5) in a Python program that uses the Z3 SMT solver. The results show that a single component (i.e. agent) of an abstract system has a definite number of different insecurity configurations (e.g. 53 using RCC5 over a topological structure) and only 1 secure (i.e. expected) configurations. The configurations are reported as models satisfying the abstract system semantics.

We considered the philosophical definition of truth behind our approach, rejecting "proof" by induction from partial empirical evidences. Our theory can be applied to system engineering and we show a concrete application of our theory to the risk assessment of an ad-hoc system. Finally, we provide a number of ideas to support the engineering of secure systems (e.g. purely cyber or cyber-physical).

1 Introduction

Humanum est errare

Seneca the Elder

The European Commission states in[9] that: "Cybersecurity is one of the priority areas [...] of the Commission initiative on ICT Standards, which is part of the Digitising European Industry[10] strategy launched on 19 April 2016. The aim is to identify the essential ICT standards and present measures to accelerate their development in support of digital innovations across the economy". The same document (i.e.[9]) states that "The EU will invest up to €450 million [...], under its research and innovation programme Horizon 2020". The EU, in 2016 published a press release[11] in which they present a strategy to invest €1.8 *billion* to "increase measures to address cyber threats". The EU is not the only investor in cybersecurity, most of the developed countries and several companies are investing enormous amount of money towards various aspects of cybersecurity (e.g. The US vulnerability databases[34] maintained by the National Institute of Standards and Technologies, i.e. NIST, of the US Department of Commerce).

The cybersecurity industry is growing fast, e.g. as reported in[7]. For example, in[37], published by the Forbes, is stated that €5.3 billion of funding where poured by venture capitalist into cybersecurity companies in 2018. The Forbes, in the same article, also highlights another peculiar (as seemly contradictory) trend: "[...] during the same time period, the number of cybersecurity breaches increased exponentially". The data reported by the NIST through the official CPE (Common Platform Enumeration) Dictionary Statistics on the NVD websites in [35], show that in 2016 the number of reported vulnerabilities reported where around 6000 while in 2019 the number of vulnerabilities was above 16000. The scientific community also reports similar findings. In fact, in[17], Cormac Herley (Microsoft Research) shows how basic cybersecurity principles (such as the confidentiality benefit over the clear text for passwords typed into forms, e.g. for logins in websites) are not fully understood or shared between the cybersecurity research community[26]. The lack of understanding of basic security principle, the inverse proportionality between investments in cybersecurity and the number of reported vulnerabilities year after year, can be linked to the lack of a foundational theory on cybersecurity, as already highlighted by Cormac Herley in[19].

In this article, we give the first scientific theory (to the best of our knowledge) on security.

Structure. In Section 2 we define and formalize the problem statement. In Section **??** we outline our security theory, and in Section **??** we describe the implementation of the theory and some empirical tests of the theory. Finally, in Section **??** we conclude the paper with an overview of the related work.

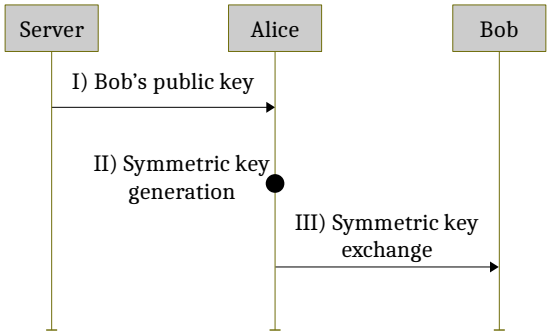

Figure 1: Abstraction of an ad-hoc esemplificative protocol execution

2 Problem Statement

In[19], Cormac Herley explores what he calls "an asymmetry in computer security", which he defines as follows: "Things can be declared insecure by observation, but not the reverse. There is no observation that allows us to declare an arbitrary system or technique secure". Herley then uses this argument to show that "claims that any measure is necessary for security are empirically unfalsifiable". Given that, any theory which is not falsifiable by an empirical experiment is well known[1] to be nonscientific (i.e. unfalsifiability is a fallacy of a theory), Herley concludes that there is no scientific theory on cybersecurity; which means that cybersecurity lays in the realm of pseudo-sciences[18]. Herley, e.g. in[16], discusses the implications of a nonscientific approach to cybersecurity, and highlights the tremendous impact on all the scientific research and engineering of systems; leading often to terrorism and wars, and wasting of resources in useless protections or overspending. While the criticism is investigated in[19], no solution is provided. On the contrary, the goal of this work *is* to lay the foundations of a scientific cybersecurity theory. Furthermore, in Section 2.1, we consider the problem raised by Herley not confined to "computer security" but to any abstract system (so that our theory may hold for any sound implementation such as networks, mechanical, cyber, or cyber-physical system, or even a single computer or a single device such as an hard-drive). There is also an apparent inconsistency in[19] that we seek to clarify before following (as we agree) the scientific path draw by Herley: cybersecurity is defined as an abstract property in many formal approaches to the investigation of the security of systems, and the security of the design of a formally verified protocol is indeed falsifiable. For example, in the protocol verification community, security is often defined as a formalization of the high-level properties confidentiality, integrity, and availability. The problem in such approaches is

