Tree-formed Verification Data for Trusted Platforms

Andreas U. Schmidt and Andreas Leicher
Novalyst IT AG
Robert-Bosch-Straße 38, 61184 Karben, Germany
Email at: http://andreas.schmidt.novalyst.de/

Yogendra Shah and Inhyok Cha
InterDigital Communications, LLC
781 Third Avenue, King of Prussia, PA 19406
Email: {yogendra.shah,inhyok.cha}@InterDigital.com

Abstract—The establishment of trust relationships to a trusted platform relies on the process of validation. Validation allows an external entity to build trust in the expected behaviour of the platform based on provided evidence of the platform’s configuration. In a validation mechanism such as remote attestation, the trusted platform exhibits verification data created during a start up process. These data consist in hardware-protected values of platform configuration registers, containing nested measurement values, i.e., hash values, of all loaded or started components. The values are created in linear order by the secured extend operation. Fine-grained diagnosis of components by the validator, based on the linear order of verification data and associated measurement logs, is inefficient. We propose a method to create a tree-formed verification data, in which component measurement values represent leaves and protected registers represent roots. It is shown how this is possible using a limited number of hardware-protected registers and the standard extend operation. In this way, the security of verification data is maintained, while the stored measurement log is consistently organised as a tree. We exhibit the basic mechanism of validating a platform using tree-formed measurement logs and verification data.

I. INTRODUCTION

In a nutshell, the process of building trust in computing platforms follows a unique, common pattern [1]. During start up of the platform, all components are measured by a protected entity on the platform before they are loaded and executed. The generation of a chain of trust is an important concept for a Trusted Computing System. This chain must extend without gaps from system boot up to the current system state, including all executed instructions and programs. Every component is required to measure and report the following component before executing it. Measurement of the direct successor prevents un-monitored execution of code between measurement and actual execution. The measurement process is protected by the root of trust for measurement, and can be implemented for instance by computing a digest value over code and configuration data. Verificaton data is compiled from the measurement values by a protected operation and stored in protected storage. The verification data identifies, after completion of secure start up, the platform’s state uniquely. Important embodiments of these processes are authenticated and secure boot specified by the Trusted Computing Group (TCG). In [2], authenticated boot is specified for PC clients, whereas [3] specifies secure boot for mobile platforms. The difference is essentially that secure boot adds a local verification and enforcement engine that lets components start only if their measurements are equal to trusted reference values.

TCG proposes to compute verification data via the extend operation of the Trusted Platform Module (TPM, [4]), respectively, the Mobile Trusted Module (MTM, [5]), from measurement values, which are hashes of component code and/or data. The data are stored in Platform Configuration Registers (PCRs, a minimum of 16 according to version 1.1 of the specification, at least 24 in version 1.2) in the TPM, where they can only be accessed by authorized commands. The extend operation builds a linearly ordered, nested chain of hash values, akin to the Merkle-Damgård transform, as follows:

\[ V_i \leftarrow V_i \& m \iff H(V_i || m) \]

where \( V_i \) denotes a verification data register (\( i = 0, \ldots, 23 \) for PCRs), \( H \) is a collision-resistant hash function (SHA-1 in case of the TPM), and \( m = H(\text{data}) \) is a measurement value.

In validation toward an external entity, verification and other data, such as the SML, is signed by the platform and transferred to the validator. The validator is then able, in principle, to assess the trustworthiness of the platform to any desired granularity, limited only by the total information conveyed during validation. Again, paradigmatic embodiments for validation are defined by the TCG in the attestation protocols [6]. It is envisaged by TCG, that validation may eventually be used to take remedial steps on trusted platforms, for instance upon first network or service access, as envisioned by the Trusted Network Connect working group of the TCG [7].

We propose a method to organise verification data and SML differently from the linear order foreseen by TCG specifications, in a tree, more precisely a Merkle hash tree [8]. [9]. In Section IV, the efficiency problem with linearly chained verification data is highlighted from the viewpoint of applications. The central security problem in organising verification data as a tree is to make their generation as secure as the measurement-extend operations of TCG specifications. We point out why this problem is not yet covered in the existing literature. Section V presents the core method and algorithm to generate verification data in a limited set of hardware protected registers, which truthfully represents the root nodes of a hash tree. Section VI shows how tree-like verification data and SML can efficiently and effectively be used for validation.
Section V discusses implementation options for tree-formed verification data. Section VI concludes the paper with plans for further work.

