On Cybersecurity Science and Engineering[*]

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Abstract

The objective of this research is the development 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, due 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. The implementation allows us to apply our theory to system engineering and showing concrete applications of our theory to the risk assessment of an ad-hoc system.

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1 Introduction

Humanum est errare

Seneca the Elder

The cybersecurity industry is growing fast (see Appendix A for a longer economic motivation), e.g. as reported in[25]. For example, in[90], 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 [83], show that in 2016 the number of reported vulnerabilities were around 6000 while in 2019 the number of vulnerabilities was above 16000. The scientific community also reports seemingly unjustifiable findings. In fact, in[41], 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[61]. 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[43]. An important issue raised by Herley is that the methodology applied by the security research community is quite often implicit and not always scientifically "correct". Herley equates correct to what Popper defined in [64] even if, we believe, the comments made by Hintikka in [45] should be taken into account. Therefore, we start by explicitly mention our method of enquiry.

Methodology The method applied in our line of research follows what (to the best of our knowledge) the scientific method mandates. We start, in Section 2, by detailing the problem statement, reporting a literature review on the main concepts and definitions related to security. We formulate a security hypothesis in Section 3; which we use to propose a theory on system security in Section 4. In Section 5, we apply our theory to an abstract and standard (i.e. based on standards) secure process development lifecycle, following the principle of requirement engineering (with an ad-hoc running example, based on the SWaT testbed [56]). This application shows how our theory can be used to predict all of the possible security weaknesses of a system, allowing the falsification of our theory. In fact, if any security weaknesses were to be found in a system and not predicted by our theory, the theory could be declared incomplete. Similarly, if a security weakness would be predicted by our theory but found to be impossible to have our theory could be declared as wrong. In order to apply our theory we implemented, as described in Section 6, the theory in a prototype tool that can be used for the risk assessment of a design of cyber-physical systems.

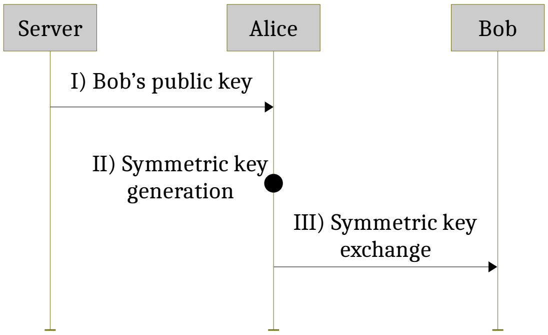


Figure 1: Abstraction of an ad-hoc esemplificative protocol execution

2 Problem Statement and Literature Review

Before going into the details of the literature review, we show that the lack of agreement on what security is can actually be found in the literature, and can be categorized with respect to the method of enquiry. In the following, we provide three examples based on the categorization provided by Sextus Empiricus in [32], since it appear to us to be comprehensive. “The natural result of any investigation is that the investigators either discover the object of search or deny that it is discoverable and confess it to be in-apprehensible or persist in their search. [...] This is probably why”[32]:

- The *dogmatists* “have claimed to have discovered the truth”
  - Wikipedia defines cybersecurity in [51] as the protection of computer systems and networks from the theft of or damage to their hardware, software, or electronic data, as well as from the disruption or misdirection of the services they provide.
- The *academics* “have asserted that it cannot be apprehended”
  - Eugene H. Spafford, Professor at Purdue University, defines cybersecurity as follow. “The only truly secure system is one that is powered off, cast in a block of concrete and sealed in a lead-lined room with armed guards — and even then I have my doubts.” [78]
- The *skeptics* “go on inquiring”
  - Cormac Herley reaches the conclusion that cybersecurity has no definition. “There is an inherent asymmetry in computer security: things can be declared insecure by observation, but not the reverse. There is no test that allows us to declare an arbitrary system or technique secure. This implies that claims of necessary conditions for security are unfalsifiable. ” [43]. Therefore, we propose our investigation.

In[43], 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[42]. Herley, e.g. in[40], 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[43], 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[43] 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 (against the security properties verified). 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 not the definition of what cybersecurity is but the generality of the results, since they takle a specific step (and not the first) of the engineering process (of system). Therefore, the theories underlying the verification are based on assumptions which non-evidently apply to a general security theory. As an example, the so called Dolev-Yao attacker model[2][30] 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 non-justifiable assumptions on the abstraction of the system of which security is verified. More specifically, 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[34]), (iii) honesty/dishonesty of the peers (e.g. in the ASLan++ language[91]), and (iv) the abstraction of

[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[64]

[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.

the cryptographic primitives (e.g. ProVerif vs CryptoVerif[7]). While many tools and theories improves the issues we discussed, there is no agreement on which should be the definitive approach if any and, more importantly, some of the choices made by the modelers/engineers using those formal apporaches may completely change the results of the formal verification of the system (an interesting example on how difficult it is to even just compare the approaches is given in [16]). 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-falsifiable theory of system security[4].

2.1 Terminology: Safety or 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 while incidents are not) of the causes that generates a 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

[3] As defined in[70]: "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[88, 5, 3, 71]"

[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 people in our society, without a scientific underlying theory but based on partial empirical evidences or inductive reasoning based on partial empirical evidences.

[6] "The belief–desire–intention software model (BDI) is a software model developed for programming intelligent agents."[49]. In the BDI model, the intents represents the deliberative 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 even if due to the lack of skills.

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" [53], 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)[54].
  - 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" has raised 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 materializes a threat.
- *Vulnerability*[8], as defined in[60] (and adopted in[6]), 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) On the other hand, 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[60] may be identified with both Nature and Mankind, not differentiating between safety and security.

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 are defined (e.g. in standards such as the IEC 61508 or 61511[1]), are based on empirical tests and measurements (therefore should be considered hypothesis and not definitions). While reasoning by induction based on the empirical observation should be avoided, since it may easily lead to false beliefs, this approach is often justified by the supposed impossibility of defining a theory that correctly predicts failures. To the best of our knowledge, and supported by[43], there is no scientific theory that defines what a secure sys-

[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"[8]) 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 [39]

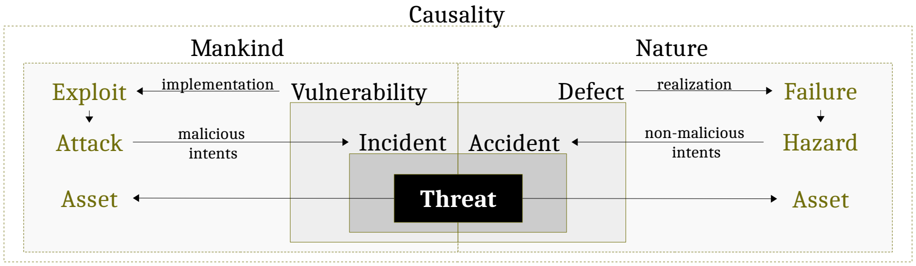


Figure 2: Overview of keywords related to security and safety

tem is. Therefore, (inductive[10]) research efforts in predicting malicious effects are accepted (and published) in scientific conferences (e.g. [69]). 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 for security (e.g. for security testing).

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 [...]"[60]. For example, a software or procedure that takes advantage of the vulnerability causing an *attack* to the system 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[26] 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".

[10] "So, whenever they argue "Every man is an animal and Socrates is a man; therefore Socrates is an animal," proposing to deduce from the universal proposition "every man is an animal" the particular proposition "Socrates therefore is an animal," which in fact goes (as we have mentioned) to enstablish by way of induction the universal proposition, the fall into the error of circular reasoning, since they are enstablishing the universal proposition inductively by means of each of the particulars and deducing the particular proposition from the universal syllogistically." Sextus Empiricus, Outlines of Pyrrhonism II-195 [32]

- An *Exploit*[11] "[...] (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)."[52].

- 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 (as, e.g. in [79]).

- A *Threat*, as defined in[60], 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"[68] (i.e. a characteristic of an object which hinders its proper usability).

- *Failure*, as defined in[47] as "a state of inability to perform a normal function". The term is structured and detailed in [60, 33] but relying on an abstract notion of failure without a specific definition.

- *Hazard*, "a potential source of harm"[33].

Our literature review shows that most of the definitions relates insecurity to dis-honesty (also called maliciousness or adversarial) of an agent (often called adversary or attacker). This, however, just moves the problem of defining what cybersecurity is as the problem of defining what an dishonest agent can or cannot do in a system[12] As in the Dolev-Yao theory, we may correlate "being dishonest" to "not following the intended behavior/rules". In the case of a generic system, a dishonest agent is, therefore, any agent that doesn't follow the intended behavior (or functionality or logic) of the system. Given the generality of the definition, and its high level of abstraction, we may conclude that the hypothesis seems evident. For example, a software can be considered an agent of the system and whenever it has a bug, it can be exploited causing an Incident. However, this hypothesis has lead to the un-testable conclusion that the dishonest behaviors of agents cannot be defined in general (e.g. due to the heterogeneity of agents

[11] We note that the term exploit is only used as a verb in[81]

[12] where an agent is any virtual or physical entity of the system or using the system (e.g. a device, a software, or a human being) and dishonesty is not necessarily related to malicious motivation but also to incompetence or lack of skills.

and systems) and that huge repository of dishonest behaviors should be kept as definition, such as CWE[24], CVE[15], CAPEC[13], NVD[82]; or that dishonesty of an agent with respect to a security protocol should be defined as a number of predefined actions as in [88, 5, 3, 71] (to name a few).

3 Formalization of a Security Hypothesis

A formalization requires a formal logic and a formal language. We base our formalization on first order logic (FOL) with the standard truth-value semantics[13].

We consider a first-order language $\mathcal{L}$ over a signature Σ_P where $P, P', \ldots, P^n$ represent terms, and $\varphi, \varphi', \ldots, \varphi^n$ represent formulas. The syntax is defined as follows.

$$\varphi := P \mid \neg\varphi \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid \varphi \Rightarrow \varphi' \mid \forall P.\ \varphi \mid \exists P.\ \varphi$$

where $\wedge$, $\neg$, $\vee$, and $\Rightarrow$ are connectives representing conjunction, negation, disjunction, and (material) implication respectively; while $\forall$ and $\exists$ represent the standard universal and existential quantifiers (resp.). Finally, the symbol "." is just syntactic sugar. We consider $\sigma \subset \Phi \times \{\top, \bot\}$ as the interpretation function, where Φ is any collection of sentences in $\mathcal{L}$ and $\top$ and $\bot$ represent the concepts of "Tautology/True" and "Contradiction/False" respectively.

Following Figure 2, we start by formalizing the outermost term: Causality.

3.1 Causality Principle

We formalize the Causality Principle starting from a K modal logic[36] so that (i) we use a de-facto standard way of defining the Causality Principle, and (ii) we do not restrict the causality relation (between worlds) in any way (so we are as general and abstract as possible). The standard definition of K modal logic is given in Definition 3.1 in terms of an interpretation function (which we named σ with a slight abuse of notation) defined in Definition 3.2.

Definition 3.1. K Modal Logic – A K-frame is a frame $\mathbf{K} = \langle G, R \rangle$ in the K modal logic where R is a binary relation (i.e. a set of ordered pairs) between possible worlds $R \subseteq G \times G$, where G represents the possible worlds, and $G \neq \emptyset$. An actual world $\omega * \in G$ is assumed. For any proposition P, an interpretation function $\sigma(\omega, P)$ returns the truth value of P; e.g. $\sigma(\omega, P) = \top$ means that P holds in ω. A model is defined as the tuple $M = \langle G, R, \sigma \rangle$.

Definition 3.2. Causality as K Modal Interpretation Function – Causality is (recursively) defined as the modal interpretation function σ, as follows.

(σ0) if $\sigma(\omega, P) = \top$ then $\omega \models P$
(σ1) $\omega \models \neg P$ iff $\omega \not\models P$

[13] The choice of this logic is usefull for the fomal treatment of the theory we'll define in Section 4. We do not provide a proof that the choice of FOL doesn't impede the formulation of a correct security theory, nor that the semantics of English isn't an issue. So, we believe that this doesn't pose an issue for the formulation of the security hypotheses.

Table 1: RCC3, RCC5, and RCC8 relations between Regions X, Y and Z

RCC3	RCC5	RCC8	Name	Notation	Definition
			Connects with	$C(X, Y)$	$X \subseteq Y$
			Disconnected from	$\neg C(X, Y)$	$X \nsubseteq Y$
			Part of	$P(X, Y)$	$\forall Z\ C(Z, X) \rightarrow C(Z, Y)$
			Overlaps	$O(X, Y)$	$\exists Z\ P(Z, X) \wedge P(Z, Y)$
●			**Overlaps Not Equal**	$ONE(X, Y)$	$O(X, Y) \wedge \neg EQ(X, Y)$
●	●	●	**Equal to**	$EQ(X, Y)$	$P(X, Y) \wedge P(Y, X)$
●	●	●	**DiscRete from**	$DR(X, Y)$	$\neg O(X, Y)$
	●	●	**Partial-Overlap**	$PO(X, Y)$	$O(X, Y) \wedge \neg P(X, Y) \wedge \neg P(Y, X)$
	●		**Proper-Part-of**	$PP(X, Y)$	$P(X, Y) \wedge \neg P(Y, X)$
	●		**Proper-Part-of-*i*nverse**	$PPi(X, Y)$	$P(Y, X) \wedge \neg P(X, Y)$
		●	**Externally Connected**	$EC(X, Y)$	$C(X, Y) \wedge \neg O(X, Y)$
		●	**Tangential PP**	$TPP(X, Y)$	$PP(X, Y) \wedge \exists Z\ [EC(Z, X), EC(Z, Y)]$
		●	**Tangential PPi**	$TPPi(X, Y)$	$TPP(Y, X)$
		●	**Non-Tangential PP**	$NTPP(X, Y)$	$PP(X, Y) \wedge \neg\exists Z\ [EC(Z, X), EC(Z, Y)]$
		●	**Non-Tangential PPi**	$NTPPi(X, Y)$	$NTPP(Y, X)$

(σ2) $\omega \models P \wedge Q$ iff $\omega \models P$ and $\omega \models Q$

(σ3) $\omega \models \Box P$ iff for any world $\omega' \in G$ if $\omega R \omega'$ then $\omega' \models P$

(σ4) $\omega \models \Diamond P$ iff there exists a set of worlds $\Omega' \subset G$ such that for any $\omega' \in \Omega'$, if $\omega R \omega'$ then $\omega' \models P$

(σ5) $\models P$ iff $\omega* \models P$

where truth is defined as necessary with $\Box$ and possible with $\Diamond$.

As mentioned before, the accessibility relation R is free from any axiomatic restriction (e.g. it's not reflexive nor anti-reflexive). We note that we have defined the Causality principle without considering it a *threat source* since, given that this is the first and outermost concept in Figure 2, we lack the concept of intent and maliciousness (which are not inherent to the Causality Principle). In other words, the Causality principle or the Kripke structure doesn't correlate cause-effect (or worlds) due to any other principle but causality itself; therefore, in order to distinguish nominal or honest cause-effects and non-nominal or dishonest ones we would need to add additional constraints, defining what honesty is in a factious way. Similarly, in the next sections we won't be able to discriminate between Nature and Mankind due to their honesty. We argue that the concept of honesty, even if we do not state that it is not intrinsic to all the definition of Nature or Mankind, requires additional constraints or statements in order to be defined. **FIX**[14]

3.2 Agents: Mankind and Nature

Mankind and Nature are considered as two abstract agents, both defined as collections (i.e. an abstract type that does not imply a specific implementation) of their sub-agents (i.e. humans for Mankind and plants, animals, &c. for Nature). Similarly to[75], we define Mankind and Nature, and any other agent in

[14] **mr:** is connects with an equivalence? can it be correctly represented by $\subseteq$?

the reminder of this article, as a meronomy (an hierarchy of Part-Whole relations) based on a standard definition of mereology, i.e. based on the definition of Parthood relation between *Parts*. Due to the necessity of considering different types of Part (as we'll show afterwards) we extend the mereology to a mereo-topology[77, 89, 65], considering the relations in Table 1. For the sake of readability, we use the term *Region* both to refer to a mereological Part and to a topological Region. The choice of mereotopology is also correlated to the objective of defining a formal ontology, which we use to define the (formal) semantics of the terms (Parts) in Section 2, and of the concepts of safety and security (whole). We aim at creating a meronomy instead of the taxonomies such as the one provided in[82, 67] or instead of the poorly justified CVSS[59] scoring system.

A mereotopology, as defined e.g. in[65], is an ordered mathematical structure where the basic relation between Regions is the reflexive and symmetric**FIX**[15] *Parthood* relation $\subseteq$.

