Morpheus: Bringing The (PKCS) One To Meet the Oracle

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ABSTRACT

This paper focuses on developing an automatic, black-box testing approach called Morpheus to check the non-compliance of libraries implementing PKCS#1-v1.5 signature verification with the PKCS#1-v1.5 standard. Non-compliance can not only make implementations vulnerable to Bleichenbacher-style RSA signature forgery attacks but also can induce interoperability issues. For checking non-compliance, Morpheus adaptively generates interesting test cases and then takes advantage of an oracle, a formally proven correct implementation of PKCS#1-v1.5 signature standard, to detect non-compliance in an implementation under test. We have used Morpheus to test 45 implementations of PKCS#1-v1.5 signature verification and discovered that 6 of them are susceptible to variants of the Bleichenbacher-style low public exponent RSA signature forgery attack. 1 implementation has a buffer overflow, 33 implementations have incompatibility issues, and 8 implementations have minor leniencies. Our findings have been responsibly disclosed and positively acknowledged by the developers.

CCS CONCEPTS

- Security and privacy → Digital signatures; Formal security models; Logic and verification; Security protocols.

KEYWORDS

PKCS#1 signature verification; non-compliance checking; reference implementation; adaptive combinatorial testing

1 INTRODUCTION

RSA digital signature scheme is a fundamental cryptographic primitive that enjoys a widespread deployment in many different application domains including secure communication protocols (e.g., SSL/TLS, IPSec), software signing, X.509 certificates, to name a few. As an example, 95% of the X.509 certificates in the Censys dataset [2] use RSA digital signatures. A common security requirement for digital signature schemes is the (existentially) unforgeable under chosen-message attacks property which we write in short as the Padding Oracle attack, also attributed to Daniel Bleichenbacher [26], which exploits RSA private-key operations and can manifest via various side channels [27, 41, 50, 55, 59]. With RSA signatures being implemented in many different languages and platforms, implementation flaws causing violations of the REP property can be catastrophic. It is thus paramount to develop an approach to check an implementation’s non-compliance to the standard [45–47, 56]. Non-compliant implementations can not only suffer from the violation of the REP property but also induce interoperability issues.

Prior efforts that analyzed PKCS#1-v1.5 implementations have been mostly manual [38, 53]. Recently, Chau et al. [33] developed an approach based on symbolic execution for testing non-compliance of PKCS#1-v1.5 implementations. However, due to the need for intrusive source-code level changes and toolchain limitations (especially for programming languages that lack a mature LLVM front-end to translate programs into the subset of LLVM IR supported
by KLEE), their study only considered open source C implementation, leaving a large landscape of PKCS#1-v1.5 implementations written in other programming languages untested and potentially vulnerable. To make matters worse, PKCS#1-v1.5 have also been implemented in embedded devices for which one only has black-box access, further complicating non-compliance checking. To improve the unsatisfactory state of affairs, in this paper, we set out to develop an automated, black-box non-compliance checker called MORPHEUS. Performing non-compliance checking in a black-box fashion makes MORPHEUS agnostic to the subject implementations’ programming languages, and thus enables it to cover a diverse set of PKCS#1-v1.5 libraries, many of which were not studied before.

As capturing the PKCS#1-v1.5 standard requirements warrants a context-sensitive grammar, the underlying non-compliance checking problem that MORPHEUS addresses can be stated as follows: Given black-box access to a PKCS#1-v1.5 signature verification implementation I and the PKCS#1-v1.5 standard requirements represented as a context-sensitive grammar Γ, is the grammar implemented by I inequivalent to Γ? Unfortunately, this is an undecidable problem even when the grammar implemented by I is given.

**Proposed approach (MORPHEUS).** MORPHEUS addresses this problem through the introduction of two components, namely, the input sampler and the oracle. At a high level, to test implementation I, MORPHEUS’s input sampler keeps selecting concrete inputs from the input space, and feeds them to both I and MORPHEUS’s oracle. If responses from I and the oracle differ, the concrete input in question is then an evidence of I being non-compliant. One can instantiate the input sampler with any (grammar-based) fuzzer but due to the lack of feedback information under the black-box settings, we observed that the fuzzer-based input sampler was having limited success in identifying non-compliance instances. To address this, we developed a specialized input sampler, based on our domain knowledge, which intelligently samples the input space in an adaptive fashion. This is similar to an adaptive, combinatorial testing approach in which once a non-compliance (synonymously, leniency in the implementation) is discovered by a generated test case, it adaptively generates more test cases of the same class to reveal if the leniency in the subject implementation can be exploited for Bleichenbacher-style low public exponent RSA signature forgery.

We instantiate MORPHEUS’s oracle with a formally proven correct implementation of the PKCS#1-v1.5 standard. We implement the oracle in Gallina [34] and use Coq’s interactive theorem prover to verify that the implementation complies with the requirements of the PKCS#1-v1.5 standard. We then use Coq’s extraction mechanism to obtain an OCaml source code.

**Findings.** To show the efficacy of MORPHEUS, we analyzed the recent versions of 45 PKCS#1-v1.5 signature verification implementations, written in 18 different programming languages. We have discovered that 40 of these libraries are non-compliant with the standard. Among them, 6 implementations have leniencies leaving significant areas of the PKCS#1-v1.5 encoded message structure unchecked, enabling an attacker to launch the Bleichenbacher-style low public exponent RSA signature forgery attack. For some PKCS#1-v1.5 libraries (e.g., node-forge), the size of unchecked area is so large that the Bleichenbacher-style low exponent signature forgery, typically possible for \( e = 3 \), become practical even for \( e = 5 \) or \( e = 17 \).

Although \( e = 3 \) is seldom used currently by certificates on the Internet [36], we note that small public exponents are not yet extinct. From the Censys [2] certificates dataset (2019 snapshot) containing a total of 1,234,185,668 certificates, we found that 0.07% has \( e = 3 \) and 0.14% has \( e = 17 \) as their RSA public exponents. More importantly, many Linux distributions continue to have some trusted root CA certificates with \( e = 3 \) in their default CA bundle. \( e = 3 \) is also sometimes mandated by key generation programs [5] and has been historically recommended for better performance [37], especially in resource-constrained devices. Also, mathematically it is interesting to see how such leniency enable attackers to target slightly larger public exponents, and how the forgery attack is counter-intuitively easier to succeed under a choice of parameter that is supposed to improve security (i.e., using a longer RSA modulus).

We have found other minor leniencies in 8 libraries that cause some invalid signatures to be mistakenly accepted as valid signatures. Although these leniencies do not directly lead to signature forgeries, there are some that contribute towards the success of attacks when exploited in tandem. Besides these semantic correctness issues in the lenient libraries’ signature verification logics, we have also discovered 1 buffer overflow vulnerability in Rel1c. Our results also show that 33 libraries have incompatibility issue where a valid signature, whose encoded message uses implicit NULL for hash algorithm parameter, is being mistakenly rejected, which can create an interoperability issue. Based on a random sampling performed on Censys certificates dataset, we observed 4% of the certificates use implicit NULL parameter in their signatures.

**Responsible disclosure.** Following the practice of responsible disclosure, we have notified all of the vendors mentioned in this paper about our findings. The vendors have also acknowledged our findings and 12 CVEs have been assigned. Furthermore, we have participated in the design and/or verification of the patches.

**Contributions.** This paper makes the following contributions:

1. We have implemented a formally verified PKCS#1-v1.5 signature verification that can be used as the oracle to perform the non-compliance checking of PKCS#1-v1.5 libraries.

2. We propose an adaptive combinatorial testing approach (MORPHEUS) to generate effective test cases — adhering to PKCS#1-v1.5 signature scheme’s context-sensitive grammar — in order to do non-compliance checking of a diverse set of PKCS#1-v1.5 libraries in a black box fashion.

3. We evaluated MORPHEUS by analyzing 45 PKCS#1-v1.5 libraries and discovered 6 of them to suffer from Bleichenbacher-style low exponent signature forgery, along with other bugs. We responsibly disclosed our findings to the affected vendors, and contributed in the design and/or testing of the proposed patches. Our findings are also accompanied by theoretical analysis and proof-of-concept attacks in Section 6.

## 2 PRELIMINARIES

The PKCS#1-v1.5 signature scheme delineates signature generation (i.e., sign) operation and signature verification (i.e., verify) operation. We use the notation in Table 1 as a reference throughout the paper.

**Signature generation operation.** Given \( d, m, \) and \( H \) as input, the signature generation operation outputs \( S \) as follows. It first computes the hash value of \( m \) based on the given hash function \( H \).
in which `digestAlgorithm` is the structure where the algorithm ID resides and `digest` is the structure for the hash value. Let ASN.1 DER encoding of the `DigestInfo` be `T`, it then forms the encoded message, `EM`, by concatenating these bytes as follows:

\[
EM = 0x00 \; | \; BT \; | \; PS \; | \; 0x00 \; | \; T
\]

where `0x00` is the value for leading byte, `BT` for signature scheme is `0x01`, `PS` is padding string at least 8 octets long with hexadecimal value `0xFF` for each padding byte, ending with a byte with value `0x00` showing the end of padding. All these bytes are considered as a prefix to `T`, and the length of `PS` is computed as `|PS| = |n| − |T| − 3 to make the length of the encoded message equal to the length of the public modulus (i.e., `|EM| = |n|`). Once `EM` is formed, the signature `S` is computed as `S = EM^e mod n`.

**Signature verification operation.** Given `(n, e, m_v, S, H)`, the signature verification operation verifies whether `S` is a valid signature. For this, it first checks if the length of the signature `S` is equal to `|n|`; otherwise, it returns “invalid signature”. Then, it obtains the encoded message from `S` using `EM_v = S^e mod n`. After this, it can follow one of the following approaches to complete verification.

**Encoding approach:** In this approach (a.k.a., construction-based approach), the verifier first computes `H(m_v)` and uses it to construct the ASN.1 DER encoding of `DigestInfo` to eventually form its version of the encoded message, `EM_v`, following the same approach as the signer. Once `EM_v` is constructed, the verifier checks `EM_v = S^e mod n`. In case they are equal, the verifier outputs “valid signature”. Otherwise, “invalid signature” is returned.

**Decoding approach:** In this approach (a.k.a., parsing-based approach), the verifier parses `EM_v` and strips off the prefix bytes to obtain the hash value and `digestAlgorithm` structure from `T`. It then checks that the `digestAlgorithm` to be consistent with the given `H`, and once passed, the verifier computes its own version of the hash value of the given message (i.e., `H(m_v)`). Finally, the computed hash value is compared against the obtained hash value (from the encoded message `EM_v`). If they are equal, the verifier outputs “valid signature”. Otherwise, it returns “invalid signature”.

**To NULL or not to NULL.** The PKCS#1-v1.5 standard has evolved through multiple RFCs (see Appendix A), and a point of confusion concerns the parameter field of the hash algorithm meta-data encoded in the DER format. As the SHA family of hash functions do not need a parameter, the question then becomes how should this NULL parameter be encoded. The initial recommendation was that the parameter field be absent for such hash functions; denoting an implicit NULL parameter. The recommendation was later changed to have the parameter field be present with an explicit NULL. Recently, this recommendation has been updated to allow both explicit and implicit NULL values [56]. As discussed in Section 6, confusions over this has led to some incompatibility issues.

### 3 OVERVIEW OF MORPHEUS

In this section, we discuss the problem definition Morpheus addresses along with its high-level approach.

#### 3.1 Problem Definition

In this paper, we focus on checking whether a given implementation (I) of PKCS#1-v1.5 scheme is non-compliant with its standard. The requirements of PKCS#1-v1.5 standard can be represented as a context-sensitive grammar `Γ`. This is due to the context-sensitivity needed to capture the requirements associated with the PS (padding string) and `T` (ASN.1 DER encoded `DigestInfo`) fields of the encoded message `EM`. Based on this, we can define our problem as follows: Given a context-sensitive grammar `Γ` capturing the requirements of the PKCS#1-v1.5 standard and given only black-box access to an implementation `I` of the PKCS#1-v1.5 scheme, is `I` non-compliant with `Γ`? We say `I` is non-compliant with the standard `Γ` if and only if there exists an input `x` such that one of the following holds: `NC_1(x) \notin Γ` but `I(x) = true`; `NC_2(x) \in Γ` but `I(x) = false`. We write `x \in Γ` to denote that `x` is accepted (resp., rejected) by the grammar `Γ`. Similarly, an implementation `I` of PKCS#1-v1.5 scheme returns true for a given input `x` if and only if `x` is legitimate according to `Γ`.

