ARMOR: A Formally Verified Implementation of X.509 Certificate Chain Validation (Full Version)

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***Abstract*—We present ARMOR, the first substantial effort towards an X.509 certificate chain validation logic (CCVL) implementation with formal, machine-checked correctness guarantees for a large portion of RFC 5280. ARMOR is designed with the twofold goal of providing 1) a formal, machine checked alternative to the RFC specifications, and 2) a reference implementation and test oracle. ARMOR features a modular architecture in which the X.509 CCVL is decomposed into several modules, each of which is independently specified, implemented, and verified. Currently, the formally verified modules of ARMOR include those for the specification and parsing of (subsets of) the PEM and ASN.1 X.690 DER languages, certificate chain building, and many *semantic* properties concerning required properties of fields within a single certificate and across certificates in a chain. To empirically evaluate its achievement of these goals, we compare ARMOR with 11 open-source X.509 implementations and an open-source certificate linter for its specificational accuracy and runtime overhead. In our evaluation, although ARMOR incurs a high overhead, through its use we are able to detect several noncompliances. Finally, we show an end-to-end application of ARMOR by integrating it with the TLS 1.3 implementation of BoringSSL and testing it with Curl.**

1. Introduction

X.509 certificate chain validation logic (CCVL) implementations, hailed as the "*most dangerous code in the world*" [1], are critical for ensuring the authentication guarantees promised by the X.509 PKI [2]. Along with its authentication guarantees, X.509 provides a scalable and flexible mechanism for public-key distribution. The guarantees of X.509 PKI are fundamental building blocks for achieving security assurances such as *confidentiality*, *integrity*, and *non-repudiation* in many protocols and applications such as IPSec, HTTPS, Email, Wi-Fi, code signing, secure boot, firmware/software verification, and secure software update. Given its pivotal role in system, software, and communication security, ensuring the *correctness* of X.509 CCVL implementations is of utmost importance. Incorrect validation could lead to a system accepting a malicious or invalid certificate, potentially exposing the system to man-in-the-middle (MITM) and impersonation attacks; incorrectly rejecting a valid certificate could induce interoperability issues.

The majority of prior work focuses on developing software testing mechanisms specialized for checking the correctness of different X.509 libraries. These efforts can be categorized into approaches that use *Fuzzing* [3], [4], [5], [6], [7] and those that use *Symbolic Execution* [8], [9]. While these methods have been beneficial in identifying numerous vulnerabilities, they often fall short of providing any formal correctness guarantees. This is corroborated through many high impact bugs and vulnerabilities in some widely used and tested applications and open-source libraries [10], [11], [12], [13], [14]. One of the main challenges that these approaches have to address is the lack of a *test oracle*. Most of the prior approaches rely on differential testing [3], [4], [5], [9], where different implementations are used as *cross-checking test oracles*. However, differential testing cannot guarantee the absence of bugs, as it is possible that the tested implementations have the same error.

In contrast, a formally verified X.509 CCVL implementation can provide rigorous assurances of its correctness, setting a benchmark for developing other implementations and reducing undetected bugs during differential testing. However, of the minority of relevant prior work featuring formal correctness guarantees [15], [16], none have X.509 CCVL as their intended scope. For example, while ASN1* [15] provides a general, formally verified library for parsing ASN.1 X.690 DER (Distinguished Encoding Rules) [17], it does not perform chain building or enforce the additional semantics of the *decoded* values required for X.509 CCVL.

In summary, prior work has at least one of the following limitations: it (1) has no formal guarantees [3], [4], [5], [6], [7], [8], [9], [18], [19], [20], [21], [22]; (2) focuses only on parsing and lacks formal correctness guarantees of semantic aspects [15], [23], [24]; (3) lacks explicit proof of *soundness* and *completeness* of certificate parsing [15], [23], [24], [25]; (4) focuses only on verified encoding of certificates, not parsing [16]. *The current paper takes a major step to address this research gap with* ARMOR, *a substantial effort towards developing a high-assurance implementation of X.509 CCVL with formal, machine-checked proofs of compliance with the standards.* At time of writing, ARMOR boasts a formalization of the grammar of X.509 certificates, with proofs these grammars satisfy certain desirable properties, and formally verified implementations of X.509 certificate parsing, certificate chain building, and several standards-required semantic checks for certificates and certificate chains. Though

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still a work in progress, ARMOR is, to the best of our knowledge, the first implementation of X.509 CCVL with such an extensive scope of machine-checked correctness proofs.

Overall Design. ARMOR is designed and developed with modularity in mind. Inspired by prior work [18], [22], [25], we decompose the whole X.509 certificate chain validation process into several modules, making both the implementation and formal verification efforts manageable. In particular, we formulate correctness guarantees for *most* modules, which can then be discharged independently. ARMOR is organized into five modules: parser, chain builder, string canonicalizer, semantic validator, and driver. The *driver*, written in `Python`, stitches together the different components and exposes an interface expected from an X.509 implementation. The rest of the modules, written in the dependently typed functional programming language `Agda` [26], [27], implement all the intermediate stages of certificate chain validation. Notably, one can both write programs in `Agda` and prove their correctness using *interactive theorem proving*, and `Agda`'s built-in termination checker ensures these are *total correctness* proofs. Once these proof obligations are discharged, we use `Agda`'s extraction mechanism to obtain an executable, which is then invoked by the driver.

Verification Philosophy. Our general approach of verification carefully separates the specificational elements from the implementation elements by using *implementation-independent, relational* specifications. In particular, we use *parser-independent* specifications of the PEM, X.690 DER, and X.509 formats. Compared to approaches that verify parsers with respect to serializers, such as EverParse [24] and ASN1* [15], our approach reduces the complexity of the specifications and provides a clear distinction between correctness properties of the *language* and the *parser*. Furthermore, implementation-independence affords our specification greater utility as a formal, machine-checked alternative to natural language specifications of the standard.

Guarantees and Scope. ARMOR's machine-checked guarantees include the following (see Table 1 for the full listing). For our X.690 DER and X.509 *parsers* we proved *soundness* (bytestrings accepted by the parser conform to the format specification) and *completeness* (bytestrings that conform to the format specification are accepted by the parser). For our X.690 DER and X.509 *language formalizations*, we proved *unambiguousness* (e.g., one bytestring cannot encode two distinct X.509 certificates) and *non-malleability* (e.g., two distinct bytestrings cannot encode the same X.509 certificate). For our *chain builder*, we proved *soundness* and *completeness* (the chain builder produces all and only chains satisfying the chain specification). For our *semantic validator*, each semantic check is proven *sound* and *complete* (a certificate or chain passes the check iff it satisfies the property).

ARMOR's current guarantees do not include the driver and string canonicalizer modules. It also does not yet have support for certificate revocation or hostname verification. We discuss these limitations further in Section 7.

Evaluation. As ARMOR, or any formally verified software, is only as good as its specification, it is crucial to compare ARMOR to other implementations to gain assurance that our formalization of the natural language specification is correct. We *differentially test* ARMOR against 11 open-source X.509 libraries, sampling randomly from 4 million certificates from four different datasets. We observe that ARMOR agrees with most libraries at least 99.48% of the time. For the remaining 0.52% (~10K certificates), five of these ARMOR rejected due to a specificational inaccuracy in one semantic check; for all others, ARMOR either more strictly follows the requirements in RFC 5280 [2] than the other libraries, or implements aspects of X.509 CCVL in the RFC unsupported by the other libraries. We also compare ARMOR's parser with X.509 certificate linter ZLint [28], finding that ZLint is more lenient than ARMOR in most cases (which we expected), but in two instances ZLint is more restrictive, and its restrictiveness is noncompliant with RFC 5280. Finally, to evaluate the practicality of ARMOR, we measure its runtime overhead in terms of computational time and memory consumption. We notice that ARMOR has a much higher overhead compared to the X.509 libraries written in `C/C++`, `Python`, `Java`, and `Go`. Our empirical evaluation signifies that ARMOR *may be a reasonable choice of X.509 CCVL application in domains where formal correctness is more important than runtime overhead.*

Impact. ARMOR can substantially improve the security of critical applications that rely on X.509 PKI (e.g., SSL/TLS). As an example, the existing formally verified TLS 1.2 implementation [29] still needs a correct X.509 implementation to ensure its end-to-end guarantees, which ARMOR can fulfill. To evaluate the practicality of using ARMOR as part of a TLS implementation, we integrate it with the TLS 1.3 implementation of BoringSSL [30] and evaluate its performance. Unfortunately, in our evaluation, we observed that ARMOR incurs substantial runtime overhead, which is to be expected as ARMOR prioritized formal correctness over efficiency. ARMOR can also be used as an oracle for testing other X.509 implementations. Finally, our relational language specifications can serve as a separate, formal reference for programmers to consult. With ARMOR, our main goal is to develop a relational specification for X.509 certificate chain validation and demonstrate its formally verified, *not necessarily performant*, realization. This is a substantial first step toward developing a performant, low-overhead, and formally verified X.509 CCVL implementation in the future.

Contributions. We make the following five technical contributions in this work.

1) We are the first to present *modular*, *implementation-independent* formalizations of the X.509 certificate format, certificate chains, and several semantic requirements, facilitating development of other (especially formally verified) implementations of X.509 CCVL.
2) We prove that our parser-independent specification of the X.509 certificate format is *unambiguous* and *non-malleable*. Since we carefully distinguish between languages and parsers, these results serve as further assurance that X.690 DER and X.509 certificate *formats*, not a particular parser for them, is fit for purpose.
3) We prove *total correctness* (*soundness*, *completeness*, and *termination*) for our parser, chain builder, and se-

mantic validator modules.

4) We evaluate ARMOR with respect to its specificational accuracy and overhead against 11 open-source X.509 CCVL libraries and the X.509 certificate linter ZLint, and analyze its performance and effectiveness.
5) We show an end-to-end application of ARMOR, integrating it with TLS 1.3 implementation of BoringSSL and testing with the widely-used application Curl [31].

Artifacts. The artifacts of ARMOR are available here: https://github.com/joyantaDebnath/armor/.

Responsible Disclosure. We have responsibly disclosed all our findings to the corresponding library developers.

2. Background

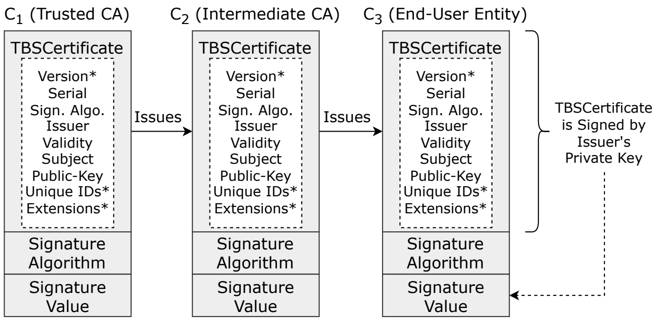
This section presents a primer on X.509 CCVL.

Overview of X.509 PKI. The X.509 PKI standard [2] provides a scalable way to verify the authenticity of the binding of an entity's identity with its public key. This identity-public-key binding is represented as an X.509 certificate, which is digitally signed by an issuer (*e.g.*, certificate authority or CA), signifying the issuer's trust in the authenticity and integrity of this binding. To scalably establish the authenticity and integrity of a certificate, the X.509 standard takes advantage of the *transitivity* of this "*trust*" relationship. This intuition is realized in the X.509 standard [2] through a *certificate chain validation* algorithm (or, CCVL). Concretely, when an entity e_1 wants to check whether the certificate (given as part of an input chain of certificates) of another entity e_2 is authentic, this algorithm *conceptually* starts with the certificate of a trust anchor (*i.e.*, an issuer who is unconditionally trusted by e_1) and then attempts to transitively extend this absolute trust through a chain of the input certificates, all the way down to e_2.

Internal Structure of a Certificate. Though the X.509 standard is primarily defined in ITU-T X.509 [32], RFC 5280 [2] provides additional restrictions and directions to use X.509 certificate for the Internet domain. Particularly, RFC 5280 concentrates on version 3 of the certificate standard and the usage of different extensions, which is the main focus of this work. A version 3 certificate comprises of three top-level fields, namely, TBSCertificate, SignatureAlgorithm, and SignatureValue. The TBSCertificate field contains information such as the certificate version, a unique serial number, the validity period, the certificate issuer's name, and the certificate owner's name (*i.e.*, subject). It also includes the public key, the algorithm employed by the issuer for signing the certificate, and a few *optional* fields such as the unique identifiers and a sequence of extensions, specifically for version 3 of the X.509 standard. The issuer CA signs the entire TBSCertificate content, generating a signature, denoted as SignatureValue, which is appended to the end of the certificate, creating a digitally secure and tamper-proof container. The SignatureAlgorithm field specifies the algorithm used by the issuer CA for generating the signature.

Certificate Chain Validation. A certificate chain $\mathcal{C}$ can be *conceptually* viewed as an ordered sequence of certificates, $\mathcal{C} = [C_1, C_2, \ldots, C_{n-1}, C_n]$, in which C_1 to C_{n-1} are the (intermediate) CA certificates whereas C_n is the end-user certificate to be authenticated. Each certificate C_i is issued by its predecessor C_{i-1} (see Figure 1). Roughly, the certificate chain validation logic can be *conceptually* decomposed into the following stages: *parsing*, *transformation and preprocessing*, and *semantic condition checking* (See Figure 2).