[1] "A theory which is not refutable by any conceivable event is nonscientific. Irrefutability is not a virtue of a theory (as people often think) but a vice." – Karl Popper, Conjectures and Refutations[27]

not the definition of what cybersecurity is, but the use of theories (such as the Dolev-Yao attacker model[2][12]) that only applies to specific instances (often called scenarios) and abstraction of the protocol. This, in turn, creates a false sense of security since requires assumptions on the abstraction of the system of which security is verified. As an example, for the formal security verification of the system in Figure 1, a formalized scenario needs to be defined by a modeler who chooses (among others): (i) a scope of the formalization (e.g. excluding the server that distributes the public key is often done when verifying the security of authentication protocols), (ii) the number of sessions (even tough some approaches do reason on an infinite number of sessions such as[14]), (iii) honesty/dishonesty of the peers (e.g. in the ASLan++ language[38]), and (iv) the abstraction of the cryptographic primitives (e.g. ProVerif vs CryptoVerif[5]). Some of the choices will completely change the results of the formal verification of the system. For example, under the perfect cryptography assumption[3] and assuming that no violation to any security property is done after message I); in Figure 1, the freedom of choosing the scope determines that the flaws related to the dishonest impersonation of the Server may or may not be considered in the verification process. This choice has tremendous impact on the focus and findings of the verification of the security of the protocol. While this may seem to turn upon minutiae and foreseeable, this highlights the false sense of security that may derive from a non-scientific theory of system security[4].

2.1 Sicurezza: Safety and Security

In most of the natural languages, and in Italian too, the concepts of safety and security are not syntactically differentiated and both terms (safety and security) are expressed by the same word, e.g. sicurezza in Italian. A semantic distinction between safety and security is correlated to a belief[5] that safety deals with *accidents* (i.e. an unfortunate incident) posed by the natural environment (e.g. natural events such as wearing of hardware components) while security deals with *incidents* posed by mankind (e.g. attackers and bugs). The fundamental difference between nature and mankind (and, in turn, between safety and cybersecurity) is believed to be on the different intents[6] (accidents are unfortunate

[2] For the sake of simplicity, the Dolev-Yao attacker can be considered as an abstraction of an active attacker who controls the network but cannot break cryptography.

[3] As defined in[30]: "In the so called perfect cryptography assumption, the security encryption scheme is suppose to be perfect, without any exploitable flaw, and so the only way for the attacker to decrypt a message is by using the proper key. That assumption is widely accepted in the security protocol community, and most of the formal reasoning tools for the analysis of security protocols abstract away the mathematical and implementation details of the encryption scheme[36, 3, 2, 31]"

[4] "To the superficial observer, the analysis of these forms seems to turn upon minutiae. It does in fact deal with minutiae, but they are of the same order as those dealt with in microscopic anatomy." – Karl Marx, Capital Volume 1, 1867

[5] A belief has to be intended as a proposition which is supposed to be true by the majority of humans in our society without a scientific underlying theory but based on partial empirical evidences or inductive proofs.

[6] "The belief–desire–intention software model (BDI) is a software model developed for programming intelligent agents."[21]. In the BDI model, the intents represents the deliberative

while incidents are not) of the causes that generates the threat; namely, nature is believed not to have malicious intents (but unfortunate causes-effects) while threats generated by mankind are believed to be malicious[7]. An overview on the aforementioned aspects of safety and security is depicted in Figure 2 and is used as a baseline for a definition of the terms that structure our current understanding of safety and security.

- *Mankind* "refers collectively to humans" [23], while the concept of *Nature* is related "to the intrinsic characteristics that plants, animals, and other features of the world develop of their own accord" (e.g. the physical universe)[24].
  - So far, we have used several terms to refer to an *attacker*, i.e. threat agent or threat source, considering those terms to be semantically equivalent. This "shallowness" raise form the necessity of properly citing the different sources, but, in the reminder of this paper, we consider the Causality principle to be the *threat source*, Nature or Mankind to be the *threat agents* and an *attacker* as a specific malicious threat agent which materialize a threat.
- *Vulnerability*[8], as defined in[25] (and adopted in[4]), is "weakness in an information system, system security procedures, internal controls, or implementation that could be exploited by a threat source". On the one hand, the definition is broad to enclose as much causes (that generates a vulnerability) as possible; on the other hand, it derives from empirical evidences (which should be considered beliefs[9] since they are partial results in nature) while a vulnerability should be defined in a way that is empirically falsifiable. This means that the term vulnerability should have a complete and sound definition, so that no other causes (e.g. other sources) but the ones in the definition are responsible for a vulnerability. Furthermore, the term "threat sources" used in the definition in[25] may be identified with both Nature and Mankind, not differentiating between safety and security. In Definition **??**, we provide a formal theory of vulnerability (so that the scientific community can identify tests for the completeness and soundness of the definition itself).

state of an agent which determines the choice of that agent on what to do.

[7] Of course, logical flaws or bugs may be introduced by other means (e.g. ignorance) without explicit malicious intents, but the exploitation of those flaws is considered (for now, and detailed afterwards in the article) malicious, and then we consider any vulnerability to be malicious (without loss of generality) even if due to the lack of skills.