In the non-compliance checking problem, we are only given black-box access to `I`. Even if we were given access to the underlying context-sensitive grammar `Γ*` that `I` implements, checking non-compliance with the standard `Γ` would entail checking the non-emptiness of the following two sets: (a) `Γ* \backslash Γ`; (b) `Γ \backslash Γ*`. As checking non-emptiness of a context-sensitive grammar is an undecidable problem, checking non-compliance problem is also undecidable.

#### 3.2 Non-compliance and Security

Non-compliance to the PKCS#1-v1.5 scheme may result in breaking the security of a RSA signature scheme. There are basically four classes of attacks applicable to any digital signature scheme [63, 64], which are listed as follows from the strongest to the weakest security assumptions: (i) total break; (ii) universal forgery; (iii) selective forgery; (iv) existential forgery. A signature scheme is deemed to have the strongest security requirement, if it is secure against the weakest attack (i.e., existential forgery). The strongest security requirement of a signature scheme is thus Resistance to Existential Forgery (REF), which ensures that for a secure signature scheme

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>n</code></td>
<td>RSA public modulus</td>
</tr>
<tr>
<td>`</td>
<td>n</td>
</tr>
<tr>
<td><code>e</code></td>
<td>RSA public exponent</td>
</tr>
<tr>
<td><code>(n, e)</code></td>
<td>The signer’s public key</td>
</tr>
<tr>
<td><code>d</code></td>
<td>RSA private exponent</td>
</tr>
<tr>
<td><code>m</code></td>
<td>Message to be signed</td>
</tr>
<tr>
<td><code>m_v</code></td>
<td>Message received by verifier</td>
</tr>
<tr>
<td><code>EM</code></td>
<td>Encoded message, an octet string input to the sign operation</td>
</tr>
<tr>
<td><code>S</code></td>
<td>Signature, an octet string computed as <code>EM^d mod n</code> by signer</td>
</tr>
<tr>
<td><code>EM_v</code></td>
<td>Encoded message, an octet string computed as <code>S^e mod n</code> by verifier</td>
</tr>
<tr>
<td><code>H</code></td>
<td>Hash function</td>
</tr>
<tr>
<td><code>H(m_v)</code></td>
<td>Sign operation version of <code>H(m_v)</code>, contained inside <code>EM_v</code></td>
</tr>
<tr>
<td><code>H(m)</code></td>
<td>Verify operation <code>v</code> computed hash of <code>m_v</code></td>
</tr>
<tr>
<td><code>EM_v</code></td>
<td>Encoded message, an octet string constructed by verify operation</td>
</tr>
<tr>
<td><code>BT</code></td>
<td>Block type byte</td>
</tr>
<tr>
<td><code>PS</code></td>
<td>Padding string</td>
</tr>
<tr>
<td><code>T</code></td>
<td>ASN.1 DER encoding of the <code>DigestInfo</code> value</td>
</tr>
</tbody>
</table>
there does not exist a message for which an attacker can forge a legitimate signature without knowing the private key.

We now discuss which types of non-compliance to the PKCS#1-v1.5 standard can result in an insecure RSA digital signature scheme implementation (i.e., breaking REF). In what follows, we use I to denote the implementation-under-test of PKCS#1-v1.5 standard, S to denote the universe of all signatures, and Γ to denote the context-sensitive grammar capturing the PKCS#1-v1.5 standard requirements. We characterize the non-compliance into the following 3 sets, and show their relationships to REF security property.

\[ L_I = \{ s \mid s \in S \land s \notin \Gamma \land I(s) = true \} \]

Forgery Set (F_I). This set contains signatures that I mistakenly accepts but is rejected by \( \Gamma \). Concretely, \( L_I = \{ s \mid s \in S \land s \notin \Gamma \land I(s) = true \} \). Forging Set (F_I). This is the set of signatures that I mistakenly accepts (albeit, rejected by \( \Gamma \)) and causes I to be susceptible to existential forgery attack. Clearly, we have \( F_I \subseteq L_I \).

Overly-Restrictive Set (OR_I). This is the set of signatures that I mistakenly rejects whereas it is accepted by \( \Gamma \). Concretely, \( OR_I = \{ s \mid s \in S \land s \in \Gamma \land I(s) = false \} \) and \( OR_I \cap L_I = \emptyset \). Operationally, we say \( I \) is non-compliant to the standard \( \Gamma \) iff \( L_I \neq \emptyset \) or \( OR_I \neq \emptyset \). A given PKCS#1-v1.5 implementation-under-test \( I \) has the REF property iff the set \( F_I \) for \( I \) is empty (i.e., \( F_I = \emptyset \)).

3.3 High-Level Approach of MORPHEUS

For checking non-compliance of a PKCS#1-v1.5 implementation \( I \) with the standard \( \Gamma \), MORPHEUS tries to find signatures \( s \in S \) such that \( s \in L_I \), \( s \in F_I \), or \( s \in OR_I \). As the cardinality of \( S \) can be large (i.e., \( 2^{2048} \) for a 2048-bit RSA exponent), exhaustively enumerating the space \( S \) is infeasible.

For finding non-compliance instances, MORPHEUS uses an input sampler that samples the space \( S \) intelligently to find signatures to test a given implementation \( I \). To check whether a given signature \( s \in S \) is a valid signature, we need a representation of the standard \( \Gamma \) to denote the universe of all signatures, and \( \Gamma \) to denote the context-sensitive grammar capturing the PKCS#1-v1.5 standard requirements. We characterize the non-compliance into the following 3 sets, and show their relationships to REF security property.

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4 THE ORACLE OF MORPHEUS

MORPHEUS’s oracle is a formally proven correct implementation of PKCS#1-v1.5 signature verification standard. Developing the oracle involves four main steps: (1) consulting the standard to extract the specifications and formalizing them as the correctness criteria; (2) developing the actual implementation of PKCS#1-v1.5 signature verification function; (3) proving that the implementation satisfies the specification using an interactive theorem prover (ITP); and finally (4) extracting an executable binary of the oracle to be used as a reference implementation for further non-compliance checking purposes. We use Coq [34] as the interactive theorem prover.

4.1 Formalizing the Specifications

From the English descriptions provided in the RFC8017 standard, we have formalized the specifications of the signature verification in Coq’s specification language, Gallina. The formal specification serves as the correctness criteria for the signature verification function. Using the reference notation in Table 1, the original inputs to PKCS#1-v1.5 signature verification are \( S, m, H \), and \((n, e)\). Separating cryptographic primitives (such as hash function operation and modular exponentiation) from signature verification operation, we can invest our efforts to the verifier’s logic itself. We design the interface so that instead of the signature value \( S \), the oracle accepts the encoded message \( EM_e \) (as a buffer calculated by \( S^e \mod n \)). For the next argument, instead of the message \( m \), it takes the computed hash value \( h_2 = H(m) \). Since all cryptographic operations are performed outside this verification, we can replace the signer’s public key \((n, e)\) in the inputs with the length of public modulus \( n \), denoted by \( n_1 \). Based on that, we can describe SIGNATURE_VERIFICATION’s correctness using the following theorem:

**Theorem 4.1 [Signature verification correctness]**

\[ \forall (EM_v, h_v : list byte) (n_1 : nat) (H : hash_id), \]

\[ (\{ \text{SIGNATURE_VERIFICATION} EM_v, n_1 h_v, H = true \}) \iff (\text{(Pow 2 (Log2 n_1) = n_1)} \land (\text{LENGTH EM_v = n_1}) \land (\text{LENGTH h_v = (H2LEN H)}) \land (\text{EM_v[0] = 0x00}) \land (\text{EM_v[1] = 0x01}) \land (\exists (l_1, l_2 : nat) (a_1, a_2 : asb), \]

\[ ((H2Asn H h_v) = \{(a_1, l_1), (a_2, l_2)\}) \land (\text{ASB.IS_VALID a_1}) \land (\text{ASB.IS_VALID a_2}) \land ((n_1 - l_1 - 3 >= 8) \land ((n_1 - l_2 - 3 >= 8) \land ((\forall (i : nat), ((i >= 2) \land (i < ((n_1 - l_1) - 1)))) \implies (O[i] = 0x0F) \land (\text{EM_v}[(n_1 - l_1) - 1] = 0x00) \land (\forall (j : nat), ((j > 0) \land (j < l_1)) \implies (\text{EM_v}[(n_1 - l_1 + j)] = (\text{ASB2Byte} a_1[j])) \land ((\forall (i : nat), ((i >= 2); \land (i < ((n_1 - l_2) - 1)))) \implies (\text{EM_v}[(i + 1)] = 0x0F) \land (\text{EM_v}[(n_1 - l_2) - 1] = 0x00) \land (\forall (j : nat), ((j > 0) \land (j < l_2)) \implies (\text{EM_v}[(n_1 - l_2 + j)] = (\text{ASB2Byte} a_2[j]))))) \]

where \( n_1 = |n|, h_2 = H(m_2), \) and \( H \) is an enumeration denoting the hash function whose element is drawn from the set \( \text{hash_id} = \{\text{SHA-1}, \text{SHA-224}, \text{SHA-256}, \text{SHA-384}, \text{SHA-512}\} \). Here, \((\text{Pow} \ x \ y)\) is the power function that raises \( x \) to \( y \) whereas \((\text{Log2} \ x)\) is the base-2 logarithm function. We have \( (\text{LENGTH} \ x) \) function that takes a list as input and returns its length. \((\text{H2LEN} \ x)\) function is defined such that given a hash function ID as input, it returns the length of hash value of to-be-signed message. Also, \( \text{asb} \) is the type for ASN.1 DER encoded portion of the signature scheme structure and \((\text{H2Asn} \ x)\) is a function that given \( x \) as a hash function ID and \( y \) as a hash value byte list, it returns a pair of pairs \( \{(a_1, l_1), (a_2, l_2)\} \) such that \( a_1 \) is the constructed ASN.1 DER encoded bytes of type \( \text{asb} \) which contains the given hash function ID and hash value byte list with explicit hash algorithm parameter; and \( l_1 \) is \( a_1 \)'s length, while \( a_2 \) and \( l_2 \) are for the implicit NULL algorithm parameter counterpart. \((\text{ASB.IS_VALID} \ x)\) is a function that checks whether the given \( \text{asb} \) structure, \( x \), is valid (i.e., it conforms to the ASN.1 DER encoded
bytes of the signature scheme). Finally, \((\text{Asb2Byte } x)\) takes \(asb\) typed value, \(x\), and returns its serialized version.

Basically, Theorem 4.1 has two parts that express the following:
(1) If the oracle returns \(true\) for any input, then that input is valid according to the formal specifications (i.e. \textit{soundness});
(2) For all inputs accepted by the specification, the oracle must return \(true\) (i.e. \textit{completeness}).

4.2 Developing the PKCS#1 Implementation

Our oracle follows the construction-based approach where two versions of the encoded message are constructed (for both explicit and implicit NULL parameter cases) where they are compared for equality against the input encoded message (see Algorithm 1).

Concretely, our oracle named \textbf{Signature\textunderscore verification} first checks whether \(n_1\) is the power of two. It also checks that the \(EM_v\)'s length is equal to the public modulus length \(n_1\). It then checks that the length of hash value matches with a given hash function's output length. If these checks fail, then the oracle returns \(false\); otherwise, it builds the ASN.1 DER structure from the given hash value \(H\) and the hash value \(h_v\) for both explicit and implicit NULL parameter cases using the \textit{H2Asn} function. \textbf{Signature\textunderscore verification} then constructs two PKCS#1-v1.5 signature scheme structures by adding the leading byte, block type byte, padding bytes, and the end of padding to the both ASN.1 DER versions.

The necessary number of padding bytes is computed as \((n_1-l_1)-3\) for those two PKCS structures, where \(l_1\) is replaced with the ASN.1 sub-structure's length for each version (i.e., \(l_1\) for explicit version and \(l_2\) for implicit version). Once the PKCS structures are constructed, they are checked for validity with \textbf{PKCS\_FORMAT\_IS\_VALID} (Algorithm 2). This function verifies that all components in PKCS structure have a correct value and a correct length. If this check fails, \textbf{Signature\textunderscore verification} returns \(false\); otherwise, it converts both PKCS structures (for explicit and implicit formats) into the list of bytes (via \textbf{PKCS\_FORMAT\_TO\_BYTE} function) and then it checks the equality between the PKCS converted byte list and the given encoded message \(EM_v\). Only when \(EM_v\) matches with either of the explicit or implicit PKCS byte lists, \(true\) is returned.

4.3 Proof Sketch

Our proof proceeds by proving both soundness and completeness parts of the correctness theorem. We provide a proof sketch here.