The parsing stage checks to see whether each certificate C_i in $\mathcal{C}$ is syntactically well-formed and then parses it in an intermediate representation. After parsing, the intermediate representation of $\mathcal{C}$ goes through a series of transformations and pre-processing. The semantic condition checking stage checks to see whether the standard-prescribed semantic conditions are fulfilled. These conditions can be on a single certificate (*e.g.*, the certificate is not expired, the signature is verified) or across certificates (e.g., the subject name of the certificate C_{i-1} is the same as the issuer name of the certificate C_i). Finally, one checks to see whether C_1 is present in the trusted root store. All of these checks together allows one to extend the unconditional trust of C_1 through the intermediate CA certificates (C_2 to C_{n-1}), all the way down to the end-user certificate (C_n).



Fields marked with * are optional

Figure 1: Representation of an X.509 certificate chain

For ease of exposition, the CCVL described here is intentionally simplified and left to be abstract. An implementation additionally has to take into account different corner cases, such as the presented input certificate chain $\mathcal{C}$ not being in the correct hierarchical order, the chain not including some CA certificates, or even containing duplicates. It is the implementation's responsibility to construct potential chains and try to verify them. For a detailed description of the entirety of CCVL, interested readers can consult RFC 5280 [2].

3. Design of ARMOR

We now present the design of ARMOR along with its verification philosophy and technical challenges.

3.1. Technical Challenges

Complexities in Specifications. The X.509 specification is distributed across different documents (*e.g.*, ITU-T X.509 [32], RFC 5280 [2], RFC 6125 [33], RFC 4158 [34], RFC 2527 [35], RFC 4518 [36]). The natural language specification has been shown to suffer from inconsistencies, ambiguities, and under-specification [22], [25], [37]. As an example, consider the following requirements of a certificate's *serial number*, quoted from RFC 5280 [2].

> *"The serial number MUST be a positive integer assigned by the CA to each certificate. [...] CAs MUST force the serialNumber to be a non-negative integer."*

The two requirements here are inconsistent, as one part excludes zero as a serial number while the other allows it.

Moreover, RFC 5280 encompasses rules not only for the certificate issuers (*i.e.*, *producer* rules) but also for the implementations that validate certificate chains (*e.g.*, *consumer* rules). Alternatively, RFC 5280 rules can be categorized into *syntactic* and *semantic* rules. While the syntactic rules are concerned with the parsing of an X.509 certificate serialized as a byte string, the semantic rules impose constraints on the values of individual fields within a certificate and on the relationships between field values across different certificates in a chain. Unfortunately, these intertwined sets of rules further complicate the specification, making it a challenge to determine how an X.509 consumer implementation should respond in certain cases (*i.e.*, whether to accept a chain).

Complexities in DER Parsing. The representation of an X.509 certificate, while described in the *Abstract Syntax Notation One* (ASN.1), is eventually serialized using the X.690 Distinguished Encoding Rules (DER) [17]. This DER representation of the certificate byte string internally has the form $\langle t, \ell, v \rangle$, where t denotes the type, v indicates the actual content, and ℓ signifies the length in bytes of the v field. Additionally, the v field can include multiple and nested $\langle t, \ell, v \rangle$ structures, adding additional layers of complexity to the binary data. Parsing such binary data is challenging and error-prone since it always requires parsing the value of the ℓ field (length) to accurately parse the subsequent v field. Since the internal grammar of a DER-encoded certificate is *context-sensitive*, developing a *correct* parser for such a grammar is non-trivial [20], [25].

To make matters worse, just correctly parsing the ASN.1 structure from the certificate byte string is insufficient, because the relevant certificate field value may need to be further decoded from the parsed ASN.1 value. Take the example of X.509 specification for using the UTCTime format in the certificate validity field. It uses a two-digit year representation, YY, and here lies the potential for misinterpretation. In this format, values from 00 to 49 are deemed to belong to the $21st$ century and are thus interpreted as $20YY$. In contrast, values from 50 to 99 are associated with the $20th$ century and are consequently translated into $19YY$. These restrictions on the UTCTime format allow the representation of years only from 1950 to 2049. Therefore, library developers need to be very careful when decoding the actual value of UTCTime to avoid potential certificate chain validation errors, a mistake previously found by Chau *et al.* [9] in some TLS libraries (*e.g.*, MatrixSSL, axTLS).

Supporting Different Certificate Representations. An X.509 implementation has to support different representations of an X.509 certificate. As an example, the certificates in a root store are often saved in the PEM format whereas the certificates obtained during a TLS connection are represented as a DER encoded byte string.

Complexities in Individual Stages. The X.509 CCVL can be conceptually decomposed into different stages, each of which has its own challenges. To give a few examples: (1) building a valid *certification path* can be difficult due to the lack of concrete directions as well as the possibility of having multiple certificate chain candidates [38]; (2) string canonicalization [36], where strings are converted to their *normalized* forms, is also a complex process, since the valid character sets vary depending on the chosen string type; and (3) during signature verification, the implementation needs to carefully parse the actual contents of the SignatureValue field with relevant cryptographic operations to prevent attacks (*e.g.*, *RSA signature forgery* [39], [40]). While these intermediate stages are conceptually straightforward, implementing them securely and proving their correctness, however, is non-trivial.

3.2. ARMOR's Verification Philosophy

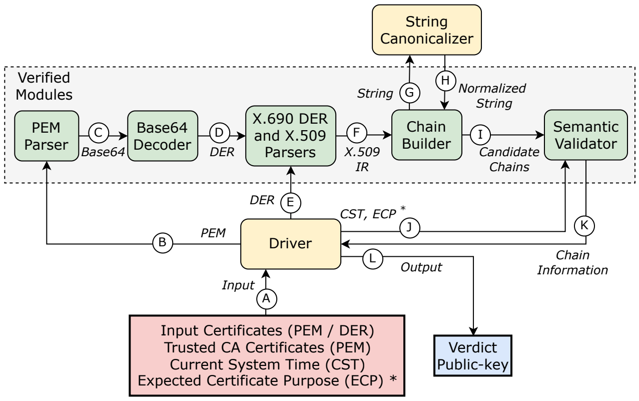
Relational Specifications. The central tenant of our approach to formally verifying ARMOR is to use high-level, relational, and implementation-independent specifications. We have remained faithful to this tenant except in the case of the *Base64 decoder* module, whose correctness is instead given with respect to an encoder. Our motivation for adhering to this discipline is two-fold.

1) **Specifications are part of the trusted computing base (TCB).** Formally verified software is only as trustworthy as its specification. *Relational* specifications that describe how the input and output are related without referencing implementation details are, in general, simpler. Such specifications are also easier for humans to evaluate for trustworthiness than those that reference implementation details [25].
2) **A specification can be valuable in its own right.** Specifications are useful documentation, and made all the more valuable by being applicable to a wide range of implementations for a particular software task. Due to the inherent complexity of X.509 CCVL, there is a vast space for non-trivial variations in implementations (*e.g.*, combining parsing with semantic validation), something that RFCs specifying X.509 CCVL explicitly acknowledge and aim to accommodate. Rather than providing correctness proofs that are limited to our particular implementation, we seek to provide a formal, machine-checked alternative to the RFCs by giving *implementation-agnostic* correctness specifications.

As a concrete example, consider the task of formally verifying a particular sorting algorithm. We could either prove it correct by showing it is extensionally equal to some other sorting algorithm (*e.g.*, *mergesort*), *or* state the correctness property relationally: *the output of the sorting function is a permutation of the input with the property that for every adjacent pair of elements, the first is no greater than the second.* Not only is it clear that it is the second, relational property that we ultimately care about for a sorting algorithm, if we did not already have this as our intuition for *what sorting should achieve*, then the usefulness of the first property *as a form of communication* is limited.

Modularity. We decompose ARMOR into independent modules (see Figure 2), which facilitates both our implementation and verification efforts. Also lying behind this design choice is a philosophical concern, namely *what should the formal end-to-end guarantees of X.509 CCVL even be?* The input to ARMOR is a character string and the result is a verdict and a public key. While we could present a relational join of each of the correctness properties of each module as an end-to-end guarantee, in our view this "leaks" implementation details, specifically our modular decomposition of X.509 CCVL (an approach not shared by most implementations). We thus refrain from positioning our results as an end-to-end guarantee, leaving such a task for future work.

Strict Adherence to the Standards. We believe that strict adherence to the standards governing X.509 PKI is the best practice for application developers and CAs to ensure security and trust across the digital ecosystem. While it is sensible for many applications to accommodate certain widespread, low risk deviations from the standard (such as permitting 0 for a certificate serial number), we have chosen not to do this for ARMOR. One goal of ARMOR is that its correctness specifications should serve as a formal, machine-checked, and implementation-independent alternative to the natural language specifications for X.509 PKI, and so codifying common deviations would run counter to this.



Inputs marked with * are optional

Figure 2: Conceptual design and workflow of ARMOR

3.3. ARMOR's Architecture

Figure 2 shows the architecture and workflow of ARMOR. ARMOR Ⓐ takes a certificate chain, a list of trusted CA certificates, the current system time, and optionally the expected certificate purpose as input, and Ⓛ outputs the certificate validation result (*i.e.*, verdict) as well as the public key of the end-user certificate. Ⓑ The PEM parser reads a PEM certificate file and converts each certificate into its Base64 encoded format (sextets, *i.e.*, unsigned 6 bit integers). Ⓒ The Base64 Decoder converts the sextet strings into octet strings (*i.e.*, unsigned 8-bit integers). Ⓓ The X.690 DER parser and X.509 parser collaboratively parse the DER byte string and convert each certificate into an intermediate representation (X.509 IR). Note that if a certificate is already given in DER format as input, Ⓔ we directly call the DER parser. Next, Ⓕ The chain builder constructs candidate chains from the parsed certificates, Ⓖ – Ⓗ utilizing the string canonicalizer to normalize strings in the certificate's Name field for accurate comparison. The semantic validator evaluates each candidate chain against certain semantic rules upon receiving Ⓘ the candidate chains, Ⓙ the current system time, and the expected certificate purpose and Ⓚ informs the driver whether any chain passes all the semantic checks. In this design, the driver is the central component that orchestrates the entire process. The driver's role is multifaceted: (1) it activates the parser modules with the correct input; (2) it initiates the chain builder to form candidate chains; (3) it directs the semantic validator with the required input; and (4) upon success of the previous stages, the driver verifies signatures of the chain, and finally displays the validation outcome to the verifier.

4. Verification Goals and Correctness Proofs

We now discuss ARMOR's correctness proofs. We provide formal correctness guarantees for the following modules of ARMOR: *parsers (i.e., PEM, X.690 DER, and X.509 parsers)*, *Base64 decoder*, *Semantic validator*, and *Chain builder*. See Table 1 for a listing and brief description of all formal guarantees proven.

For these verification tasks, which took 12 person months to complete, we use the `Agda` interactive theorem prover [26], [27]. We choose `Agda` over other dependently typed languages (*e.g.*, `Coq`, `F*`) for three reasons. *First*, `Agda` provides features convenient for proof development (*e.g.*, dependent pattern matching) and essential to our proof goals (*e.g.*, runtime erasure of proof terms). *Second*, `Agda`'s TCB is small relative to languages that integrate with SMT solvers (*e.g.*, `F*`). *Finally*, we have significant expertise in `Agda`.

TCB for `Agda` Modules. Our TCB comprises of the `Agda` toolchain (v2.6.2.2), which includes its native type-checker, compiler, and standard library (v1.7.1). Our use of `Agda`'s standard library includes the module `Data.Trie` (for the *String canonicalizer*), which requires the `--sized-types` language feature, and the module `IO`, which requires the `--guardedness` feature. Using these two features together *in the declaration of a coinductive type* causes logical inconsistency [41]. The only module enabling both features is the `Agda` main module (the execution entry point). It, however, does not define any coinductive types. ARMOR also uses `Agda`'s FFI for two Haskell packages: `time` (~9.7K Haskell LoC) and `bytestring` (~13K Haskell LoC).