[8] The term vulnerability is not present in the Encyclopedia of Cryptography and Security, while it is used in 12 entries (such as in the definition of "penetration testing"[6]) highlighting how commonly this word is used without a proper supporting semantics

[9] "For this view, that *That Which Is Not* exists, can never predominate. You must debar your thought from this way of search, nor let ordinary experience in its variety force you along this way, (namely, that of allowing) the eye, sightless as it is, and the ear, full of sound, and the tongue, to rule; but (you must) judge by means of the Reason (Logos) the much-contested proof which is expounded by me." – Parmenides of Elea, On Nature (circa 500 B.C.), fragments B7.1–8.2 [15]

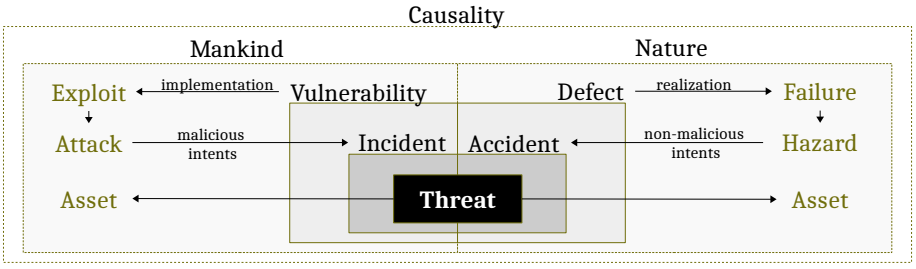

Figure 2: Overview security and safety keywords

Most of the safety-preserving principles in the field of engineering of safety-critical cyber-physical systems (such as elevators and aircraft), upon which safety requirements (e.g. in standards such as the IEC 61508 or 61511[1]) are defined, have been defined following empirical tests and measurements. While reasoning by induction based on the empirical observation should be avoided, since it may easily lead to false beliefs instead of scientific theories, this approach is often justified by the supposed impossibility of defining a theory that correctly predicts failures which, in turn, pose hazards to a system. To the best of our knowledge, and supported by[19], the correlation between predictability of environment and believed unpredictability of attackers (i.e. a malicious environment) has not been correlated to a theory on cybersecurity. Therefore, inductive research efforts in predicting malicious effects are accepted (and published) in scientific conferences (e.g. [29]). A failure of a wire due to environment (e.g. due to humidity, dust, heat &c) is defined from empirical evidences and processes have been standardized to test qualities of hardware components This process completely breaks down when a malicious environment (i.e. an attacker) is considered instead of the (supposedly honest and predictable) natural environment. Therefore, the same approach that is in use for safety, seems not to be applicable to test security.

Going back to Figure 2, a vulnerability does not necessarily become a threat for the system, unless exploited "through a channel that allows the violation of the security policy [...]"[25] (e.g. a software or procedure) that takes advantage of the vulnerability causing an *attack* to the system, which may result in several correlated incidents and threats. The process of exploitation of a defect as a vulnerability is reported in Figure 2 such that the difference between exploit and failure, and attack and accident is to be found just in the maliciousness of the intents that causes this process (i.e. excluding the intent, the terms are just syntactic transformation from a vulnerability to defect, from accident to incident). In the following, we conclude the informal definition of the terms that we used in this section and in Figure 2.

- *Causality* refers to the causality principle; defined in[8] as "Causality is a genetic connection of phenomena through which one thing (the cause) under certain conditions gives rise to, causes something else (the effect).

The essence of causality is the generation and determination of one phenomenon by another. In this respect causality differs from various other kinds of connection, for example, the simple temporal sequence of phenomena, of the regularities of accompanying processes".

- An *Exploit*[10] is "An exploit (from the English verb to exploit, meaning to use something to one's own advantage) is a piece of software, a chunk of data, or a sequence of commands that takes advantage of a bug or vulnerability to cause unintended or unanticipated behavior to occur on computer software, hardware, or something electronic (usually computerized)."[22].
- An *Attack*, as defined by the International Standard ISO/IEC 27000 is an "attempt to destroy, expose, alter, disable, steal or gain unauthorized access to or make unauthorized use of an asset"; where an *Asset* is "anything that has value to the organization". We note that for the purpose of this article, we do not want to focus on a specific organization or business to define asset but, in general, on any abstract organization (e.g. a company or a society). We do not consider ethical hackers as attacking a system. In fact, we consider the term *hack* as non-malicious (see Hacker[32]).
- A *Threat*, as defined in[25], is "Any circumstance or event with the potential to adversely impact organizational operations (including mission, functions, image, or reputation), organizational assets, individuals, other organizations, or the Nation through an information system via unauthorized access, destruction, disclosure, modification of information, and/or denial of service".
- *Defect*, "anything that renders the product not reasonably safe"[28] (i.e. a characteristic of an object which hinders its proper usability).
- *Failure*, as defined in[20] as "a state of inability to perform a normal function". The term is structured and detailed in [25, 13] but relying on an abstract notion of failure without a specific definition.
- *Hazard*, "a potential source of harm"[13].

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