\textbf{Soundness} (i.e., first direction \(\Rightarrow\)):
(1) We assume (\textbf{Signature\textunderscore verification} \(EM_v, n_1, h_v, H\)) = \(true\), then we prove the consequent of the logical implication; (2) By unfolding \textbf{Signature\textunderscore verification} definition from Algorithm 1 in our hypotheses section, we can destruct the condition of the first \(if\) and then prove:

\[(\text{Pow 2 (Log2 } n_1) = n_1) \land ((\text{Length } EM_v) = n_1) \land ((\text{Length } h_v) = (H2Len H))\]

(3) Continuing down the first \(if\)'s true branch, and having validated the constructed PKCS format given the \textbf{PKCS\_FORMAT\_IS\_VALID} algorithm in 2, we get into the second \(if\)'s true branch where the constructed PKCS format is converted into byte list. No matter which versions of structure it is (i.e., structure for explicit or implicit versions), we can prove that the first and second elements in the lists are \(0x00\) and \(0x01\), respectively, based on the PKCS construction and the subsequent serialization; hence, we can prove:

\[(EM_v[0] = 0x00) \land (EM_v[1] = 0x01)\]

(4) Since the two versions of PKCS structure are validated in the second \(if\)'s true branch, and those contain the ASN.1 sub-structures generated by \textit{H2ASN}, then the ASN.1 sub-structures must be valid. That is, having \textbf{PKCS\_FORMAT\_IS\_VALID} for a PKCS structure implies \textbf{ASB\_IS\_VALID} for the engulfing ASN.1 sub-structure (see algorithm 2). Therefore, we have the proofs for:

\[(\textbf{ASB\_IS\_VALID } a_1) \land (\textbf{ASB\_IS\_VALID } a_2)\]

(5) For a valid PKCS format, it has been checked that the padding bytes are at least 8. It is done by \textbf{Padding\_bytes\_length\_of\_8\_and\_all\_ff} padding function inside the algorithm 2, \textbf{PKCS\_FORMAT\_IS\_VALID}. Therefore, if we just subtract the lengths of ASN.1 sub-structure and three bytes from the length of PKCS structure (for leading byte, block type byte and padding end byte), we will end up with the length of padding bytes block which is at least 8 bytes. Therefore, we have proved:

\[(n_1 - l_1 - 3 >= 8) \land ((n_1 - l_2 - 3 >= 8)\]

\begin{algorithm}
\begin{algorithmic}
\STATE \textbf{Algorithm 1 Signature\_verification's definition}
\STATE \textbf{Definition signature\_verification} \((EM_v : \text{list byte}) (n_1 : \text{nat}) (h_v : \text{list byte}) (H : \text{hash id}) : \text{bool} = \)
\STATE \hspace{1em} if \(((\text{is\_power\_of\_two } n_1) \&\&
\hspace{1em} ((\text{Length } EM_v) = n_1) \&\&
\hspace{1em} ((\text{Length } h_v) = (H2Len H)))\) then
\STATE \hspace{2em} match \((H2Asn \ H)\) with
\STATE \hspace{3em} | \(\text{alp \ a}_1 \ \text{a}_2 \ \text{a}_3 \ \text{a}_4\) \(=\)
\hspace{3em} if \((\text{PKCS\_FORMAT\_IS\_VALID})
\hspace{3em} (pkcs \ (0x00) \ (0x01) \ (\text{Repeat } 0xFF ((n_1 - l_1) - 3)) \ (0x00) \ a_1))
\hspace{3em} \&\& \ (\text{PKCS\_FORMAT\_IS\_VALID})
\hspace{3em} (pkcs \ (0x00) \ (0x01) \ (\text{Repeat } 0xFF ((n_1 - l_1) - 3)) \ (0x00) \ a_2))
\STATE \hspace{3em} then
\STATE \hspace{4em} \((\text{List\_EQ } EM_v, \text{ PKCS\_FORMAT\_TO\_BYTE})
\STATE \hspace{4em} (pkcs \ (0x00) \ (0x01) \ (\text{Repeat } 0xFF ((n_1 - l_1) - 3)) \ (0x00) \ a_3))
\STATE \hspace{3em} \| \ ((\text{List\_EQ } EM_v, \text{ PKCS\_FORMAT\_TO\_BYTE})
\hspace{3em} (pkcs \ (0x00) \ (0x01) \ (\text{Repeat } 0xFF ((n_1 - l_1) - 3)) \ (0x00) \ a_2)))
\STATE \hspace{3em} \text{false}
\STATE \else \text{false} \end{algorithmic}
\end{algorithm}

\begin{algorithm}
\begin{algorithmic}
\STATE \textbf{Algorithm 2 PKCS\_FORMAT\_IS\_VALID's definition in Coq}
\STATE \textbf{Definition PKCS\_FORMAT\_IS\_VALID} \((st : \text{pkcs format}) : \text{bool} = \)
\STATE \hspace{1em} match \(st\) with
\STATE \hspace{2em} | \(\text{pkcs leading\_byte block\_type\_byte padding\_bytes padding\_end asn\_block}\)
\hspace{2em} \(\Rightarrow\) \((\text{Byte\_eq \ leading\_byte \ 0x00}) \&\&
\hspace{2em} (\text{Byte\_eq \ block\_type\_byte \ 0x01}) \&\&
\hspace{2em} (\text{Padding\_bytes\_length\_of\_8\_and\_all\_ff \ padding\_bytes}) \&\&
\hspace{2em} (\text{Byte\_eq \ padding\_end \ 0x00}) \&\&
\hspace{2em} (\text{Asb\_is\_valid \ asb\_block}))
\STATE \end{algorithmic}
\end{algorithm}
(6) Given the \text{LIST\_EQ}'s correctness as well as being in the second \text{If}'s true branch from the initial assumption, we know that one of the \text{LIST\_EQ} function calls in the disjunction must be true. Therefore, \text{EM}_t\text{.c} must be equal to one of the \text{PKCS\_structures}.

Completeness (i.e., second direction \(\Rightarrow\)): (1) We assume the right portion of the equivalence to be true, then we need to prove \((\text{SIGNATURE\_VERIFICATION} \ EM_t, n_t, h_t, H) = \text{true}\); (2) Given the following conjunction in our hypotheses section,

\[
((\text{POW} 2 (\text{LOG2} n_t) = n_t) \land ((\text{LENGTH} \ EM_t) = n_t) \land ((\text{LENGTH} h_t) = (\text{H2LEN} H)))
\]

we can prove that the conditions of the first \text{if} statement in \text{SIGNATURE\_VERIFICATION} definition are true; (3) Then, using the following lemma,

\text{Lemma ifF} : b \Rightarrow (\text{if} b \text{ then true else false}) = \text{true}. \)

we rewrite the second \text{if}'s expression. Now we have to prove the body of the second \text{if} is true as well as its assumed condition expression; (4) The body of the second \text{if} has a disjunction; so, we have to prove them one at a time. For the left side of the disjunction, we unfold the definition of \text{PKCS\_FORMAT\_TO\_BYTE} which after simplification, we get the following expression:

\[
(\text{LIST\_EQ} \ EM_t, [0\times00; 0\times01]) + + \text{(Repeat} 0xFF (n - l_1 - 3)) + + [0\times00] + + \text{(ASB\_TO\_BYTE} a_1))
\]

(5) On the other hand, we have in our hypotheses a specification expressing a list of byte. So, we use the following Lemma:

\text{Lemma build\_from\_spec} : \forall (a_{len} b_{len} : \text{nat}) (a : b : \text{list byte}), \((\text{Datatypes.length} a = a_{len} \land \text{Datatypes.length} b = b_{len}) \land 7 < a_{len} - b_{len} {\cdot} 3) \land a[0] = 0\times00 \land a[1] = 0\times01 \land (\forall i : \text{nat}, (1 < i) \land (i < a_{len} - b_{len} {\cdot} 1) \Rightarrow a[i] = 0xFF) \land a[a_{len} - b_{len} {\cdot} 1] = 0\times00 \land (\forall j : \text{nat}, (0 \leq j) \land (j < b_{len}) \Rightarrow a[a_{len} - b_{len} + j]) = b[j] = b = a[0\times00; 0\times01] + + \text{(Repeat} 0xFF (a_{len} - b_{len} - 3)) + + [0\times00] + + b.

(6) On one hand, we have in our hypotheses section, the one we have achieved by applying the above lemma, and thus get the following expression: \((\text{LIST\_EQ} EM_t, EM_t)\), which by simplification and \text{LIST\_EQ\_CORRECTNESS} lemma we have it to be true; (6) Same steps also apply to the right side of the disjunction as above and \(\therefore\), we get the proof completed. The full formal proof in Coq and other resources can be found in [20].

5 TESTING WITH MORPHEUS

We now describe the concrete approach taken by MORPHEUS to find noncompliance in a PKCS#1-v1.5 signature verifier.

5.1 Architecture of MORPHEUS

MORPHEUS comprises of two main components, namely, the \text{input sampler and bug detector} (See Figure 1). The input sampler samples the possible input space of PKCS#1-v1.5 encoded messages and selects interesting concrete inputs, possibly using feedback from the bug detector. These concrete inputs are then fed into the bug detector. The bug detector takes these inputs, then does the following for each input in parallel: (1) it pre-processes the input; (2) feeds the input to both the oracle and implementation-under-test; (3) compares their outputs, and if there is a discrepancy, then reports the input as an evidence of non-compliance of the test subject; (4) finally, it reports back the output comparison status as a feedback to the input sampler. The pre-processing is done to take into account the difference between the interfaces of the oracle and the test subject. The status of the output comparison is used adaptively by the input sampler for generating more inputs of a particular class when a non-compliance has been detected. We now provide more details on the MORPHEUS’s input sampler component as the functionality of the bug detector has been discussed already.

5.2 Insight of MORPHEUS’s Input Sampler

One may question the rationale of designing a custom input sampler for MORPHEUS instead of using a mutation engine from an existing fuzzer. As we will demonstrate in Section 6.2.1, due to the lack of domain-specific knowledge, existing mutation approaches fail to achieve the same level of proficiency in identifying non-compliance instances compared to MORPHEUS’s input sampler.

The input sampler design follows the \text{adaptive combinatorial testing approach}, which takes the union of two different test generation strategies, namely, \text{combinatorial testing} and \text{adaptive domain-specific test generation strategy}. Precisely, MORPHEUS individually generates inputs with each of these approaches and then unify them into a single set of test cases. For both these approaches, we decompose the PKCS#1-v1.5 encoded message (i.e., \text{EM}_t) into different components (e.g., BT, PS).

On one hand, combinatorial testing is a general testing method to verify interactions among test factors. It has been traditionally used for software testing with the goal of reducing the cost of test case generation while maintaining the effectiveness, with the key insight that not every input parameter contributes to every failure [28, 35, 51, 61, 62]. In our context, each of the components serve as a test factor in our test generation. Precisely, for each of the components, we have a set of interesting byte sequences, chosen...
5.3 Component Decomposition

A PKCS#1-v1.5 encoded message has the following structure depicted in Figure 2. The length of padding bytes is \(8 + L_{RP}\) where \(L_{RP}\) is the length of the rest of padding bytes, excluding the minimum required 8 bytes. The ASN.1 DER component’s length is denoted by \(L_{ASN}\) variable and its value is denoted using \(\psi\) representing a sequence of bytes. Given that we have \([n] = 1 + 1 + 8 + L_{RP} + 1 + L_{ASN}\).

![Figure 2: PKCS#1 v1.5 encoded message structure](image)

A closer look at the ASN.1 DER component brings us to the internal structures illustrated in Figure 3, for the case it uses the explicit hash algorithm parameter. Besides the correlations within TLV triplets (i.e., \((\text{Type}, \text{Length}, \text{Value})\)), there is a relation between the value of hash ID value component and the length of hash value’s value. For example, if we use SHA-256 as the hash function, then \(HID = 0x6E865A4816503049201\) (which is an object identifier for SHA-256) and since SHA-256 produces a 256-bit (32 bytes) hash value, the length of the hash value’s content octet must be 32 bytes (i.e., \(L_{HID} = 0x28\)). Understanding this internal structure, we can also conclude \(L_{ASN} = L_{HID} + 2\).