Finally, ARMOR's `Agda` source code TCB constitutes: the specifications for its parsers and the PEM, X.690 DER and X.509 formats (4826 LoC); the specifications for its Base64 decoder (202 LoC); the X.509 certificate and chain semantic validator specifications (627 LoC); the unverified *String canonicalizer* (4077 LoC); and Haskell FFI bindings

Table 1: Total Correctness Guarantees

Property	Purpose	Proven For	Description
Unambiguous	Format security	PEM, X.690 DER, X.509	One string cannot be the encoding of two distinct values.
NonMalleable	Format security	X.690 DER, X.509	Two distinct strings cannot be the encoding of the same value.
UniquePrefixes	Format security	X.690 DER, X.509 ($\langle t, \ell, v\rangle$)	At most one prefix of a string is in the language.
Isomorphism	Impl. correctness	Base64 decoder	The Base64 decoder forms an isomorphism with a specificational encoder between the set of octet strings and the subset of sextet strings that are valid encodings.
MaximalParser	Impl. correctness	PEM	If the parser consumes a prefix, that prefix is the longest one in the language.
Sound (parser)	Impl. correctness	PEM, X.690 DER, X.509	If the parser accepts some prefix, that prefix is in the language.
Complete (parser)	Impl. correctness	PEM, X.690 DER, X.509	If the string is in the language, the parser accepts some prefix of it.
StronglyComplete	Impl. correctness	PEM, X.509	If a string is in the language and encodes value v, the parser consumes *exactly* that string and produces v.
Valid chain	Impl. correctness	X.509	Our specification *Chain* for chains consisting of a sequence of n certificates satisfies the following properties by construction: (a) for all $x \in \{1 \ldots n{-}1\}$, the subject of certificate x is the issuer of certificate $x{+}1$; (b) certificate 1 is issued by a trusted CA; (c) certificate n is the certificate to be validated
Chain uniqueness	Impl. correctness	X.509	Under the following assumptions, sequences of certificates satisfying our *Chain* specification have no duplicates. • The input certificate sequence has no duplicates. • The certificate to be validated is not in the trusted root store.
Sound chain builder	Impl. correctness	X.509	The chain builder produces only chains satisfying the specification *Chain*.
Complete chain builder	Impl. correctness	X.509	The chain builder generates all certificate lists satisfying the specification *Chain*.
Sound semantic checker	Impl. correctness	X.509	If a certificate/chain passes the semantic check, it satisfies the semantic property.
Complete semantic checker	Impl. correctness	X.509	If a certificate/chain satisfies the semantic property, it passes the semantic check.

(including IO) (435 LoC). A full listing of ARMOR's Agda files considered to be part of the TCB, with a script reporting LoC, can be found in the artifact repository.

Termination. ARMOR's correctness guarantees are *total*, with Agda enforcing termination. By default, Agda employs a syntactic termination checker that ensures recursive functions respect a certain well-founded ordering [42]. This syntactic termination checker can be disabled through the explicit use of certain pragmas, or replaced with a *type-based* termination checker through the use of sized types. ARMOR does not use any pragmas that disable termination checking, so its termination is guaranteed by Agda's syntactic checker everywhere except the *String canonicalizer* and its co-dependencies, whose termination guarantee additionally rests on the correctness of Agda's type-based checker.

Other Assumptions. We also make the following assumptions: (1) the GHC Haskell compiler correctly generates the executable; (2) the specifications for the formally verified libraries HACL* [43] and Morpheus [44] are correct (3) the verifier's trusted root CA store is up-to-date and does not contain any malicious certificates; (4) the system time is accurate.

4.1. Preliminaries on Agda

Agda is *dependently-typed*, meaning that types may involve program-level expressions. This capability helps express rich properties of programs *in the types of those programs*, and checking that programs satisfy those properties reduces to typechecking. This paradigm, known as the *Curry-Howard* correspondence [45], means we can view Agda's types as *propositions* and its programs as *proofs* of the propositions expressed by their types.

Consider the example shown in Figure 3 of nonnegative integers *strictly* less than some upper bound, provided as part of the Agda standard library as *Fin*. *Fin* defines an *inductive family* of types, where the family is indexed by a non-negative integer. In other words, each type in the family is *parameterized* by a nonnegative integer: for every $n : Nat$, $Fin\ n$ is a unique type whose inhabitants correspond to the nonnegative integers strictly less than n.

```
data Fin : Nat → Set where
  fzero : { n : Nat } → Fin (1 + n)
  fsuc : { n : Nat } → (i : Fin n) → Fin (1 + n)
toNat : ∀ { n } → Fin n → Nat
toNat fzero = 0
toNat (fsuc i) = 1 + (toNat i)
```

Figure 3: Bounded natural numbers in Agda

We now explain the declaration of *Fin*.

- The **data** keyword introduces a new inductive type or type family, in this case *Fin*.
- *Set* is the type of (small) types (we omit the details of Agda's universe hierarchy).
- *Fin* has two constructors, both of which have dual readings as "mere data" and as axiomatizations of the *"is strictly less than"* relation. As mere data, *fzero* corresponds to the integer 0; as an axiom, it states that 0 is strictly less than the successor $1 + n$ of any nonnegative n. Similarly, as mere data *fsuc* is a primitive successor operation (like the Peano numbers), and as an inference rule, it states that if i is strictly less than n, then its successor is strictly less than $1 + n$.
- Curly braces {} indicate function arguments that need not be passed explicitly. For example, if i has type

Fin 5, then `Agda` can determine *fsuc i* has type *Fin* 6.

Since *Fin* is inductive, we can define functions over it by *pattern matching* and *recursion*. This is shown with function *toNat*, which takes a nonnegative *n* and a *Fin n* and returns a nonnegative integer; we can think of *toNat* as extracting the "mere data" contained in the *Fin n* argument.

- In the type signature, we use the syntactic sugar ∀ to omit the type of the parameter *n*, as `Agda` can infer this from the occurrence of *n* in the rest of the type.
- The definition of *toNat* is given with two equations, one each for the two constructors of *Fin*.
  - In the first equation, we map *fzero* to 0.
  - In the second equation, our argument is of the form *fsuc i*. We make a recursive call *toNat i* and increment the result by 1. `Agda`'s termination checker accepts this, as *i* is structurally smaller than *fsuc i*.

4.2. Input Strings and Base64 Decoding

Fin plays a central role as the type of the language alphabet for our X.690 DER and X.509 parsers, as well as the input and output types for Base64 decoding. In general, parser inputs have types of the form *List A*, where *A* is the type of language alphabet; for our X.690 DER and X.509 parsers, this is *UInt8*, an alias for *Fin* 256, modeling an octet. The ultimate result of our PEM parser is a string of sextets, *i.e.*, a value of type *List UInt6*, where *UInt6* is an alias for *Fin* 64.

The hand-off between the result of PEM parsing and the input to X.509 parsing (Figure 2, Ⓒ – Ⓓ) is managed by the Base64 decoder, whose formal correctness properties are established with respect to a specificational encoder. Specifically, we prove: (1) the encoder always produces a result accepted by the decoder; and (2) the encoder and decoder pair forms an *isomorphism* between octet strings and valid sextet strings for encoding them. This is summarized below in Figure 4 (definitions omitted), which we now explain.

```
Valid64Encoding : List UInt6 → Set

encode : List UInt8 → List UInt6
decode : (bs : List UInt6) → Valid64Encoding bs → List UInt8

encodeValid : ∀ bs → Valid64Encoding (encode bs)

encodeDecode : ∀ bs → decode (encode bs) (encodeValid bs) ≡ bs
decodeEncode : ∀ bs → (v : Valid64Encoding bs)
                 → encode (decode bs v) ≡ bs
```

Figure 4: Base64 encoding and decoding (types only)

- *Valid64Encoding* is a predicate for sextet strings that expresses what it means for them to be valid encodings of an octet string. Recall that Base64 decoding proceeds by mapping each group of four sextets to three octets (24 bits in total).
  - If a single sextet remains after this grouping, then the sextet string is invalid (6 bits is not enough to encode an 8 bit value).
  - If two sextets remain, then they encode a single octet iff the last 4 bits of the second sextet are set to 0.
  - If three sextets remains, then they encode two octets iff the last 2 bits of the third sextet are set to 0.
- Next in the figure are the encoder, *encode*, and decoder, *decode*. While the domain of the encoder is all octet strings, for the decoder the domain is restricted to only those sextet strings for which the predicate *Valid64Encoding* holds.
- Lemma *encodeValid* is a proof that the specificational Base64encoder always produces a valid Base64 encoding.
- Finally, our main correctness result for the Base64 module is given by the proofs *encodeDecode* and *decodeEncode*, which together state that the encoder and decoder form an isomorphism (≡ is the symbol for propositional equality). In the first direction (*encodeDecode*), we pass to the decoder the result of encoding octet string *bs* together with a proof that this encoding is valid, and the result we get is the very same octet string *bs*. In the second direction, we assume that the given sextet string *bs* is already a valid encoding, and we obtain that the result of first decoding and then re-encoding *bs* is *bs* itself.

4.3. Verification of Parsers

We conceptually separate each parser verification task into *language specification*, *language security verification*, and *parser correctness verification*.

4.3.1. Language specification. We provide parser-independent formalizations of the PEM, Base64, X.690 DER, and X.509 formats, greatly reducing the complexity of the specification and increasing trust that they faithfully capture the natural language description. Much current research [15], [24] on applying formal methods to parsing uses serializers to specify their correctness properties. Formal proofs of correctness (in any context) are only ever as good as the specification of those correctness properties, and this earlier research swells the trusted computing base by introducing implementation details for serialization. To avoid this issue, we use *relational* specifications of languages. This has two other advantages: (1) it allows for a clear distinction between correctness properties of the *language* and *parser*; and (2) it brings the formal language specification into closer correspondence with the natural language description. This second point also means the formal specification can serve as a machine-checked, rigorous alternative for the developers seeking to understand the relevant specifications.

The relational specifications we give are of the following form. For a given language *G* with alphabet *A*, we define a family of types *G* : *List A* → *Set*, where the family *G* is indexed by strings *xs* : *List A* over the alphabet. Such a family serves dual roles: a value of type *G xs* is both the proof that *xs* is in the language *G* and the internal representation of the value decoded from *xs* (*e.g.*, the X.509 IR).

```
MinRep : UInt8 → List UInt8 → Set
MinRep hd [ ] = ⊤
MinRep hd (b₂ ∷ tl) =
  (hd > 0 ∨ (hd ≡ 0 ∧ b₂ ≥ 128))
  ∧ (hd < 255 ∨ (hd ≡ 255 ∧ b₂ ≤ 127))
record IntegerValue (@0 bs : List UInt8) : Set where
  field
    @0 hd : UInt8
    @0 tl : List UInt8
    @0 minRep : MinRep hd tl
    val : ℤ
    @0 valₑq : val ≡ Base256.twosComp bs
    @0 bsₑq : bs ≡ hd ∷ tl
```

Figure 5: Specification of integer values

We illustrate our approach with a concrete example: our specification of X.690 DER integer values, shown in Figure 5. This specification takes the form of an `Agda` record that is parameterized by a bytestring bs.

- **Erasure annotations.** The annotation @0 marks the accompanying identifier as *erased at runtime*. In *IntegerValue*, only val (the integer encoded by bs) is present at runtime; the remaining fields and parameter bs are erased by `Agda`'s GHC backend. Erasure annotations not only improve performance but also document the components that serve only specificational purposes for programmers using ARMOR as a reference.
- **Minimum representation.** X.690 DER requires the two's complement encoding of an integer value consists of the minimum number of octets. We *express* this property with *MinRep*, which defines a relation between the first byte of the encoding and the remaining bytes. We *enforce* the property with field *minRep* of *IntegerValue*: in order to construct an expression of type *IntegerValue bs*, one must prove that *MinRep* holds for the head and tail of bs.
  The definition of *MinRep* is by pattern matching on tl.
  1) If tl is empty, we return the trivially true proposition $\top$, because a single byte is always minimal.
  2) Otherwise, if the first byte is 0, the second byte must not be less than 128; and if the first byte is 255, then the second byte must not be greater than 127.
- **Nonempty encoding.** Fields hd, tl, and bs_{eq} together ensure the encoding of an integer value "consists of one or more octets" [17]. Specifically, bs_{eq} ensures that bs is of the form $hd :: tl$, where hd is the first content octet and tl contains the remaining octets (if any).
- **Linking the value and its encoding.** Field val_{eq} enforces that val be populated with a value equal to the result of decoding bs as a two's complement binary value (*Base256.twosComp* is the decoding operation).

4.3.2. Language security verification. A major advantage of our approach to specifying X.509 is that it facilitates proving properties *about the grammar* without having to reason about parser implementation details. We have proven: *unambiguousness* for the supported subsets of formats PEM, X.690 DER, and X.509; *non-malleability* for the supported subsets of formats X.690 DER and X.509; and *unique prefixes* for all $\langle t, \ell, v\rangle$ structures.

Unambiguous– We formally define unambiguousness of a language G in `Agda` as follows.

```
Unambiguous G = ∀ {xs} → (a₁ a₂ : G xs) → a₁ ≡ a₂
```

Read this as saying for every string xs, any two inhabitants of the internal representation of the value encoded by xs in G are equal. In the context of X.509, format ambiguity could result in interoperability issues between standards-compliant producers and consumers (*e.g.*, rejection because the decoded certificate does not match the encoded certificate).

Challenges. One challenging aspect in proving unambiguousness for X.690 DER is its support for sequences with *optional* and *default* fields, that is, fields that might not be present in the sequence. We are threatened with ambiguity if it is possible to mistake an optional field whose encoding is present for another optional field whose encoding is absent. To avoid this scenario, the X.690 format stipulates that every field of any "block" of optional or default fields must be given a tag distinct from every other such field. Our proof of unambiguousness for X.509 relies heavily on lemmas proving the X.509 format obeys this stipulation.