II. PROBLEM STATEMENT AND RELATED WORK

The present section introduces the requirements for more expressive methods to communicate a platform state to an external validator. We then state the basic security issue for the formation of verification data which represents structured sets of measurements on started/loaded components in authenticated or secure boot. Finally, we highlight the novelty of our approach relative to previous, related work.

A. The Need for Structured Verification Data

Verification data provide information about a system’s state with unconditional security. In particular, they are secure independently of the SML, which, according to TCG standards, has no particular protection on the platform or in a validation (it is not part of the signed attestation data). Only the signed PCR values, i.e., verification data itself, provides an implicit integrity control for the SML. For this, the verification data must be recalculated from the measurements in the SML, by retracing all extend operations. The TCG-standardised way to use PCR values in authenticated boot to secure the measurement log is based on the technique introduced by Schneier and Kelsey for securing audit logs on untrusted machines [10], [11]. In fact, it is a simplification, since only the last element of the hash chain is kept in a PCR, while the SML normally contains only the measurement values and not the intermediate entries of the hash chain. Integrity measurement using the TPM is implemented in the Integrity Measurement Architecture (IMA) [12] as a Linux kernel module to measure the integrity using the TPM and to generate a linear SML.

Thus, the state-of-the-art of verification data, created by linearly chaining extend operations, is only of limited value for remote diagnostics of a platform, and advanced management such as component-wise remediation. Essentially, the position of a manipulation of the SML, either by tampering with a measurement value before it is extended into a PCR, or by tampering with the SML itself after secure start up, cannot be localised with certainty. Furthermore, the space complexity of real world SMLs with many hundreds, or thousands, of measured components, makes sifting it through for components which fail validation, i.e., for which measurement value differs from a “good” reference value, costly. In fact, for checking of code and data there are a variety of cryptographic checksum functions available, and all obviously require that the integrity of the checksums for the "correct" data be maintained. The requirement for a centralised database of all software in all valid versions on the various machines is a significant management problem, in need of an efficient solution.

Future, large scale deployments of networked devices, such as required in machine-to-machine communication scenarios, require a solid device- and network-side, balanced and efficient trust infrastructure [1], [13]. Security requirements are particularly high for devices loosely connected to networks and operating semi-autonomously. Scenarios considered by the industry [14], always entail the high-level requirement for remote integrity check, or validation, of a connecting device. To make validation expressive, efficient, and secure, is a primary necessity. The specifications of the TCG Infrastructure working group contain an approach to this problem, hierarchically distinguishing between verified components and sub-components [6]. On the academic side, Lo Presti [15] proposed a Tree of Trust (ToT) concept and notation to represent a platform’s structure. A ToT’s nodes represent platform components, from TPM up to applications, annotated with trust and security statements. It can be used to assess the trust that should be put into the platform, or even to reorganise the platform according to certain constraints. Another technical domain where the shortcomings of a merely linear chain of trust becomes imminent is virtualisation. Virtual machines are created and destroyed dynamically on potentially many layers, resulting in “a tree-like, dynamic structure of trust dependencies” [16, p. 6]. While the community has acknowledged that structured validation data is required to truly assess platforms’ trustworthiness, a granular association of such tree-formed data hierarchies to verification data (PCR values) is lacking.

B. Basic Idea and Security Issue

Here we propose to organise verification data and SML into a binary tree structure. In such a structure, verification data registers are the roots, the SML data structure contains the inner nodes and the leaves, which in turn are the component measurement values. The whole structure is a representative of the class of Merkle hash trees [8], [9]. The method can be generalised to $n$-ary and arbitrary trees. Figure 1 shows the general concept.

Fig. 1. General structure of tree-formed SML and according verification data. The star represents the root of the tree stored in a verification data register. Components (code and/or data) are indicated by packets at the leaves. Measurements hashes of the components are indicated by slip knots. Inner nodes (coloured balls) transport verification information upstream to the root. The golden lines hint at the traversal of the tree for validation, explained in more detail in Section IV.