Definition 3.3. Parthood – Given any pair of mereotopological Regions X and Y,

1. Reflexivity: $\forall X.\ (X \subseteq X)$
2. Symmetry: $\forall X, Y.\ (X \subseteq Y \Rightarrow Y \subseteq X)$

The Parthood relation orders a universe of agents Ag (later defined in Definition 3.5) by defining the so called *Connects with* (see in Table 1) relation between Regions. We want this universe Ag to be expressible in FOL. In this way, we can reason both on the constituent of security, and on the evolution of those constituent w.r.t. cause-effects relations according to the modal structure of causality we defined. This will allow us (in Section 5 and Section 6) a better**FIX**[16] positioning w.r.t. risk assessment technologies (which most often reason on the constituent of a system design), and protocol verification tools (which requires some formalization of a cause-effect relation, e.g. in Linear Temporal Logic).

In order to correlate the definition of agents (i.e. Mankind and Nature) to the mathematical structure of the logic that defines them, we express Mankind and Nature as formulas over the theory of mereology and then in terms of mereotopological Regions, extending the interpretation function σ to include a formal theory of mereotopology. We use the Region Connection Calculus (RCC), as defined in [55, 37], to provide an axiomatization of the spatial concepts and relations in FOL to correlate the algebraic structure to mereology. In its broader definition, the RCC theory is composed by eight axioms, and is known as RCC8. In the text, for brevity, we will often focus only on RCC5 (without loss of generality) by not considering tangential connections between spatial Regions. We discuss the choice of RCC5 in more detail in Section 4.3. In Table 1, we summarize the axioms of the Region Connection Calculus (see, e.g., [38]).

[15] **mr:** I guess it must be monotonic as defined in[65] but I don't find it consistently in other papers.

[16] **mr:** Can we prove this by construction?

Definition 3.4. RCC axiomatization – For any X, Y pair of Regions in a mereotopology:

(σ6) $\sigma(X \subseteq Y)$ iff $[\sigma(X \subseteq X) = \top$, and $\sigma(X \subseteq Y) = \bot$ or $\sigma(Y \subseteq X) = \top]$**FIX**[17]
(σ7) $\omega \models C(X,Y)$ iff $\omega \models X \subseteq Y$
(σ8) $\omega \models \neg C(X,Y)$ iff $\omega \not\models X \subseteq Y$
(σ9) $\omega \models P(X,Y)$ iff $\omega \models \forall Z.\ C(Z,X) \Rightarrow C(Z,Y)$
(σ10) $\omega \models O(X,Y)$ iff $\omega \models \exists Z.\ P(Z,X) \wedge P(Z,Y)$
(σ11) $\omega \models EQ(X,Y)$ iff $\omega \models P(X,Y) \wedge P(Y,X)$
(σ12) $\omega \models DR(X,Y)$ iff $\omega \models \neg O(X,Y)$
(σ13) $\omega \models PO(X,Y)$ iff $\omega \models O(X,Y) \wedge \neg P(X,Y) \wedge \neg P(Y,X)$
(σ14) $\omega \models PP(X,Y)$ iff $\omega \models P(X,Y) \wedge \neg P(Y,X)$
(σ15) $\omega \models PPi(X,Y)$ iff $\omega \models P(Y,X) \wedge \neg P(X,Y)$

where Z is a mereotopological Region.

Definition 3.5. Agent: Mankind or Nature – An agent $a \in Ag$ is a tuple $\langle rcc(\chi', \chi''), \ldots, rcc(\chi^{n-1}, \chi^n)\rangle$ of RCC relations rcc over mereotopological Regions $\chi', \ldots, \chi^n \subseteq$ X.

As depicted in Figure 2, Causality, Mankind, and Nature have a dashed border representing their correlation in terms of cause-effect and then in terms of formal structure which defines them: Modal Logic. Vulnerability, Defect, Incident, Accident, and Threat, similarly, are correlated (depicted as a solid border) in terms of underlying formal structure: Mereotopology.

We have now defined the concept of agent, and defined Mankind and Nature as agents. Given that, as we stated beforehand, they are defined by their subagents, and that we are not interested in a general definition of Mankind and Nature but in the one that serves our purpose (i.e. defining a security theory), in the following sections we focus on those terms identified in the literature review.

3.3 Regions: Vulnerability and Defect (and Weakness)

As informally defined in Section 2, a Vulnerability or a Defect is a *Weakness*. As an example, a categorization of weaknesses is given in[24] with 808 weaknesses categorized as “Research Concepts”, distributed as follows:

- Incorrect Calculation - (682)
- Incorrect Access of Indexable Resource (“Range Error”) - (118)
- Use of Insufficiently Random Values - (330)
- Improper Interaction Between Multiple Correctly-Behaving Entities - (435)
- Improper Control of a Resource Through its Lifetime - (664)
- Insufficient Control Flow Management - (691)

[17] **mr:** would it be better/clearer or just correct to write $\sigma(X \subseteq Y)$ iff $\sigma(X \subseteq X \wedge [X \subseteq Y \vee Y \subseteq X]) = \top$

- Protection Mechanism Failure - (693)
- Incorrect Comparison - (697)
- Improper Check or Handling of Exceptional Conditions - (703)
- Improper Enforcement of Message or Data Structure - (707)
- Improper Adherence to Coding Standards - (710)

The definition given by the MITRE in[35] of weakness is: “Software weaknesses are errors that can lead to software vulnerabilities. A software vulnerability, such as those enumerated on the Common Vulnerabilities and Exposures (CVE) List, is a mistake in software that can be directly used by a hacker to gain access to a system or network”. The definition is circular if we interpret the word “error” and “mistake” with the same semantics: a weakness is an error that leads to a vulnerability and a vulnerability is a mistake which, in turn, is a weakness. The only difference (between weakness and vulnerability) seems to be that one can consider weakness as a ground term and state that a vulnerability is caused by a weakness, i.e. $\Omega, W \models \Diamond V \wedge W$ where W, V are Regions of Weaknesses and Vulnerabilities (resp.); accepting (for now) the hierarchy in the CWE[14] as ground truth. Similarly, we consider the CVE[15] (a database of Vulnerability), or the CVE reported in the NVD, as a ground truth in the case of Vulnerability. It is then obvious that without the formalization of the concept of error, we cannot properly formalize the concepts of Weakness (and Vulnerability); which remains one of the sub-region of errors with the only constraint that it must be connected to another region called Vulnerability (which in turn depend on the definition of error).

Definition 3.6. Region: Weakness and Vulnerability – A Region $W \subseteq E$ of a region E of errors, is defined as Weakness[18] iff there exists $\omega \in G$ such that $\omega \models W$, $\omega \models \Diamond V$, and $\omega \models \Diamond \neg DR(W, V)$.

Example 1. *CWE-116: Improper Encoding or Escaping of Output[46]* –

- *Description: The software prepares a structured message for communication with another component, but encoding or escaping of the data is either missing or done incorrectly. As a result, the intended structure of the message is not preserved.*

- *Example: This code displays an email address that was submitted as part of a form. Example language JSP.*

  ```
  <% String email = request.getParameter("email"); %>
  ...
  Email Address: <%= email %>
  ```

  The value read from the form parameter is reflected back to the client browser without having been encoded prior to output, allowing various XSS attacks (CWE-79).

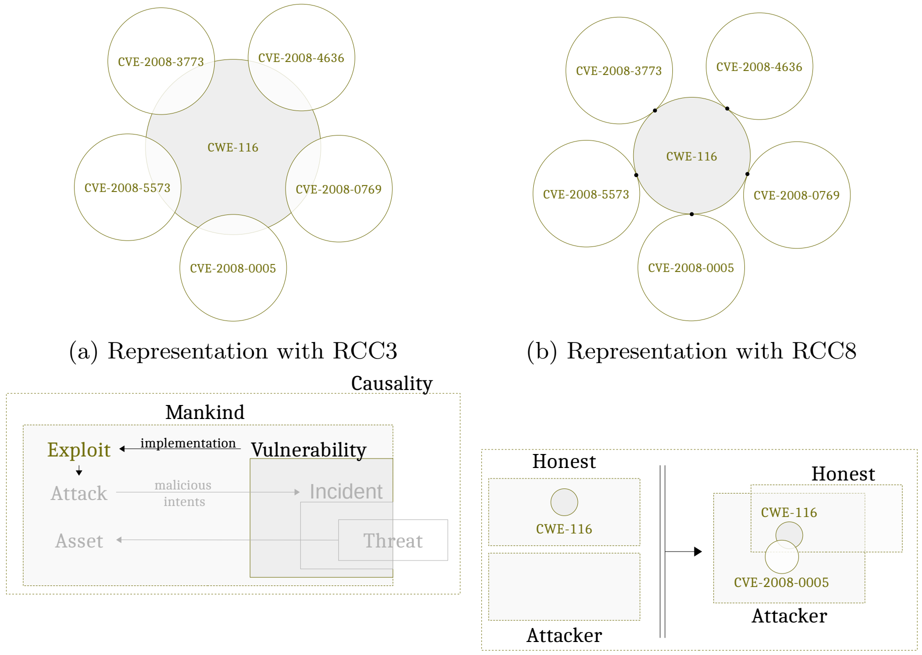
[18] i.e. representing an error introduced by the agent into any phase of production, e.g. of the secure process development life-cycle, of any system or subsystem

- *Observed Examples*
  - *CVE-2008-4636[22]: OS command injection in backup software using shell metacharacters in a filename; correct behavior would require that this filename could not be changed.*
  - *CVE-2008-0769[20]: Web application does not set the charset when sending a page to a browser, allowing for XSS exploitation when a browser chooses an unexpected encoding.*
  - *CVE-2008-0005[18]: Program does not set the charset when sending a page to a browser, allowing for XSS exploitation when a browser chooses an unexpected encoding.*
  - *CVE-2008-5573[23]: SQL injection via password parameter; a strong password might contain &*
  - *CVE-2008-3773[21]: Cross-site scripting in chat application via a message subject, which normally might contain & and other XSS-related characters.*
  - *CVE-2008-0757[19]: Cross-site scripting in chat application via a message, which normally might be allowed to contain arbitrary content.*

Definition 3.6 states that CWE-116 is a weakness iff there exists a world in K Modal Logic, representing the system in which this weakness exists, such that the natural evolution of this system (i.e. formalized by the causality principle) make it possible to reach another state of the system (i.e. another, accessible world) where there exist a vulnerability that can be implemented from CWE-116 (and this relation is not DR). The CWE website proposes the connection between CWE-116 and, for example, CVE-2008-5573; a vulnerability of the login subsystem of the Poll Pro v2.0[86] system. The formal relation between the two is given as a link (i.e. URI) between the CWE and the CVE, the description of the relation is not defined but it is supposed to be inferred from the descriptions of the CWE-CVE. We can formally represent this link as the ONE connection in RCC3, depicted in Figure 3a, or EC connection in RCC8 (Figure 3b).

It is interesting to note that the CWE-CVE relation expresses the correlation between weaknesses and vulnerabilities in the most simple form, such that we can formalize all the relation as ONE in RCC3 or EC in RCC8. To express a more complex relation between the two we shall analyze the definition of CWE-116. This is related to the Weakness-Vulnerability-Incident process (i.e. to the details on the implementation/realization in Figure 2) that we analyze in Section 3.4.

Attacker as a Dis-honest Agent As we mentioned in Section 2 when we postulated the security hypothesis, Weaknesses and Vulnerability are the two core security concepts of the current understanding of what security is. However, we see two (opposed in terms of abstraction) possibility to better defined



(a) Representation with RCC3

(b) Representation with RCC8

(c) Representation in K-Modal Logic

Figure 3: Relations between CWE-116 and correlated CVEs

those concepts: defining how an agent (Mankind or Nature) can maliciously use Weaknesses to produce Vulnerability (and, in turn, Exploits), or how Errors can be defined (since Error is a term from which Weakness are, in turn, defined). The former, in our current formalization, implies detailing and constraining the Causality Principle by introducing constraints on how agents acts. For example, introducing the concept of intentionality, motivation, or desire (see the BDI framework defined in [66] for a general overview of those concepts). The symbolic approach (also called Dolev-Yao model) in the formal verification of security and communication protocols, can be used in this spirit. The attacker can be seen as an additional agent (often identified with the network where the messages are exchanged) that sees the network traffic and manipulates it. The actions are generic (the attacker can combine two messages, split a message into its components, or decrypt/encrypt if it has the proper security key) but not something that an honest agent cannot do. The main difference is that an honest agent follows the nominal specification of the protocol while the attacker doesn't. The attacker non-deterministically opens as many new sessions as it wants and the causality structure in which this scenario (protocol + attacker) has been defined, can be analyzed for a state that is considered erroneous with respect to some security requirements decided a priori. Therefore, as we mentioned in Section 2, the formal verification of the security of protocols can be considered a scientific security theory; the implementations resulting from the formalized (and verified) design can be tested against the formalized security requirements. So, it is not completely true that "Thus, formal approaches offer no escape from our basic problem; only by making unfalsifiable assumptions (about what an attacker can do) will they allow derivation of a necessary condition" (as Herley describes in[41]) rather, the unfalsifiability-related issue seems to stem from how security conditions are defined, i.e. how security requirements are defined. One can easily see that this is not just an issue in the formal protocol verification community but the very foundations of the concept of Weakness and Vulnerability are defined in a way that makes it impossible (they are necessary conditions) to make a general security statement on any system (even if we tested every single Weakness on the CWE on our system it may be the case that a Weakness han yet to be discovered). Therefore, we hypothesize that a security theory should define in a complete way how errors (and then Weaknesses, Vulnerability, and Exploits) may be introduced.

We now conclude (for completeness) the analysis of the various security-related terms we identified in the literature review, without formally defining what Errors are (which will be defined in the reminder of the paper).

Definition 3.7. Region: Vulnerability and Defect − A region $\chi \subseteq a$ of an agent $a \in Ag$ is called *Vulnerability* if the agent a is referred to as Mankind, *Defect* if the agent is referred to as Nature.

3.4 Process: Incidents and Accidents

In our informal definition depicted in Figure 2, an Incident is generated through a process caused by a Vulnerability (which, in turn, is caused by a Weakness). Symmetrically, Nature has a process from Defect to Accidents. We start by analyzing the process generated by Mankind, which is divided into the following phases (as shown in Figure 5):

1. An agent (Mankind or Nature) defines a system, e.g. by following an engineering process for creating a new system, or for redesigning or improving an existing system (e.g. a component or a collection of components)

2. The axiomatic/dogmatic definition of a system contains a Weakness (i.e. the agent, Mankind or Nature, introduces an unintended behavior), for example as an un-intended behavior or as an architectural fallacy, and this Weakness can be applied to the abstract definition of the system.

3. The Weakness can be defined as a malicious process for a system, called Vulnerability (or Defect for Nature)

4. The process expressed by the Vulnerability can be made operational for a specific implementation of the system (i.e. implemented by Mankind or realized by Nature)

Those additional details are depicted in Figure 4, an update of Figure 2.

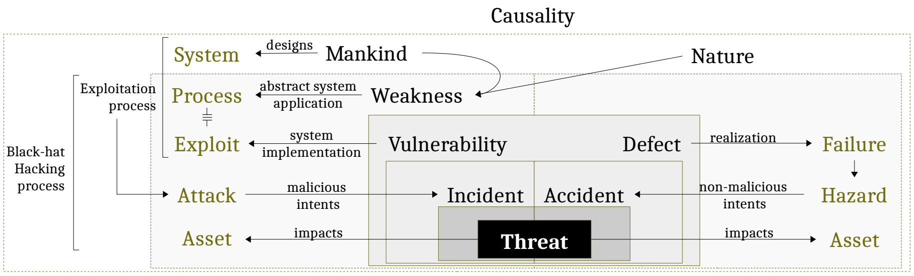


Figure 4: Updated overview security and safety keywords, where Process has to be intended as "Abstract Exploitation Process"

Definition 3.8. Exploitation Process – An *Exploit* is an *implementation* of a Vulnerability, where a Vulnerability describes how to transform a Weakness into an abstract malicious process, which can be applied[19] to one or many systems. So, the act of an agent (Mankind) of "exploiting a Vulnerability" is the process of making the Vulnerability operational, by implementing the Vulnerability w.r.t. a specific target system. Whenever the agent is Nature, the implementation is more broadly considered a realization[20].

The Common Attack Pattern Enumeration and Classification[13] (CAPEC) online service provides a "community resource" which aims at "identifying and understanding attacks". The MITRE writes on the CAPEC homepage that "Understanding how the adversary operates is essential to effective cyber security. CAPEC helps by providing a comprehensive dictionary of known patterns of attack employed by adversaries to exploit known weaknesses in cyber-enabled capabilities. It can be used by analysts, developers, testers, and educators to advance community understanding and enhance defenses.". We can extrapolate two major concepts:

- While understanding the exploitation process is the aim of the CWE and CVE initiatives, understanding the malicious (or black-hat) hacking process is the aim of the CAPEC initiative.
- CAPEC provides a *dictionary* of *known* attack patterns. As stated in details in Section 2, this dictionary contains empirical evidences and should not be used to induce a cybersecurity theory; but it can be used to validate a theory.