Non-malleable– Informally, in the context of X.509 non-malleability means that two distinct bytestrings cannot be encodings for the same certificate. Compared to unambiguousness, non-malleability requires more machinery to express, so we begin by discussing the challenges motivating this machinery. Since the bytestring encodings are part of *the very types of internal representations*, *e.g.*, *IntegerValue xs*, it is impossible to express equality between internal representations $a_1 : G\ xs_1$ and $a_2 : G\ xs_2$ without *already assuming* xs_1 *is equal to* xs_2. Thus, to make non-malleability nontrivial, we must express what is the "raw" internal datatype corresponding to G, discarding the specificational components. We express this with *Raw*, given below.

```
record Raw (G : List A → Set) : Set where
  field
    D : Set
    to : {@0 xs : List A} → G xs → D
```

An inhabitant of *Raw G* consists of a type D (the "mere data" of G) together with a function to that extracts this data from any inhabitant of $G\ xs$. Consider the case for *IntegerValue* below.

```
RawIntegerValue : Raw IntegerValue
Raw.D RawIntegerValue = ℤ
Raw.to RawIntegerValue = IntegerValue.val
```

This says that the raw representation for X.690 DER integer values is $\mathbb{Z}$, and the extraction function is just the field accessor *IntegerValue.val*. Note that the integer type used for the raw representation is *unbounded*, and so the size of the bytestring encoding for an integer value can be multiple KB.

Once we have defined an instance of *Raw G*, we express non-malleability of G with respect to that raw representation with the following property: given two "proof-carrying" internal representations $g_1 : G\ xs_1$ and $g_2 : G\ xs_2$, if the mere data of g_1 and g_2 are equal, then not only the strings xs_1 and xs_2 are equal but also the g_1 and g_2 are equal. In `Agda`, we write:

```
NonMalleable : { G : List A → Set } → Raw G → Set
NonMalleable { G } R =
  ∀ { @0 xs₁ xs₂ } → (g₁ : G xs₁) (g₂ : G xs₂)
  → Raw.to R g₁ ≡ Raw.to R g₂ → (xs₁ , g₁) ≡ (xs₂ , g₂)
```

Proving *NonMalleable RawIntegerValue* requires proving *Base256.twosComp* is injective.

Unique prefixes– The final language property we discuss, dubbed as *"unique prefixes,"* expresses that a language permits parsers no degrees of freedom over which prefix of the input it consumes. Striving for *parser independence*, we formulate this property as follows: for any two prefixes of an input string, if both prefixes are in the language G, then they are equal. In `Agda`, we express this as *UniquePrefixes* below.

```
UniquePrefixes G = ∀ { xs₁ ys₁ xs₂ ys₂ }
  → xs₁ ++ ys₁ ≡ xs₂ ++ ys₂ → G xs₁ → G xs₂ → xs₁ ≡ xs₂
```

Given that X.509 uses $\langle t, \ell, v \rangle$ encoding, it is unsurprising that we are able to prove *UniquePrefixes* holds. However, we call explicit attention to this property for two reasons: (1) it is an essential lemma in our proof of *strong completeness* of our X.509 parser (see Section 4.3.3); and (2) this property *does not hold* for the PEM format due to leniency in end-of-line encoding, so to show strong completeness for PEM parsers we need an additional parser property, *maximality*.

4.3.3. Parser correctness.

We now describe our approach to verifying parser soundness and completeness. For a language G, parser *soundness* means every prefix it consumes is in the language, and *completeness* means if a string is in the language, it consumes a prefix of it (we later show a strengthening of this notion of completeness). Our approach to verifying these is to make our parsers *correct-by-construction*, meaning that parsers do not merely indicate *success* or *failure* with *e.g.* an integer code, but return *proofs*. Precisely, our parsers are correct-by-construction by being proofs that membership of an input's prefix in G is decidable: parsers return either a proof that some prefix of its input is in the language, or a proof that *no* prefix is.

Correct-by-construction parsers. Our first step is to formally define success. In first-order logic (FOL), we would express the condition for the parser's success on a prefix of xs as $\exists ys\ zs, xs = ys +\!\!+ zs \land G\ ys$. That is to say, on success the parser consumes some prefix of the input string that is in the language G. In `Agda`, we express this as the record *Success*, shown below. In the definition, parameters G and xs are the language denoted by a production rule and an input string, respectively. The fields of the record are: *prefix*, the consumed prefix of the input (erased at runtime); *suffix*, the remaining suffix of the input from which we parse subsequent productions; ps_{eq}, which relates *prefix* and *suffix* to the input string xs (also runtime erased); and *value*, which serves dual roles as both the internal data representation of the value encoded by *prefix* **and** a proof that *prefix* is in the language G. As a consequence, *soundness will be immediate.*

```
record Success
  (G : List UInt8 → Set) (@0 xs : List UInt8) : Set where
  field
    @0 prefix : List UInt8
    suffix : List UInt8
    @0 ps_eq : prefix ++ suffix ≡ xs
    value : G prefix
```

Figure 6: Success conditions for parsing

Failure is the negation of the success condition, ¬ *Success G xs*, meaning *no* prefix of the input xs is in the language of G. To have the parser return *Success G xs* on success and ¬ *Success G xs* on failure, we use the `Agda` standard library datatype *Dec*, shown below.

```
data Dec (Q : Set) : Set where
  yes : Q → Dec Q
  no : ¬ Q → Dec Q
```

Reading *Dec* as programmers, *Dec Q* is a tagged union type which can be populated using either values of type Q or type ¬ Q; as mathematicians, we read it as the type of proofs that Q is *decidable*. Expressed as a formula of FOL, *Dec Q* is simply $Q \lor \neg Q$; however, note that constructive logic (upon which `Agda` is based) does not admit LEM (law of excluded middle). Therefore, this disjunction must be proven on a case-by-case basis for each Q (there are some undecidable propositions).

We can now complete the definition of *Parser*, shown in Figure 7. *Parser* is a family of types: for each language G, type *Parser G* is the proposition that, for all bytestrings xs, it is decidable whether some prefix of xs is in G.

```
Parser : (List A → Set) → Set
Parser G = ∀ xs → Dec (Success G xs)

MaximalSuccess : ∀ (G : List A → Set) xs
                 → Dec (Success G xs) → Set
MaximalSuccess G xs (no _) = ⊤
MaximalSuccess G xs (yes s) = ∀ pre suf → pre ++ suf ≡ xs
  → G pre → length pre ≤ length (Success.prefix s)

record MaximalParser (G : List A → Set) : Set where
  field
    p : Parser G
    max : ∀ xs → MaximalSuccess (p xs)
```

Figure 7: Definition of *Parser* and *MaximalParser*

Challenges. The parser's guarantee of ¬ *Success G xs* on failure is very strong, as it asserts a property concerning *all prefixes* of the input. This strength is double-edged: while having this guarantee makes proving completeness straightforward, *proving* it means ruling out all possible ways the input *could* be parsed. In some cases, we implemented parsers to facilitate the proofs concerning the failure case (see *Proof Engineering* in Section 7 for further discussion).

Maximal parsers. The PEM format does not enjoy the *unique prefixes* property. To facilitate our implementation of

```
Sound : (G : List A → Set) → Parser G → Set
Sound G p =
  ∀ xs → (w : IsYes (p xs)) → G (Success.prefix (toWitness w))
Complete : (G : List A → Set) → Parser G → Set
Complete G p = ∀ xs → G xs → IsYes (p xs)
soundness : ∀ { G } → (p : Parser G) → Sound G p
soundness p xs w = Success.value (toWitness w)
trivSuccess : ∀ { G } { xs } → G xs → Success G xs
completeness : ∀ { G } → (p : Parser G) → Complete G p
completeness p xs inG = fromWitness (p xs) (trivSuccess inG)
```

Figure 8: Parser soundness and completeness

correct-by-construction PEM parsers and prove a stronger completeness result, we have augmented the specifications of these parsers to guarantee they consume *the largest prefix of the input compliant with the format.* The formalization of this in `Agda` is shown in Figure 7. Definition *MaximalSuccess* expresses that if parsing xs was successful ($yes\ s$), then any other prefix pre of xs in G is not greater than that consumed by the parser. In the record *MaximalParser*, we couple together a parser p with a proof max that, for ***every*** input string xs, if p is successful parsing xs then that success is maximal.

Correctness properties. We now show our definitions and proofs of parser soundness and completeness.

Soundness– The `Agda` definition and proof of soundness for all of our parsers is shown in Figure 8. Beginning with *Sound*, which expresses that parser p is sound with respect to language G, the predicate *IsYes* (definition omitted) expresses the property that a given decision (in this case, one of type *Dec* (*Success* G xs)) is affirmative (*i.e.*, constructed using yes). The function *toWitness* : ∀ { Q } { d : *Dec* Q } → *IsYes* d → Q takes a decision d for proposition Q and the proof that it is affirmative, and produces the underlying proof of Q. Thus, we read the definition of *Sound* G p as: "for all input strings xs, if parser p accepts xs, the prefix it consumes is in G." The proof *soundness* states that *all parsers are sound*. As our parsers are correct-by-construction, the definition is straightforward: we use *toWitness* to extract the proof of parser success (*i.e.*, an expression of type *Success* G xs), and then the field accessor *Success.value* obtains the desired proof that the consumed prefix is in G.

Completeness– Figure 8 also shows our definition and proof of *completeness* in `Agda`. The definition of *Complete* directly translates our notion of completeness: for every input string xs, if xs is in G, then parser p accepts some prefix of xs. For the proof, a straightforward lemma *trivSuccess* (definition omitted) states any proof that xs is in G can be turned into a proof that some prefix of xs (namely, xs itself) is in G. With this lemma, the proof of *completeness* uses the function *fromWitness* : { Q : *Set* } → (d : *Dec* Q) → Q → *IsYes* d, which intuitively states that if a proposition Q is true, then any decision for Q must be in the affirmative.

Strong completeness– In isolation, completeness does not rule out all bad behavior that threatens security. Specifically, it does not constrain the parser's freedom over (1) which prefix it consumes and (2) how the internal data-structure is constructed. As discussed in Section 4.3.1, these should be thought of as *language* properties. To rule out both bad behaviors, it suffices that G satisfies the properties *Unambiguousness* and *UniquePrefixes*.

```
StronglyComplete : (G : @0 List A → Set) → Parser G → Set
StronglyComplete G p = ∀ xs → (inG : G xs)
  → ∃ (w : IsYes (p xs)) (let s = toWitness w in
        (xs , inG) ≡ (Success.prefix s , Success.value s))
strongCompleteness
  : ∀ { G } → Unambiguous G → UniquePrefixes G
    → (p : Parser G) → StronglyComplete G p
strongCompletenessMax : ∀ { G } → Unambiguous G
  → (m : MaximalParser G)
  → StronglyComplete G (MaximalParser.p m)
```

Figure 9: Strong completeness (types only)

Figure 9 shows the types used in our proof of our strong completeness. *StronglyComplete* G p says that, if we have a proof inG that xs is in G, then not only does there exist a witness w that the parser accepts some prefix of xs but also this prefix is xs and the proof it returns is inG. Recall that the assumption inG and the *value* field of the *Success* record serve dual roles: they are not only the proofs that a string is in a language but also the internal data representation of the value encoded by xs. Therefore, saying they are equal means the internal representations are equal.

Strong completeness from maximality. For PEM, even though the format lacks the *unique prefixes* property, we can still prove strong completeness by leveraging the fact that our parsers are guaranteed to be *maximal*. Intuitively, this is because: if xs is in G, then the largest possible prefix of xs in G is the xs itself. We show the formal statement of the theorem in Figure 8, omitting the proof for space considerations.

4.4. Verification of Chain Builder

The section presents the *Chain builder*, for which we have proven soundness and completeness with respect to a partial specification. Adhering to our discipline of providing high-level, relational specifications, we dedicate the bulk of this section to describing the specification used, presenting at the end the type of our sound-by-construction chain builder and its proof of completeness.

4.4.1. *Chain* Specification.

Our operative definition of correctness for the *Chain Builder* module is as follows (cf. RFC 5820, Section 6.1). Given a list of certificates $c_1 \ldots c_n$ where $n \geq 2$, this list forms a chain when:

- c_1 is the certificate to be validated;
- c_n is a certificate in the trusted root store;
- for all $i \in \{1 \ldots n-1\}$, the issuer field of c_i matches the subject field of c_{i+1}; and
- if c_1 is not a self-signed certificate that is present in the trusted root store, then for all $i, j \in 1 \ldots n$, if $c_i = c_j$ then $i = j$.

```
_IsIssuerFor_ : ∀ {@0 xs₁ xs₂} → Cert xs₁ → Cert xs₂ → Set
issuer IsIssuerFor issuee =
  NameMatch (Cert.getIssuer issuee) (Cert.getSubject issuer)

_IsIssuerFor_In_ : ∀ {@0 xs₁ xs₂} → Cert xs₁ → Cert xs₂
                   → (certs : List (∃ Cert)) → Set
issuer IsIssuerFor issuee In certs =
  issuer IsIssuerFor issue ∧ (-, issuer) ∈ certs

removeCertFromCerts : ∀ {@0 xs} → Cert xs
                      → List (∃ Cert) → List (∃ Cert)
removeCertFromCerts cert certs = filter (λc → c ≢? (-, cert)) certs

data Chain (trust candidates : List (∃ Cert))
  : ∀ {@0 xs} → Cert xs → Set where
  root : ∀ {@0 xs₁ xs₂} {c₁ : Cert xs₁} (c₂ : Cert xs₂)
         → c₂ IsIssuerFor c₁ In trust
         → Chain trustedRoot candidates c₁
  link : ∀ {@0 xs₁ xs₂} (issuer : Cert xs₁) {c : Cert xs₂}
         → issuer IsIssuerFor c In candidates
         → Chain  (removeCertFromCerts issuer trust)
                  (removeCertFromCerts issuer candidates)
                  issuer
         → Chain trust candidates c
```

Figure 10: Definition of a sound *Chain*

Note that it is the *Semantic validator* that checks whether the certificate validity period contains the current time, that cryptographic signature verification is outsourced to external libraries (see Section 5), and that we currently perform no policy mapping. Thus, our specification is *partial* in the sense that we do not claim it captures the full set of desired correctness properties of chain building.