Secure creation of verification data which represents root nodes of hash trees poses a particular problem. In the normal extend operation, only the measurement value taken by the Root of Trust for Measurement (RoTM) on a component, and the current verification data register value $V_n$ are used, and the operation itself is carried out in the hardware protected TPM.
Thus, in particular, previous measurements stored without protection in the SML, are not used in the generation process. This is not possible for a hash tree, where adding a new leaf always affects \( d - 2 \) inner nodes of the tree, where \( d \) is the tree’s depth. The challenge is to generate tree-formed verification data exclusively inside a limited number of hardware protected registers (PCRs), using only a single leaf measurement value as input, and employing only the normal TPM extend operation and other TPM capabilities. This problem is solved in Section \[11\].

While we are leaning on TCG-nomenclature and some concepts, it will be clear from the minimal requirements required on a system creating and protecting tree-formed verification data, that the concepts developed in the following sections are not restricted to platforms and secure hardware elements adhering to TCG standards.

C. Related Work

Verification of programs before loading and while booting was first mentioned in \[17\] Sections 6.2 and 6.3, where a formalisation of the process is given and the concept of attestation appears. Code authentication is among the primary goals of Trusted Computing \[18\]–\[20\]. Early work on protecting executed code by securing start up of a platform, such as Dyad \[21\], proposes hardware mechanisms to bootstrap trust in the host with secure coprocessors on standard PC hardware, and shows the first important applications of trusted platforms. Secure hardware must be involved in the secure boot process. For instance, a secure coprocessor may halt the boot process if it detects an anomaly. This assumes that the bootstrap ROM is secure. To ensure this, the system’s address space could be configured such that the boot vector and the boot code are provided by a secure coprocessor directly or the boot ROM itself could be a piece of secure hardware. Regardless, a secure coprocessor verifies the system software (OS kernel, system related user-level software) by checking the software’s signature against known values \[21\].

Tamper resistance of code has been considered by many researchers. A prototypical approach to the problem is rooting trust for program execution in hardware, such as the XOM (eXecute Only Memory \[22\]) processor architecture, and the XOM Operating System \[23\] building on it. This does not solve the problems of secure loading a program, and attesting to external entities. AEGIS \[24\] shows secure boot on a PC. AEGIS uses a signed hash to identify each layer in the boot process, as does Terra \[25\], which can attest loaded components with a complete chain of certificates ending in attestation of virtual machines.

Existing TCG specifications define a bi-lateral remote attestation to verify the integrity of a platform remotely, by verifying the binary executables. All executed code is measured when it gets loaded. The measurements are stored in PCRs as verification data, and the TPM attests to these data by signing them with a TPM protected key. The verifier can, upon receipt of these metrics, decide if the platform can be considered trustworthy. Since the whole configuration is transmitted and verified, the verifier needs to know all configurations of all machines. Furthermore, binary attestation discloses the complete configuration and thus poses a privacy risk. In \[26\] and \[27\], \[28\] “property,” respectively, “property-based attestation” (PBA) are proposed. PBA allows to assure the verifier of security properties of the verified platform without revealing detailed configuration data. A trusted third party (TTP) is used to issue a certificate which maps the platforms configuration to the properties (in particular desired/undesired functionality) which can be fulfilled in this configuration. The TPM can then, using a zero-knowledge proof, attest these properties to the verifier without disclosing the complete configuration. Essentially, PBA moves the infrastructural problem of platform validation to a TTP, similarly to, but extending the role of, the TCG’s privacy CA.

Another alternative is presented by the Nexus OS \[29\] which builds on a minimal Trusted Computing Base (TCB) to establish strong isolation between user space and privileged programs. Nexus has secure memory regions and monitoring and enforcement machines to protect them. One application is to move device drivers into user space \[30\]. Attestation by Nexus attaches descriptive labels to monitored programs and thus allows for expressiveness similar to PBA, but system-immanent. Both the PBA concept, as well as the Nexus approach do not have means to validate a complex system comprised of a multitude of components, which furthermore shall be dynamically managed. Both approaches are orthogonal to the present one, and could be combined with it.