Example 2. *The CWE-116 doesn't just relate the Weakness to a number of Vulnerability in the CVE but also relates the Weakness to a number (4 for the CWE-116) of abstract attack path in the CAPEC:*

- *CAPEC-104[9] Cross Zone Scripting*

[19] Meaning that the malicious process, i.e. any structured procedure such as a protocol, can be somehow made operational, e.g. implemented

[20] "The state of being realized"[48]

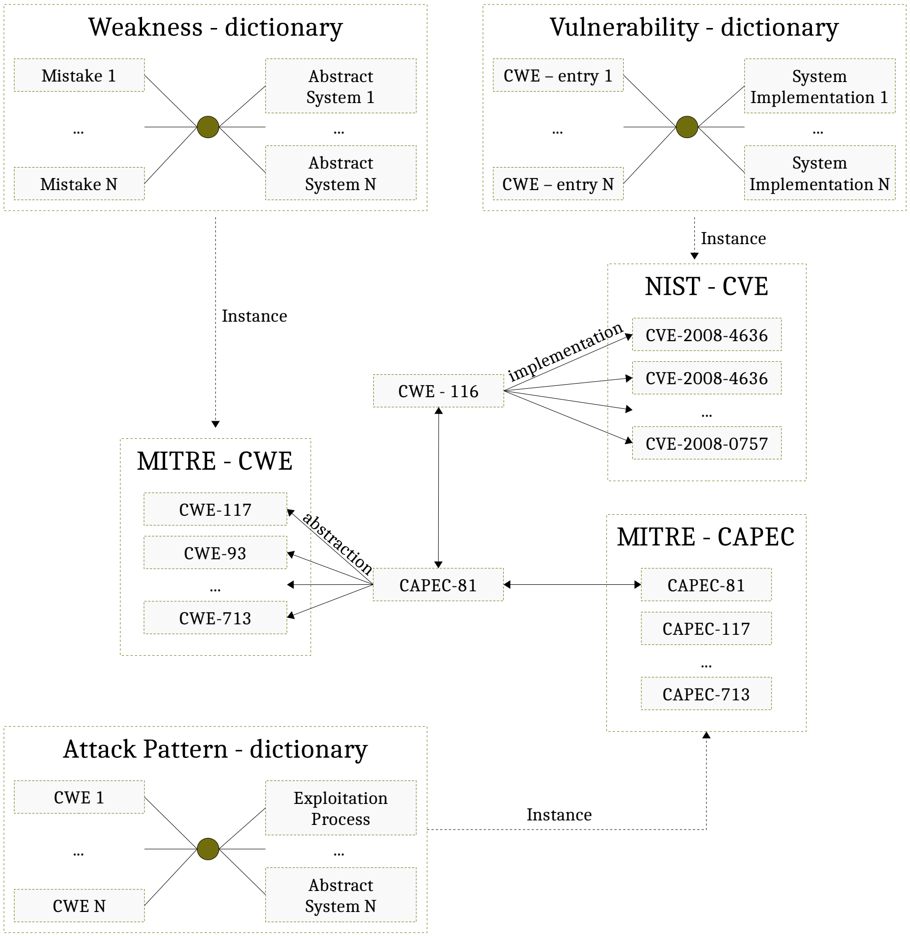


Figure 5: Cybersecurity online dictionaries and connections

- *CAPEC-73[10] User-Controlled Filename*
- *CAPEC-81[11] Web Logs Tampering*
- *CAPEC-85[12] AJAX Fingerprinting*

Each CAPEC entry has a reference to one or many CWE, including CWE-116.

After the exploitation process, as depicted in Figure 5, another process starts and transforms a Vulnerability in an Incident by Attacking the system with a malicious Hack, as follows.

5. An agent (Mankind[21]) starts the exploitation process to hack a system.

[21] For the sake of readability we focus only on Mankind as an agent

We use the term hack (as hacking) to stress that nothing prevents this process from being honest (i.e. the so called honest-but-curious attacker), however, for the sake of simplicity, we focus on Attacks which are malicious by definition.

6. An Attack is applied to a system with malicious intent by an agent
7. The application of the attack results in an Incident which impacts, i.e. poses a Threat to, an Asset

Definition 3.9. Black-hat Hacking Process An *Attack* is the act of making operational an *Exploitation Process* causing an Incident.

Example 3. *CAPEC-81[11] Web Logs Tampering –*

- *Description: An attacker is able to cause a victim to load content into their web-browser that bypasses security zone controls and gain access to increased privileges to execute scripting code or other web objects such as unsigned ActiveX controls or applets. This is a privilege elevation attack targeted at zone-based web-browser security. In a zone-based model, pages belong to one of a set of zones corresponding to the level of privilege assigned to that page. Pages in an untrusted zone would have a lesser level of access to the system and/or be restricted in the types of executable content it was allowed to invoke. In a cross-zone scripting attack, a page that should be assigned to a less privileged zone is granted the privileges of a more trusted zone. This can be accomplished by exploiting bugs in the browser, exploiting incorrect configuration in the zone controls, through a cross-site scripting attack that causes the attackers' content to be treated as coming from a more trusted page, or by leveraging some piece of system functionality that is accessible from both the trusted and less trusted zone. This attack differs from "Restful Privilege Escalation" in that the latter correlates to the inadequate securing of RESTful access methods (such as HTTP DELETE) on the server, while cross-zone scripting attacks the concept of security zones as implemented by a browser.*
- *Execution Flow:*
  1. *Explore: Find systems susceptible to the attack: Find systems that contain functionality that is accessed from both the internet zone and the local zone. There needs to be a way to supply input to that functionality from the internet zone and that original input needs to be used later on a page from a local zone.*
  2. *Experiment: Find the insertion point for the payload: The attacker first needs to find some system functionality or possibly another weakness in the system (e.g. susceptibility to cross site scripting) that would provide the attacker with a mechanism to deliver the payload (i.e. the code to be executed) to the user. The location from which this code is executed in the user's browser needs to be within the local machine zone.*

3. *Exploit: Craft and inject the payload: Develop the payload to be executed in the higher privileged zone in the user's browser. Inject the payload and attempt to lure the victim (if possible) into executing the functionality which unleashes the payload.*

- *Prerequisite: The target must be using a zone-aware browser.*
- *Consequences:*
  - *Integrity: Modify Data*
  - *Confidentiality: Read Data*
  - *Confidentiality, Access Control, Authorization: Gain Privileges*
  - *Confidentiality, Integrity, Availability: Execute Unauthorized Commands*

The formalization of the Exploitation and Black-hat Hacking processes is the formalization of two foundational cybersecurity concepts which lay the basis for the definition (and formalization) of the cybersecurity theory in the next Section (Section 4). The formal definition of those processes shall:

- in Section 4, formally define a system as a structure of agents, and
- in Section 5, correlate the formal definition of agents (i.e. the Definition 3.5) with the Causality principle (i.e. the formalization of the Kripke structure in Definition 3.1).

The main outcome of this section is that there is no evidence that properly considering the malicious intent of an agent necessarily results in a falsifiable or general security theory. On the other hand, the complete definition of Errors, predicted by a (sound w.r.t. Errors) security theory seems to be a proper research goal. In other words, system *in-security* and *security* should not be searched on those malicious events which produces negative effects on a systems (incidents), but in the potential designs and implementations due to vague specifications. Therefore, we will consider a security-by-design approach based on a requirement-based engineering process.

4 $\mathcal{ABF}$ – A Security Theory

In order to address the problem raised by Herley, we shall define how to distinguish between a secure and an insecure system. While most of the literature have correlated the problem of in-security to the maliciousness of agents interacting with the system, we show that security doesn't seem to stem from a malicious nature but, rather, insecurity raises from the lack of well-defined security requirements for the development process of a system. We argue that the high number of security vulnerability reported today are simply the realization of potential system configurations, which deviate from the nominal behavior because the *intended (or nominal) behavior* of the system is not precisely defined in the specification at the very early stages of the engineering process.

4.1 A Reference Model for Cybersecurity Engineering

A reference engineering process (so called, system security lifecycle of a product) is described, in Section 5. For the sake of simplicity, we now give an high-level overview of a reference engineering model focusing on the first three stages of the, so called, engineering V-Model. Our definition is partial and we only use it for the sake of simplicity and to better present the theory.

The development process of a new product (a CPS in our case) should follow an engineering model. Our reference engineering process (inspired by the waterfall V-Model), as depicted in Figure 6, is structured as the following ordered list of abstraction refinement steps.

1. The process starts with the definition of a *specification* where the general requirements of the CPS are defined (e.g. functional, physical, network, and design). As an example, an RFC of a communication or security protocol can be considered as the result of this first phase (e.g. see RFC-1[17]. In this first phase, we consider the architectural aspects of a CPS such as the draft physical and functional architectures.

2. The process then continues with the definition of a design where the requirements of the previous phase holds; structuring the physical architecture along with its logic (e.g. the physical-layer encoding of the information), and the functional architectures and its logic (e.g. the protocol logic of communication over a number of potential sessions).

3. Finally, the design is implemented as hardware (HW) for the physical architecture and software (SW) for the functional architecture.

Given that we apply our theory to *systems engineering* and that the two foundational processes (exploitation and hacking) are based on the concept of a system, we shall begin by defining what a system is, in its abstract form.

4.2 Abstract System

The ISO/IEC/IEEE 15288:2015 (System Life Cycle Processes) provides a definition of system as "A combination of interacting elements organized to achieve one or more stated purposes."[80]. Therefore, a system can be considered as a single agent where its interacting elements are the constituents of the agent itself. For the sake of simplicity we first define a system as an agent and then extend the definition to a "combination of interacting" agents.

There is no agreement between the research communities (e.g. Multi-Agent-System, Epistemic Logic) on which are the constituent of an agent as a system. However, the same ideas revolved around for thousands of years. Some relevant examples for our objective are the following.

- In [44], Hintikka describes the difference between Knowledge and Belief (as epistemological concepts), and the whole Doxastic logic defines in details how Beliefs can be formalized.

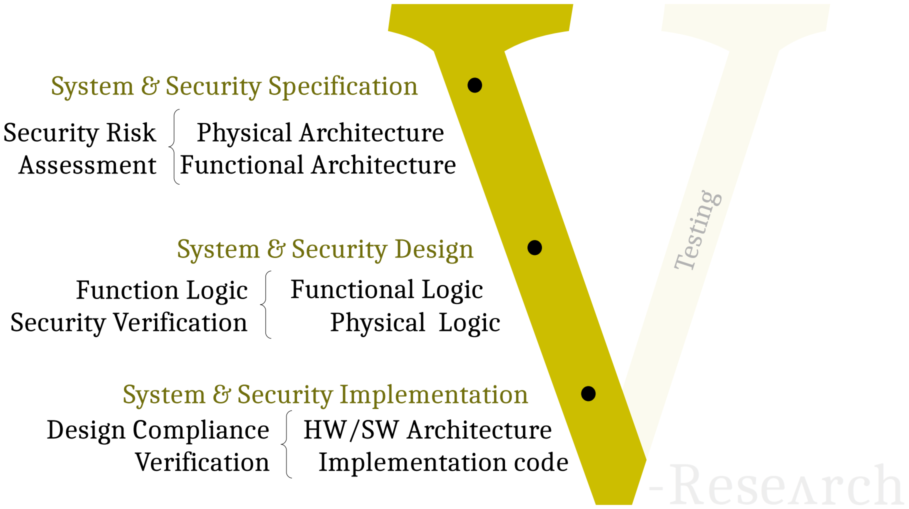


Figure 6: Cybersecurity Engineering Life-cycle

- In [45], Hintikka describes the concept of Information and the difference with Knowledge and Belief.
- In [75], the authors defines an agent as a tuple of Assertions, Beliefs, and Facts.

Methodology The concept of Knowledge [44] (from an epistemological point of view) can be defined as the way to get to the Truth. Anything that is known is considered true[22] In contrast, Beliefs [44] are potentially true and leads to new hypothesis. Due to the structure of deductive reasoning we can only start from unproven hypothesis and test the deductive conclusions on the reality. Therefore, whatever a scientific-security-theory may be, it can only be defined starting from hypotheses. A sound reasoning should lead to conclusion that shall be tested on a real system. Therefore, only at the end of the reasoning we will be able to test, and judge, the quality of the theory itself. The identification of hypotheses should start from probably true beliefs (e.g. from Information [45]), and then from the state of the art.

For our argument, as in [75], an agent is composed by its knowledge, beliefs, and the information or assertions it provides; where knowledge is defined, as in [84], as a set of proposition known by an agent, such that: (i) knowledge requires belief, (ii) knowledge require truth, (iii) knowledge must be *properly justified*, and the only objective of Information is to exchange beliefs between agents. As defined in [45], "Information is specified by specifying which alternatives concerning the reality it admits and which alternatives excludes". This means

[22] It is also believed that Knowledge, defined as we did, is in-apprehensible [32], but this shouldn't be an issue since it is a common problem to every scientific search

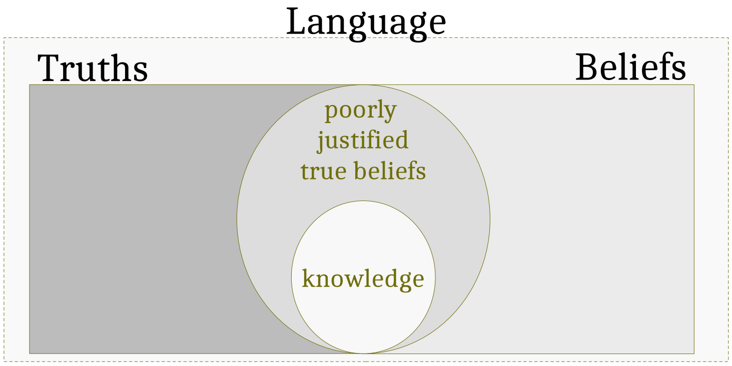


Figure 7: Informal representation of Knowledge and Belief

that if we consider a propositional variable (which admits the two alternatives True/False) its information is defined as Believed to be True/False and not Believed to be the opposite. Due to the definition of Information and then with its relation to the probabilistic correlation to truth/reality, we consider information in relation with an agent's beliefs. Similarly, we consider beliefs to define the actual behavior of an agent or a system. On the contrary, this view is not considered in most (if not all) the approaches to formal protocol verification in the symbolic model. In fact, the security reasoning is usually applied to a representation/abstraction of a protocol that only considers knowledge and transfer of knowledge (i.e. if an agent sends a message, the recipient knows that message). However, we believe that the security of a system is tightly related to the differences between the nominal behavior and the actual (e.g. the implemented) one and only in the nominal one (as hypothetical) one should consider agent's knowledge.

Definition 4.1. System State and State-Space – The state of a system (or a sub-system or an agent) s is defined as the tuple $s = \langle rcc(\mathbb{K}, \mathbb{B}), rcc(\mathbb{K}, \mathbb{I}), rcc(\mathbb{B}, \mathbb{I})\rangle$, where $\mathbb{K}, \mathbb{B}, \mathbb{I}$ are Regions of Knowledge, Beliefs, and Information respectively, and rcc is a specific relation between Regions. The state-space of a system is then defined by the different rcc relations between the three pairs of Regions defining the system and all the sub-systems.

Therefore, a system state space can be seen as a superposition of multiple agent states where knowledge, beliefs, and information are related between each other (in a mereotopological space) through all the admissible RCC relations. A *system state* (as an instance of the system state space) is a specific configuration of the rcc relations between the three regions. Therefore, a collection of system states defines a collection of choices for those rcc relations.

The difference between Knowledge and Belief is depicted in Figure 7 (see [50]). However, according to[87], Knowledge[23] as an epistemological concept is

[23] "*Theaetetus*: [...] He said that knowledge was true opinion accompanied by reason, but

difficult to formally define. Similarly for the concept of information, Hintikka in [45] states that "A purely logical definition of information is impossible". In this work, however, we are not interested in how knowledge, information, or belief can be precisely formalized from an epistemic standpoint. We assume that a semantic of a correct (i.e. commonly believed to be true) definition of epistemic knowledge exists, for example the one given in[44] by Hintikka, and we then define knowledge in terms of the Kripke structure defined in Definition 3.1; similarly for Belief.

Definition 4.2. Knowledge – Given an abstract collection of Agents Ag, and the modal operator K_a (where $a \in Ag$), Knowledge is defined as a region of predicates known by an agent $\mathbb{K}_a = \bigcup_\Phi K_a\varphi$ (for all $\varphi \in \Phi$ where Φ is the collection of all the propositions known by a). Given a proposition P, we extend the semantics of the Causality structure with:

(σ16) $\omega \models K_aP$ iff $\omega' \models P$ for all ω' such that $\omega R \omega'$.