Figure 10 lists our formalization of the specification for a sound chain, defined as *Chain*, which we now describe.

- _IsIssuerFor_ is a binary relation on certificates expressing that the subject field of the first certificate matches the subject of the second. In `Agda`, one can define mixfix operators and relations by using underscores in the identifier to mark the locations of arguments. This allows us to write *issuer IsIssuerFor issuee* as syntactic sugar for _IsIssuerFor_ *issuee issuer*.
- The three-place relation _IsIssuerFor_In_ augments the previous relation by allowing us to track *where* the issuer came from using the membership relation _ ∈ _.
  - In the signature of _IsIssuerFor_In_, the type of the third argument, *List* (∃ *Cert*), is the type of *lists of tuples* of byte strings *xs* : *List UInt8* together with proofs *Cert xs* that the byte string encodes a certificate.
  - In the definition of _IsIssuerFor_In_, since *certs* is a list of tuples, to express that *issuer* is present in certs we must tuple it together with its octet string encoding. This is neatly achieved with (-, *issuer*), which forms a tuple where only the second component need by passed explicitly, leaving `Agda` to infer the value of the first component.
- Function *removeCertFromCerts* takes a certificate *cert* and list of tupled certificates *certs* and uses the `Agda` standard library function *filter* to remove all certificates from *certs* that are equal to *cert*.
- Finally, we come to the definition of *Chain*, an inductive family of types indexed by: *trust* : *List* (∃ *Cert*), the certificates in the trusted root store; *candidates* : *List* (∃ *Cert*), the intermediate CA certificates provided by the end entity to facilitate chain building; and the certificate we are attempting to authenticate. *Chain* has two constructors, axiomatizing the two ways we can extend trust to the end entity.
  - Constructor *root* expresses that we can trust certificate c_1 when we can find a certificate c_2 in the trusted root store representing an issuer for c_1.
  - Constructor *link* expresses that we can trust certificate *c* if we can find an issuer's certificate *issuer* in *candidates*, and furthermore that we (inductively) trust *issuer* through the construction of a *Chain*. To avoid duplicate certificates in the chain (and ensure termination by ruling out cycles), the chain of trust extended to *issuer* must use a trusted root store and candidate certificate list from which *issuer* has been removed; we express this using function *removeCertFromCerts*.

```
toList : ∀ {trust candidates} {@0 xs} (c : Cert xs)
         → Chain trust candidates c → List (∃ Cert)
toList c (root issuer _) = (-, c) :: [issuer]
toList c (link issuer isIn chain) = (-, c) :: toList issuer chain

ChainUnique : ∀ {trust candidates} {@0 xs} {c : Cert xs}
  → Chain trust candidates c → Set
ChainUnique c = List.Unique (toList c)

chainUnique
  : ∀ trust candidates {@0 xs} {issuee : Cert xs}
   → (-, issuee) ∉ candidates → (-, issuee) ∉ trust
   → (c : Chain trust candidates issuee) → ChainUnique c
```

Figure 11: Chain Uniqueness

4.4.2. Chain Uniqueness.

As we did with our language formalizations, by having an implementation-independent, relational specification *Chain* we can prove that certain properties hold of *all* chains constructed by our chain builder, *without* reasoning about its implementation details. Given the limited scope of our specification of correctness for chains, we are primarily interested in verifying the *uniqueness* property: "A certificate MUST NOT appear more than once in a propsective certification path." We are able to verify this property under the assumption that the end entity certificate is neither in the candidate list (ensured by a preprocessing step before the *Chain Builder* is invoked) nor in the trusted root store.

The specification and proof of chain uniqueness are listed in Figure 11, which we now describe.

- Function *toList* extracts the list of certificates from the chain, including the issuer found in the trusted root.

```
buildChains
  : ∀ trust candidates {@0 bs} (issuee : Cert bs)
    → List (Chain trust candidates issuee)
ChainEq : ∀ {trust candidates} {@0 bs} {issuee : Cert bs}
          → (c₁ c₂ : Chain trust candidates issuee) → Set
ChainEq c₁ c₂ = toList c₁ ≡ toList c₂
buildChainsComplete
  : ∀ trust candidates {@0 bs} (issuee : Cert bs)
    → (c : Chain trust candidates issuee)
    → Any (ChainEq c) (buildChains trust candidates issuee)
```

Figure 12: Verified chain builder

- Predicate *ChainUnique* expresses the uniqueness of each certificate in a chain by first using *toList* to extract the underlying list of certificates, then uses the predicate *List.Unique* from `Agda`'s standard library.
- Finally, the proof *chainUnique* (definition omitted) establishes that the predicate *ChainUnique* holds for every chain *c*:*Chain trust candidates issuee*, provided that *issuee* is not present in either the candidate certificate list or the trusted root.

4.4.3. Sound and Complete Chain Building. We now present our chain builder, verified sound and complete with respect to the specification *Chain*, in Figure 12. First, observe that by its type *buildChains* (definition omitted) is *sound by construction*: every chain that it returns has type *Chain trust candidates issuee*. Of course, the *trivial* chain builder (one that always returns the empty list) is also sound by construction, and so the other property we are interested in is *completeness:* if there *exists* a chain of trust extending to the *issuee* from the *trust* store using intermediate certificates pulled from *candidates*, then our chain builder enumerates it. This is formalized in the remainder of the figure, which we now describe.

- Relation *ChainEq* expresses that the underlying certificate lists of two chains c_1 c_2 : *Chain trust candidates issuee* are equal. Observe that were we to define *ChainEq* c_1 c_2 as $c_1 \equiv c_2$, this would be much stronger than is required: a value of type *Chain trust candidates issuee* carries with it not only the underlying certificate list, but also proofs relating each certificate with the next and with *trust* and *candidates*. It is not necessary that these proof terms are also equal, so *ChainEq* discards these using *toList*.
- In the type signature of *buildChainsComplete*, we use *Any* from the `Agda` standard library *Any*. Given any type *T*, a predicate *Q* : *T* → *Set* and a list *xs* : *List T*, *Any Q xs* is the proposition that there exists *some* element of xs for which *Q* holds.
- Putting these together, we can read the type signature of *buildChainsComplete* as follows: for every chain *c* : *Chain trust candidates issuee*, there exists a chain in the result of *buildChains trust candidates issuee* which is equal to *c* modulo some proof terms (*i.e.*, the proofs that issuers are present in either *candidates* or *trust* and the proofs that for each adjacent pair of certificates, the issuer of the first matches the subject of the second).

4.5. Verification of Semantic Validator

We now describe our verification approach to the task of *semantic validation*. The checks performed by the *Semantic validator* are separated into two categories: those that apply to a single certificate, and those that apply to a candidate certificate chain. For each property to validate, we formulate in `Agda` a predicate expressing satisfaction of the property by a given certificate or chain, then prove that these predicates are decidable (*Dec*, Section 4.3.3). In what follows, we illustrate with two relatively simple concrete examples: one predicate for a single certificate and one for a certificate chain.

Before we illustrate with examples, we stress that the purpose of this setup is *not* merely to give decidability results for the semantic checks of the X.509 specification, as this fact is intuitively obvious. Instead, and just like with our approach to verified parsing, formulating these semantic checks as decidability proofs (1) *forces* us formalize the natural language property we wish to check *independently of the code that performs the checking,* and (2) *enables* us to write the checking code that is *correct-by-construction*, as these decidability proofs are themselves the very functions called after parsing to check whether the certificate or chain satisfies the property in question.

4.5.1. Single Certificate Property. For a given certificate, it must be the case that its `SignatureAlgorithm` field contains the same algorithm identifier as the `Signature` field of its `TBSCertificate` (R1 in Table 2 of the Appendix). As a formula of FOL, we could express this property with respect to certificate c as

$$\forall s_1\, s_2, \mathit{SignAlg}(s_1, c) \wedge \mathit{TBSCertSignAlg}(s_2, c) \implies s_1 = s_2$$

where $\mathit{SignAlg}(s_1, c)$ and $\mathit{TBSCertSignAlg}(s_2, c)$ express respectively the properties that s_1 is the signature algorithm identifier of c and that s_2 is the signature algorithm identifier of the `TBSCertificate` of c. In `Agda`, we express this property, and the type of its corresponding decidability proof, as follows (we omit the proof for space considerations).

```
R1 : ∀ {@0 bs} → Cert bs → Set
R1 c = Cert.getTBSCertSignAlg c ≡ Cert.getCertSignAlg c
r₁ : ∀ {@0 bs} (c : Cert bs) → Dec (R1 c)
r₁ c = ...
```

The predicate *R1* expresses that the two signature algorithm fields are equal using the binary relation ≡, which is defined in `Agda`'s standard library. Compared to the proof r_1, *R1* is relatively simple: ≡ is *parametric* in the type of the values it relates (meaning it uses no specifics about the *SignAlg* type family), and is defined as the smallest reflexive relation. In contrast, the checking code r_1 *must* concern itself with the specifics of *SignAlg*. In X.509, signature algorithm fields

```
IsConfirmedCA : ∀ {@0 bs} → Cert bs → Set
isConfirmedCA? : ∀ {@0 bs} (c : Cert bs) → Dec (IsConfirmedCA c)
R23 : ∀ {trust candidates} {@0 bs} (issuee : Cert bs)
    → Chain trust candidates issuee → Set
R23 issuee c = All (IsConfirmedCA ∘ proj₂) (tail (toList c))
r23 :  ∀ {trust candidates} {@0 bs} (issuee : Cert bs)
    → (c : Chain trust candidates issuee) → Dec (R23 c)
r23 c = All.all? (isConfirmedCA? ∘ proj₂) (tail (toList c))
```

Figure 13: Semantic check for R23

are defined as a pair where the first component is an object identifier (OID) and the second is an optional field for parameters whose type *depends upon that OID*. So, to implement r_1 we must prove equality is decidable for OIDs *and* for all the signature algorithm parameter types we support.

4.5.2. Certificate Chain Property. For a certificate chain, it must be the case that every issuer certificate is a CA certificate. Specifically, RFC 5280 (Section 6.1.4) makes the following requirement for issuer certificates:

> *"If certificate i is a version 3 certificate, verify that the basicConstraints extension is present and that cA is set to TRUE. (If certificate i is a version 1 or version 2 certificate, then the application MUST either verify that certificate i is a CA certificate through out-of-band means or reject the certificate. Conforming implementations may choose to reject all version 1 and version 2 intermediate certificates.) "*

In ARMOR, we take the approach suggested in the last line of the quote (see entry R19 of Table 2 in the Appendix), so our task reduces to checking that for each issuer certificate, the `basicConstraints` extension is present and its `cA` field is set to true.

We formalize this semantic condition, listed as R23 in Table 2 in Figure 13. Predicate *IsConfirmedCA* (definition omitted) expresses the condition that the `basicConstraints` extension is present in a certificate with field `cA` set to *true*, and function *isConfirmedCA?* (definition omitted) is the correct-by-construction implementation of that check. Predicate *R23* is extends this property to all issuer certificates of a chain.

- The `Agda` standard library definition *All* is to *Any* (see Section 4.4.3) what ∀ is to ∃. Given a predicate $Q : A \to Set$ and a list $xs : List\ A$, $All\ Q\ xs$ is the proposition that every element of xs satisfies Q.
- The list we are concerned with in predicate *R23* is every certificate in the chain except the first (*i.e.*, the end entity). This is expressed by $tail\ (toList\ c) : List\ (\exists\ Cert)$.
- Since the elements of this list are *tuples* of type $\exists\ Cert$ (where the first component is an octet string and the second is a proof that string encodes a certificate), we form the predicate supplied to *All* by precomposing *IsConfirmedCA* with $proj_2 : (c : \exists\ Cert) \to Cert\ (proj_1\ c)$.

Finally, the sound-by-construction checker for this semantic condition is *r23*, which is defined using *All.all?*, defined in the `Agda` standard library. *All.all?* takes a decision procedure that applies to a single element (in this case, $isConfirmedCA? \circ proj_2$) and returns a decision procedure that decides whether the predicate holds for *all* elements of the given list.