By flattening ASN.1 DER structure, we can decompose an encoded message \(EM_c\) structure into 17 components, which are then based on the neighboring components, that we can use to test an implementation. We combinatorially combine these different interesting bytes sequences for each component to generate test cases. Note that, we do not shuffle the order of the components as doing so generally destroys the structure and are rightly rejected by most implementations. On the other hand, the adaptive domain-specific test generation strategy as the name suggests uses domain-specific knowledge about PKCS#1-v1.5 and the Bleichenbacher-style low public exponent RSA signature forgery. It particularly leverages the notion of byte stealing and byte hiding. Without loss of generality, we will explain these two concepts using an example. Suppose an implementation does not check the well-formedness (e.g., the correct length) of two components \(c_1\) and \(c_2\), each of which is 8-bytes long. In this case, we can possibly steal a byte from \(c_1\) and hide it in \(c_2\). Concretely, we have a test case in which the length of \(c_1\) is 7-bytes whereas \(c_2\) is 9-bytes long. The amount of bytes one can steal should be equal to the amount of bytes one can hide to make sure that the resulting message is always of length \(n\) (i.e., the RSA modulus size). As discussed in section 6, stealing and hiding bytes allow an attacker to possibly launch signature forgery attacks on an implementation. The more bytes one can hide, the higher the chances of such an attack. The adaptive nature of this test generation comes into play when the input generator observes as feedback that it was able to steal a byte from one component and hide it in another component. It then adaptively tries to steal and hide more and more bytes.

![Figure 3: ASN.1 DER encoded structure with explicit hash algorithm parameter](image)

A component is specified using 5-tuple \((N, O, L, V, I)\), where \(N\) is of string type representing the component name; \(O\) is an integer type representing the order of the component within the whole sequence of byte string; \(L\) represents the correct length of the component (in bytes); \(V\) is the correct value for this component; and \(I\) is an array list of values of interest for the component. Note that, for a given component \(c\), its field \(I\) is manually determined, possibly based on neighboring components. As an example, \((\text{"leading_byte"}, 0, 1, 0x09, [0x01, 0x0F])\) describes leading byte component which mandates the test case generator to place its candidate value at the first of the generated sequence for the test case (i.e., 0 index); and occupies 1 byte (i.e., the correct length is 1) whose correct value is 0x09. It also suggests some values of interest from \([0x01, 0x0F]\) list to be used in test case generation process. These specific values are suggested because these are also the values of some neighboring components.

**Other parameters**. Besides the above 17 components of the encoded message structure \((EM_c)\), the signature verification algorithm accepts other arguments (e.g., size of modulus, hash algorithm, the received message). To reduce the search space, the test generation approach fixes those other parameters.

**Component mutator**. When the test generation approach selects a component \(c\) for analysis, the component mutator randomly chooses a set of values from the interesting values \(I\) as part of the \(c\)’s component specification (See Figure 4). Each element of the interesting values \(I\) for a given component \(c\) is pair of the form \((\ell, b)\) where the \(b\) field is actual byte sequence (in hexadecimal) to be used for testing whereas the \(\ell\) field is a descriptive label used for debugging purposes capturing the exact mutation performed on
the desired byte sequence. Note that, these interesting values can be described to be parametric and we use the following macros to define them. The \texttt{Repeat}(x, y) macro returns a byte sequence that repeats \texttt{y} times the input byte sequence \texttt{x} whereas the \texttt{Random}(y) macro returns a \texttt{y-byte} random byte sequence.

\textbf{Test case generator.} The combinatorial test case generator takes three arguments \texttt{min}, \texttt{max}, and \texttt{C} where \texttt{C} is the component specification (discussed before). It is responsible for generating test cases by mutating \texttt{x} components where \texttt{min} \leq \texttt{x} \leq \texttt{max}. At each step, it randomly selects \texttt{x} components to mutate. For each of those components, their corresponding component mutators are called. Each component mutator returns a random number of the mutated byte sequences for that component. A cartesian product is taken between the different component byte sequences where unmutated components use their original value. As an example, suppose \texttt{x = 2} and hence two components \texttt{c}_1 and \texttt{c}_2 will be randomly selected for mutation. Let us also suppose that component mutators for \texttt{c}_1 and \texttt{c}_2 returned \texttt{y} and \texttt{z}, respectively, number of mutated values to consider. In that case, the test case generator will end up with \texttt{y \times z} possible test cases. Note that, from these test cases, we throw away any test case which results in an encoded message whose length is greater than the RSA modulus as implementations trivially reject those test cases.

5.5 Adaptive Test Generation

At each step, our adaptive domain-specific test generation strategy randomly selects a component \texttt{c}_1. It then tries to randomly select a byte to steal from \texttt{c}_1 and hide it in all other remaining components \texttt{c}_2. This results in \texttt{c}_1 to decrease its length by 1 whereas \texttt{c}_2’s length increases by 1. Stealing byte is analogous to deleting a byte from \texttt{c}_1 whereas hiding a byte in \texttt{c}_2 is analogous to adding a random byte to \texttt{c}_2. If the stealing and hiding operations result in a signature rejected by the oracle but accepted by the implementation-under-test, then the test generator would try to steal and hide more bytes, and in some cases also search the range of accepted values. This way, the test generator can identify the amount of bytes (and values) the attacker can use to launch a Bleichenbacher-style low public exponent RSA signature forgery attack.

6 EVALUATION

In this section, we first demonstrate the efficacy of \textsc{Morpheus} in finding non-compliance in recent implementations, and then compare it against some general-purpose fuzzers and a recent work [33].

6.1 Findings

We evaluated \textsc{Morpheus} against 45 implementations of PKCS#1-v1.5 signature verification and found 9 of them are lenient, while 33 implementations have incompatibility issue. Table 2 shows a summary of \textsc{Morpheus’s} test results against various PKCS#1-v1.5 implementations. Among 9 lenient implementations, we have discovered 6 of them suffer from Bleichenbacher-style low public exponent RSA signature forgery, 1 implementation is susceptible to buffer overflow attack, and 8 implementations with some minor leniencies (i.e., accepting signatures that should have been rejected but the leniencies are such that they cannot be exploited for signature forgery). There are also 5 implementations with no bugs found.

Here we discuss the significant findings and the related attacks, and leave the details of other leniency in Appendix D. For details on the concrete parameter values used in our evaluation, see Appendix B.

6.1.1 node-forge (v0.10.0).

Forge library [3] contains a native implementation of the TLS protocol in JavaScript and a set of cryptography utilities for application development. The PKCS#1-v1.5 signature verification in node-forge employs decoding approach. Using \textsc{Morpheus}, we found that it suffers from the following exploitable vulnerabilities in its verification logics.

1) \textbf{Accepting less than 8 bytes of padding:} The node-forge PKCS#1-v1.5 signature verification implementation does not check whether PS has a minimum length of 8 bytes. After root-cause analysis, we found that after the block type value is checked to be 0x01 (line 1 in Appendix D.1.1), the implementation skips all padding bytes until it reaches to the end of padding. This leniency enables an attacker to steal all the padding bytes and then inject new bytes (with same length as those stolen) in other places that are left unchecked, which can be used together with the other findings below for signature forgeries.

2) \textbf{Ignoring digestAlgorithm structure (CVE-2021-30247):} Once the encoded message is obtained from modular exponentiation, node-forge decodes the structured message to obtain the hash value. However, we found that node-forge only checks the obtained digest value (by comparing it against the computed hash value of the received message) and ignores verifying the decoded digestAlgorithm structure, leaving some unchecked area exploitable for attacker to launch signature forgery.

3) \textbf{Accepting trailing bytes (CVE-2021-30249):} node-forge fails to check that after DigestInfo ASN.1 structure, there should not be any trailing bytes. This is a classical flaw previously shown in other implementations as well [38]. Together with the fact that node-forge accepts less than 8 bytes of padding as described above, this creates an large unchecked room exploitable for signature forgery.

   - \textbf{Signature forgery:} Based on our findings, node-forge would accept a malformed $\tilde{E}_M$ in the form of $0x00 || 0x01 || 0x00 || T || \text{GARBAGE}$. Knowing this, the attacker can prepare $\tilde{E}_M$ where $T$ contains a hash of an attacker-chosen message $\tilde{m}$, and \textsc{GARBAGE} contains some fixed values (e.g., all $0xFF..FF$) as the trailing bytes. One can then take the $e$-th root of $\tilde{E}_M$ to find the attack signature $\tilde{S}$ (without knowing the private exponent). Notice that the attacker-prepared $\tilde{E}_M$ might not be a perfect power of $e$, and thus $\tilde{S}$ might not be the perfect $e$-th root of $\tilde{E}_M$. However, as long as the imprecision stays in the unchecked trailing \textsc{GARBAGE}, the signature forgery would succeed. To further maximize the number of unchecked \textsc{GARBAGE} bytes, we can exploit the vulnerability of ignoring digestAlgorithm to modify $T$ such that the digestAlgorithm structure in DigestInfo encoded structure is replaced with a minimum number of bytes that makes the decoding operation of node-forge pass through (e.g., $0x0100$ where $0x01$ is the ASN.1 tag for boolean and $0x00$ denotes a zero-length content). This works because after the value is decoded, it is not going to be checked by the verifier, and shortening the digestAlgorithm structure allows the attacker to have even more trailing garbage bytes.

   The difficulty of finding a working $\tilde{S}$ is bound by the the distance between two consecutive perfect power of $e$. For instance, when
The length octets in A have been adjusted to use definite long form whenever possible (e.g., the length of 0x81f1 and 0x81cd for the DigestInfo and AlgorithmIdentifier structures, respectively) to maximize the length of GARBAGE.

Since the unchecked area resides in the middle of $\hat{E}M_v$, an attacker can forge a signature $\hat{S} = (k_1 + k_2)$, where $k_1$ and $k_2$ are two integers chosen such that once $S$ is processed by the verifier (i.e., when $e = 3$, verifier obtains $\hat{E}M_v = 3^3 = (k_1 + k_2)^3 = k_1^3 + 3k_1^2k_2 + 3k_1k_2^2 + k_2^3$ after processing $S$), the following properties hold for the malformed encoded message $\hat{E}M_v$:

1. The most significant bits of $k_1^3$ should match $0x00 || 0x91 || PS || 0x00 || A$, the octet string right before the unchecked area;
2. The least significant bits of $k_2^3$ should match B, the octet string right after the unchecked area;
3. The least significant bits of $k_1^3$ along with $3k_1^2k_2 + 3k_1k_2^2 + k_2^3$, should stay in the unchecked area, indicated by GARBAGE.

Success of the forgery attempt hinges on whether there are enough unchecked bytes to be exploited. Otherwise, the terms of $(k_1 + k_2)^3$ expansion would overlap with each other, and as a result, it becomes difficult for the above properties to hold. However, according to the above vulnerabilities, the number of unchecked bytes grows linearly with larger $|n|$ (fixing the same public exponent), which is yet another example of longer RSA modulus further weakens instead of strengthens security.

How to find $k_1$: Finding $k_1$ is quite similar to finding the attack signature for the case of trailing garbage bytes, as we have seen in attacking node-forge. That is, constructing $C = 0x90 || 0x91$
PS || 0x00 || A || GARBAGE with the length equals to |n| and then find the cubic root. However, here we cannot hide the inaccuracy of cubic root of the malformed construct in the least significant bits of the obtained encoded message. Therefore, we need to adjust the $k_1$ such that once raised to the power $e = 3$, the obtained encoded message contains as many as zero bits in its least significant bits. For that, we compute $t_1 = \lceil \sqrt[3]{n} \rceil$ and then sequentially search for the largest possible $r$ such that $(t_1/2^r + 1) \cdot 2^r$ yields a number of the form $0x00 || 0x01 || PS || 0x00 || A || GARBAGE$. Once the largest $r$ has been found, then we can compute $k_1 = (t_1/2^r + 1) \cdot 2^r$.

**How to find $k_2$:** Finding $k_2$ is similar to finding signature attack for the case we have forwarding garbage bytes in an encoded message, as in GARBAGE || B. In this case the the modular exponentiation can be seen as computed over a much smaller modulus $n'$, instead of $n$. In RSA, finding $\phi(n)$ often requires factorizing $n$, which is believed to be impractical when $n$ is large, now by having a special $n'$ it is easy to compute $\phi(n')$. The attacker first needs to compute $n' = 2^b$ where $b = |B|$, and then compute $\phi(n') = 2^{b-1}$, because $\phi(2^i) = 2^{i-1}$ when $p$ is prime and $i \geq 1$. Notice that $k_2$ should satisfy $k_2 \equiv B \pmod{n'}$. Since $n'$ is a power of 2, we can guarantee $k_2$ and $n'$ are coprime by choosing an odd numbered $B$ with a fitting hash value. By knowing $\phi(n')$ and $e = 3$, attacker can find a fake private exponent $f$ which acts similar to $d$. Attackers uses Extended Euclidean Algorithm to find $f$ such that $ef \equiv 1 \pmod{\phi(n')}$ and use $f$ to compute $k_2$ as $k_2 = B^f \pmod{n'}$.