Definition 4.3. Belief – Given an abstract collection of Agents Ag, and the modal operator B_a (where $a \in Ag$), Belief is defined as a region of predicates believed by an agent $\mathbb{B}_a = \bigcup_\Phi B_a\varphi$ (where Φ is the collection of all the propositions believed by a). Given a proposition P, we extend the semantics of the Causality structure with:

(σ17) $\omega \models B_aP$ iff $\omega \models \neg K_a \neg P$ (i.e. the agent a considers P possible) and $\omega' \models P$ for all ω' such that $\omega R \omega'$.

Definition 4.4. Information – Given an abstract collection of Agents Ag, and the modal operator I_a (where $a \in Ag$), Information is defined as a region of beliefs asserted by an agents a. $\mathbb{I}_a = \bigcup_\Phi I_a\varphi$ (where Φ is the region of all the propositions believed and asserted by a). Given a proposition P, we extend the semantics of the Causality structure with:

(σ18) $\omega \models I_aP$ iff $\omega \models \mathbb{B}_aP$ (i.e. the agent a considers P possible), $\omega \models \neg\mathbb{B}_a\neg P$

4.3 Operational System

When dealing with a specification of a system (i.e. the design if the system for a specific operation (as a generic operating/operational system), considering abstract and general concepts such as knowledge, belief, or information may result to be too abstract for the objectives of the overall engineering process (e.g. verification and validation). As an example, we are usually not interested in information in abstract but to the transfer of that information, which we

that unreasoning true opinion was outside of the sphere of knowledge; and matters of which there is not a rational explanation are unknowable – yes, that is what he called them – and those of which there is are knowable. [...] *Socrates*: [...] the primary elements of which we and all else are composed admit of no rational explanation; for each alone by itself can only be named, and no qualification can be added, neither that it is nor that it is not, for that would at once be adding to it existence or non-existence, whereas we must add nothing to it, if we are to speak of that itself alone. [...]" Plato – Theaetetus 201 [63] call Assertions, made by a subset of agents. Therefore, we now define how we consider an agent for the engineering of CPS.

1. We consider Information only when the intention of exchanging that Information is from a sender to recipient is defined; and we call it *Assertion*
2. Similarly, the portion of Beliefs we consider for system engineering is the one that builds (input) or describes (output) the behavior of an agent (strategy rules [24]), and
3. We consider a set of axiomatic *Facts* (definitory rules**FIX**[25]) instead of considering the more general epistemic definition of Knowledge. Specifically, Facts describes:
    - The functional architecture of each agents
    - The physical/structural (HW/SW) architecture of each subsystem of agents and agent within a subsystem
    - Assets and security properties

We give a graphical representation of (sub-)system and agent in Figure 8.

We note here (and describe with more details afterwards in this paper) that the data flow can be defined as a transfer of Beliefs through Assertions (i.e. the Beliefs flow).

Definition 4.5. Assertion – An assertion is an intended transfer of beliefs between two agents a and b such that

(σ19) $\omega \models \mathcal{A}_{a \to b} P$ iff $\omega \models \mathbb{B}_a P$, $\omega \models \neg \mathbb{B}_a \neg P$, $\omega' \models rcc(\mathbb{B}_a P, \mathbb{B}_b P)$, for all ω' such that $\omega R \omega'$.

Definition 4.6. Behavior – The behavior of an agent is defined as the transformation process (e.g. defined as a protocol, or a functional architecture) that determines the output-beliefs based on input-beliefs and vice versa (where input-beliefs and output-beliefs are beliefs taken as input or output respectively).

(σ20) $\omega \models \bigcup \mathcal{B}(\mathbb{B}_I, \mathbb{B}_O)$ and $\omega \models \mathbb{B}_I \wedge \mathbb{B}_O$, where a is an agent, $\mathbb{B}_I$ and $\mathbb{B}_O$ are input and output-beliefs respectively.

[24] "The logical structure of information is one of the most basic and one of the most basic and one of the simplest thing in the wide and wonderful world of logical analysis. This point can be put in a deeper perspective. A distinction [. . .] ought to be made [–] between two kinds of rules (or principles) in any strategic activity like knowledge seeking. On the one hand you have the rules that define the game, e.g. how chessmen are moved on a board. The can be called *definitory* rules. They must be distinguished from rules [. . .] that deal with what is better and what is worse in the game in question. Definitory rules do not say anything about this subject. Rules which do can be called *strategic rules*" – Hintikka in [45]

[25] **mr:** facts are definitory rule, as they don't define how a real system is finally implemented (curently) but how it should, trugh a series of requirements which may not be respected, through insecurity, in the implemented system

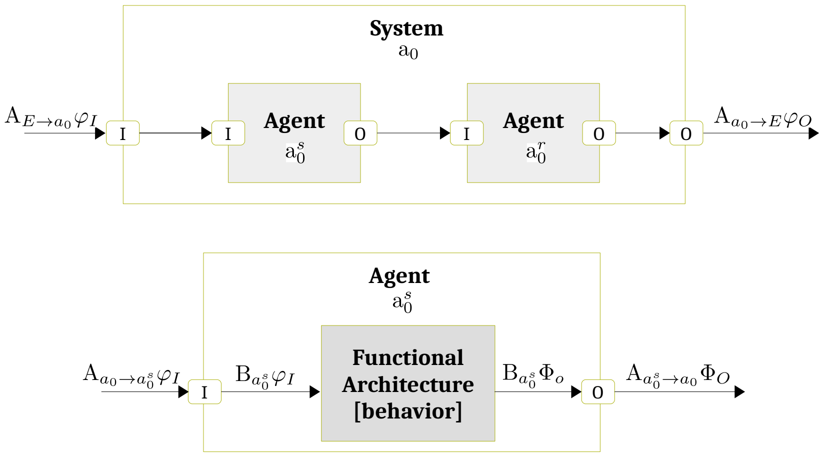


Figure 8: Example of system and agent structure

Definition 4.7. Fact – Facts are defined as $\mathcal{F} = \bigcup_\Phi K_a\varphi$ that predicate in a factive way, e.g. if a knows that P then P, and the region of facts is monotone (no revision).

(σ21) $\omega \models \mathcal{F}_a P$ iff $\omega \models \Box P$.

Definition 4.8. Operational System State – An operational system (or a sub-system) state is defined as the tuple $s = \langle rcc(\mathcal{F}, \mathcal{B}), rcc(\mathcal{F}, \mathcal{A}), rcc(\mathcal{B}, \mathcal{A})\rangle$, where $\mathcal{A}, \mathcal{B}, \mathcal{F}$, are regions of assertions, behavior (i.e. the beliefs generated by the behavior), and facts respectively.

As already presented in [75] it follows that, defining a system (or an operational system) with a fixed number of regions, there exist an upper-bound to the number of possible configuration of a system, defined by the possible relations between the different regions. For completeness, we report in the next paragraph the calculation done in [75].

Number of different configurations of a system The general formula to calculate the number of different types of agents is $r^{\binom{n}{k}}$, where r is the number of relations with arity k, between n different sets, where r^e is the number of permutation of r relations over e elements with repetitions, with e being the number of k-ary combinations of n sets, $\binom{n}{k}$. In our case, $\binom{n}{k} = 3$ since we consider 3 sets ($\mathcal{A}, \mathcal{B}, \mathcal{F}$), and all the relations considered in the RCC are binary. Hence, using RCC5 (with five different spatial relations) over three sets, we can theoretically define up to 125 different type of agents. However, only 54 of the 125 (as showed in [37]) combinations are topologically correct with respect to the definition of the relations of RCC5. Generalizing to all the RCCs:

- *RCC3* — theoretical: $3^3 = 27$, correct: 15

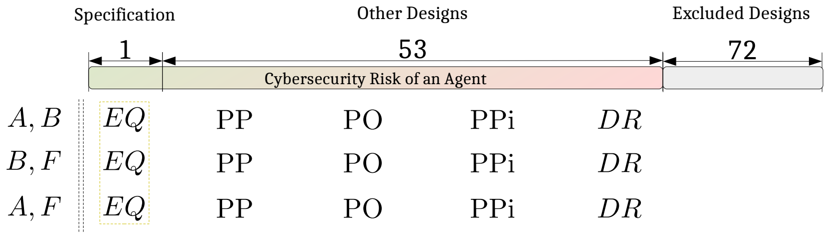

Specification
Other Designs
Excluded Designs
1
53
72
Cybersecurity Risk of an Agent
A, B EQ PP PO PPi DR
B, F EQ PP PO PPi DR
A, F EQ PP PO PPi DR

Figure 9: Quantitative representation of the cybersecurity risk for a single agent

- *RCC5* — theoretical: $5^3 = 125$, correct: 54
- *RCC8* — theoretical: $8^3 = 512$, correct: 193

Hence, even if considering a different number of sets than the three $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{F}$ exponentially affects the number of theoretical agents, the application of RCC downscales that number of a factor that ranges from 1.8 to 2.5. In addition, using RCC5 we consider 3.6 times more (different) types of agents than RCC3, but using RCC8 would allow us to consider 3.5 times more different agents.

In the quantitative evaluation of a single agent, depicted in Figure 9, we argue that only 1 configuration represents the nominal (expected) behavior of the agent while the other configurations are either impossible to implement or diverge from the intended nominal behavior. We note that, the numbers reported here do not consider the details of the engineering process and should be considered a limit of an abstract representation of the system. In Section 5 we detail this numeric evaluation to faithfully represent the number of insecurity configurations, while in this section we consider the general abstract definition given in Defintion 4.8.

As described beforehand in this section, the collection of Facts shall define the functional and the physical architecture of an agent, but Assets and security properties are defined as Facts, i.e. true. Given that understanding why an Asset is considered as such by the user doesn't necessarily allow us to better qualify an Asset, we consider the fact of "being an asset" as a predicate of a component of a system.

Definition 4.9. Asset – For any agent $a \in Ag$ in a collection of Agents Ag, an agent is considered an asset iff

$(\sigma 22)$ $\omega \models \text{asset}(a)$ iff $\omega \models \Box\text{asset}(a)$.

The definition of the security properties is given in Section 5.1

4.4 Qualitative Evaluation of Agent Space in $\mathcal{ABF}$

While a quantitative analysis reveals how many possible configurations of an agent (i.e. a system) exist w.r.t. the $\mathcal{ABF}$ theory (i.e. 54/125 in RCC5), a qualitative analysis of the different configurations describes the configurations

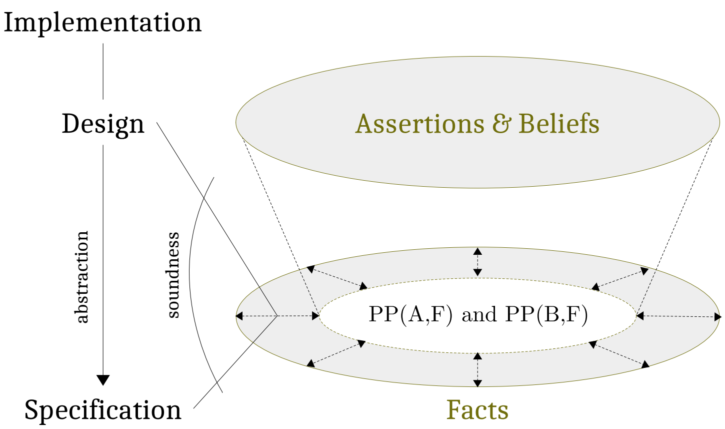


Figure 10: Example relation between Facts, and Assertions and Beliefs

allowed by the $\mathcal{ABF}$ theory, and how those configurations can be categorized. In Table 2 we provide the generic composition table of RCC5 over 3 regions instantiated over $\mathcal{A}, \mathcal{B}, \mathcal{F}$, which shows the whole state space for a single agent. The color coding of the table represents the security risk related to a generic agent.

As depicted in Figure 10, the relation between Facts, and Assertions and Behavior defines the soundness of the design (admissible configurations of Assertions, Behaviors and, in turn, Beliefs) w.r.t. the specification (what the specification mandates, such as by the nature of the physical/functional architectural models). We categorize agents by first analyzing the relations between each pair of Regions defining an agent (i.e. $\mathcal{A}, \mathcal{B}, \mathcal{F}$), and then we categorize the different agents as tuple of the three Regions. For the sake of simplicity, soundness is opposed to non-soundness in the following, however, with the RCC one should consider different "degrees" of non-soundness. For example, in RCC5, if we consider EQ between two Regions as representing soundness, DR over the same Regions represents non-soundness; while PP, PO, PPi represents the different degrees of non-soundness. A similar argument can be done for completeness. **tofix:** it's missing the relation with equivalence. missing parallelism with knowledge-belief/assertion (see slide v-research-demo)

rcc($\mathcal{A}$,$\mathcal{B}$) – Collaboration In order to reason on the relation between assertions and behavior we first need to consider that, by definition, assertions are defined as transfer of information between two agents, e.g., a and b. Therefore, as depicted in Figure 8, an agent has two main categories of assertions, input and output assertions. Given an agent a and a collection of asserted predicates Φ, the Input assertions are those received by a from an agent s acting as a sender, $\mathcal{A}_{s\to a}\Phi$; similarly, output assertions are sent from a to a receiver r,

$\mathcal{A}_{a\to r}\Phi$. We shall consider two pairs of regions[26]:

- rcc($\mathcal{A}_{s\to a}$,$\mathcal{B}$), where the relation between Input-assertions and behavior describes the soundness of the execution of the functional architecture w.r.t. input elicitation. With more details, the ideal specification of the functional architecture, along with the expected inputs, defines the functional behavior of an ideal system. If all the inputs (Assertions) are correctly handled in the functional specification (behavior) the specification is complete.

- rcc($\mathcal{A}_{a\to r}$,$\mathcal{B}$), where the relation between behavior and outputs describes the completeness of the behavior defined in the specification w.r.t. the input elicitation. With more details, if all the outputs (assertions) of the functional architecture can be produced, the functional architecture is complete.

rcc($\mathcal{A}$,$\mathcal{F}$) and rcc($\mathcal{B}$,$\mathcal{F}$) – Honesty and Competence While Assertions and Beliefs generated by the Behavior determines how a system should work, and the relation between the two defines the quality (i.e. the completeness w.r.t the specification) of the agent, the relation of Assertions and Behavior with Facts determines the quality with respect to the nominal (specified) system. Given that Facts defines what must be true in the system, the relation of Assertions an Facts determines the degree of quality between the information circulating in a system (or within an agent) and reality**FIX**[27]. Since the transfer of information through Assertions generates Beliefs, a dishonest agent may circulate false information, generating false Beliefs. We note that it is often implied that the intention behind circulating false information discerns a dishonest and an incompetent agent, however, we consider honesty related to sharing truths[28]. The relation between Beliefs and Facts determines the competence (on the subjects defined by the Facts) of an agent (i.e. the more competent an agent is, the more likely a Belief of that agent is true).

4.4.1 $\mathcal{ABF}$ Security Enumeration (SE)

The following security requirement for a CPS specification can be summarized:

SE-1 Proper interaction between correctly-behaving agents (in contrast with the "Improper Interaction Between Multiple Correctly-Behaving Entities" defined by the CWE–435 as one of the top "view" of the "research concepts"

[26] "I am not asserting, as Lotze did, that a relation between X and Y consists of a quality in X and a quality in Y – a view which I regard as quite indefensible. – I assert that a relation Z between X and Y involves the existence in X of the quality "having the relation Z to Y" so that a difference of relations always involves a difference in quality, and a change of relations always involves a change of quality." – Ellis J. McTaggart, The Unreality of Time[58]

[27] **mr:** assertions are reality while facts are dogmatic assertions at specification level, i.e. requirements

[28] "[. . .] truth exists only in the good man, but the true in the bad man as well; for it is possible for the bad man to utter something true." Sextus Empiricus, Outlines of Pyrrhonism, II-83[32]

in [24]) is defined as $EQ(\mathcal{A}_a, \mathcal{B}_a)$ for an agent a while can be detailed as follows when multiple agents are considered.

SE-1.1 The equality relation $EQ(\mathcal{A}_{s \to a}, \mathcal{B}_a)$ describes the intended secure behavior as: the beliefs generated by the behavior of the functional architecture shall be complete w.r.t. the specified inputs of the agent. Therefore, *the assertions received by an agent or a system shall be compliant with the expected inputs of the functional architecture.* For example, the inputs of the user of a SW must be sanitized to exclude deviations w.r.t. the expected inputs of the functions implemented in the SW. Another example is the type checking between allowed inputs and expected inputs.

SE-1.2 Similarly, the equality relation $EQ(\mathcal{A}_{a \to r}, \mathcal{B}_a)$ defines that the outputs of an agent a shall be the outputs of the functional architecture.

SE-2 Sufficient Control Flow Management (in contrast with the "Insufficient Control Flow Management" defined by MITRE in the CWE–691 as one of the top "view" of the "research concepts" in[24]) is defined as $EQ(\mathcal{A}, \mathcal{F})$.