5. Implementation

Driver and Input Interface. ARMOR's driver module is developed using `Python` and `Agda`. The `Python` component is responsible for taking inputs from users such as certificates (DER/PEM) to be validated, trusted CA certificates (PEM), and optionally the expected purpose of the end-user certificate (*e.g.*, Server/Client Client Authentication, Code Signing). After receiving these inputs, the `Python` driver invokes the `Agda` component passing the user inputs directly. The `Agda` component then invokes the parsers, builds the candidate certificate chains, and conducts semantic validation. Finally, it returns a verdict along with some parsed information (*i.e.*, TBSCertificate bytes, SignatureValue bytes, SignatueAlgorithm) to the `Python` side, which performs signature verification. The final result of chain validation is then output by the `Python` component. Notably, for the certificate expiration check, the `Agda` component reads the current time directly from the user's system.

Chain Building and String Canonicalization. After parsing, the `Agda` component calls the chain builder module to build all candidate chains for semantic validation. For ease of formal verification, we first create all candidate chains and then check each for their validity, terminating when we have either identified one valid chain, or exhausted all candidates. Our chain builder module uses name matching, instead of AKI (Authority Key Identifier) and SKI (Subject Key Identifier) extensions as these may not be present in an input certificate. For name matching, we normalize the names using LDAP StringPrep profile described in RFC 4518 [36]. Our chain building module's total correctness ensures that we consider all potential chains, all chains start with a CA certificate in the trust anchors, and the chain builder terminates.

Semantic Validation. For semantic validation, we consider a total of 27 rules. The complete list is provided in Table 2. The first 18 rules (R1 - R18) are applicable to individual certificates in a chain, whereas the last 9 rules (R19 - R27) are for a chain of certificates. Note that all rules except R26 are implemented in `Agda`. R26 (signature verification) is enforced by the `Python` side of driver module. Also, R24 (subject and issuer name chaining) and R25 (trust anchor check) are not explicitly enforced by the semantic validator since these checks are already enforced by the chain builder. Some rules such as R7, R11, R14, and R16 are also directly enforced by the parser.

Signature Verification. ARMOR currently only supports RSA signature verification, as our analysis of the 1.5 billion Censys [46] certificates finds that 96% of certificates employ RSA public keys. Since we do not model or verify cryptography in `Agda`, we use `Python`'s cryptography library for doing *modular exponentiation* of RSA. However, for high-assurance, we utilize HACL* [43] and Morpheus [44].

Table 2: Semantic restrictions enforced by ARMOR

Name	Description
R1	SignatureAlgorithm field MUST contain the same algorithm identifier as the Signature field in the sequence TbsCertificate.
R2	Extension field MUST only appear if the Version is 3 .
R3	The Serial number MUST be a positive integer assigned by the CA to each certificate. Certificate users MUST be able to handle Serial number values up to 20 octets.
R4	The Issuer field MUST contain a non-empty distinguished name (DN).
R5	If the Subject is a CA (*e.g.*, the Basic Constraints extension, is present and the value of CA is TRUE), then the Subject field MUST be populated with a non-empty distinguished name.
R6	Unique Identifiers fields MUST only appear if the Version is 2 or 3. These fields MUST NOT appear if the Version is 1.
R7	Where it appears, the PathLenConstraint field MUST be greater than or equal to zero.
R8	If the Subject is a CRL issuer (*e.g.*, the Key Usage extension, is present and the value of CRLSign is TRUE), then the Subject field MUST be populated with a non-empty distinguished name.
R9	When the Key Usage extension appears in a certificate, at least one of the bits MUST be set to 1.
R10	If subject naming information is present only in the Subject Alternative Name extension , then the Subject name MUST be an empty sequence and the Subject Alternative Name extension MUST be critical.
R11	If the Subject Alternative Name extension is present, the sequence MUST contain at least one entry.
R12	If the KeyCertSign bit is asserted, then the CA bit in the Basic Constraints extension MUST also be asserted. If the CA boolean is not asserted, then the KeyCertSign bit in the Key Usage extension MUST NOT be asserted.
R13	A certificate MUST NOT include more than one instance of a particular Extension.
R14	A certificate-using system MUST reject the certificate if it encounters a critical Extension it does not recognize or a critical Extension that contains information that it cannot process.
R15	A certificate policy OID MUST NOT appear more than once in a Certificate Policies extension.
R16	While each of these fields is optional, a DistributionPoint MUST NOT consist of only the Reasons field; either distributionPoint or CRLIssuer MUST be present.
R17	The certificate Validity period includes the current time.
R18	If a certificate contains both a Key Usage extension and an Extended Key Usage extension, then both extensions MUST be processed independently and the certificate MUST only be used for a purpose consistent with both extensions. If there is no purpose consistent with both extensions, then the certificate MUST NOT be used for any purpose.
R19	Conforming implementations may choose to reject all Version 1 and Version 2 intermediate CA certificates .
R20	The PathLenConstraint field is meaningful only if the CA boolean is asserted and the Key Usage extension, if present, asserts the KeyCertSign bit. In this case, it gives the maximum number of non-self-issued intermediate certificates that may follow this certificate in a valid certification path.
⋆ R21	For DistributionPoint field, if the certificate issuer is not the CRL issuer, then the CRLIssuer field MUST be present and contain the Name of the CRL issuer. If the certificate issuer is also the CRL issuer, then conforming CAs MUST omit the CRLIssuer field and MUST include the distributionPoint field.
R22	A certificate MUST NOT appear more than once in a prospective certification path.
R23	Every non-leaf certificate in a chain must be a CA certificate.
R24	Certificate users MUST be prepared to process the Issuer distinguished name and Subject distinguished name fields to perform name chaining for certification path validation.
R25	Validate whether the chain starts from a trusted CA.
R26	Validate RSA signatures.
R27	For every non-leaf certificate in a chain, if the Key Usage extension is present, the KeyCertSign bit must be asserted.

⋆ This check is omitted in the latest version of ARMOR since it depends on processing CRL, which ARMOR does not support.

HACL* is a formally verified cryptographic library developed in F^* and compiled down to C. In ARMOR, we utilize HACL*'s *hash function* implementations. In contrast, Morpheus is a formally verified implementation of RSA $PKCS\#1-v1.5$ [47] signature verification. Morpheus checks the correctness of the signature format after performing modular exponentiation of the SignatureValue using the public exponent of the certificate issuer's RSA public key, avoiding signature forgery attacks [39].

Supported Extensions. ARMOR supports 14 certificate extensions for parsing: Basic Constraints, Key Usage, Extended Key Usage, Authority Key Identifier, Subject Key Identifier, Subject Alternative Name, Issuer Alternative Name, Certificate Policy, Policy Mapping, Policy Constraints, Inhibit anyPolicy, CRL Distribution Points, Name Constraints, and Authority Information Access. These extensions are selected based on their frequencies of occurrence in practice, providing a comprehensive coverage for the most common scenarios encountered in certificate parsing [25]. When any other extension is present, our parser only consumes the corresponding bytes of the extension and continues parsing rest of the certificate fields. Our supported semantic validation rules are spread across the following 4 extensions: Basic Constraints, Key Usage, Extended Key Usage, and Subject Alternative Name. ARMOR rejects any unrecognized *critical* extensions in compliance with RFC 5280.

From Agda to Executable. The Agda toolchain can produce executable binaries by compiling Agda code to Haskell, then use the GHC [48] compiler to generate an executable.

6. Empirical Evaluation

This section evaluates ARMOR's efficiency, robustness, and applicability in real-world scenarios. Particularly, we aim to find answers to the following research questions.

Q1. Correctness of Specification's Interpretation. How accurate is our interpretation of the RFC 5280 specification?

Q2. Runtime Overhead. What are the execution time and memory consumption overheads of ARMOR?

Q3. Performance in a Real Application. What delay does ARMOR introduce when it is used in a practical application?

6.1. Experimental Setup

Table 3 shows a high-level overview of our experiments to find answers to the questions Q1, Q2, and Q3.

Datasets. We used the following 4 certificate datasets across our experiments: Censys [46], Frankencert [3], OpenSSL [49], and EFF [50]. Notably, among these datasets, only OpenSSL comes with a ground truth; that means each certificate in this dataset contains a verdict from the OpenSSL regression testing.

1) Censys is a large-scale certificate repository, from which we took a snapshot of 1.5 billion real certificates in January 2022. We then randomly sampled 2 million certificates from this snapshot. As the original dataset contained only leaf certificates (*i.e.*, Censys (leaf)), we

Table 3: Summary of experimental setup

Evaluation Question	CCVL Coverage	Input Type	Dataset Used	Dataset Size	Test Subjects vs ARMOR	Testbed Config.
Specificational Accuracy (Q1)	End-to-End	Full Chain	Censys Frankencert	2,000,000 2,000,000	11 X.509 Libraries	OS: Linux CPU: Intel Xeon 2.10 GHz 100 core
	Parser Only	Certificate	OpenSSL EFF	2242 12,387	11 X.509 Libraries	
	Parser with RFC 5280 Restrictions	Certificate	Censys (leaf) ⋆ EFF	2,000,000 12,387	ZLint	
Runtime Overhead (Q2)	End-to-End	Full Chain	Censys	100,000	11 X.509 Libraries	OS: Linux CPU: Intel Core-i7 3.10 GHz
Performance in Real Application (Q3)	End-to-End	List of Websites to Visit	Alexa's Top 100 Websites	100	Curl with BoringSSL	

⋆ considered only the leaf certificate of a chain

used the cert-chain-resolver [51] tool to retrieve the associated CA certificates from the web.

2) The Frankencert dataset contains 2 million synthetic certificate chains generated by the Frankencert fuzzer [3] to mimic bad inputs.
3) The OpenSSL dataset contains 2242 certificates, which are used as part of OpenSSL's regression testing, each time the library is updated. It includes a comprehensive collection of known ASN.1 vulnerabilities and additional variants created through fuzzing.
4) The EFF dataset is part of the SSL Observatory project and is created by attempting TLS handshakes with all accessible IPv4 addresses on port 443, and recording the received certificates. For our evaluations, we used a subset of this EFF dataset ($12,387$ certificates).

Tested X.509 Implementations. We tested the latest versions (till June 2023) of 11 open-source X.509 implementations: OpenSSL-v3.1.1 [49], Mbed TLS-v3.4.0 [52], GnuTLS-v3.7.9 [53], BoringSSL-vfips-20220613 [30], MatrixSSL-v4.7.0 [54], WolfSSL-v5.6.2 [55], Sun-v1.20 [56], Certvalidator-v0.11.1 [57], Crypto-v1.21rc2 [58], Bouncy Castle-v1.75 [59], and CERES [25]. Among these, OpenSSL, Mbed TLS, GnuTLS, BoringSSL, MatrixSSL, and WolfSSL are written in `C/C++`, Sun and Bouncy Castle are in `Java`, Certvalidator and CERES are in `Python`, and Crypto is in `Go`. We developed *test harness* for each X.509 implementation, consulting the official documentation of their certificate parsing and validation APIs.

Evaluation Plan for Q1. For addressing Q1, we performed 3 types of experiments: (a) testing the end-to-end CCVL, (b) testing the core certificate parser, and (c) testing the certificate parser considering RFC 5280 restrictions. For (a) and (b), we performed differential testing of 11 X.509 implementations against ARMOR. For (c), we compared ARMOR against a certificate linter tool named ZLint [28]. ZLint is a `Go`-based linter for X.509 certificates, designed to ensure compliance with standards such as RFC 5280 and the CA/Browser Forum Baseline Requirements [60]. However, its functionality is limited to parsing and evaluating individual certificates against semantic rules. That means, ZLint lacks the capability to test CCVL. To facilitate a direct comparison, we modify ARMOR to similarly focus on single certificate parsing and relevant semantic rule enforcement (*i.e.*, R1–R18 except R17 since ZLint does not check certificate expiration), and run ZLint constrained to just the RFC 5280 profile. Note that, for any end-to-end CCVL testing, we used certificate datasets with full chain (*i.e.*, Censys and Frankencert datasets). For testing certificate parsers, we only need to feed a single certificate in the test harness (*i.e.*, OpenSSL, EFF, Censys (leaf) datasets).

Evaluation Plan for Q2. We computed runtime overhead of end-to-end CCVL for 11 X.509 implementations and ARMOR. For this, we used $100,000$ certificate chains randomly sampled from our 2 million Censys certificate chains.

Evaluation Plan for Q3. We modified TLS 1.3 implementation of the BoringSSL library to integrate ARMOR. This modified BoringSSL was then linked to the Curl [31], a popular data transfer utility. Using this setup, the top 100 websites (till 2022) from Alexa were visited [61]. To evaluate the impact of the ARMOR integration, these visits were also conducted using the standard (unmodified) BoringSSL implementation, and we compared the execution times and outcomes between the normal and modified cases. Steps taken to modify the BoringSSL library are listed in Appendix A.1.

Adjustment of System-Time. There is a 2 years time difference between the collection of our Censys certificate dataset and our actual evaluation. Therefore, using these certificate chains directly in the experiment could result in the expiration of many of the certificate chains. To solve this challenge, we implemented a probabilistic approach within our experimental setup. Specifically, for 95% certificate chains (randomly selected), we adjusted the system-time to older dates falling within the validity periods of the leaf certificates. For the remaining 5% cases, we maintained the current system-time. Our time adjustment process is based on the Libfaketime [62] library, which allows modifying the system-time a program sees without having to change the time system-wide. This strategy allowed us to evaluate all the semantic rules, not only navigating the issue of certificate expiration but also ensuring a comprehensive and realistic assessment of the certificate validation process.