- **Real-world impact:** Because of this flaw, systems (e.g. resource-constrained embedded devices) that use v2.9 of wpa_supplicant or hostapd rely on its internal TLS implementation, will be susceptible to signature (certificate) forgery attacks. This can be exploited in tandem with a WPA2-Enterprise Evil Twin attack for stealing user credentials [24], especially when the WPA2-Enterprise setup is configured to use the system CA store as the trust anchor for certificate validation.

Despite the experimental nature of the internal TLS implementation, we found that the signature forgery discussed above can indeed lead to practical attacks in the real world. We purchased a commodity Wi-Fi router and replaced its factory firmware with OpenWRT, one of the most popular open-source Linux-based router firmware, and installed the ca-bundle, wpa_supplicant and hostapd packages from its package manager (opkg). The OpenWRT ca-bundle package is based on the same set of trusted CA certificates distributed and used by Debian Linux, and contains two CA certificates that have a public key with $e = 3$, namely the Go Daddy Class 2 Certification Authority and the Starfield Class 2 Certification Authority. In fact, as long as there is one such certificate included in the trust anchors, a certificate forgery attack exploiting the signature verification flaw can succeed. We generated an attack certificate pretending to be issued by Go Daddy (by filling in appropriate information in the issuer field), and followed the aforementioned steps to forge a signature that can trick wpa_supplicant. Then we used a Raspberry Pi 4 to act as the Evil Twin and tried to trick the wpa_supplicant running on OpenWRT (configured to establish a WPA2-Enterprise EAP-TTLS Wi-Fi connection automatically, using the system CA store to validate the certificate of the authentication server). With the help of the attack certificate, the Evil Twin was able to pass the certificate validation of wpa_supplicant, pretend to be the legitimate authentication server, and steal user credentials. The same attack also works if the victim supplicant setup is configured to use PEAP instead of EAP-TTLS.

Similarly, for hostapd, under the WPA2-Enterprise EAP-TLS mode, users typically perform a certificate-based authentication to the server during TLS handshake. However, due to the signature verification flaw, we were able to generate fake certificates that appear to be issued by a legitimate authority (e.g., Go Daddy), and then gain access to a EAP-TLS WPA2-Enterprise Wi-Fi network safeguarded by hostapd on OpenWRT as any legitimate users.

**6.1.3 RELIC (git commit 32eb4c25).** RELIC [7] is a cryptographic library developed with the goal of improving efficiency and flexibility. Therefore, it can be tailored to meet specific security levels and algorithmic choices. RELIC’s PKCS#1-v1.5 signature verification uses decoding approach to parse the given signature’s encoded message, however, as identified by MORPHIEUS, it is susceptible to signature forgery and buffer overflow attacks.

1) **Leniency in checking the prefix bytes (CVE-2020-36315):** The implementation’s signature verification logic is lenient in checking the prefix bytes of $EM_c$, which includes leading byte, block type byte, and padding strings. For the first two bytes, although there are some checks in place to identify the errors, the implementation mistakenly continues the verification operation (instead of terminating it) when the errors occur, and as a result, the identified errors are eventually overwritten. Afterwards, the code attempt to peel of the padding bytes without checking their values, until the end-of-padding zero is reached. Because of this, a new variant of signature forgery attack is possible.

- **Signature forgery:** We can exploit this with a similar strategy used to forger signatures for wpa_supplicant and hostapd. The only difference is that the unchecked (padding) bytes cannot contain the value of zero. This affects how we find $k_2$. The trick is that, after finding $k_1$ and $k_2$ like before, we set some randomly chosen high bits of $k_2$ to 1, so that the output of $k_2^2 \pmod{n}$ might have random but non-zero padding. Assuming we can sample output values of the modular exponentiation uniformly at random by this trick, the success probability is $(\frac{x^2}{2^x})^2$ where $x$ is the size of the padding bytes, which amounts to about 40% chance of success under $|n| = 2048$ bits and SHA-256 hash. To the best of our knowledge, this is a new attack variant not discussed by previous work.

2) **Buffer overflow caused by missing length checks (CVE-2020-36315):** Another vulnerability identified by MORPHIEUS, is caused by the lack of necessary checks to ensure that components of $EM_c$ have correct lengths. After peeling off the prefix bytes, the implementation checks $T$’s ASN.1 encoded content up to hash value bytes. Afterwards, it copies all bytes of the hash value to a pre-allocated buffer using a computed length based on the size of padding it peeled off. Because RELIC also does not enforce proper length checks on the padding, it is possible for an attacker to use a very short padding in an attack signature to mislead the code into using a very large computed length, larger than the size of the pre-allocated buffer, when attempting to copy the hash value, hence inducing a buffer overflow. Such attack signatures can be generated similar to the signature forgery discussed for node-forging. As a proof of concept, we managed to forge signatures that can crash a verifier using RELIC.
6.1.4 phpseclib v3.0 (relaxed mode). phpseclib [6] is a PHP library that provides pure-PHP implementations of cryptographic protocols with active supports for three versions (v1.0, v2.0, v3.0). phpseclib v3.0 has two modes of operation for PKCS#1-v1.5 signature verification, known as relaxed and strict modes. The relaxed mode of phpseclib v3.0 is implemented to support BER encoding of ASN.1 data value in the encoded message obtained from the signature value. The differences between DER and BER occur mainly in length octets: DER does not allow indefinite length form and forbids the definite long form when the length can be encoded directly. Interestingly, phpseclib v3.0 (relaxed mode) uses the decoding approach for signature verification, while the other versions all take the encoding-based path. Unfortunately due to leniency in its parser, phpseclib v3.0 (relaxed mode) suffer from 2 vulnerabilities which enable signature forgery, and 2 bugs causing interoperability issue.

1) Leniency in checking parameter field (CVE-2021-30130) Similar to the second bug of wpa_supplicant and hostapd, phpseclib v3.0 (relaxed mode) fails to properly check the parameter field associated to the hash algorithm in AlgorithmIdentifier structure. Once it parses the NULL tag (i.e., 0x05), it returns an empty string without actually checking the length is zero and there is no content octets to consume. In fact, the tag does not even have to be NULL because any tags will be accepted by the parser. This bug leaves an unchecked area enabling an attacker to launch signature. Given that indefinite form for length octet is allowed in BER and supported by phpseclib v3.0 (relaxed mode), attacker can further maximize this unchecked area to increase the chance of success. Notice that the signature forgery attack is similar to that of wpa_supplicant and hostapd, where we have GARBAGE bytes in the middle of the malformed encoded message.

2) Leniency in decoding hash function OID's content octets The AlgorithmIdentifier structure contains a TLV encoding of the hash function OID used during the sign operation on m. OIDs (object identifiers) are identifier mechanism standard [9] for naming any object with a globally unambiguous persistent name, where it has its own encoding/decoding rules. The implementation, however, has a logical flaw in decoding a dotted decimal integer whose value is is greater than or equal to 128. Therefore, an attacker can inject garbage bytes after a correct hash algorithm OID the signature still verifies. The injected garbage bytes cannot be arbitrarily chosen, where every byte has to have its most significant bit set (i.e., its value should be in this range [0x80, 0xff]). That being said, it is not practical to launch Bleichenbacher-style low public exponent RSA signature forgery because the garbage bytes injected in the middle cannot be freely chosen; however, it has interoperability issue where an invalid signature is mistakenly accepted.

6.1.5 Incompatibility issues. The PKCS#1-v1.5 specification has evolved since it was first proposed, and historically there were some confusions over whether the presence of a NULL parameter field of AlgorithmIdentifier is optional, sometimes leading to incompatibility issues among different implementations. According to the latest revision of the standard as described in RFC8017, “for the SHA algorithms, implementations MUST accept AlgorithmIdentifier values both without parameters and with NULL parameters”. However, we found that there are significant number of implementations (33 of them in Table 2) that reject the implicit NULL parameter case. Although most RSA certificates have the explicit NULL parameter field, our empirical study on Censys [2] certificates dataset found that the implicit NULL parameter case still exists on 4% of RSA certificates, which suggests this issue can indeed damage interoperability. We detail the evolution of the specification in Appendix A.

6.2 Comparison with different approaches

6.2.1 General-purpose fuzzers. We now empirically show the rationale for designing a new input sampler instead of using the mutation engine of an existing fuzzer. The main reasons that contribute to the complexity of generating effective test cases for analyzing PKCS#1-v1.5 signature verifiers are as follows. First, we aim at covering many implementations (written in different languages, for different platforms/architectures, and sometimes proprietary), thus we consider the most generic black-box setting without instrumentation. This limits the use of rich source-level feedback (e.g., coverage metrics) for generating effective test cases. Second, even if one assumes a 512-bit modulus (which is not recommended by today’s security standard [48]), a fuzzer with random test case generation will have to deal with EM0 inputs of 512-bit long, effectively exploring in a space of $2^{512}$ test cases. Combining with the first reason, this substantially reduces the chance of exposing interesting non-compliance. Third, a PKCS#1-v1.5 encoded message is highly structured and requires a context-sensitive grammar to faithfully capture the format. Bit-level mutation strategy is unlikely to be successful in exposing interesting non-compliances.

Fuzzer selection. We selected AFL [13] and AFL++ [14] to compare against Morpheus. As we consider a purely black-box setting, our evaluation is thus a comparison between mutation strategies without source-level feedback. Roughly, most fuzzers differ from each other in the type of feedback (e.g., code coverage) and how they use the feedback. We chose AFL because of its generality and effectiveness in identifying weaknesses in a wide-variety of applications. On the other hand, as the PKCS#1-v1.5 encoded message is highly structured one can envision that a representative (context-free) grammar-based fuzzer like AFL++ may have a better chance in generating interesting test cases.

Incorporating AFL and AFL++ into Morpheus workflow. Like many other general-purpose fuzzers, AFL and AFL++ are designed to discover inputs that can cause a crash in the target program. We replaced our input sampler with AFL and AFL++ in the Morpheus architecture (See Figure 1). We have, however, observed that by just running AFL and AFL++ against those subject implementations do not lead to any interesting discovery as the semantic bugs reported by Morpheus do not necessarily cause a crash in the system. Hence, we tested the bug detector component by modifying it to generate an artificial crash whenever a deviation is found and thus provide AFL/AFL++ with some behavioral feedback.

Configuring AFL and AFL++. AFL takes seed inputs and applies a variety of mutation techniques to generate new test cases. Seeds used to run AFL (and, AFL++) contain correct PKCS#1-v1.5 signature structures for some given fixed parameters (e.g., hash algorithm, modulus size), similar to what is presented in Appendix section B. Although the mutator of AFL is grammar-blind, we take advantage of the support of user-defined dictionaries to make it
aware of the basic structure of the test cases in order to maximize its effectiveness. We created our own dictionary containing meaningful/interesting byte sequences that may occur in PKCS#1-v1.5 signature structure irrespective of the message being signed.

AFL++ is based on AFL and supports custom mutators. We use the open-source grammar mutator [17] and configured AFL++ to only use this mutator to evaluate the grammar mutator performance. We then created a context-free grammar — an approximation to describe the PKCS#1-v1.5 structure — in order to give it some guidance on dealing with the input structure.

Results. Our evaluation on AFL and AFL++ adopts suggestions from Klee et al. [49] and refers to the setups in the latest fuzzers UNIFUZZ [54] and WINNIE [44]. We launched 5 trials for each target implementation and ran 24 hours for each trial. We omitted Apple Security Framework’s Crypto and STM32-crypto for this set of comparison experiments since they cannot be run natively on a x86-64 Ubuntu 20.04 machine, where we have the setups of AFL and AFL+++. As can be seen in Table 2, AFL and AFL++ are able to detect some of the bugs reported by MORPHEUS, with the help of our oracle as well as domain knowledge. However, their test case generations still struggle to generate high quality test cases to reveal all the bugs discovered by MORPHEUS, and they also did not detect any new bugs not caught by MORPHEUS. It is also interesting that when AFL++ was configured to only use the grammar mutator, it did not outperform AFL’s basic mutators in our case study.