SE-3 Correct Calculation (in contrast with the "Improper Calculation" defined by MITRE in the CWE–682 as one of the top "view" of the "research concepts" in[24]) is defined as $EQ(\mathcal{B}, \mathcal{F})$.

We are now in the position to define what a secure system is (with respect to the $\mathcal{ABF}$-theory) and, based on that definition, what the security risk is and how to quantify it in a risk matrix.

Definition 4.10. Security of a System or an Agent – A secure system is a system where SE-1, SE-2, and SE-3 holds for each agent composing the system.

The ISO 31000 consider risk as the "effect of uncertainty on objectives" and the refers both of positive and negative consequences of uncertainty. Accordingly, we consider risk as follows.

Definition 4.11. Risk – The whole space of potential designs of a specification with respect to the $\mathcal{ABF}$-theory.

The definition of Risk leads to the risk matrix in Figure 9, defined as follows.

Definition 4.12. Risk Matrix – The risk matrix is a function between the three relations $s = \langle rcc(\mathcal{F}, \mathcal{B}), rcc(\mathcal{F}, \mathcal{A}), rcc(\mathcal{B}, \mathcal{A}) \rangle$, where the maximum risk is defined by the DR relation between the three groups of Regions, and the minimum risk by the EQ relation over the same Regions. In between the two extremes, the granularity of possible intermediate configuration is defined by the calculus used (RCC5 in our case).

We note that often the risk matrix is defined by the relation between likelihood and impact which we discuss in the next section.

	DR($\mathcal{A}$,$\mathcal{B}$)	PO($\mathcal{A}$,$\mathcal{B}$)	PP($\mathcal{A}$,$\mathcal{B}$)	PPi($\mathcal{A}$,$\mathcal{B}$)	EQ($\mathcal{A}$,$\mathcal{B}$)

DR($\mathcal{B}$,$\mathcal{F}$)	T($\mathcal{A}$,$\mathcal{F}$)	DR($\mathcal{A}$,$\mathcal{F}$)
		PO($\mathcal{A}$,$\mathcal{F}$)
		PP($\mathcal{A}$,$\mathcal{F}$)
			DR($\mathcal{A}$,$\mathcal{F}$)	DR($\mathcal{A}$,$\mathcal{F}$)
				PO($\mathcal{A}$,$\mathcal{F}$)
				PP($\mathcal{A}$,$\mathcal{F}$)
					DR($\mathcal{A}$,$\mathcal{F}$)

PO($\mathcal{B}$,$\mathcal{F}$)	DR($\mathcal{A}$,$\mathcal{F}$)
	PO($\mathcal{A}$,$\mathcal{F}$)
	PP($\mathcal{A}$,$\mathcal{F}$)
		T($\mathcal{A}$,$\mathcal{F}$)	DR($\mathcal{A}$,$\mathcal{F}$)
			PO($\mathcal{A}$,$\mathcal{F}$)
			PP($\mathcal{A}$,$\mathcal{F}$)
				PO($\mathcal{A}$,$\mathcal{F}$)
				PPi($\mathcal{A}$,$\mathcal{F}$)
					PO($\mathcal{A}$,$\mathcal{F}$)

PP($\mathcal{B}$,$\mathcal{F}$)	DR($\mathcal{A}$,$\mathcal{F}$)
	PO($\mathcal{A}$,$\mathcal{F}$)
	PP($\mathcal{A}$,$\mathcal{F}$)
		PO($\mathcal{A}$,$\mathcal{F}$)
		PP($\mathcal{A}$,$\mathcal{F}$)
			PP($\mathcal{A}$,$\mathcal{F}$)	PO($\mathcal{A}$,$\mathcal{F}$)
				EQ($\mathcal{A}$,$\mathcal{F}$)
				PP($\mathcal{A}$,$\mathcal{F}$)
				PPi($\mathcal{A}$,$\mathcal{F}$)
					PP($\mathcal{A}$,$\mathcal{F}$)

PPi($\mathcal{B}$,$\mathcal{F}$)	DR($\mathcal{A}$,$\mathcal{F}$)	DR($\mathcal{A}$,$\mathcal{F}$)
		PO($\mathcal{A}$,$\mathcal{F}$)
		PPi($\mathcal{A}$,$\mathcal{F}$)
			T($\mathcal{A}$,$\mathcal{F}$)	PPi($\mathcal{A}$,$\mathcal{F}$)	PPi($\mathcal{A}$,$\mathcal{F}$)

EQ($\mathcal{B}$,$\mathcal{F}$)	DR($\mathcal{A}$,$\mathcal{F}$)	PO($\mathcal{A}$,$\mathcal{F}$)	PP($\mathcal{A}$,$\mathcal{F}$)	PPi($\mathcal{A}$,$\mathcal{F}$)	EQ($\mathcal{A}$,$\mathcal{F}$)

Table 2: RCC5 composition table over 3 regions. The results show that there exist 54 possible relations and the coloring anticipates the ideal risk matrix (green the secure state with low risk, red the high risk state, and a gradient of medium risk states). T($\mathcal{A}$,$\mathcal{F}$) = {DR($\mathcal{A}$,$\mathcal{F}$), PO($\mathcal{A}$,$\mathcal{F}$), PP($\mathcal{A}$,$\mathcal{F}$), PPi($\mathcal{A}$,$\mathcal{F}$), EQ($\mathcal{A}$,$\mathcal{F}$)}

5 Cybersecurity Engineering Process

> The difference between ideas and reality is like the difference between philosophy and engineering. The work to transform one into the other is scientific research
>
> *V-Research*

Several standards mandates a secure-by-design approach in which cybersecurity shall be considered at the very early stages of the design process. For example,

1. DO-326A – “Airworthiness Security Process Specification” requires a cybersecurity risk assessment of the design and is the “are the only Acceptable Means of Compliance (AMC) by FAA & EASA for aviation cybersecurity airworthiness certification, as of 2019” as pointed out by SAE in [73].
2. NIST 800-82 [85] – “guide to Industrial Control System (ICS) Security”
3. J3061:2016-1 [72] – “Cybersecurity Guidebook for Cyber-Physical Vehicle Systems” defines “set of high-level guiding principles for Cybersecurity as it relates to cyber-physical vehicle systems” and states that “incorpo-

> rate Cybersecurity into cyber-physical vehicle systems from concept phase through production, operation, service, and decommissioning"

Companies which develop CPS (e.g. aerospace systems or elevator systems), must adhere to strict regulations and quality assurances processes. Introducing tools and procedures in their processes requires a detailed and justified overview on how those tools and procedures can be used. In Figure 11, we provide an overview of a process that consider cybersecurity in the specification, design, and implementation stages. The overall process start with the specification of the architectural (both physical and functional) requirements from which the Weaknesses are automatically identified. Based on the Assets, architectures, and the Weaknesses the cybersecurity risk is calculated based on the $\mathcal{ABF}$-theory. An iterative process between the user (e.g. the engineer) and the V-SecRA module of the ABFtool allows the user to move to the design phase when the risk level is considered acceptable. The design phase starts by automatically mapping the Weaknesses into Vulnerabilities which are, in turn, fed into the V-DesignVerif module along with the final specification. The Module returns a list of Vulnerabilities and potential Mitigations. The user then procees in implementing the CPS and the SW/HW choices can be tested by the V-ATG. **tofix:** While we have described the overall view, from specification to implementation, in this text we only consider the process from specification to design.

In order to explain in details the SPDL, we use the following running example.

Example 4. *As depicted in Figure 12, the use case of the running example (a small part of a subprocess of the SwAT testbed [56]), shows*

- *a tank that is filled with raw water coming from the inlet pipe*
- *a motorized valve (a valve with an actuator) such that:*
  - *if opened, allows the raw water to flow into the tank*
  - *if closed, stops the raw water to flow into the tank*
- *a sensor that reads the meters of raw water in the tank*
- *a PLC controller, connected to the sensor and the actuator, that receives the readings from the sensor and regulates the quantity of water in the tank by communicating a change in the state of the actuator based on the following logic*
  - *if the readings from the sensor reports a water level in the tank above (or equal) to 10m, the actuator shall close the valve*
  - *if the readings are below 10m the actuator shall open the valve.*

5.1 Specification – Elicitation of Security Requirements

The first step of the SPDL is the definition of the requirements and then, for the purpose of this paper, of (i) security requirements, (ii) architectural (physical and functional) requirements. Our focus in mainly on security requirements but

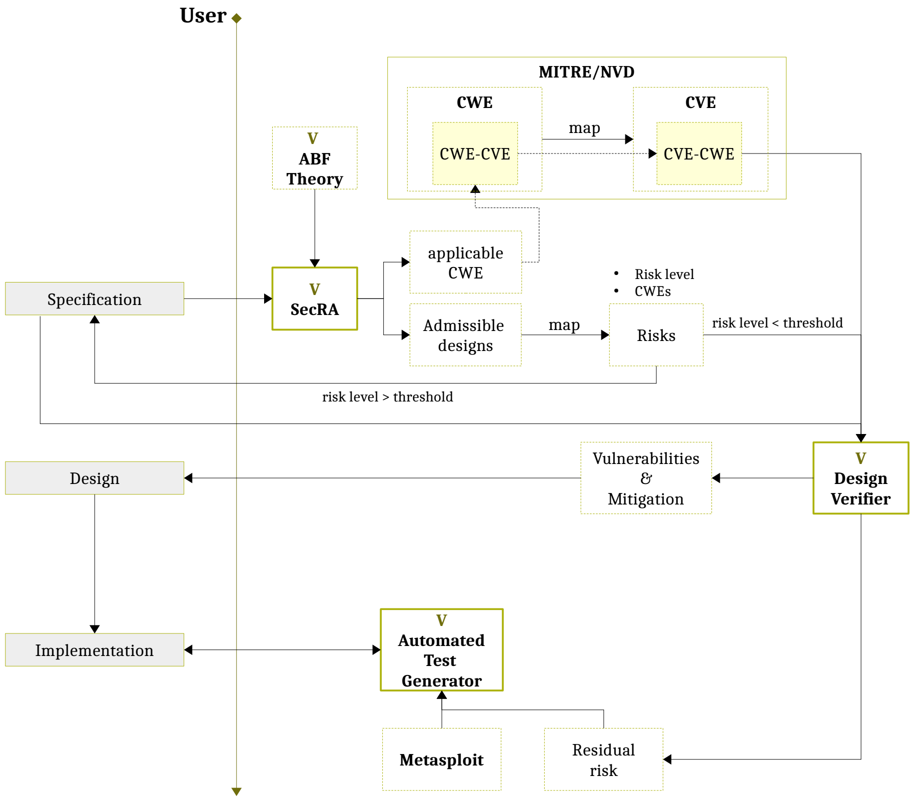


Figure 11: Secure-by-design System Development Life-cycle

they are necessarily intertwined with the architectural requirements, as we will show afterwards in this section. A complete study on how to properly define the architectural requirements is outside the scope of this paper so we propose a method that is convenient for the purpose of our assessment.

System Requirements In our running example, there is a system (a CPS) composed by 5 main subsystem which we consider atomic (i.e. not themself composed by subsystems) and then agents: the tank, the sensor, the controller, the actuator, and the motorized valve (valve from now on). The whole specification (which we now describe) of the physical and functional architecture is depicted in Figure 13. In the use case, the communication flow is as follows:

1. the sensor reads the level of water in the tank (tank → sensor) [29]
2. the sensor communicates the readings to the controller (sensor → controller)

[29] this communication depends on the technology in use for the readings. We assume a unidirectional communication without loss of generality

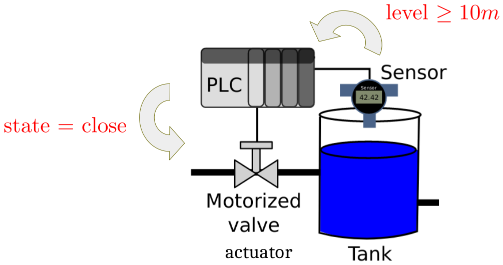
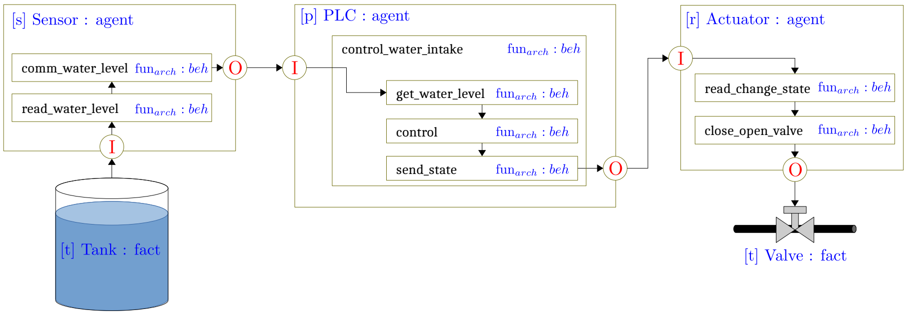


Figure 12: Use Case – Running Example



[s] Sensor : agent
comm_water_level fun_arch : beh
read_water_level fun_arch : beh
O
I
[t] Tank : fact
[p] PLC : agent
I
control_water_intake fun_arch : beh
get_water_level fun_arch : beh
control fun_arch : beh
send_state fun_arch : beh
O
[r] Actuator : agent
I
read_change_state fun_arch : beh
close_open_valve fun_arch : beh
O
[t] Valve : fact

Figure 13: Specification – Running Example

3. the controller calculates the state of the valve and communicates it to the actuator (controller → actuator)

4. the actuator translates (digital to analog) the state received and communicates[30] it to the valve

Each agent has an input or output port from which it communicates with other agents. It is also composed by the functional blocks that defines its functional architecture and physical boundaries that defines its physical architecture, as detailed in Appendix D.

While *agents* and *communication* between agents are described and defined in Section 4, the concepts of *port* (depicted in Figure 14), *channel* (depicted in Figure 15), *functional and physical architecture*, and *functional block* have not yet been defined with respect to the $\mathcal{ABF}$-theory. Informally, a channel[31] identifies the place where the communication takes place. In this work, we only consider mono-directional channels and communication but the extension to bi-directional channel can be considered as the union of two unidirectional

[30] we do not distinguish, for the sake of simplicity between different types of channels and assume that communicating to the valve produces the expected change of physical state

[31] for now, we rely on the intuitive notion of channel as "something" that transfers information as Assertions between output and input port, i.e. mono-directional

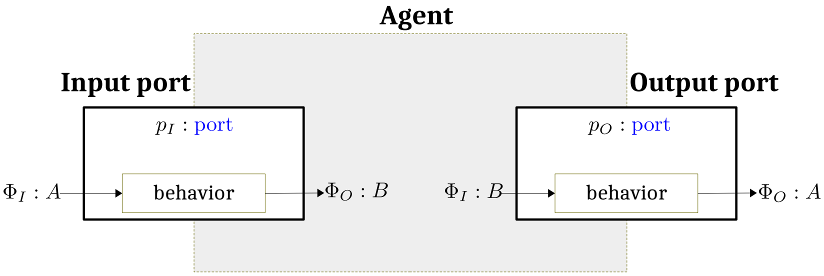


Figure 14: Input and Output Port of an agent

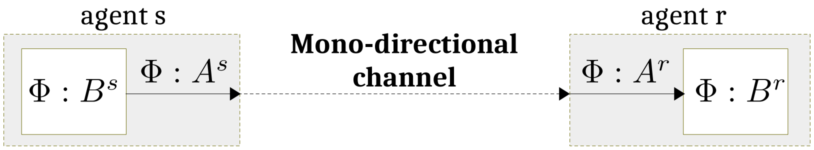


Figure 15: Communication over a Mono-directional Channel

channels. A mono-directional channel is defined by the assertions sent or received (over the channel).

5.1.1 Input and Output Ports

Since the $\mathcal{ABF}$-theory is a theory of agents, we consider ports as agents that allows the exchange of information between a channel and another agent. However, a port must be considered as a special type of agent to avoid an *infinite regress* in which a port needs a port to transfer information between the outside of the port to the inside of itself.

Definition 5.1. Input or Output Port – Ports are agents with the following predefined behavior: an input-port changes the type of information from assertion from a sender s to an agent a, $\mathcal{A}_{s\to a}$ to belief of the agent a ($\mathbb{B}_a$) while an output-port from belief to assertion; forwarding information from the outside of an agent's boundary to the inside (input-port) or vice versa (output-port).

The *quality of a port* is determined by the *rcc* relation between the assertions received or sent and the belief, i.e. $rcc(\mathcal{A}_s, \mathbb{B}_a)$ for the input-port or $rcc(\mathcal{A}_r, \mathbb{B}_a)$. We only define secure input port but the definition of a secure output port is symmetrical.