Hierarchical Integrity Management (HIM), see \[31\], presents a dynamical framework for component-wise integrity measurement and policy-enabled management of platform components. Components and sub-components are related in HIM via dependency graphs, the most general structure that is useful for this purpose \[32\], \[33\]. But HIM is not aimed at (remote) platform validation and does not protect structured platform verification data in a PCR. Rather, it holds measurements are together in a global Component Configuration Register (software registers) table.

The main intended application of the hash trees introduced by Merkle for integrity protection of large datasets is in certificate management in a PKI. This yields long-term accountability of CAs, using Merkle trees \[34\], or authenticated search trees \[35\]. Various groups have extended the use of hash trees to general long-term secure archiving for digital data \[36\], \[37\]. Corresponding data structures have been standardised in the so-called Evidence Record Syntax, by the IETF \[38\].

A lot of research work has gone into the usage of hash trees for run-time memory protection. See Elbaz et al. \[39\] and Hu et al. \[40\] for a recent topical overviews over the state-of-the-art. Typical systems employing hash trees for storage and memory protection \[41\]–\[43\] separate a system into untrusted storage and a TCB. A program running on the TCB uses hash trees to maintain the integrity of data stored on an untrusted storage, which can be, e.g., some easily accessible, bulk store in which the program regularly stores and loads data which does not fit into the TCB. Gassend, et al. \[42\] also propose to
store the root of the entire tree in an on-chip trusted register of constant size, but keep all other nodes in main memory or cache.

The work most closely related to the present one is constituted by the proposal of Sarmenta, van Dijk, et al. [44], to protect arbitrary memory objects via hash trees which in turn are protected by a root in TPM non volatile memory. In [44] a new TPM command TPM_ExecuteHashTree is introduced which allows to add, delete, and update so called TPM_COUNTER_BLOB objects, and which issues a certificate, signed by an AIK, that attests to the successful verification of that object’s data with respect to the hash tree’s root. While this is a fully general method for handling arbitrary data sets in a TPM-protected hash tree, it does not address the special problem of building the tree from sequentially arriving measurement values maintaining the same security properties as the normal TPM_Extend command, cf. Section II-B.

A different usage of hash trees is proposed in [45], where it is shown how they can be used to hash authentication of distributed code in Wireless Sensor Networks (WSN). Also in WSN, data aggregation involving multiple nodes may be integrity protected using hash trees [46]. Different from hash trees, another potential approach to make verification data searchable are Authenticated Append-only Skip Lists [47], which are sorted linked lists designed to allow fast lookup of the stored data elements by taking "shortcuts." However, trees are better suited for validation of a platform’s state, in particular to efficiently determine the subset of components at the leaves failing validation.

Relative to the cited state-of-the-art, our present contributions are twofold. First, we introduce a new method to generate a binary Merkle tree from component measurement values using only a limited set of tamper-resistant verification data registers, and existing capabilities of the TPM, i.e., the standard extend operation. The algorithm is small enough to be executed within a TCB, in particular on-chip. This part of our proposed method increases security of the generation of the root of a hash tree, which in turn provides more security to the tree nodes. This problem is, to the best of our knowledge, not considered in the literature. Second, we show how to exploit the tree structure for efficient validation with enhanced diagnostic capabilities over common PCR values and SMLs, to increase security features of remote platform validation, and concurrently benefiting from the efficiency of tree-like structures in the search for failure points. This use of tree-structured data for secure diagnostics, validation, or attestation (all fields to which the proposed concepts apply), has also not been considered elsewhere, to the best of our knowledge.

III. SECURE GENERATION OF TREE-FORMED VERIFICATION DATA

In this section, we show a practical solution for the problem described, using only a limited number of verification data registers to securely generate one root verification value.

It should be noted that every reference to the concrete embodiments of Trusted Computing specified by the TCG made in this paper, in particular TPM operations, PCRs, and SML, are examples for possible realisations of the presented concepts. The algorithms and procedures can in principle be applied to every security technology with the minimum capabilities which are used by them.