6.2.2 A KLEE-based approach in previous work [33]. We first use MORPHEUS to revisit the old implementations that were found to be problematic in [33]. The test results can be found in Table C1 in Appendix C. We note that all of the flaws that can lead to signature forgery and buffer overflow as reported by previous work can also be found by MORPHEUS. Moreover, we realized that due to how symbolic execution was being setup in previous work, MORPHEUS actually uncovered more findings regarding incompatibility and minor leniency. First, previous work did not investigate the incompatibility issues regarding an implicit NULL algorithm parameter. More intricately, because of scalability reasons, previous work used concrete bytes for ASN.1 tags [33] in all its test harnesses, and thus cannot detect leniency in the parsing of tags (e.g., ignoring the class and form bits). Similarly, with respect to the 3 test harnesses (TH1, TH2, TH3) used by previous work, the ASN.1 length variables take concrete values in TH1 and TH2, and the symbolic length variables used by TH3 is always 1-byte long [33], and thus KLEE was not able to detect leniency in the parsing of leniency in the parsing of tags. Hence, it may still struggle to detect conforming test cases. Hence, it may still struggle to detect conforming test cases. However, to revisit the old implementations that were found to be problematic in [33], 11 and 8 lines in the source tree were modified respectively, for injecting the concolic test buffer. Apache milagro did not require any source tree modifications due to its API design.

### Table 2: Bugs found by MORPHEUS, AFL, and AFL++

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Source code language</th>
<th>Bug(^1)</th>
<th>MORPHEUS</th>
<th>AFL</th>
<th>AFL++</th>
</tr>
</thead>
<tbody>
<tr>
<td>wpa_supplicant v2.9</td>
<td>C</td>
<td>SF#1</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>hostapd v2.9</td>
<td>C</td>
<td>SF#1</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>IPP Crypto v2021 update 3</td>
<td>C</td>
<td>SF#1</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>SunBasilgicOpenSSL v11.0.10</td>
<td>Java</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Amazon Corete Crypto Provider v1.5.0</td>
<td>Java</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Boost Crypto RSA v0.5.0</td>
<td>Rust</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>pyca/cryptography v2.1.14</td>
<td>Python</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>phpcssdb v1.0</td>
<td>PHP</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>phpcssdb v2.0</td>
<td>PHP</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>phpcssdb v3.0 (relaxed mode)</td>
<td>PHP</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>ppcssdb v1.0 (strict mode)</td>
<td>PHP</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Crypto++ v0.8</td>
<td>Perl</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>pyCyanite v1.18.1</td>
<td>Python</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>buddy-core v1.9.0</td>
<td>Clojure</td>
<td>⊗</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>node-forg v0.10.0</td>
<td>JavaScript</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Node Crypto v14.16.0</td>
<td>JavaScript</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Node-RSA v1.1.1</td>
<td>JavaScript</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>node-per v4.0.0</td>
<td>TypeScript</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Apple Security Framework’s Crypto v2021.05.26</td>
<td>Swift</td>
<td>IN</td>
<td>⊗</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>asmCrypto v2.3.2</td>
<td>JavaScript</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>pjem-pkt v0.1</td>
<td>Haskell</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>go-rsa v1.16.2</td>
<td>Go</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>solidity-RA PKCS1 Verifcation git commit b0235db</td>
<td>Solidity</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Apache milagro v2.0.1</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>py-pkcs1 v0.9.6</td>
<td>Python</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Crypto++ v1.5</td>
<td>C++</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>RELIC git commit 3c8b6c2a5</td>
<td>C</td>
<td>BO#1</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Seed? git commit 10e4942</td>
<td>Seed?</td>
<td>SF#1</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>GaloisLwe RSA v2.1.5</td>
<td>Haskell</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>STM32-crypto v5.0</td>
<td>Firmware binary</td>
<td>IN</td>
<td>⊗</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>aesTLS v2.1.3</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Matroska v0.3.8</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>MinTLS v2.20.0</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>LiteTomCrypt v1.14.2</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>strongswan v5.9.2</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>OpenSwan v3.0.6</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Erlang’s public_key v1.1.7</td>
<td>Erlang</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>tens v0.1.1</td>
<td>Scala</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>OpenSSL v1.1.1k</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>OpenSSL v3.0.0-openssl13</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>GnuTLS v3.6.15</td>
<td>C</td>
<td>IN</td>
<td>⊗</td>
<td>⊗</td>
<td></td>
</tr>
</tbody>
</table>

1 SF: Signature Forgery; ML: Minor Leniency; BO: Buffer Overflow; IN: Incompatibility issue
2 Configured to only use the grammar mutator
3 At the time of writing, we are not aware of applications that use its TLS implementation
In the end, similar to Morpheus, no unwarranted leniency was found in Apache milagro. For RELIC, the KLEE-based approach used in [33] also found its leniency in checking the prefix bytes [ML#1], as well as its acceptance of trailing bytes after the hash digest. However, because of how it was setup to avoid scalability issues, only 2 bytes can be moved around [33], and thus KLEE did not directly uncover the potential buffer overlap [BO#1]. For wpa_supplicant, the KLEE-based approach also found its incorrect extended tag decoding of identifier octets [ML#3], leniency in checking the length octet of DigestInfo [ML#4], and leniency in checking AlgorithmIdentifier structure [SF#1]. However, this approach was unable to find the lax length octet checking for DER [ML#1] and leniency in checking bit of an identifier octet [ML#2] due to limitations of its test harnesses as discussed above.

7 RELATED WORK
PKCS#1-v1.5. Despite its theoretical security guarantees [40], many implementations of PKCS#1-v1.5 signature scheme exhibit flaws that can lead to signature forgery, which were identified through manual inspection and hand-crafted test cases [1, 11, 12, 30, 38, 42, 53]. A recent work proposed an approach based on symbolic execution [33], but many implementations were not considered due to limitations of the toolchain, which greatly motivates this work. Previous work also attempted to implement a secure parser [58], but to the best of our knowledge it does not directly enforce all the signature verification requirements stipulated by the specification.

Orthogonal to its signature scheme, the PKCS#1-v1.5 cryptographic standard also includes an encryption scheme, and many implementations of which were found to be susceptible to a padding oracle attack also attributed to Daniel Bleichenbacher [26]. This padding oracle is notoriously difficult to avoid, as the leakage can manifest via various side channels, including but not limited to error messages [27, 50] and timing [41, 55, 59].

Finding logical bugs. Fuzzers (such as AFL [13], LibFuzzer [19], and Honggfuzz [18]) have shown to be effective in finding low-level memory bugs and runtime errors. Scalable infrastructures (e.g., OSS-Fuzz [21], ClusterFuzz [15], and FuzzBench [16]) have been designed to promote their use. Several fuzzers (e.g., AFL++ [14], SPIKE [23], and Peach [22]) support some forms of grammar representation, mostly based on a context-free grammar, to allow them to explore deeper in the source code when dealing with structured inputs. However, whether these techniques are effective in discovering logical bugs often depends on the problem at hand. One potential issue is that context-free grammar might not be sufficiently expressive to capture the intricacies of the input format, possibly generating many test cases that are trivially rejected. Another general challenge concerns the lack of an oracle which prior work alleviates by adopting differential testing [29, 32, 33, 57].

8 DISCUSSION
Formalization. We manually go over the English specification of the PKCS#1-v1.5 standard and formalized it in Gallina. It is thus our interpretation of the specification. Unfortunately, there are currently no approaches to verify that the correctness requirements we formalized indeed correspond to the natural language description.

Differential testing. A differential testing approach alleviates the lack of a test oracle by comparing pairs of implementations-under-test to find behavioral deviations. The implementations are used as cross-checking oracles. When a deviation is detected, it is not clear which implementation is noncompliant, requiring manual intervention to triage the noncompliance. Also, when the compared implementations suffer from the same noncompliance, then it will get undetected. Both of these weaknesses are subverted by Morpheus by using a formally proven test oracle.

Limitations. Morpheus’s oracle currently recognizes the object identifiers of the SHA family hash algorithms. Signatures using other hash algorithms will thus be wrongly rejected by it. In addition, the correctness of PKCS#1-v1.5 oracle critically hinges of the correctness of Coq’s extraction mechanism as well as the OCaml’s toolchain. The PKCS#1-v1.5 oracle does not perform the cryptographic operations for a signature verification and instead only focus on the format checking of the PKCS#1-v1.5 standard. Finally, Morpheus being a testing approach is incomplete, that is, it is not guaranteed to discover all noncompliances of an implementation.

Manual efforts. Realizing Morpheus required manual efforts in the following three aspects: (1) formalizing the correctness theorem by consulting the standard; (2) developing the oracle and proving its correctness; (3) generate a test harness to test a given implementation, which sets up the key, signature and message, and invokes the corresponding signature verification procedure. Among these, (1) and (2) are one-time efforts whereas (3) has to be carried out for any new implementations to be tested. In our case, (1) and (2) required approximately 180 person-hours whereas depending on the availability of sample code and document, (3) required a couple of person-hours on average for each implementation-under-test.

9 CONCLUSION
We developed an automated black-box non-compliance checker dubbed Morpheus that we used to check compliance of 45 various PKCS#1-v1.5 signature verification implementations developed in 18 different programming languages. Our analysis revealed that 40 implementations are non-compliant and 6 out of them suffer from Bleichenbacher-style low public exponent RSA signature forgery. The results suggest that variants of the Bleichenbacher-style low public exponent RSA signature forgery attack still work even after its initial discovery more than a decade ago.

Acknowledgments
We thank the reviewers for their insightful comments and suggestions on how to improve this paper. We would also like to thank the developers for taking the time to investigate and fix the issues found by Morpheus. This work was supported in part by the departmental startup budget NEW/SYC, GRF matching fund GRF/20/SYC, and Project Impact Enhancement Fund 3133292C from The Chinese University of Hong Kong (CUHK), as well as US Department of Defense (DARPA) Grant D19AP00039, and US National Science Foundation (NSF) grants CNS-2007512 and CNS-2006556. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the policies or endorsements of the funding agencies.
message to follow DER. This RFC also adds SHA-1 to the recommended list of hash functions and removes MD4 from it (flagged as being vulnerable). As specified in this RFC, the parameter field for associated to the hash function in an AlgorithmIdentifier shall have type NULL.

The RFC3447 [47] (which obsoletes RFC2437) introduces a new signature scheme, called RSASSA-PSS, although no attack has found in PKCS#1-v1.5, and emphasizes it is still appropriate for the new applications to use PKCS#1-v1.5 signature scheme. This RFC also suggests a cautious implementor to support BER encoding as long as the overall structure is correct. It then describes the encoding-based and decoding-based approaches are two alternatives for the verification, while not promoting one over the other. This RFC also adds three more hash functions, SHA-256, SHA-384, and SHA-512 to the previous recommended list and suggest the parameter field associated to SHA hash function family should be omitted, but if present, shall have a value of type NULL.

Finally, in RFC8017 [56] (the latest version to the date), although keeping the most of specifications from its predecessor, it adds support for three more hash functions: SHA-224, SHA-512/224, and SHA-512/256 and recommends SHA-256 for new families onwards. RFC8017 also emphasizes that "for the SHA algorithms, implementers MUST accept AlgorithmIdentifier values both without parameters and with NULL parameters." However, it mentions in formatting the DigestInfo to generate the encoded message (during signature generation operation), the parameter field associated with hash function family shall have a type of value NULL to maintain existing implementations.

B  CONCRETE PARAMETERS SETTING IN MORPHEUS

Concrete parameter used in the evaluation. In the reference notation introduced in Table 1 and the input parameters discussed in Section 5.4, we have used the following concrete values in our evaluation of MORPHEUS.

\[
\begin{align*}
\text{min}, \text{max} & = 1, 2 \\
C's\text{ labels} & = ['leading\_byte', 'block\_type', 'padding\_bytes', 'pad\_dinding\_end', 'asb@type', 'asb@length', 'hash\_algo@type', 'hash\_algo@length', 'hash_id@type', 'hash_id@length', 'hash_id@value', 'param@type', 'param@length', 'param@value', 'hash\_val@type', 'hash\_val@length', 'hash\_value@length']
\end{align*}
\]

C's labels = ['leading_byte', 'block_type', 'padding_bytes', 'padding_dinding_end', 'asb@type', 'asb@length', 'hash_algo@type', 'hash_algo@length', 'hash_id@type', 'hash_id@length', 'hash_id@value', 'param@type', 'param@length', 'param@value', 'hash_val@type', 'hash_val@length', 'hash_value@length']

<table>
<thead>
<tr>
<th>n</th>
<th>256 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>256 bytes</td>
</tr>
</tbody>
</table>
C COMPARING MORPHEUS WITH PREVIOUS WORK [33]

The results of comparing Morpheus with respect to the prior to Chau et al. [33] can be found in Table C1 and Table C2.