6.2. Findings on Q1

6.2.1. End-to-End CCVL with Real-world Certificates.

Our findings on Censys dataset is summarized in Table 4, which illustrates the rigorous approach ARMOR takes toward certificate chain validation compared to most libraries. This is particularly evident in the 'Rej-Acc' column, highlighting instances where ARMOR rejected a certificate chain that some other libraries accepted, and in the 'Acc-Rej' column, highlighting instances where ARMOR accepted a certificate chain that some other libraries rejected. A closer investigation of these discrepancies reveals that they stem from violations of guidelines specified in RFC 5280, signifying ARMOR's strict adherence to RFC 5280. Moreover, ARMOR agrees with most certificate chain validations conducted by the test libraries. In the 'Acc-Acc' and 'Rej-Rej' columns, ARMOR matches the results with almost all test libraries (*i.e.*, $> 99\%$ similarity). The noncompliance issues found based on the Censys dataset are discussed below.

Table 4: Analysis on validation outcomes of Censys chains

Acc = Accept Rej = Reject Sim = Similarity Diff = Difference

ARMOR **vs Others**	**Acc-Acc**	**Acc-Rej**	**Rej-Acc**	**Rej-Rej**	**Sim**	**Diff**
BoringSSL	1,435,897	0	5058	559,045	99.75%	0.25%
GnuTLS	1,435,897	0	5058	559,045	99.75%	0.25%
MatrixSSL	1,435,897	0	5058	559,045	99.75%	0.25%
Mbed TLS	1,435,897	0	5058	559,045	99.75%	0.25%
OpenSSL	1,435,897	0	5058	559,045	99.75%	0.25%
WolfSSL	1,435,897	0	5058	559,045	99.75%	0.25%
Crypto	1,435,897	0	5058	559,045	99.75%	0.25%
Bouncy Castle	1,430,644	5253	5058	559,045	99.48%	0.52%
Sun	1,430,644	5253	5058	559,045	99.48%	0.52%
Certvalidator	1,435,806	91	5058	559,045	99.74%	0.26%
CERES	1,430,629	5268	0	564,103	99.74%	0.26%

a. Allowing invalid serial number. ARMOR rejected 5053 certificate chains because at least one certificate in those chains had 0 as a serial number, contrary to the RFC 5280 requirement for a positive integer (violation of R3). This violation is present in all the libraries except CERES. For example, Sun represents certificate serial number as a BigInteger, which includes the value 0.

b. Failure to build valid chain. There are 5253 inputs for which Bouncy Castle, Sun, and CERES failed to build any valid certificate chain, indicating the presence of bugs in their chain building algorithms. On a closer look of those inputs, we found that multiple candidate chains can be built from the given input certificates; however, just one chain is rooted to a trust anchor. Since the input list of certificate did not have the certificate of that trust anchor, these libraries failed to find the trusted path. We anticipate such cases to arise in practice and implementations should be prepared to handle such cases and prioritize finding a certificate for an issuing CA *in the trusted root store*, which may be absent in the input list of certificates.

c. No support for `emailAddress` in Name. There were 15 chains CERES rejected, due to parsing failure of the `Name` field, that ARMOR accepted. These certificates contain strings of type IA5String to represent `emailAddress`. Although RFC 5280 recommends new certificates include `emailAddress` in the `Subject Alternative Name` extension, the specification does not prohibit including it in `Name` (see 4.1.2.6 in RFC 5280). ARMOR correctly accepts those certificate chains.

d. No support for standard extension. Certvalidator rejected 91 certificate chains that ARMOR accepted. Upon examination, we found that this discrepancy arises from Certvalidator's lack of support for the `Subject Alternative Name` (SAN) extension, reporting errors for these chains. However, this is a standard extension documented in RFC 5280, essential for hostname verification. When `Subject` field contains an empty sequence, CAs can mark this extension as *critical* as well.

e. Incorrect Semantic Validation for CRL DistributionPoint Fields. ARMOR found 5 certificate chains to be in violation of semantic rule R21 (Table 2), which places requirements on the presence and values of fields used in the certificate revocation list (CRL) distribution point extension. Lacking full CRL processing in ARMOR, we wrote a preliminary specification for this requirement. Upon further analysis, however, we determined this specification was incorrect, and have suspended enforcement of this semantic requirement in ARMOR, pending a fully verified implementation of CRL processing. This result is discussed further under *Threats to Validity* in Section 7.

6.2.2. End-to-End CCVL with Synthetic Certificates.

Surprisingly, we found the Frankencert fuzzer could not generate a single valid certificate chain for our dataset, and almost all of our test libraries rejected those chains for different parsing issues. This highlights a potential limitation of the Frankencert fuzzer in creating valid certificate chains, also pointed out in a prior work [25]. However, we still found noncompliance issues through Frankencert dataset.

a. Missing length restriction checks in Name. When RFC 5280 explicitly states the minimum length requirement for a string in subject or issuer `Name`, except ARMOR and CERES, no other implementations enforce this. For example, OpenSSL, GnuTLS, Mbed TLS, and others do not reject a certificate with empty (*e.g.*, "") strings in its `Name`, despite the specification mandating a minimum string length of 1.

b. Extensions with random bytes. We found that most Frankencert certificates are generated with one or more extensions containing random bytes that are not further parseable. However, some implementations permit random bytes for certain extensions, including known extensions like `Certificate Policies` (*i.e.*, OpenSSL, GnuTLS, WolfSSL, MatrixSSL, Sun) and the `Subject Alternative Name` (*i.e.*, Sun). Surprisingly, widely-used implementations like OpenSSL, GnuTLS, and WolfSSL do not reject such random `Certificate Policies` extension even if the extension is marked as *critical* (violation of R14).

c. Lenient certificate version check. The RFC 5280 specification permits only `version` 1, 2, and 3 certificates, explicitly restricting the use of extensions to version 3 certificates. Notably, any other versions is considered an invalid version according to the specification. Despite this, few implementations do not enforce checks on the version value. For example, Crypto and Certvalidator allows presence of (version 3) extensions even if the certificate version is 1 or 2. Unexpectedly, OpenSSL, GnuTLS, and Certvalidator allow presence of extensions even if the version is greater than 3. Listing 1 shows an example of weaker version check in OpenSSL (see the unexpected '>=' in 'if' condition).

```
static int check_extensions(...) {
  ...
  if (X509_get_version(x) >= X509_VERSION_3) {
    // processes certain extensions
    ...
  } else { // error: extensions require version 3
    ...
  }
}
```

Listing 1: Lenient version check in OpenSSL

6.2.3. Parser Only.

From the set of 2242 OpenSSL certificates, ARMOR's DER parser accepted 55 certificates and rejected 2187 certificates. In contrast, out of $12,387$

EFF certificates, it accepted $10,958$ certificates and rejected 1042 certificates. This significant difference in acceptance rates between the two datasets was anticipated because the OpenSSL dataset was primarily composed of intentionally flawed certificates, while the EFF dataset contained real-world certificates. A comparison with other libraries under test showed that ARMOR's results were consistent with those libraries. Further manual inspection of both "accepted" and "rejected" cases confirmed that ARMOR's parser correctly enforced syntactic restrictions.

6.2.4. Parser with RFC 5280 Restriction. ZLint is developed as a library for integration within CA software and does not differentiate between rules applicable to certificate *consumers* and *producers*. This is in contrast to ARMOR, leading to significant discrepancies in our findings–specifically, $252,700$ instances where ZLint and ARMOR diverge. ZLint, for example, flags errors for missing AKI extensions, non-critical status of certain extensions (*e.g.*, basic constraints and name constraints), and absence of the SKI extension in CA certificates. These are overlooked by ARMOR, under the premise that such rules are the responsibility of CAs during the certificate issuance process (*i.e.*, producer rules), not mandated during certificate chain validation. Additionally, we found several instances where ZLint is too lenient or incorrectly interprets characters.

a. Lenient restriction on country name attribute. RFC 5280 requires that the country name within the subject or issuer `Name` must consist of *two* printable string characters. ZLint does not enforce this length restriction under the RFC 5280 profile, instead enforcing it under the CA/Browser Forum Baseline Requirements profile.

b. Lenient parsing of default values. Based on X.690 DER restrictions, when encoding a set or sequence, any field that is equal to its default value should not be included in the encoding. Nevertheless, ZLint's parser does not adhere to this requirement for specific fields that have default values, such as the CA flag of the `Basic Constraint` extension, the critical flag of extensions, and the `Version`.

c. Incorrect restriction on subject Name. RFC 5280 allows for certain text attribute values in a subject `Name`, such as X520CommonName, to be encoded in a variety of ways: PrintableString, UTF8String, BMPString, UniversalString, and TeletexString. When checking that text values are free of nonprintable control characters, ZLint assumes these are UTF-8 encoded. However, this is only true of PrintableString and UTF8String, and in particular BMPStrings are encoded using UTF-16. This results in ZLint mistakenly flagging certificates with printable BMPString common names as containing nonprintable control characters.

6.3. Findings on Q2

Tables 5 and 6 show our execution time and memory consumption analysis of the test libraries during runtime, respectively. Considering the different programming languages in which the libraries are written, `C/C++` libraries (*i.e.*, OpenSSL, GnuTLS, Mbed TLS, WolfSSL, MatrixSSL, BoringSSL) generally exhibit greater efficiency regarding memory usage and execution time. However, libraries written in higher-level languages, such as ARMOR and the rest, tend to consume more memory and have longer execution times. We found ARMOR on average takes 2.641 seconds when a certificate chain is accepted and 2.518 seconds when a certificate chain is rejected. In terms of memory consumption, it on average takes 1049 megabytes when a certificate chain is accepted and 1069 megabytes when a certificate chain is rejected. Compared to other libraries, ARMOR's runtime overhead is very large.

Table 5: Execution time analysis on Censys chains

S.D. = Standard Deviation

	Accept						Reject					
Library	Count	Min sec	Max sec	Mean sec	Median sec	S.D. sec	Count	Min sec	Max sec	Mean sec	Median sec	S.D. sec
BoringSSL	74,956	0.004	1.119	0.029	0.029	0.009	25,044	0.004	0.340	0.028	0.028	0.006
GnuTLS	74,956	0.004	0.340	0.028	0.028	0.006	25,044	0.001	0.952	0.015	0.014	0.006
MatrixSSL	74,956	0.009	0.257	0.011	0.011	0.003	25,044	0.003	0.065	0.009	0.009	0.004
Mbed TLS	74,956	0.008	0.125	0.009	0.009	0.002	25,044	0.007	0.129	0.009	0.008	0.002
OpenSSL	74,956	0.026	1.014	0.051	0.050	0.011	25,044	0.026	0.491	0.051	0.049	0.011
WolfSSL	74,956	0.006	1.039	0.009	0.009	0.006	25,044	0.007	0.072	0.009	0.008	0.002
Crypto	74,956	0.187	8.891	0.269	0.260	0.101	25,044	0.006	3.484	0.194	0.246	0.138
Bouncy Castle	74,956	0.573	6.019	0.956	0.920	0.382	25,044	0.251	5.714	0.709	0.627	0.219
Sun	74,956	0.129	2.140	0.285	0.271	0.085	25,044	0.147	1.882	0.215	0.194	0.075
Certvalidator	74,951	0.221	2.855	0.269	0.263	0.060	25,049	0.143	1.779	0.254	0.254	0.061
CERES	74,801	0.033	5.735	0.755	0.821	0.338	25,199	0.151	5.621	0.541	0.594	0.263
ARMOR	74,801	2.207	4.553	2.641	2.618	0.118	25,199	0.053	4.665	2.518	2.544	0.300

Table 6: Memory consumption analysis on Censys chains

S.D. = Standard Deviation

	Accept						Reject					
Library	Count	Min mb	Max mb	Mean mb	Median mb	S.D. mb	Count	Min mb	Max mb	Mean mb	Median mb	S.D. mb
BoringSSL	74,956	4.01	4.49	4.21	4.21	0.06	25,044	3.62	4.36	4.13	4.17	0.12
GnuTLS	74,956	8.18	8.82	8.51	8.52	0.13	25,044	4.50	8.57	7.74	8.00	0.91
MatrixSSL	74,956	3.02	3.50	3.31	3.32	0.08	25,044	2.34	3.49	3.17	3.29	0.30
Mbed TLS	74,956	3.82	4.20	3.99	3.98	0.07	25,044	3.80	4.19	4.00	4.01	0.07
OpenSSL	74,956	6.72	7.51	6.90	6.89	0.08	25,044	6.60	7.06	6.87	6.87	0.08
WolfSSL	74,956	7.86	8.61	8.35	8.41	0.17	25,044	8.27	8.58	8.44	8.46	0.06
Crypto	74,956	59.59	68.30	64.41	62.89	2.54	25,044	60.52	68.29	64.10	62.66	2.53
Bouncy Castle	74,956	84.34	130.99	105.79	101.91	8.42	25,044	82.55	119.71	89.96	86.02	6.44
Sun	74,956	47.50	62.83	53.60	53.19	1.19	25,044	44.42	61.52	50.30	49.88	1.86
Certvalidator	74,951	26.67	28.42	27.06	27.04	0.14	25,049	23.90	27.30	26.62	26.79	0.71
CERES	74,801	21.03	40.70	39.08	39.45	2.24	25,199	21.02	31.79	27.03	28.04	3.23
ARMOR	74,801	998	1187	1049	1032	61	25,199	994	1185	1069	1075	135

6.4. Findings on Q3

We found that both the modified and unmodified versions of the BoringSSL library, when linked to Curl, successfully connected to the tested websites. However, there was a noticeable difference in the time taken for these connections. With the modified BoringSSL (which integrated ARMOR), the average time for a visit was 3.45 seconds. In contrast, using the unmodified BoringSSL, the average time was significantly shorter, at 0.75 seconds. This shows that the integration of ARMOR into BoringSSL substantially increases the time required for connecting to a website ($4.6\times$).