Definition 5.2. Secure Input Port – A secure input port ($s\boxed{\rightarrow}a$) allows information as incoming assertions to flow from a sender s to the behavior of the recipient a (agent). If p_I is a secure input port, $\omega \models \varphi$, $\varphi \in \mathcal{A}_{s\to a}$, and a has the only input port p_I, $\omega' \models \mathbb{B}_a$ and $\varphi \in \mathbb{B}_a$ for any $\omega R \omega'$.

Port Weaknesses From this definition, it follows that there exist only the following *six* types of weaknesses, generating six types of insecure port in RCC5 (the notation is reported for input-ports, i.e. on the lef-hand side of the arrow):

W1) *replace port* ($s\boxed{\circ\!\!-\!\!\!\rightarrow}a$), where assertions reaches the port but do not pass the boundary of the agent (i.e. do not become belief of the agent)

W2) *drop port* ($s\boxed{\circ\!\!\rightarrow}a$), where assertions reaches the port but do not pass the boundary of the agent (i.e. do not become belief of the agent)

W3) *insertion port* ($s\boxed{\bullet\!\!\rightarrow}a$), where some new information is believed by a as incoming from the port but s didn't send it

W4) *injection port* ($s\boxed{\LEFTcircle\!\!\rightarrow}a$), where information coming from s is substituted with new information which becomes believed by a

W5) *selective port*, where some information passes the port and part is either:

W4.1) drop ($s\boxed{\circ\!\!\mapsto}a$),

W4.2) drop+insert ($s\boxed{\bullet\!\!\mapsto}a$), or

FIX[32]

Proof. An input port is, in the $\mathcal{ABF}$-theory, defined secure as long as the relation between the two regions of input assertions $\mathcal{A}$ and output beliefs $\mathbb{B}$ are equal, i.e. $EQ(\mathcal{A}, \mathbb{B})$. Therefore, any other relation should result in a weakness (related to an insecurity flaw) of that input port. Using RCC5, there exist exactly other 4 different type of relations, one of which is the discrete-from (DR) relation, i.e. $DR(\mathcal{A}, \mathbb{B})$. When two regions are related by the DR relations, they have no subregion in common. Lets define a function weight $|X|$ such as, for any region X, it represents the smallest possible cardinality of a (mereo)topological base for X; where a base is a collection of regions in a (mereo)topology such that every open region can be written as union of elements of that base. We distinguish between Regions that contain Information and Regions that don't by writing the latter as $\emptyset$.

1. if $EQ(\mathcal{A}, \mathbb{B}))$ then either $\mathcal{A} = \mathbb{B} = \emptyset$ (no communication) or $\mathcal{A} = \mathbb{B} \neq \emptyset$ (forward communication)

2. if $DR(\mathcal{A}, \mathbb{B}))$ then $\mathcal{A} = \emptyset \oplus \mathbb{B} = \emptyset$ (we call *insert* the former and *full drop* the latter case), or $\mathcal{A} \neq \emptyset \wedge \mathbb{B} \neq \emptyset \wedge \mathcal{A} \neq \mathbb{B}$ which we call *replace* (i.e. drop and insert)

3. if $PP(\mathcal{A}, \mathbb{B}))$ then $\mathbb{B}$ contains and extend $\mathcal{A}$ which we call *injection*

4. if $PPi(\mathcal{A}, \mathbb{B}))$ then $\mathcal{A}$ contains and extend $\mathbb{B}$ which we call *selective drop*

5. if $PO(\mathcal{A}, \mathbb{B}))$ then a part of the $\mathcal{A}$ is contained in the $\mathbb{B}$ which is a combination of *selective drop and generation*

□

[32] **mr:** this proof needs to be restructured as in slides v-research-demo

5.1.2 Communication Channels

We start by considering the difference between a (communication) mono-directional channel (channel from now on) and an agent, as we did for the ports, since the $\mathcal{ABF}$-theory is a theory of agents. In fact, if a channel were considered an agent (channel-agent) then the question would be how an agent would transfer its Assertions to the channel-agent. If the channel between the agent and the channel-agent is again an agent, we would generate an *infinite regress*. Therefore, we do allow channel-agents but we assume a finite depth (of detail) for a channel, where there exists a bottom-channel which is not an agent. For now, we do not constrain a channel-agent in any way so there is no difference between a channel agent and agent. Therefore, for the sake of simplicity, we consider, in this text, channels to be bottom-channels, defined as agents with the pre-defined behavior (i.e. defined in a axiomatic way) of forwarding any input-assertion as output-assertion, without modifying it[33]. A port is, in fact, syntactic sugar to express the relation between Assertions and Beliefs.

Definition 5.3. Secure Mono-directional Channel (bottom-channel) – A mono-directional channel between the two agents ($s \to r$) is defined as an agent which behavior is (dogmatically) defined as: to forward any Assertion received from s over an input-port, to the output-port where r is listening to.

The *quality of a mono-directional* channel is defined as the *rcc* relation between the Assertions made by the sender and the ones received by the receiver, i.e. $rcc(\mathcal{A}_s, \mathcal{A}_r)$.

Channel Weaknesses Given that a mono-directional bottom-channel is assumed to be perfectly forwarding any Assertion from its input-port to its output-port, there is no insecure behavior but only the combination of the weaknesses of the input and output port; therefore there exists $(7^2) - 2 = 47$ theoretical configurations (7^2 because there are 6 insecure types of port, plus 1 secure type, on both input and oupput side; and we exclude the configuration with 2 secure types as input and ouput, -2); where only 43 are possible.

W6) *secure output port* and *input drop port* ($s \rightarrow\!\circ\ r$),

W7) *secure output port* and *input insertion port* ($s \rightarrow\!\bullet\ r$),

W8) *secure output port* and *input injection port* ($s \rightarrow\!◐\ r$),

W9) *secure output port* and *input selective drop port* ($s ⇥\!\circ\ r$),

W10) *secure output port* and *input selective insertion port* ($s ⇥\!\bullet\ r$),

W11) *secure output port* and *input selective injection port* ($s ⇥\!◐\ r$),

W12) *output drop port* and *input drop port* ($s\ \circ\!\!\rightarrow\!\circ\ r$)

[33] Nothing prevents us from introducing additional constraints to the channel as storing Assertions that are transferred over the channel, or filter out some input-assertions.

W13) *output drop port* and *input insertion port* (*s* ○→● *r*)

W14) *output drop port* and *input secure port* (*s* ○→ *r*)

W15) *output insert port* and *input drop port* (*s* ●→○ *r*)

W16) *output insert port* and *input insert port* (*s* ●→● *r*)

W17) *output insert port* and *input injection port* (*s* ●→◐ *r*)

W18) *output insert port* and *input selective drop port* (*s* ●→|○ *r*)

W19) *output insert port* and *input selective insertion port* (*s* ●→|● *r*)

W20) *output insert port* and *input selective injection port* (*s* ●→|◐ *r*)

W21) *output insert port* and *input secure port* (*s* ●→ *r*)

W22) *output injection port* and *input drop port* (*s* ◐→○ *r*)

W23) *output injection port* and *input insertion port* (*s* ◐→● *r*)

W24) *output injection port* and *input injection port* (*s* ◐→◐ *r*)

W25) *output injection port* and *input selective drop port* (*s* ◐→|○ *r*)

W26) *output injection port* and *input selective insertion port* (*s* ◐→|● *r*)

W27) *output injection port* and *input selective injection port* (*s* ◐→|◐ *r*)

W28) *output injection port* and *input secure port* (*s* ◐→ *r*)

W29) *output selective drop port* and *input drop port* (*s* ○⊢→○ *r*)

W30) *output selective drop port* and *input insertion port* (*s* ○⊢→● *r*)

W31) *output selective drop port* and *input injection port* (*s* ○⊢→◐ *r*)

W32) *output selective drop port* and *input selective drop port* (*s* ○⊢→|○ *r*)

W33) *output selective drop port* and *input selective insertion port* (*s* ○⊢→|● *r*)

W34) *output selective drop port* and *input selective injection port* (*s* ○⊢→|◐ *r*)

W35) *output selective drop port* and *input secure port* (*s* ○⊢→ *r*)

W36) *output selective insertion port* and *input drop port* (*s* ●⊢→○ *r*)

W37) *output selective insertion port* and *input insertion port* (*s* ●⊢→● *r*)

W38) *output selective insertion port* and *input injection port* (*s* ●⊢→◐ *r*)

W39) *output selective insertion port* and *input selective drop port* (*s* ●⊢→|○ *r*)

W40) *output selective insertion port* and *input selective insertion port* (*s* ●⊢→|● *r*)

W41) *output selective insertion port* and *input selective injection port* ($s \bullet\!\!\mapsto\!\!| \LEFTcircle\ r$)

W42) *output selective insertion port* and *input secure port* ($s \bullet\!\!\mapsto r$)

W43) *output selective injection port* and *input drop port* ($s \LEFTcircle\!\!\mapsto\!\circ\ r$)

W44) *output selective injection port* and *input insertion port* ($s \LEFTcircle\!\!\mapsto\!\bullet\ r$)

W45) *output selective injection port* and *input injection port* ($s \LEFTcircle\!\!\mapsto\!\LEFTcircle\ r$)

W46) *output selective injection port* and *input selective drop port* ($s \LEFTcircle\!\!\mapsto\!\!| \circ\ r$)

W47) *output selective injection port* and *input selective insertion port* ($s \LEFTcircle\!\!\mapsto\!\!| \bullet\ r$)

W48) *output selective injection port* and *input selective injection port* ($s \LEFTcircle\!\!\mapsto\!\!| \LEFTcircle\ r$)

W49) *output selective injection port* and *input secure port* ($s \to\!\LEFTcircle\ r$)

In Appendix C, we report the proof which is exhaustive on all possible combinations.

Ports and Channels – Discussion It is important to note that all the results of the application of the $\mathcal{ABF}$ to channels is the analysis of the relation $rcc\mathcal{A}_o\mathcal{A}_i$ leads to the same results of the analysis of a pair one input and one output port (i.e. $rcc\mathbb{B}_1\mathcal{A}_2 \wedge rcc\mathcal{A}_2\mathbb{B}_3$ The same result can be obtained by analyzing the relation between the outputs of a functional block and the inputs of another functional block. As depicted in Figure 16, so far, we have considered Information generated by a Port P_I and then sent through a channel C to another (recipient) port P_O. In this scenario where Ports and then Channels are atomic (otherwise raising infinite regress), we can only consider the relations between Ports and Channel; considering both input-port to channel and channel to output-port. In fact, the Weaknesses of a channel are defined in terms of the Weaknesses of Ports. We now introduce the concept of functional architecture and its decomposition into functional blocks. Io order to define a functional block without encountering a infinitely recursive definition, we must reach the same conclusions as for the Channel. Therefore, describing the information as flowing over a channel or in a functional block is purely syntactic sugar.

We can summarize these results by saying that the relations between Assertions and Beliefs, Output Assertions of an Agent and Input Assertions of another Agent, or Output Beliefs of a Functional Block and Input Beliefs of another Block can *only* be affected by the following weaknesses: replace, drop, injection, insertion, selective drop, and selective drop + insertion. We can, then, propose the following security properties:

- *Order-preserving* – it shall be known if Information is *replaced*
- *Availability* – it shall be known if Information is *dropped* or *selectively dropped*
- *Integrity* – it shall be known if Information is *injected*
- *Authentication* – it shall be known if Information is *inserted*

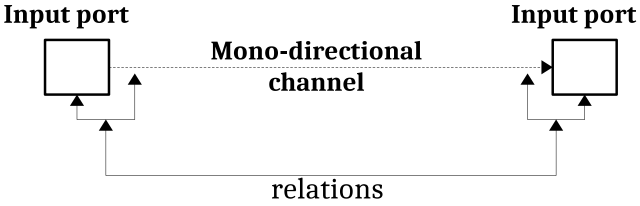


Figure 16: Relations between Ports and Channel

5.1.3 Functional Block

A Functional Architecture, as already described beforehand, takes Information as input-Beliefs and transforms the Information into output-Beliefs. Those transformations occurs within the Functional Architecture, where Functional Blocks transforms Beliefs into other Beliefs. Similarly to channels, we could consider a Functional Block as a Functional Architecture occurring in an infinite regress. Therefore, we consider Functional Blocks as executing an abstract undefined behavior, of which we only observe the inputs and the resulting outputs (Beliefs).

Definition 5.4. Functional Block and Architecture – A functional block of an agent takes a region of input-Beliefs and outputs a region of output-Beliefs. A functional architecture is an interconnected system of functional blocks.

It is evident that the quality of a functional block cannot be determined by the difference between its inputs and outputs (as we did for ports and channels). The behavior of a functional block cannot be determined in general; since any functional block will have its own purpose based on functional requirements. Therefore, while a port semantics is determined by the relation between Assertions and Beliefs, the semantics of a Functional Block is determined by the relation between Facts/Requirements and I/O Beliefs.

In other words, a functional block is a generic agent with no pre-defined general behavior (while ports and channels have a pre-defined behavior).

- $PO(\mathcal{B}, \mathcal{F})$ the component has a Byzantine behavior where occasionally outputs the expected output given the correct inputs. Not all the inputs are handled properly, nor all the expected outputs are always generated when correct inputs are given.

- $PP(\mathcal{B}, \mathcal{F})$ part of the expected outputs are not generated in response to the correct inputs

- $PPi(\mathcal{B}, \mathcal{F})$ the components correctly performs the expected behavior when the correct inputs are provided but is subject to input injections

- $DR(\mathcal{B}, \mathcal{F})$ the component never performs the expected behavior (e.g. physical damage)

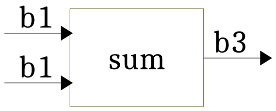


Figure 17: Example of a Functional Block

Requirements as Facts During the specification phase, for any agent, channel, port, functional block and architecture, there may exist a factorial requirement (Fact) predicating over them. In other words, any requirement is defined as a Fact since they must be true in any design or implementation. As we stated in Section 4 and depicted in Figure 10, Facts are strategic rules that defines how the system shall behave (by specification), while reality may be shown to be insecure.

As an example, consider a functional block that performs the summation of two inputs, as in Figure 17, defined by the requirement $r := b_3 = b_1 + b_2$. The possible relations between the behavior of the functional block and the requirements (i.e. $rcc(\mathcal{B}, \mathcal{F})$ is determined by the relations between the I/O Beliefs $sum(b_1, b_2) = b_3$ and the requirement $sum(b_1, b_2) = b_1 + b_2$, as follows.

- $EQ(\mathbb{B}, \mathcal{F}) = EQ(\mathbb{B}_3, \mathbb{B}_1 + \mathbb{B}_2)$, where $\mathbb{B}_3$ represents the Region of all the outputs of the functional block *sum* while the Region $\mathbb{B}_1 + \mathbb{B}_2$ represents the expected outputs of an ideal implementation of the requirement r. Therefore, the functional block correctly implements the requirements.

- $DR(\mathbb{B}, \mathcal{F}) = DR(\mathbb{B}_3, \mathbb{B}_1 + \mathbb{B}_2)$, the function block never implements the requirements.

- $PP(\mathbb{B}, \mathcal{F}) = PP(\mathbb{B}_3, \mathbb{B}_1 + \mathbb{B}_2)$, there exist some inputs for which the output is incorrect.

- $PPi(\mathbb{B}, \mathcal{F}) = PPi(\mathbb{B}_3, \mathbb{B}_1 + \mathbb{B}_2)$, there exists some outputs that are not the result of the summation of the inputs but given the correct inputs the function always outputs correctly.

- $PO(\mathbb{B}, \mathcal{F}) = PO(\mathbb{B}_3, \mathbb{B}_1 + \mathbb{B}_2)$, the component has a Byzantine behavior where occasionally outputs the expected output given the correct inputs. Not all the inputs are handled properly, nor all the expected outputs are always generated when correct inputs are given.

Methodology We have now mapped the building blocks of our theory, namely Information, Belief, Assertion, Behavior, and Fact. One may notice that the concept of Knowledge hasn't been discussed in this section so far. Our argument is that knowledge, as an epistemological concept cannot be defined due to several implication that this would have (see, for example, [32]). On the other hand, the factorial way in which requirements are imposed may be true only in the specification, while not necessarily true in the final implementation. While

Knowledge may not be apprehensible in general, we can define tests to see if Facts holds in a design or implementation. What is of our interest is to guarantee security in a system so we now correlate the potential behaviors with the standard (de-facto) understanding of security; so that we can identify test that, at the end of the engineering process, may not give Knowledge but, at last, tested Fact.

5.1.4 Security Requirements

While standards such as IEC 62443-1-3 (the Industrial communication networks - Network and system security – Part 3-3: System security requirements and security levels) defines requirements as "confidentiality of information in transit/at-rest", we believe that, at specification level, a mapping between the Infosec security concepts of the well-known CIA (Confidentiality, Integrity, Availability) triad to the system components can be used to specify a list of security requirements.