Table C1: Comparing Morpheus and previous work [33] on previously tested subjects

<table>
<thead>
<tr>
<th>Implementation name</th>
<th>Source code language</th>
<th>Bug1</th>
<th>Chau et al. [33]</th>
<th>Morpheus</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>arTLS v1.13</td>
<td>C</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>lighthttp v1.16</td>
<td>C</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>GenTLS v4.2</td>
<td>C</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>MatrixSSL v5.1 (CRL)</td>
<td>C</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>MatrixSSL v5.1 (CRL)</td>
<td>C</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>mbedTLS v2.4.2</td>
<td>C</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>OpenSSL v2.5.3</td>
<td>C</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>strongSwan v6.5.3</td>
<td>C</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

1 SF: Signature Forgery, ML: Minor Leniency, IO: Buffer Overflow, IN: Incompatibility issues
2 Libraries used for feasibility study in [35]

Table C2: Statistics of applying the KLEE toolchain from previous work [33] on new test subjects

<table>
<thead>
<tr>
<th>Implementation (version)</th>
<th>Test Harness</th>
<th>Lines Changed</th>
<th>Execution Time</th>
<th>Total Path (Accepting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apache milagro v2.8.1</td>
<td>TH1</td>
<td>&lt;9 mins</td>
<td>60582 (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TH2</td>
<td>&lt;1 min</td>
<td>42 (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TH3</td>
<td>&lt;1 min</td>
<td>6 (1)</td>
<td></td>
</tr>
<tr>
<td>RELIC git commit 32eb6c25</td>
<td>TH1</td>
<td>&lt;20 mins</td>
<td>20995 (15)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TH2</td>
<td>&lt;3 mins</td>
<td>36 (3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TH3</td>
<td>&lt;1 min</td>
<td>2 (1)</td>
<td></td>
</tr>
<tr>
<td>wpa_supplicant v2.9</td>
<td>TH1</td>
<td>&lt;2 mins</td>
<td>2695 (3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TH2</td>
<td>&lt;1 min</td>
<td>1224 (21)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TH3</td>
<td>&lt;1 min</td>
<td>163 (2)</td>
<td></td>
</tr>
</tbody>
</table>

D DETAILED FINDINGS

Here we present detailed descriptions and root cause analysis for some of our findings, and provide sample encoded messages \( EM \) and signatures \( S \) demonstrating the unwarranted leniency. Each signature \( S \) given here was generated and can be verified using the modulus and exponents given in Appendix B. More details can be found in [20].

D.1 node-forge (v0.10.0)

D.1.1 Accepting less than 8 bytes of padding [ML#1]. In the line 1575 in \_decodePkcs1_v1_5() function from node_forge/lib/rsa.js, the implementation does not check the padding bytes minimum required length of 8 or more, instead, it looks for the first byte that is not 0xFF and then counts the number of padding bytes (i.e., using padNum variable). It then checks that the end of padding, zero variable, is actually 0x00 and the number of padding bytes is \((k - 3 - T's length)\), where \( k \) is the length of public modulus \( n \) (i.e., \(|n|\)). However, the padding bytes length check performed in code (line 15) can be bypassed because it does not validate whether the top ASN.1 encoded structure (i.e., T) is malformed or not, and mistakenly trusts whatever it contains. As we show in other vulnerabilities, this bug enables attacker to steal all bytes from padding bytes and use them to expand an unchecked portion size of the encoded message structure (because of some existing leniencies) to launch Bleichenbacher-style low public exponent RSA signature forgery.

```javascript
} else if (bt === 0x01) {
    // find the first byte that isn't 0xFF, should be after all padding
    padNum = 0;
    while (eb.length() > 1) {
        if (eb.getByte() !== 0xFF) {
            --eb.read;
            break;
        }
    }
    ++padNum;
    }
    ...
    // zero must be 0x00 and padNum must be (k - 3 - message length)
    var zero = eb.getByte();
    if (zero !== 0x00 || padNum !== (k - 3 - eb.length())) {
        throw new Error('Encryption block is invalid.');}
    return eb.getBytes();
```

D.1.2 Ignoring digestAlgorithm structure (CVE-2021-30247) [SF#1]. The DigestInfo is the top ASN.1 encoded sequence structure that contains digestAlgorithm and digest octet strings, where the former encodes the hash ID information, being used in the signing process as well as the optional parameter field associated to that hash algorithm (represented by NULL parameter), and latter encodes octet string TLV containing the actual hash value of the message being signed. The implementation in node-forge, however, is lenient in checking the digestAlgorithm structure. Once DigestInfo is being decoded, the implementation, does not check the necessary elements to be present in its first child (i.e., digestAlgorithm) and just retrieves the hash value from its second child (i.e., digest) to compare it against the computed hash.
value. Hence, it is possible to build arbitrary TLV and use that instead of the `digestAlgorithm` as long as the TLV is well-formed.

Now by taking a closer look at line 11 in `verify()` function snippet below taken from `node_forge/lib/rsa.js`, we can spot that the implementation only checks that the hash value from the decoded top ASN.1 structure is equal to the given digest. However, it mistakenly ignores checking the other elements in the `digestAlgorithm` structure, decoded into `obj.value`. Hence, it is possible to build arbitrary TLV and use that in `verify()` function. However, in none of these steps, the implementation does not check that there is no garbage bytes trailing the ASN.1 structure, and thus will be ignored during the process.

```javascript
if(scheme === 'RSASSA-PKCS1-V1_5') {
    scheme = {
        verify: function(digest, d) {
            // remove padding
            d = _decodePkcs1_v1_5(d, key, true);
        }
    }
}
```

In order to reproduce triggering this bug, the below concrete values, found by Morpheus, can be used given the parameter settings provided in section B.

**Example:** 91 garbage bytes injected as the value of a TLV replaced `digestAlgorithm` structure.

**EM:** `0x0001003024010004207509e5bda0c762d2bac7f96d75b9b2263fa18
20... // do rsa decryption w/o any decoding, then verify -- which does decoding
21... var d = pki.rsa.decrypt(signature, key, false);
22... return scheme.verify(digest, d, key.n.bitLength());
23);}
```

```javascript
var length = _getValueLength(bytes, remaining);
2... var constructed = ((b1 & 0x20) === 0x20);
4... if(constructed) {
5... // parse child asn1 objects from the value
6... value = [];
7... if(length === undefined) {
8... ...
9... } else {
10... // parsing asn1 object of definite length
11... while(length > 0) {
12... start = bytes.length();
13... value.push(_fromDer(bytes, length, depth + 1, options));
14... remaining -= start - bytes.length();
15... length -= start - bytes.length();
16... }
17... }
18... }
```

In order to reproduce triggering this bug, the below concrete values, found by Morpheus, can be used given the parameter settings provided in section B.

**Example:** 215 garbage bytes added as trailing garbage bytes by exploiting another vulnerability which ignores `digestAlgorithm` structure to expand the size of unchecked trailing garbage bytes.

**EM:** `0x0001003024010004207509e5bda0c762d2bac7f96d75b9b2263fa18
20... // do rsa decryption w/o any decoding, then verify -- which does decoding
21... var d = pki.rsa.decrypt(signature, key, false);
22... return scheme.verify(digest, d, key.n.bitLength());
23);}
```

```javascript
var length = _getValueLength(bytes, remaining);
2... var constructed = ((b1 & 0x20) === 0x20);
4... if(constructed) {
5... // parse child asn1 objects from the value
6... value = [];
7... if(length === undefined) {
8... ...
9... } else {
10... // parsing asn1 object of definite length
11... while(length > 0) {
12... start = bytes.length();
13... value.push(_fromDer(bytes, length, depth + 1, options));
14... remaining -= start - bytes.length();
15... length -= start - bytes.length();
16... }
17... }
18... }
```
Example: Incorrect value (i.e., 0x0c) used for digestAlgorithm's type octet instead of the correct value of 0x30:

```
EM = 0x6001
```

```
60696664686163504920155004275759e5bda6c762d2bac7f99d7575b5b
```

```
2263fa41ccbc542ab5e3df1636eb68ecaca9
```

D.2 wpa_supplicant & hostapd (v2.9)

D.2.1 Lax length octet checking for DER [ML#1]. In ITU-T X.690 standard [10], three ways for encoding length are introduced: definite short form; definite long form; and indefinite form. Define definite short form uses one octet for the length value in the range [0, 127]. Definite long form uses an initial octet followed by one or more subsequent octets. The initial octet shall be encoded as 8th bit (MSB) is 1 while bits 7 to 1 shall encode the number of subsequent octets in the length octets, as an unsigned binary integer with bit 7 as the most significant bit. Bits 8 to 1 of the first subsequent octet, followed by bits 8 to 1 of the second subsequent octet, followed in turn by bits 8 to 1 of each further octet up to and including the last subsequent octet, shall be the encoding of an unsigned binary integer equal to the number of octets in the contents octets, with bit 8 of the first subsequent octet as the most significant bit. For the indefinite form, the length octets indicate that the contents octets are terminated by end-of-contents octets, and shall consist of a single octet. However, as in section 10.1 of DER encoding rule [10] mandates:

"the definite form of length encoding shall be used, encoded in the minimum number of octets." 

This bug alone can cause an interoperability issue where an invalid signature value can be mistakenly accepted as valid. However, allowing definite long form, even for its correct length values, will enable attacker to expand the unchecked area, if any, especially when in none of the supported hash functions we do not have any content octets in T whose length is greater than 127 bytes. In order to reproduce triggering this bug, the below concrete values, found by MORPHEUS, can be used given the parameter settings provided in section B.

Example: Incorrect encoding of the length octet of OID in AlgorithmIdentifier as definite long form with 4 bytes (0x83000009):

```
EM = 0x6001
```

```
60696664686163504920155004275759e5bda6c762d2bac7f99d7575b5b
```

```
2263fa41ccbc542ab5e3df1636eb68ecaca9
```

D.2.2 Leniency in checking

```
EM = 0x6001
```

```
60696664686163504920155004275759e5bda6c762d2bac7f99d7575b5b
```

```
2263fa41ccbc542ab5e3df1636eb68ecaca9
```

D.2.2 Leniency in checking
in checking the explicit NULL parameter TLV enables an attacker to exploit this unchecked area to launch Bleichenbacher-style low public exponent RSA signature forgery.

```c
1 if (x589_sha256_oid(Aid)) {
2     if ((signature->oid[0] == 1)) {
3         return -1;
4     }
5     goto skip_digest_oid;
6 } else {
7     return -1;
8 }
```

Reproducing this bug can be done using the below concrete values, found by MORPHEUS, given the parameter settings provided in section B.

**Example:** 194 garbage bytes (0x888) are injected in the explicit NULL parameter TLV of AlgorithmIdentifier structure:

```c
EM = 0x0001ffffffffffffffff003081f13081cd060960864801650304020188
```

Incorrect encoding of sequence type (0x10) instead of the correct encoding 0x30) used in the DigestInfo structure is accepted as a valid signature by these implementations.

```c
EM = 0x0001ffffffffffffffff003081f13081cd060960864801650304020188
```

D.2.4 Correct extended tag decoding of identifier octets [ML#3].

According to the section 8.1.2.4 of ITU-T X.690 [10] standard specifying ASN.1 encoding format, for "tags with a number greater than or equal to 31, the identifier shall comprise a leading octet followed by one or more subsequent octets."

This allows tag to be extended to support various types with higher tag numbers. For that, we have a sequence of bytes starting from leading byte, continuing by subsequent octets, as needed, followed by the last octet. These bytes need to conform the encoding rules prescribed by ITU-T X.690 standard but some important ones are as follows. The first 5 least significant bits (tag component) of the leading byte must be all 1s (0x1f). Then each subsequent octet (except the last octet) must have the most significant bit set to 1 while the last octet’s MSB must be 0. Now once these bytes are read, the extended tag is computed by concatenating all subsequent octets (including the last octet) such that all MSBs (for each byte) are eliminated. The issue with these implementations is that even though it deals with a primitive type, like object identifier type (0x06), it allows one to have an extended tag version of that as well (e.g., 0x1f06) which is against the standard that prescribes the extended tags which emphasizes "for tags with a number greater than or equal to 31". Besides, even though the standard in the section 8.1.2.4.2.c, prohibits that "bits 7 to 1 of the first subsequent octet shall not all be zero", these implementations are non-compliant. Therefore, one can create arbitrary extended tag format. Going back to the object identifier type example, we can have 0x8f080808...0806 and still be recognized as a valid identifier object for the identifier object type.

Although this bug does not lead to any signature forgery, it can cause interoperability issue by accepting some invalid signatures.