6.5. Responsible Disclosure

We diligently communicated all our findings to the corresponding library developers. GnuTLS acknowledged our findings and recently fixed most of them. The majority of other library developers have opted not to address our findings, asserting that the reported noncompliance issues may not lead to any known security risks. This indicates their reluctance to adhere strictly to RFC 5280 requirements.

6.6. Experimental Resources

Our experimental framework (including the test harnesses, the datasets, the input certificates that trigger discrepancies), and our modification of the BoringSSL library to show an end-to-end application of ARMOR are publicly available in the ARMOR's GitHub repository [63].

7. Discussion

Limitations. Although ARMOR makes a substantial stride towards having a high-assurance implementation of X.509 PKI with formally proven correctness properties, there is still the following room for improvement before it can be incorporated to an application such as a web browser.

1) In contrast to existing open-source libraries, ARMOR does not yet support *hostname verification* and *revocation*. Although hostname verification is critical for achieving the desired security guarantees of X.509 PKI, we follow the lead of RFC 5280, in which it is not part of the standard but is left to the application developer. Revocation can be useful, but traditional CRL is known to suffer from practical limitations [64], and some entities (*e.g.*, CAs [65], and mobile browsers [66], [67]) choose not to support revocation. Whether (and how) to revoke is currently application specific.
2) We currently do not support the enforcement of Subject key identifier (SKI) and Authority key identifier (AKI) extensions. For generality, we use name matching as our basis of certificate chain building instead of AKI and SKI. Both AKI and SKI are non-critical extensions. While these extensions can substantially simplify the construction of candidate certificate chains, in a recent measurement study on Censys data [25], SKI and AKI are absent in ~5% of the certificates. Thus, their presence is not guaranteed. More importantly, they are not crucial to the chain validation. Specifically, Section 4.2.1.2 of RFC 5280 states that "*Applications are not required to verify that key identifiers match when performing certification path validation.*" Because of this, mismatched AKI/SKI pairs does not imply a certificate chain should be rejected. Thus, this limitation will not cause ARMOR to mistakenly accept certificate chains[*].
3) Due to its preference of formal correctness over efficiency, ARMOR imposes a substantially high runtime overhead. Before it can be incorporated in a performance demanding application (*e.g.*, the Web browser), its high runtime overhead must be substantially reduced.
4) Not all modules of ARMOR are currently formally verified. ARMOR currently does not feature a formally verified string canonicalizer, and its current string canonicalizer does not handle bidirectional characters and only supports UTF-8 encoded unicode characters. We, however, observe that *none of the existing libraries* performs this suggested step. As ARMOR lacks a relational specification of its string canonicalizer, we currently do not compose the module level specifications and proofs to provide *end-to-end* correctness guarantees of the overall certificate chain validation.
5) Browsers often enforce additional requirements (*e.g.*, CA/B) that are not in RFC 5280. These are currently missing from ARMOR. ARMOR also yet to support name constraints and policy checking, which are also unsupported by some mainstream libraries. Improving ARMOR in these directions is left as future work.
6) ARMOR currently only supports the RSA signature algorithm. Extending ARMOR with other signature algorithms (*e.g.*, ECDSA) is a subject of future work.

Threat to Validity. Although ARMOR's compliance with its specification is mechanically proven, we cannot in principle guarantee the specification's consistency with the natural language description in RFC 5280. Our empirical evaluation evidences this gap: in the tested version of ARMOR, we included a preliminary specification of semantic check R21 (Table 2) that, upon analysis of the results, we realized was incorrect (it has now been removed). This result underscores a core tenent of our verification philosophy: *specifications are part of the TCB,* and thus it is important to keep it simple to facilitate human review. Note that none of ARMOR's other guarantees depend upon R21, so its removal does not break any other proofs. In addition, ARMOR does not include formal guarantees on its cryptographic operations, instead outsources signature verification to external libraries like HACL* and Morpheus. Notably, an attempt to use the formally verified WhyMP library [68] for *modular exponentiation* proved unsuccessful for some inputs, leading to our reliance on `Python`'s cryptography library for this task.

Proof Engineering. While formal methods is a field rooted in mathematical rigor, *proof engineering* [69] is in many respects similar to software engineering in that it is concerned with design principles and best practices. In developing each verified module of ARMOR, we pursued a *type-driven development* [70], starting with high-level correctness specifications as types and writing implementations that were *correct by construction* with respect to them. An effect of this approach is that in some cases, our implementations prioritize meeting proof obligations rather than efficiency. For instance, to parse the ASN.1 CHOICE construct, we used backtracking to facilitate the refutation case, which allows us to prove the negation of a disjunction by proving the conjunction of negations. More performant parsers avoid backtracking by reading the tag, which determines the type of the CHOICE construct. We believe there is a workable solution for this, but did not implement it in time for the submitted version of ARMOR.

Lessons Learned. Some constraints RFC 5280 places on issuers lack clear directions regarding whether *consumers* should reject noncompliance. For example, several legacy CA certificates with a serial number 0 are accepted by most

[*]. Following RFC 5280, certificates with critical extensions that ARMOR cannot process will be rejected.

libraries. As discussed in Section 3.2, ARMOR rejects such certificates since one of our goals is to develop a formal, machine-checked specification of RFC 5280 and test oracle for X.509 CCVL. We believe ARMOR's strict adherence to RFC 5280 does not diminish its usefulness as a reference implementation for future formally verified X.509 CCVL implementations with greater weight placed on interoperability. Overall, we believe the specification should be substantially simplified and streamlined, removing bloat due to historical features (such as the widely unsupported string canonicalization), to ensure improved interoperability and security.

8. Related Work

Extensive research has previously been conducted to test the X.509 CCVL of SSL/TLS libraries using techniques such as fuzzing [3], [4], [5], [6], [7] and symbolic execution [8], [9]. Fuzzing is a popular software testing technique in which malformed inputs are automatically generated and injected into a target application to find implementation flaws [71]. Symbolic execution, on the other hand, is a way of executing a program abstractly so that one abstract execution covers multiple possible inputs of the program that share a particular execution path through the code [72]. Though these approaches found numerous implementation flaws and noncompliance issues, none can avoid false negatives in differential testing due to the lack of a formally-verified reference implementation of X.509 CCVL. Despite several efforts to implement and formally verify cryptographic libraries [43], [73], [74], a formally verified implementation of X.509 CCVL is still missing.

Although our work presents a major step to address this research gap, there are other works that motivate our high-assurance implementation ARMOR. As an example, we rely on the prior re-engineering effort of the X.509 specification and implementation (nqsb-TLS [18], CERES [25], Hammurabi [22]) to distinguish between the syntactic and semantic requirements of X.509 and design ARMOR in a modular way. However, in comparison to ARMOR, these works lack any formal correctness guarantees. Although Ramananandro *et al.* proposed EverParse [24], a framework for generating verified parsers and serializers from Type-Length-Value ($(\langle t, \ell, v\rangle)$) binary message format descriptions, with memory safety, functional correctness (*i.e.*, parsing is the inverse of serialization and vice versa), and non-malleable guarantees, it only focuses on parsing and lacks formal correctness guarantees of other stages of the certificate chain validation. Barenghi *et al.* proposed an approach to automatically generate a parser for X.509 with the ANTLR parser generator [23]; however, they do major simplifications of the X.509 grammar to avoid complexities in parsing.

The most relevant prior works with formal guarantees are DICE* [16] and ASN1* [15]. DICE* focuses on formally proving the correctness of certificate creation, while ARMOR does the opposite task, *certificate decoding*. ASN1* focuses on generating a memory-safe, zero-copy parser for ASN.1 DER. However, ASN1* parser does not have explicit proof of total correctness. It only proves the correctness of parsing an ASN.1 DER byte stream in terms of a pair of parser and serializer. For semantic checks in X.509 certificate chain validation, ARMOR needs to further decode the consumed DER bytes (under the value tag), which ASN1* does not do. Finally, ASN1* aims to be a general parser generator for ASN.1 DER, whereas ARMOR focuses only on the ASN.1 DER representation of an X.509 certificate.

Parallel to our research, some studies have unveiled that the X.509 PKI is intentionally deployed to allow TLS interceptions by antivirus programs, parental control applications, middleboxes, and proxy servers [67], [75], [76], [77], [78]. This intervention disrupts the end-to-end security guarantee that TLS is supposed to provide, posing potential security risks. Furthermore, several studies also underlined a key issue: *user unawareness*. Many users lack a proper understanding of X.509 PKI and TLS, potentially overlooking their browser's certificate-related warnings and, in the worst case, helping adversaries compromise users own trust anchors [79], [80], [81], [82], [83], [84].

9. Conclusion

We presented ARMOR, the first substantial effort towards a formally verified X.509 CCVL implementation. ARMOR distinguishes itself from other research on formally verifying components of X.509 through its broader coverage of the standard and its emphasis on simpler, *relational* specifications, particularly to demarcate format and parser correctness properties. Though still a work in progress, ARMOR's modular design facilitated the relatively quick development (12 person months) of each of the following aspects of X.509 CCVL, along with their total correctness proofs: formats and parsers for PEM, X.690 DER, and X.509; certificate chain building; and several semantic requirements on field values within a single certificate and across certificates in a chain. We evaluated ARMOR's specificational accuracy by differentially testing it with 11 open-source libraries and the open-source certificate linter ZLint, finding several non-compliances in these libraries and also identifying a single case of specification inaccuracy. This specification inaccuracy underscores the limits of formal methods in establishing software correctness and highlights the role of differential testing in building confidence that formally verified software faithfully captures the intent expressed in natural language specifications. We also analyzed ARMOR's runtime overhead, concluding that it is a suitable option for applications where correctness is preferred and significant overhead can be tolerated, such as serving as a test oracle. Our experience and analysis lead us to believe the current standard is bloated with historical features (*e.g.*, string types of different encoding and character sets, string canonicalization) and lacks clear distinction between producer and consumer rules, which imposes a high overhead on both engineering and formal verification efforts.

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Appendix A. Supplemental Information

A.1. Integration of ARMOR in BoringSSL

We integrate the executable binary of ARMOR in BoringSSL library in the following way. Instructions for building and linking this modified BoringSSL library in Curl are available in ARMOR's GitHub repository [63].

1) We adjust the `tls13_process_certificate` function found in `ssl/tls13_both.cc` to capture the DER-encoded certificate bytes from the incoming TLS `Certificate` handshake message. Subsequently, we save these bytes to a temporary file on the local disk.
2) We modify the `ssl_crypto_x509_session_verify_cert_chain` function in `ssl/ssl_x509.cc` to employ a pipe to execute the ARMOR binary, specifying the paths to the root CA store and the temporary DER certificate file.
3) We do not modify or disable the standard certificate verification process of BoringSSL. Rather, we determine the final result of the chain verification by also taking into account the outcome from ARMOR. If both BoringSSL and ARMOR return *true*, the certificate chain is *accepted*. If not, the connection is terminated due to a possible inconsistency or validation failure.

Appendix B. Meta-Review

The following meta-review was prepared by the program committee for the 2024 IEEE Symposium on Security and Privacy (S&P) as part of the review process as detailed in the call for papers.

B.1. Summary

ARMOR is a formally verified implementation in `Agda` of X.509 certificate chain validation. This is the first work to verify both syntactic and semantic stages of X.509.

B.2. Scientific Contributions

- Addresses a long-known issue
- Provides a valuable step forward in an established field

B.3. Reasons for Acceptance

1) X.509 certificate validation is a keystone component in many software and protocols, but it is complex and it has often been the place where critical vulnerabilities were found. Proposing a formal approach and a proved stack to handle this task clearly addresses a long-known issue.
2) By implementing ARMOR and comparing its results with 11 independent libraries, the authors proved the relevance of their tool and provided a valuable step forward in the direction of a safe library to handle X.509 certificates.

B.4. Noteworthy Concerns

As indicated in the paper rationale and the discussion section, ARMOR strictly follows the RFC 5280 standard, but real-world certificate validation can deviate (through exceptions or additions) from RFC 5280. This is a relevant point of view. It would however be interesting to accommodate common deviations to include a broader corpus of certificates that would be accepted by the tool.