Infosec, or Information Security, defines the security risks related to information as the CIA triad, which has been often criticized (as we show afterwards) for being too general or non-adequate (e.g. by adding authenticity which is often used as a building block for confidentiality and integrity) to be effectively applied to the engineering of systems. Due to this, many researchers and organization tried to improve the CIA triad. The evolutions/extensions of the CIA triad has been documented, e.g., in [74] and are summarized in Table 3.

Year	Definition	Legend
1970s	infosec = CIA	Confidentiality, Integrity, Availability
1980s	infosec += (Au, nR)	Authenticity and non-Repudiation
1990s	infosec += CSpec	Correctness in Specification
2000s	infosec += RITE	Responsibility, Integrity of people, Trust, Ethicality

Table 3: Chronological progression of the CIA triad

A representative example is the effort made by the OECD (Organisation for Economic Co-operation and Development) in [31] to define security guidelines for information system (1992) based on new principles such as "awareness, ethics, risk assessment" and maintain those improving the document with subsequent revisions (e.g. following the multistakeholder expert consultation in 2013). Other similar efforts focused on defining entirely new principles or extending the CIA triad, such as [62]. In [2, 74], CIA are defined as follows.

- *Unauthorized information release*: an unauthorized person is able to read and take advantage of information stored in the computer. This category of concern sometimes extends to "traffic analysis," in which the intruder only observes the patterns of information use. From those patterns, the intruder can infer some information content. This category also includes the unauthorized use of a proprietary program. (Confidentiality or Secrecy)

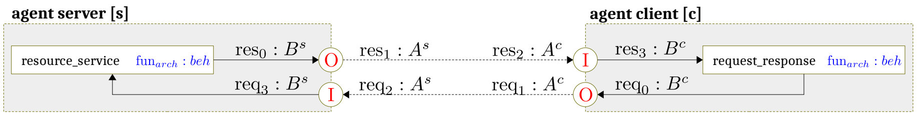


Figure 18: Client-Server paradigm in $\mathcal{ABF}$-theory

- *Unauthorized information modification*: an unauthorized person is able to make changes in stored information – a form of sabotage. It should be noted that in the case of this kind of violation, the intruder does not necessarily see the information he has changed. (Integrity)

- *Unauthorized denial of use*: an intruder can prevent an authorized user from referring to, or from modifying information, even though the intruder may not be able to refer to, neither modify the information themselves. (Availability)

We now want to generalize the CIA triad to agents and systems in the $\mathcal{ABF}$-theory (and not just Information). Given that we are currently dealing with the step that moves from specification to design, we consider architectural properties. For the sake of simplicity, we revert the order and start from availability.

Availability and Integrity (Architecture Security) Availability, again, is the denial of use of a resource. In the $\mathcal{ABF}$-theory, in order to prevent a resource to be available, there exists only (i.e. inclusively) the following cases that we illustrate using a client-server paradigm (depicted in Figure 18).

1. The resource on the server cannot be found, so that it is possible for the client to contact the server and for the server to send a response back, but the output-port does not receive the necessary information. This may be due to a software error such that the functional architecture doesn't output a response, or a problem in the flow of information (i.e. the functional architecture doesn't receive the necessary information from other resources), or an hardware failure &c. This can be formalized as an issue to be found in the relation between the beliefs produced by the functional architecture and the ones received by the output port, i.e. $rcc(\mathcal{B}_s, \{\text{res}_0\})$ or $rcc(\mathbb{B}_s, \{\text{res}_0\})$

2. The server hosting the resource is down, and then the server cannot output responses (i.e. insecure output port due to drop-related issue) or receive requests (insecure input port due to drop-related issue) or both.

3. The client cannot properly compute request (symmetric to Case 1)

4. The client is down, symmetric to Case 2

5. The channel is down due to a drop related issue in one of the two channels

We shall, then, distinguish between two cases, as we mentioned beforehand: agent (or system) and Information (which we call Infosec) availability.

Definition 5.5. Agent-Availability – when the property of availability is expressed over an agent or a system, the list of possible designs do not include those in which there exist: drop ports, or drop channels/functional-blocks.

Definition 5.6. Infosec-Availability – when the property of availability is expressed over a formula, the list of possible designs that violates the availability property is reduced to the part of the system that does not influence that specific formula.

In a similar way we can define integrity since this requirement may be expressed over an agent/system or a specific formula (i.e. element of a Region).

Definition 5.7. Agent-Integrity – when the property of integrity is expressed over an agent or a system, the list of possible designs do not include those in which there exist: insert or inject ports, or insert or inject channels/functional-blocks.

Definition 5.8. Infosec-Integrity – when the property of integrity is expressed over a formula, the list of possible designs that violates the integrity property is reduced to the part of the system that influences that specific variable.

While availability and integrity are architectural property, meaning that they can be expressed over the behavior of a port or a channel (as constituent of the physical or functional architecture), confidentiality is not. Confidentiality states that an information shall not be understood and not that the information shall not be retrieved. So, if a port leaks an entire message, there is no confidentiality issue in general, unless that message was not encrypted, in which case the confidentiality leakage is straightforward. On the other hand, if the information is not provided or altered there is an availability or integrity issue. A similar argument can be proposed for integrity sub-properties such as authenticity or non-repudiation. No wonder why it is often stated that availability and integrity are the first properties to be considered in CPS secure engineering while confidentiality takes the first place when dealing with security protocols. In fact, integrity is often assumed by pattern-matching (e.g. in AVANTSSAR [4]) and availability is hardly ever considered in protocol verification. The question is, can we express properties such as confidentiality, authentication, or non-repudiation as architectural properties in $\mathcal{ABF}$-theory? Confidentiality is based on the concept of secrecy so we shall first start from describing what secrecy is and how it can be used to guarantee confidentiality in a system.

Secrecy, Authenticity, and Key Agreement (Cryptographic Security) As Maurer puts it ([57]), there exist two types of cryptographic security (i.e. scientific theories aiming at guaranteeing security through the use of cryptographic functions): “The security of a cryptographic system can rely either on the computational infeasibility of breaking it (computational security), or on the theoretical impossibility of breaking it, even using in infinite computing power (information-theoretic or unconditional security)". We are not currently interested in detailing the difference between the two and we simplify it as follows. A computationally-secure cryptographic function (usually called encryption function) $E(\varphi) = e$ (where φ is a plain-text and e a cipher-text) can be considered perfectly secure if a malicious agent that obtains the result of the cryptographic function (e) has bounded computational power, while unconditional secure cryptographic functions are considered perfectly secure. In this context, security means that is is impossible to calculate φ from e, therefore impossible to compute $D(e) = \varphi$. As one can evince from [76], the commonality between the two types of cryptographic functions is that they both rely on the assumption about the probabilistic behavior of the universe. They do so, for the random (i.e. with high entropy [76]) generation of the so called *key*, a piece of information, parametric to the cryptographic function, used to guarantee the security. Therefore, we can assume that it is feasible for an agent that knows k to decrypt the cipher-text obtaining the clear-text (i.e. $D(k, E(k, \varphi)) = \varphi$) while it is impossible for any agent that has not the proper key. In this case, the information is considered to be *secret or confidential*.

Definition 5.9. Infosec-Secrecy or Confidentiality – When an Assertion has been generated as an output by an agent, port, or functional block such that it is said (in a factorial way) to encrypt the input, that Assertion is considered confidential.

The quality of the confidentiality of information (Assertions or Beliefs depending on the subsystem considered) is inversely proportional to the number of integrity issues of the subsystem. We now discuss more in details what secrecy of Information is when dealing with functional blocks (Behavior) and Beliefs but a similar treatment can be done in the case of Channels and Assertions.

The quality of a Functional Block is determined by the relation between the input-Beliefs formulas and the symmetric formulas in the Fact region (equivalently for output-Beliefs).

Definition 5.10. Secrecy of Functional Block and Architecture – Secrecy is preserved in a functional block if the input beliefs and output beliefs are in EQ relation with the corresponding Facts mandated by the confidentiality/secrecy requirements. A functional architecture where all the secrecy-preserving functional blocks are in EQ relation with the corresponding Facts is considered confidential/secrecy-preserving.

Confidentiality Weaknesses In a functional block, there exists the following weaknesses in the functional architecture, where $\mathbb{B}_I$ and $\mathbb{B}_O$ are input and output Beliefs respectively, and $\mathcal{F}_I$ and $\mathcal{F}_O$ are the corresponding Facts.

- $EQ(\mathbb{B}_I, \mathcal{F}_I)$ and then only specified inputs can be fed to the functional block but:

W49) $DR(\mathbb{B}_O, \mathcal{F}_O)$, not all the specified outputs are produced. This may produce a secrecy issue if, for example, the functional block is responsible for generating an encryption key since if it is not produced the encryption of the Information may not be performed

W50) $PO(\mathbb{B}_O, \mathcal{F}_O)$, only some but not all of the specified outputs are produced along with some non-specified output are produced. This strightforwardly generates a secrecy when the functionality is related to secrecy functional blocks since some outputs doesn't follow the requirements.

W51) $PP(\mathbb{B}_O, \mathcal{F}_O)$, not all the specified outputs are produced. This may pose a secrecy issue as in W49)

W52) $PPi(\mathbb{B}_O, \mathcal{F}_O)$, not all the output have been specified. This may pose a secrecy issue as in W50)

- $PO(\mathbb{B}_I, \mathcal{F}_I)$, not all the specified inputs can be fed into the functional block

W53) $DR(\mathbb{B}_O, \mathcal{F}_O)$

W54) $PO(\mathbb{B}_O, \mathcal{F}_O)$

W55) $PP(\mathbb{B}_O, \mathcal{F}_O)$

W56) $PPi(\mathbb{B}_O, \mathcal{F}_O)$

W57) $EQ(\mathbb{B}_O, \mathcal{F}_O)$ this case implies that somehow there is no input that generates an non-specified output but this is not because the inputs are secure

- $PP(\mathbb{B}_I, \mathcal{F}_I)$, not all the specified inputs can be fed into the block

W58) $DR(\mathbb{B}_O, \mathcal{F}_O)$

W59) $PO(\mathbb{B}_O, \mathcal{F}_O)$

W60) $PP(\mathbb{B}_O, \mathcal{F}_O)$

W61) $PPi(\mathbb{B}_O, \mathcal{F}_O)$

W62) $EQ(\mathbb{B}_O, \mathcal{F}_O)$

- $PPi(\mathbb{B}_I, \mathcal{F}_I)$, not all the inputs that can be fed into the functional block follows the specification

W63) $DR(\mathbb{B}_O, \mathcal{F}_O)$

W64) $PO(\mathbb{B}_O, \mathcal{F}_O)$

W65) $PP(\mathbb{B}_O, \mathcal{F}_O)$

W66) $PPi(\mathbb{B}_O, \mathcal{F}_O)$

W67) $EQ(\mathbb{B}_O, \mathcal{F}_O)$

- $DR(\mathbb{B}_I, \mathcal{F}_I)$, no specified inputs can be fed into the functional block

W68) $DR(\mathbb{B}_O, \mathcal{F}_O)$

W69) $PO(\mathbb{B}_O, \mathcal{F}_O)$

W70) $PP(\mathbb{B}_O, \mathcal{F}_O)$

W71) $PPi(\mathbb{B}_O, \mathcal{F}_O)$

W72) $EQ(\mathbb{B}_O, \mathcal{F}_O)$

Hypothesis 5.1. System Security Design – *A system security design is given by a precise system security specification over the physical and functional architectures, that uniquely, i.e. tested against the range of design possible in the $\mathcal{ABF}$-theory, defines the designs built on top of those requirements.*

Hypothesis 5.2. System Insecurity Design – *If, given a system security specification as a collection of requirements on the system, there exist a non-unique design that respect those requirements, the number of equivalent designs that fulfills the requirements quantitatively defines the magnitude of insecurity of a system design.*

Based on these hypothesis, security (S) can be expressed as the following equation.

$$S = 1 - (\prod_{a \in Ag} r^{\binom{n}{k}} - \delta_T)$$

where $r^{\binom{n}{k}}$ represents the number of possible configurations (permutations) of an agent based on the number r of relations (e.g. EQ, DR, PO) with arity k between n different sets in the $\mathcal{ABF}$ theory. δ_T represents the number of configurations which are not satisfiable with respect to the logical theory defining the algebraic structure (topology) and constraints of the calculus (RCC). Ag is the set of all the agents in the system under evaluation. The constant 1 represents the nominal configuration of the system and then the only secure configuration. The product represents all the unintended, insecure, configurations.

5.2 Abstraction Level of a Specification in $\mathcal{ABF}$-theory

The level of abstraction is always a concern when it comes to the definition of a system model. In this paper, we justified our assumptions on the atomicity of ports, channels, and functional blocks but nothing prevents a modeler to consider other atomic element of the system specification and design. Those additional elements may detail the system and may change the syntactic sugar we defined; however, it won't change the underlying (semantic) reasoning unless another calculus is used (instead of RCC). Furthermore, other Infosec properties may be considered, such as authenticity or non-repudiation. We, however, leave them as future development.

6 A Prototype for Security Risk Assessment

In order to test our theory we implemented a tool-chain for the identification of weaknesses and the precise calculation of potential insecure configurations. In this section, we describe the tool-chain and the concepts related to the risk estimantion, such as likelihood and impact of attack paths.

The engineering of the $\mathcal{ABF}$ is summarized in the UML Class diagram in Figure 19. The Class diagram represents the concepts introduced in Section 5. This allows us to define a CPS as a composition of the two (symmetric) structures depicted in Figure 20. A system can be designed in $\mathcal{ABF}$ as the composition of structures formed by 3 elements: functional architecture, ports, and channels. If the information flows from left to right the port is an output port, otherwise (right-to-left) is an input port.

6.1 V-SecRA Tool-chain

The security risk assessment process starts with the definition of the use cases (see Figure 12) and architectural requirements (see Appendix D); which we call specification. In our process, the specification is translated into a UML design where:

- a *Deployment Diagram* describes the *Physical Architecture*. Each agent is defined as a Node with (physical) Ports, and Agent's ports are connected via Information Flow connectors, representing the physical channel.
- a *Functional Architecture* is linked to each agent in the deployment diagram and is defined by an *Object Diagram*. The Object Diagram is composed by Instances of Functional Blocks, connected via Information Flow connectors.
- the connection between the two diagrams is implemented by "sockets", functional blocks with the same name of the corresponding physical port.

6.2 Impact and Likelihood

As described in [**CORASMethod**], in order to quantitatively estimate the cybersecurity *risk* of a CPS design, one needs to estimate both the *likelihood* of *attack paths* (attack from now on)**FIX**[34] along with their (negative) *impact* on a requirement which, in turn, is related to some *company assets*. An attack that has a negative impact on a requirement invalidates the requirement, leading to one or more *incidents*.