A. Tree Formation Procedure

In our proposed solution, one of the hardware protected registers $V \equiv \{V_1, \ldots, V_r\}$, e.g., PCRs, contains the root of the final tree. The tree is chosen to be binary, to keep the algorithm as compact as possible and to provide a fine grained detection of failed components. The leaves are carrying the measurement values, while the inner nodes are stored in a modified SML. The SML is modified in a way to support the tree structure of the validation data, i.e., it is no longer a linear list of measurement values but the data structure must support standard tree operations and traversals. For efficient search during platform validation, the SML must support the addition of new leaves and retain edge relations. Adding a new measurement at a leaf to the tree at depth $d$ requires recalculation of all $d-1$ inner nodes of the leaf’s reduced hash tree and the tree root which is stored in a $V \in V$. A Merkle tree has a natural colouring of edges as “left”, respectively, “right” ones, since the binary extend operation (1), is non-commutative. Leaves inherit this order and are added from left to right. The binary, $d$-digit representation of leaf $n$, $0 \leq n \leq 2^d-1$, denoted by $\langle n \rangle_k$, yields natural coordinates for the inner nodes and edges on the unique path from leaf to root. That is, the $k$-th digit (counted from the MSB, $k = 1, \ldots, d$), $\langle n \rangle_k$, determines whether the node at depth $k-1$ on this path is connected by a left, respectively, a right edge, by $\langle n \rangle_k = 0$, or, $\langle n \rangle_k = 1$, respectively.

We make the following assumptions: (1) the root of every subtree created during the execution of the algorithm must always be stored securely in a $V \in V$. (2) If two subtrees (measurement values are subtrees of depth 0) with the same depth $d'$ exist, they can be merged to a single tree of depth $d' + 1$. (3) The merge operation must preserve assumption (1), i.e., one of the two $V$ protecting the roots of the subtrees is freed after the merge operation. Using these assumptions, the update algorithm for a newly arriving measurement value can be formulated such that registers $V_1, \ldots, V_{d-1}$ always contain the current state of “active” subtrees of depth $1, \ldots, d-1$, and thus $V_d$ always contains the current global root value. “Active” here means a subtree the root of which awaits completion by merging with a subtree of the same depth. Care is taken in the formulation so that only the actual measurement value, protected registers, and the normal extend operation are used, and no unprotected memory places are involved. Denote an empty node in the full binary tree of depth $d$ by nil. The tree formation is performed by Algorithm 1.

If $n < 2^k$, the tree is incomplete at the right edge, and the cleanup procedure shown in Algorithm 2 is then needed. Algorithm 2 results in a final merge of roots such that $V_1$ ultimately contains all subtree information. Note that this cleanup procedure is only reached if the tree is not already
Algorithm 1 Tree formation algorithm

Require: $V_1, \ldots, V_d \in \mathcal{V}$, $m \in \{0, 1\} \times 160$
Ensure: $V_1,\ldots, V_d = \text{nil}$  \Comment{Initialise subtree roots empty.}

1: $n \leftarrow 0$
2: \While {($m \leftarrow \text{RoTM} \neq \text{nil}$) \Comment{Get new measurement.}}
3: \If {($n_d = 1$)} \Comment{If non-empty, add as new leaf.}
4: \Then \quad $V_d \leftarrow V_d \circ m$ \Comment{extends the root at depth $d - 1$,}
5: \Else \quad $V_d \leftarrow \text{SML}$ \Comment{which is purged to the SML.}
6: \EndIf
7: $k \leftarrow d - 1$ \Comment{A value arriving from right}
8: \While {($\langle n \rangle_k = 1 \rangle \land (k > 0)$)} \Comment{while coming}
9: \Then \quad $V_k \leftarrow V_k \circ V_{k+1}$ \Comment{from right.}
10: \Else \quad $V_k \leftarrow V_{k+1}$ \Comment{If it is arriving from the left,}
11: \EndIf
12: \EndWhile
13: \If {$k = 0$} \Comment{return “tree full”}
14: \Then \quad \Return
15: \Else \quad $V_k \leftarrow 1$
16: \EndIf
17: \Else \quad $V_k \leftarrow V_{k+1}$ \Comment{If it is arriving from the left,}
18: \EndIf
19: \EndIf
20: $n \leftarrow n + 1$
21: \EndWhile