**Example:** Incorrect encoding of object identifier type’s identifier octet as the extended tag with two bytes (0x1f06):

```c
EM = 0x0001ffffffffffffffff003081f13081cd060960864801650304020188
```

```c
D.2.3 Leniency in checking form bit of an identifier octet [ML#2].

An identifier octet in DER encoding [10] of a data value consists of three components: Class (two most significant bits), Form (6th bit, indexing from 1), and Tag (five least significant bits). The Class component is there to indicate the class of a Tag, whether it is a standard type or application specific type. For instance, 00 for class bits shows the tag is universal type. The Form component indicates if the tag does include sub-type, and thus represents a constructed type (if set), or it is just a primitive type without any sub-type (if not set). Finally, Tag represents the actual type of the data value in DER encoding. For example, the tag for a sequence type is b’100000’; including Form bit to that makes it b’110000’ because sequence tag is constructed not primitive; and given that the sequence type has universal tag class we end up having b’00110000’ (0x30 in hex) as the final encoded value for this identifier octet. In both implementations, the Form bit, however, is not being checked and thus it accepts two versions for an identifier octet (i.e., with and without Form bit being set). That being said, an identifier octet like sequence can be represented as both b’00110000’ (i.e., 0x30) and b’00010000’ (i.e., 0x10). This issue affects sequence type used in the top DER encoded ASN.1 structure (i.e., DigestInfo; sequence type in AlgorithmIdentifier structure; object identifier type of hash ID encoding structure; and octet string type of hash value TLV structure.

```c
827e0157fed6a86099326cfca7687f7c
```
D.2.5 Lieniency in checking the length octet of DigestInfo [ML#4].
The way an ASN.1 encoding structure (identifier octets (Type); length octets (Length); contents octets (Value), TLV for short) is being parsed in these implementations is that, simply put, it takes a chunk of data, with its length and then parses it to return a pointer to its header (type section of TLV). To do so, it considers the first byte as header, reads the second byte as length section, and lastly checks if the current position (which now refers to the first byte of value section) has not passed the end position (previously computed from the data length input). It also checks whether the length field of a TLV is not greater than what has remained to read (i.e., end = pos). So, as long as the value for the length section of a TLV is not greater than what has left to read, everything checks out; even though the value is less than the correct value. The length field for DigestInfo TLV suffers from this leniency; so, lower value than the correct length will also be accepted.

Example: Incorrect value for DigestInfo’s length octet as 0x0F is accepted by the verifier instead of the correct value 0x31:

Example:

Example:

D.3 RELIC (git commit 32eb4c25)

D.3.1 Lieniency in checking the prefix bytes [CVE-2020-36315] [SF#1].
The prefix bytes in the encoded message $EM_k$ consists of the leading byte (with value of 0x00), block type byte (0x01 for signature scheme), and padding bytes with an appropriate length to make the whole encoded message length equal to the public modulus length, where every byte of padding bytes has a value of 0xFF while 0x00 byte is used to indicate the end of padding. The implementation is, however, lenient in parsing these prefix bytes, and thus open the door for a signature forgery attack. pad_pks1() function in the implementation is responsible to strip off such prefix bytes. The first problem happens because of the way the leading byte and the block type flag are being handled. As can be seen in the below pad_pks1() function snippet taken from src/cp/relic_cp_rsa.c file, the leading byte and block type are being read and if they are not 0x00 and 0x01, respectively, the result becomes an error (lines 9 and 15). However, instead of

```c

... break; ...
result = (r == 0 ? RLC_OK : RLC_ERR);
result = RLC_ERR;
result = RLC_ERR;
bn_rsh(t, m, 8 * m_len);
bn_rsh(t, m, 8 * m_len);
bn_rsh(t, m, 8 * m_len);
bn_rsh(t, m, 8 * m_len);
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);
result = RLC_OK : RLC_ERR);

... break; ...
result = (r == 0 ? RLC_OK : RLC_ERR);
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;

... break; ...
result = (r == 0 ? RLC_OK : RLC_ERR);
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;

... break; ...
result = (r == 0 ? RLC_OK : RLC_ERR);
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
result = RLC_ERR;
```

In order to reproduce triggering this bug, the below concrete values, found by MORPHEUS, can be used given the parameter settings provided in section B.

Example: 202 garbage bytes (0x88 s) are added before the block type byte (0x01) without including padding bytes (0x00 bytes).
D.3.2 Buffer overflow caused by trailing garbage bytes (CVE-2020-36315) [BoI]. The implementation does not properly check that after the hash value bytes in T, there are no trailing garbage bytes. According to the implementation of RSA PKCS#1-v1.5 signature verification, cp_rsa_ver() function in snippet below, once pad_pcks1() function is called to strip off EM., the counter referring to the end of padding is updated such that to indicate the beginning of the hash value portion. Then, all checks are done to make sure the encoded message’s ASN.1 related bytes, right before hash value, matches up with the expected bytes (calculated by hash_id()). However, neither pad_pcks1() nor the callee checks that the hash value bytes has no trailing garbage bytes (i.e., the length of hash value bytes are equal to the expected length). This trailing garbage bytes can be added by borrowing bytes from the padding bytes to make sure the length of malformed encoded message is not changed. Now after unpadding and knowing the position of hash value bytes, the implementation copies everything from hash value to the end of encoded message into another memory space (pointed by h2 in the code) to be compared with the computed hash value (pointed by h2). Then, the comparison takes place to compare them with respect to the expected hash length, and thus the trailing garbage bytes are ignored, if there is any.

Example: 202 tailing garbage bytes (0x88) are added after the hash value bytes, causing segmentation fault.

```
EM = 0x0001003031300d0609608648016503040201050004207509e5bda0c762a38d7ddab345168c8488fddc45c3ab9e91b457f62326fc6f33a46336ae18636b3aebd
```

D.4 phpsseclib v3.0 (relaxed mode)

D.4.1 Leniency in checking parameter field (CVE-2021-30130) [SF#1]. The implementation in the relaxed mode, uses the parsing-based (i.e., decoding-based) approach to extract hash value and hash function from the encoded message. It then applies the hash function (whose ID is extracted from the encoded message) to the received message in order to obtain hash value, which is then compared with the extracted hash value from the encoded message. More specifically, it applies decodeBER() on the ASN.1 portion of the encoded message to obtain TLVs in the form of its internal structure (called $decoded). It then calls aslnmap() function to extract DigestInfo (i.e., hash function OID and parameter (digestalgorithm as well as the hash value (digest)). This is done by providing a blueprint specifying how the TLVs are supposed to be nested given their types (i.e., their identifier octets). More specifically, the blueprint mapping specifies, we should have a sequence TLV, that has two children called digestAlgorithm and digest, where digest has octet string type (0x04 as identifier octet), and digestAlgorithm is a sequence TLV having two children. First child is algorithm with object identifier type (0x06) and second child is called parameters whose type is specified as any (but not NULL type). This leniency, at the very least, can cause interoperability issue. The implementation mistakenly accepts a signature whose encoded message has any type (than NULL type) in its parameter TLV section. But the implication can get much worse because the parameter value (i.e., the content octets of the parameter section) are not being checked to actually match the NULL type. That is, the implementation does not verify that: (i) the parameter value should be absent; and (ii) the length octet is 0x00. Instead, aslnmap() function is recursively called to get to the parameter section, if it first decodes the type to understand what this type is, because according to the blueprint mapping it can be any type. Once decoded, if it is NULL type, the code just returns empty string, ignoring the actual content octets. But the parameter type does not even have to be NULL type as mentioned before, and some other types work as well because the aslnmap() callee accepts any type for the parameter type. Considering that length octet here uses the definite short form, we are able to inject 79 random bytes as parameter value and get validated, given our settings described in section B. Since the relaxed version accepts BER, and as we know in BER, indefinite form is also allowed for the length octet of the top ASN.1 sequence, we are able to stack more garbage bytes into the parameter value (i.e., content octets) and extend the unchecked area from 79 bytes to 114 bytes out of 256 total bytes.

By performing root cause analysis, we can spot in line 5 in the snippet below from aslnmap() function in phpsseclib\File\ASNI.php that any instead of NULL type is used in the mapping blueprint.

```
1 public static function aslnmap($decoded, $mapping, $special = [])
2 {
3     ...}
4     switch (true) {
5         case $mapping['type'] => self::TYPE_ANY:
6             $type = $decoded['type'];
7             ...}
8     $map = self::ANY_MAP[$type];
9     if (is_string($map)) {
10        return [$map => self::aslnmap($decoded, ['
11        type' => $type] + $mapping, $special) ];
12    }
13    break;
14    ...}
```

Also, as shown below in aslnmap() function, when decoded type is recognized as NULL, then the content octets are not even checked here to be absent nor are passed to be checked by callee.

```
1    ...}
2    case self::TYPE_OCTET_STRING:
3        return $decoded['content'];
4    case self::TYPE_NULL:
5        return '';
6    case self::TYPE_BOOLEAN:
```
Here is another snippet taken from the function `rsassl_pks1_v1_5_relaxed_verify()` in `phpseclib/Crypt/RSA/PublicKey.php`, where whatever is decoded as parameter is not being checked at all. The implementation only checks the hash algorithm and uses that to verify the signature.

```
1 $decoded = ASNI::asn1map($decoded[0], DigestInfo::
2           MAP);
3 if (!isset($decoded[1])) $decoded[1] = false;
4 return false;
5 }
6 if (!isset($decoded['digestAlgorithm'][1])) {
7   return false;
8 }
9 if ($hash = $decoded['digestAlgorithm'][1];
10   $hash = substr($hash, 0, 3) == 'id-'
11 ) {
12   $hash = $decoded['digest'][1];
13   $hash;
14 }
15 $em = $hash->hash($m);
16 $hash = new Hash($hash);
17 return hash_equals($em , $em2);
```

```
Example: 114 garbage bytes are added by misusing indefinite form of length octet in BER and value of parameter TLV being not checked.

```
Example: 79 garbage bytes (0x88s) are appended to a valid SHA-256 OID (we can even add more garbage bytes, 116 bytes, by misusing indefinite form of length octet in BER and removing parameter TLV):

```
```

D.4.3 Leniency in checking form bit of an identifier octet [ML#2]. Similar to wpa_supplicant and hostapd, the phpseclib v3.0 (relaxed mode) implementation has a leniency in handling an identifier octet by failing to check the form bit as discussed in Appendix D.2.3.

D.4.4 Incorrect extended tag decoding of identifier octets [ML#3]. Similar to wpa_supplicant and hostapd, the phpseclib v3.0 (relaxed mode) implementation suffers from a logical flaw in decoding of the extended tags for identifier octets, as discussed in Appendix D.2.4.

D.5 jsrsasign (v10.1.13)

D.5.1 Leniency in checking the prefix bytes [ML#1]. jsrsasign v10.1.13 is lenient in checking the prefix bytes and some other invalid signatures are mistakenly recognized to be valid. As can be seen in the below snippet from `RSAKey.prototype.verify()` function in `jsrsasign.js` file, the initial 0x90 byte will be ignored when octet strings are converted to integer (line 4) and converted back to octet strings after taking modular exponentiation to the power public exponent (line 8). Then the naive regex pattern being used in line 9 to strip the padding bytes only check for any block type byte (as in `0x01FF...FF00`) but also accepts the prefix string such as `0x01F...FF00` where block type byte is `0x01F`. Also, all padding bytes can be removed (as in `0x01F00`) or all can be of value `0x90` and still get validated by the signature verification.

```
Example: 79 garbage bytes (0x88s) are appended to a valid SHA-256 OID (we can even add more garbage bytes, 116 bytes, by misusing indefinite form of length octet in BER and removing parameter TLV):
```
D.6 CryptX (v0.070) & LibTomCrypt (v1.18.2)

CryptX is a Perl module providing a cryptography based on LibTomCrypt library. Therefore, they suffer from the same minor leminacy as explained below.

D.6.1 Legiency in checking form bit of an identifier octet [ML#1]

Similar to wpa_supplicant and hostapd, the LibTomCrypt library (and thus CryptX) suffer from a flaw where the form bit of some identifier octets are not being checked which can cause interoperability issue. This issue affects octet string type used in hash value encoding structure and the object identifier type of hash ID encoding structure.

Example#1: Incorrect encoding of octet string type (0x24 instead of the correct encoding 0x04) used in the hash value structure is accepted as a valid signature's encoded message by the implementations.

Example#2: Incorrect encoding of octet string type (0x26 instead of the correct encoding 0x04) used in the hash function OID structure is accepted as a valid signature's encoded message by the implementations.

Infrequency of signature forgery attack. As discussed above, jsr-as is signing is will be a fine choice of palette, as it is easy to compare. However, the remaining chunk (let us call it X) of ASN.1 DER structure (including the hash value) would be 460 bit long, assuming the parameter settings provided in section B.

In fact, given the context of X that we need to match fo SHA-256 case, the distance between two perfect cubes might be even larger than the size of the hash itself (256 bit).