7 Conclusion

In this paper, we proposed a foundational theory on security, arguing that security-related issues are not related to the maliciousness of an agent but to

[34] **mr:** check terminology consistency

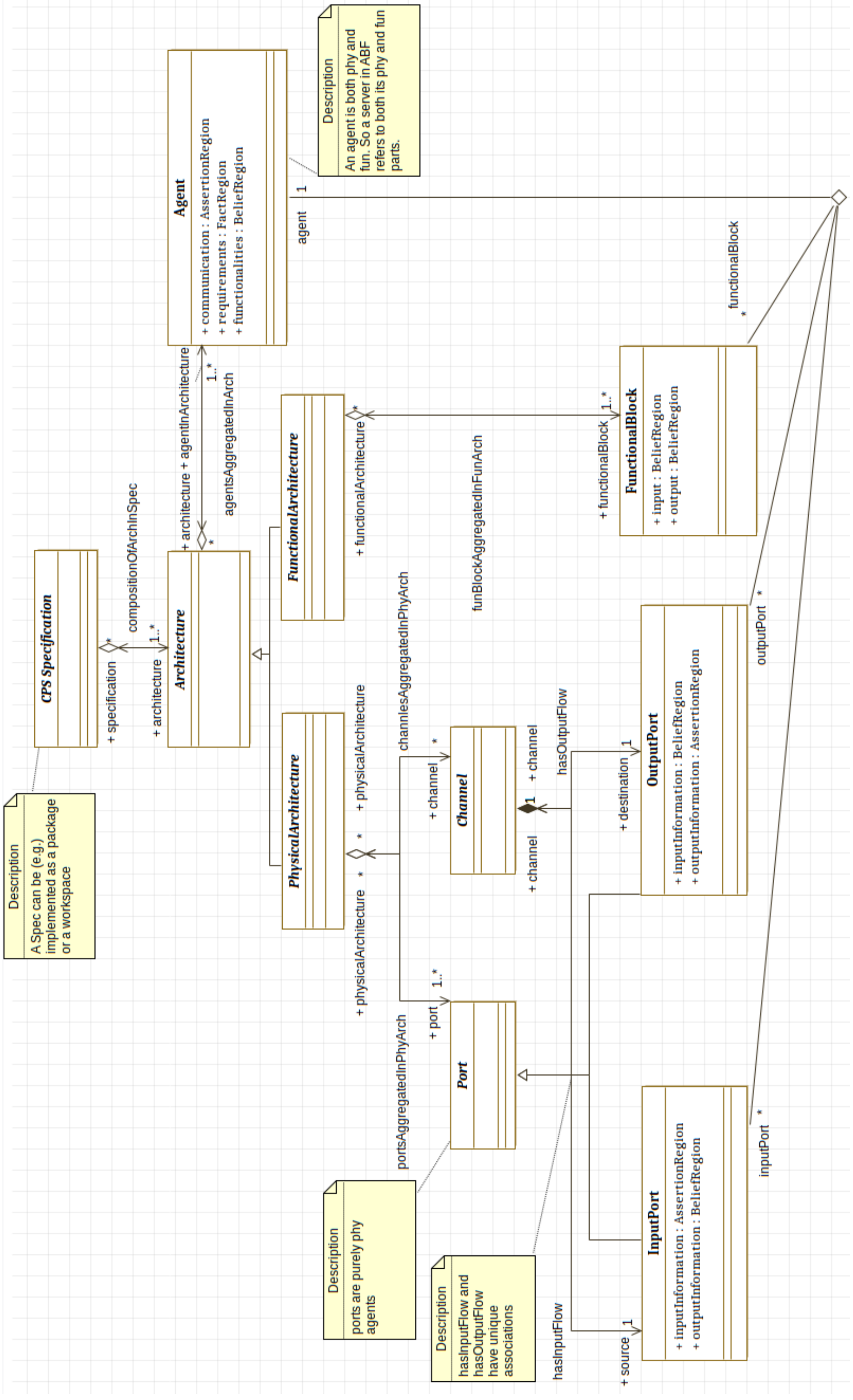

Description
A Spec can be (e.g.) implemented as a package or a workspace
CPS Specification
+ specification
*
compositionOfArchInSpec
1..*
+ architecture
Architecture
+ architecture + agentInArchitecture
*
1..*
agentsAggregatedInArch
Agent
+ communication : AssertionRegion
+ requirements : FactRegion
+ functionalities : BeliefRegion
agent
1
Description
An agent is both phy and fun. So a server in ABF refers to both its phy and fun parts.
FunctionalArchitecture
+ functionalArchitecture
*
funBlockAggregatedInFunArch
+ functionalBlock
1..*
FunctionalBlock
+ input : BeliefRegion
+ output : BeliefRegion
functionalBlock
*
PhysicalArchitecture
+ physicalArchitecture
*
+ physicalArchitecture
*
channlesAggregatedInPhyArch
+ channel
*
Channel
+ channel
1
+ channel
hasOutputFlow
+ destination
1
OutputPort
+ inputInformation : BeliefRegion
+ outputInformation : AssertionRegion
outputPort
*
portsAggregatedInPhyArch
+ port
1..*
Port
Description
ports are purely phy agents
Description
hasInputFlow and hasOutputFlow have unique associations
hasInputFlow
+ source
1
InputPort
+ inputInformation : AssertionRegion
+ outputInformation : BeliefRegion
inputPort
*

Figure 19: Security Risk Assessment – Class Diagram

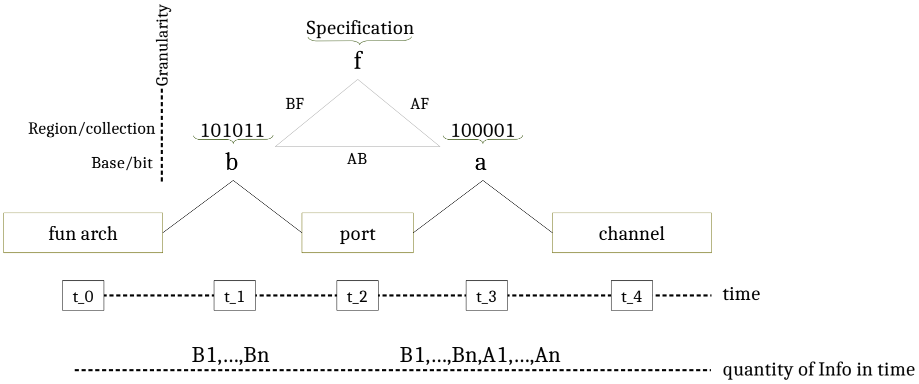


Figure 20: Summary of $\mathcal{A}, \mathcal{B}, \mathcal{F}$ Engineering Model

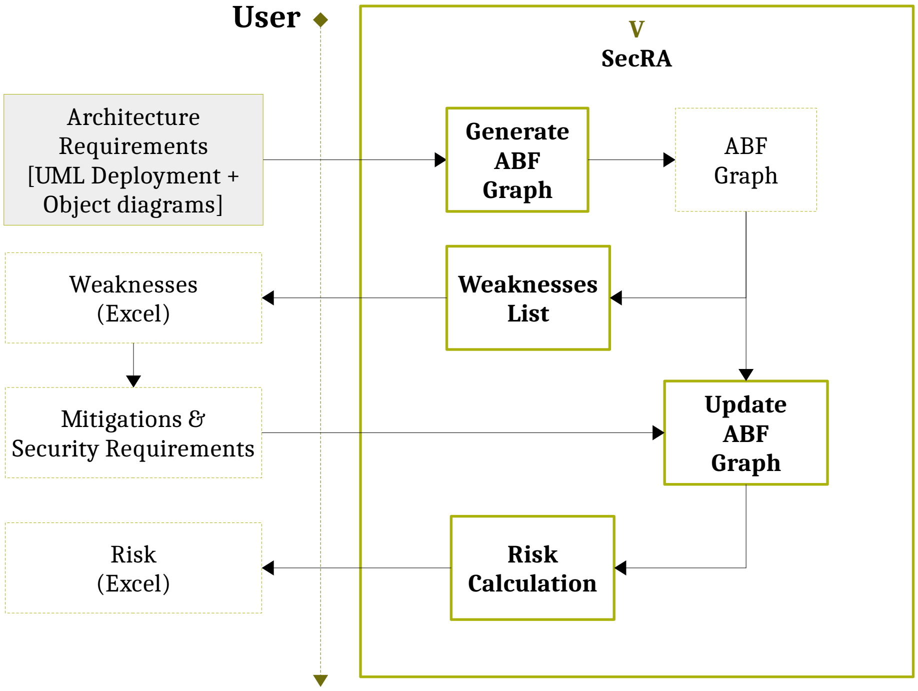


Figure 21: V-SecRA

the vagueness of the security controls on the engineering processes. The current state-of-the-art processes allows, given a specification, an engineer to design the system in such a way that security issues arise due to the lack of proper security risk assessment processes. Those design, again, lack of security verification processes based on a solid security foundational theory and then permit the generation of insecure implementation. The security verification and test-case generation will be the focus of our next steps.

We may conclude that the problem of security is a problem related to the many possible design and, in turn, implementation given a specification. Philosophically, the problem is similar to the epistemological search for truth, where the challenge is to relate Information and Belief to Human Knowledge. Scientifically, generalizing the Human to an Agent, the problem is to relate Assertions and Behaviors, to Facts. From an engineering standpoint, by generalizing the concept of Agents as architectural subsystems, the problem is to link Channels (and Ports) and Functional Architectures to Requirements.

A Brief Economic Motivation

The European Commission states in[27] that: “Cybersecurity is one of the priority areas [. . .] of the Commission initiative on ICT Standards, which is part of the Digitising European Industry[28] 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.[27]) 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[29] 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[82] maintained by the National Institute of Standards and Technologies, i.e. NIST, of the US Department of Commerce).

B Selective Injection Port

$$PO(x, y) = O(x, y) \wedge \neg P(x, y) \wedge \neg P(y, x)$$

and

$$\begin{array}{lll} O(x, y) = \exists z.\ P(z, x) & & \wedge P(z, y) \\ & \forall z'.\ z' \subseteq z \Rightarrow z' \subseteq x & \quad \forall z''.\ z'' \subseteq z \Rightarrow z' \subseteq y \end{array}$$

and

$$\begin{aligned} \neg P(x, y) =& \neg[\forall \varphi.\ (\varphi \subseteq x) \Rightarrow (\varphi \subseteq y)] \\ & \neg[\forall \varphi.\ \neg(\varphi \subseteq x) \vee (\varphi \subseteq y)] \\ & \exists \varphi.\ (\varphi \subseteq x) \wedge (\varphi \nsubseteq y) \end{aligned}$$

Therefore

$$PO(\mathcal{A}, \mathbb{B}) = (\varphi \subseteq \mathcal{A} \wedge \varphi \subseteq \mathbb{B}) \wedge (\varphi' \subseteq \mathcal{A} \wedge \varphi' \nsubseteq \mathbb{B}) \wedge (\varphi'' \subseteq \mathcal{A} \wedge \varphi'' \subseteq \mathbb{B})$$

Which means that, when a communication over an input-port results in $PO(\mathcal{A}, \mathbb{B})$, the port is:

- correctly receiving incoming communication as Assertion and sending it to the recipient agent as Beliefs, *and* $(s \rightarrow a)$
- incorrectly, dropping some input communication (Assertions) $(s\boxed{\circ\!\!\rightarrow}a)$, *and*
- incorrectly, inserting some new Beliefs $(s\boxed{\bullet\!\!\rightarrow}a)$

Which we abbreviate as a *selective injection* port: $s\boxed{\LEFTcircle\!\mapsto}a$.

C Insecure Communication Port

tofix: this proof needs to be done. The current text is not sufficient

Proof. 1. *input secure port* and

   (a) *output drop port* ($s \rightarrow\circ\, r$),

   (b) *output insertion port* ($s \rightarrow\bullet\, r$),

   (c) *output injection port* ($s \rightarrow\LEFTcircle\, r$),

   (d) *output selective drop port* ($s \rightarrow\!\shortmid\!\circ\, r$),

   (e) *output selective insertion port* ($s \rightarrow\!\shortmid\!\bullet\, r$),

   (f) *output selective injection port* ($s \rightarrow\!\shortmid\!\LEFTcircle\, r$),

2. *input drop port* (all the input-assertions are dropped) and

   (a) *output drop port* ($s \circ\!\!\rightarrow\circ\, r$), this configuration is possible but the input port doesn't forward any message therefore the output port will never have a message to drop

   (b) *output insertion port* ($s \circ\!\!\rightarrow\bullet\, r$), where all the ouput-assertions have been inserted by the output port

   (c) *output injection port*, this configuration is impossible since there is no Assertions from the input-port to inject (or it behaves as $s \circ\!\!\rightarrow\bullet\, r$)

   (d) *output selective drop port*, as in 2c there is no Assertion from the input port therfore no selective port is possible in general. In this case this configuration is impossible or behaves as $s \circ\!\!\rightarrow\circ\, r$

   (e) *output selective insertion port*, as in 2d impossible, or behaves as $s \circ\!\!\rightarrow\bullet\, r$

   (f) *output selective injection port*, as in 2d impossible, or behaves as $s \circ\!\!\rightarrow\bullet\, r$

   (g) *ouput secure port* ($s \circ\!\!\rightarrow r$)

3. *input insertion port* (where all the assertion reaching the output-port have been artificially generated by the input-port) and

   (a) *output drop port* ($s \bullet\!\!\rightarrow\circ\, r$), this configuration is possible but the drop port drops every inserted message.

   (b) *output insertion port* ($s \bullet\!\!\rightarrow\bullet\, r$), new Assertions have all been inserted both at the left-hand side and righ-hand side of the communication.

   (c) *output injection port* ($s \bullet\!\!\rightarrow\LEFTcircle\, r$), the new Assertions, inserted in the left-hand side, are then modified/injected on the right-hand side of the communication

   (d) *output selective drop port* ($s \bullet\!\!\rightarrow\!\shortmid\!\circ\, r$), where some insertions of the input port are dropped

(e) *output selective insertion port* ($s \bullet\!\!\longrightarrow\!\!|\!\bullet\ r$), where some insertions of the input port are substituted with new insertion on the right-hand side of the communication

(f) *output selective injection port* ($s \bullet\!\!\longrightarrow\!\!|\!\LEFTcircle\ r$) where some insertions of the input port are modified/injected on the right-hand side of the communication

(g) *output secure port* ($s \bullet\!\!\longrightarrow r$)

4. *input injection port* and

   (a) *output drop port* ($s \LEFTcircle\!\!\longrightarrow\!\circ\ r$)

   (b) *output insertion port* ($s \LEFTcircle\!\!\longrightarrow\!\bullet\ r$)

   (c) *output injection port* ($s \LEFTcircle\!\!\longrightarrow\!\LEFTcircle\ r$)

   (d) *output selective drop port* ($s \LEFTcircle\!\!\longrightarrow\!\!|\!\circ\ r$)

   (e) *output selective insertion port* ($s \LEFTcircle\!\!\longrightarrow\!\!|\!\bullet\ r$)

   (f) *output selective injection port* ($s \LEFTcircle\!\!\longrightarrow\!\!|\!\LEFTcircle\ r$)

   (g) *output secure port* ($s \LEFTcircle\!\!\longrightarrow r$)

5. *input selective drop port* and

   (a) *output drop port* ($s \circ\!\!\longmapsto\!\circ\ r$)

   (b) *output insertion port* ($s \circ\!\!\longmapsto\!\bullet\ r$)

   (c) *output injection port* ($s \circ\!\!\longmapsto\!\LEFTcircle\ r$)

   (d) *output selective drop port* ($s \circ\!\!\longmapsto\!\!|\!\circ\ r$)

   (e) *output selective insertion port* ($s \circ\!\!\longmapsto\!\!|\!\bullet\ r$)

   (f) *output selective injection port* ($s \circ\!\!\longmapsto\!\!|\!\LEFTcircle\ r$)

   (g) *output secure port* ($s \circ\!\!\longmapsto r$)

6. *input selective insertion port* and

   (a) *output drop port* ($s \bullet\!\!\longmapsto\!\circ\ r$)

   (b) *output insertion port* ($s \bullet\!\!\longmapsto\!\bullet\ r$)

   (c) *output injection port* ($s \bullet\!\!\longmapsto\!\LEFTcircle\ r$)

   (d) *output selective drop port* ($s \bullet\!\!\longmapsto\!\!|\!\circ\ r$)

   (e) *output selective insertion port* ($s \bullet\!\!\longmapsto\!\!|\!\bullet\ r$)

   (f) *output selective injection port* ($s \bullet\!\!\longmapsto\!\!|\!\LEFTcircle\ r$)

   (g) *output secure port* ($s \bullet\!\!\longmapsto r$)

7. *input selective injection port* and

   (a) *output drop port* ($s \LEFTcircle\!\!\longmapsto\!\circ\ r$)

   (b) *output insertion port* ($s \LEFTcircle\!\!\longmapsto\!\bullet\ r$)

(c) *output injection port* (*s* ◐↦◐ *r*)

(d) *output selective drop port* (*s* ◐↦|○ *r*)

(e) *output selective insertion port* (*s* ◐↦|● *r*)

(f) *output selective injection port* (*s* ◐↦|◐ *r*)

(g) *output secure port* (*s* →◐ *r*)

□

D System Requirements

req1) the tank has no functional architecture, it is a purely physical component which has the only purpose of containing water

req2) the communication is unidirectional from the tank to the input port of the sensor

req3) the sensor has an input-port that receives only incoming communication from the tank

req4) the sensor has two functional blocks

req4.1) read_water_level, accepts inputs only from the input-port and outputs a new reading every t seconds

req4.2) comm_water_level, accepts inputs only from the read_water_level and communicates the readings to the output-port

req5) the sensor has an output-port that only outputs the messages generated by the comm_water_level to the input-port of the controller

req6) the controller has in input-port that only receives incoming communications from the sensor and sends the messages to the functional architecture

req7) the functional architecture of the controller is composed by three functional blocks

req7.1) get_water_level, accepts inputs only from the input-port and outputs the water level to the main control function

req7.2) control, calculate the next state of the valve based on the inputs receive from the get_water_level

req7.3) send_state, receives the output of the control function and communicates it to the output-port

req8) the controller has an output-port that only outputs the messages generated by the send_state to the input-port of the actuator

req9) the actuator has an input-port that receives only incoming communication from the controller req10) the functional architecture of the actuator is composed by two functional blocks

req10.1) read_change_state, accepts inputs only from the input-port and outputs the next state of the valve to the close_open_valve function

req10.2) close_open_valve, converts the digital next state received from the read_change_state an analog signal and communicates it the output-port

req11) the valve accepts analog messages from the output port of the actuator and changes its state based on those messages

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