Algorithm 2 Cleanup of an incomplete tree

22: \For {$k \leftarrow k - 1$ \textbf{to} 1} \Comment{for}
23: \If {$\langle n \rangle_k = 1$} \Comment{if}
24: \Then \quad $V_k \leftarrow V_k \circ V_{k+1}$ \Comment{first register,}
25: \Else \quad $V_k \leftarrow V_{k+1}$ \Comment{of verification data registers, only a finite}
26: \EndIf
27: \EndIf
28: \EndFor

full, due to the test in lines 12,15 of algorithm 1. The rule by which the tree is completed is that the configuration

\[
\begin{array}{c}
  \text{x} \\
  \text{x} \quad \text{nil}
\end{array}
\]

is correct at the right edge. All inner nodes are written to the SML, even if they are the result of forwarding along a left edge (entailing minor redundancy). Formally, the above rule corresponds may be interpreted as modifying the notion of the ‘$\circ$’ operation such that $x \circ \text{nil} = x$, as explained in Appendix A.

It is interesting to note that, if leafs and inner nodes are appended to the SML in the order prescribed by algorithm 1, a natural serialisation of the resulting tree is obtained. This order is shown in Figure 2 for an incomplete tree of depth 3. The marked entries 10 and 11 in the resulting SML are identical, since 11 is created by a forward operation of the cleanup algorithm 2. The SML order can be used to address tree nodes in the SML by a binary search. Given a sequence number $K$ in the SML of length $2^{d+1} - 1$, such a search proceeds from the root, which is the last entry. The remaining $2^{d+1} - 2$ entries are equally partitioned into portions of size $2^d - 1$, and it is decided if $K$ is in the left or right part. This procedure is iterated until $K$ points to the rightmost element in the current part. The sequence of decisions made yields the sequence of left-right edges leading from the root to the node with index $K$ in the SML.

The tree-formation algorithm can easily be adapted to trees of arbitrary, uniform, arity, say $b$. For this, the binary coordinate $\langle n \rangle_k$ has to be replaced by the $b$-ary coordinate $\langle n \rangle_k^{(b)}$ and its $d$-th, respectively, $k$-th digit evaluated in line 4, respectively, 8 of algorithm 1, where the evaluated expression has to be changed to $\langle n \rangle_k^{(b)} = b - 1$, respectively, $\langle n \rangle_k = b - 1$. Algorithm 2 has to be adapted accordingly. A further generalisation to arbitrary trees requires only establishment of the associated node coordinates, i.e., of the mapping $n \rightarrow$ node. Note that at every node with arity higher than 2, since hash extension is linear for the legs connecting to it, the disadvantages mentioned in Section II-A apply, and loss of detection granularity occurs.

B. Maximum Tree Capacity

It is clear from the generation procedure that, with a limited number, $V_1, \ldots, V_r$, of verification data registers, only a finite number of components at the leaves of trees can be covered. In contrast, the hash chain created by the standard, linear extend, ending in a single PCR value, is in principle of unlimited length. The maximum capacity of trees generated with $r$ root registers can be calculated as follows. The procedure for the first register, $V_1$, can use the $r - 1$ other registers as a pipeline of length $r - 1$ to build a tree of depth $r$. When $V_1$ is occupied, the second register can support a tree of depth $r - 1$, and so on, until the last register, $V_r$, for which the pipeline has length 0 and the tree depth 1. Thus the total number of leaves carried by the trees of all registers is

\[
C_{\text{trees}} = \sum_{k=1}^{r} 2^k = 2^{r+1} - 2. \tag{2}
\]

For $r = 24$, the number of PCRs of a TPM adherent to the v 1.2 specification, this yields 33,554,430 places for component measurements at the leaves of the $r$ trees. If restricted to the last 16 PCRs, since, for instance, according to the PC Client specification of the TCG [2] PCRs 0–7 are reserved, still counts 131,070 measurements (see Section V for a discussion of implementation issues with standard TPMs).
Since the number of measurements to be taken during start up or at run-time is not a priori known, the last register can, as a fallback, be linearly extended after the capacity limit is reached. Figure 3 shows this arrangement.

Fig. 3. Maximum capacity arrangement of tree verification data. Measurement values at the leaves are indicated as $m$.

C. Complexity of Tree Formation

The spatial complexity of the tree formation algorithm is very small. As internal data needs precisely three locations:

$$d \in \{1, \ldots, r\}, n \in \{0, \ldots, 2^d - 1\}, \text{ and } k \in \{1, \ldots, d\},$$

the size of that data is at most $d + 2[\log_2 d] \leq r + 2[\log_2 r]$. Bits. Additionally, depending on implementation one register may be required to receive and hold the current measurement value, and/or as intermediate register for the operations on verification data registers. The SML increases moderately in size. For a completely filled binary tree of depth $d$, $2^{d+1} - 2$ node values, including leaf measurements, are stored in the SML (the root node is contained in a $V_r$). That is, the tree-formed SML is less than double the size of the linearly formed SML containing only measurement values.

For an estimation of the temporal complexity, we consider a full tree of depth $d$, i.e., $2^d$ leaf measurements. The various operations involved in algorithm 4 are

- $M$: Add measurement to $V_d$; $V_d \leftarrow m$. 
- $S_V$: Store a verification data register to SML; $V_k \rightarrow SML$. 
- $S_m$: Store measurement to SML; $m \rightarrow SML$. 
- $V$: Copy verification data register; $V_k \leftarrow V_{k+1}$. 
- $E_1$: Extend $V_d$ with measurement; $V_d \leftarrow V_d \diamond m$. 
- $E_2$: Extend inner node registers; $V_k \leftarrow V_k \diamond V_{k+1}$.

The symbols above denote the operations and their execution times interchangeably. The one missing operation $m \leftarrow$ RoTM can be subsumed in $S_m$.

By the structure of the tree, the occurrences of the operations are easily counted. $S_m$ occurs at each leaf, i.e., $2^d$ times. $E_1$ and $M$ occur at each inner node at depth $d - 1$, i.e., $2^{d-1}$ times. $V$ and $E_2$ occur at each inner node from depth $d - 2$ upward, i.e., $2^{d-2}$ times. Finally, $S_V$ occurs at each inner node of the tree except the root, which remains in $V_1$. That is, $S_V$ occurs $2^d - 2$ times. Altogether this yields the estimate

$$2^{d-1}(E_1 + M) + (2^{d-1} - 1)(V + E_2) + 2^d S_m + (2^d - 2) S_V$$

for the algorithm’s execution time, disregarding flow control. Grouping similar operations $\{E_1, E_2\}$, $\{M, S_V, S_m\}$ yields

$$2^{d-1}(E_1 + E_2) - E_2 + 2^{d-1}(M + 2S_V + 2S_m) - 2S_V + (2^{d-1} - 1)V.$$  

Assuming that all memory operations are approximately equally time-consuming and bounded by a common constant

$$M \approx S_V \cong \frac{1}{2} S_m \cong \frac{1}{2} V \leq S,$$

(whence a factor 2 is included in $V$ for a naive read/store implementation, and in $S_m$ for the missing operation mentioned above), and likewise for the extend operations

$$E_1 \cong E_2 \leq E,$$

a coarse estimate for the temporal complexity of tree formation for $d > 1$ is

$$\leq 2^d \left( E + 4\frac{1}{2} S \right) - (E + 2S).$$

When extend operations are the dominating factor, it is interesting to note that tree formation actually needs one extend operation less than the linear chain of authenticated boot.

IV. VALIDATION OF TREE-FORMED VERIFICATION DATA

For the validation of tree-formed verification data, generated by the procedure of the last section, we now present the validation strategy which exploits all available information at every tree node. In Section 4.2 the average computational cost is calculated in relation to the number, respectively, relative share of failed measurements.

Taking a linear chain of measurements generated and stored in an ordinary authenticated boot and sequentially extended to a PCR as the reference case, we see that tree traversal validation is significantly different. In the former case, a manipulation of the SML cannot be localised in principle, while traversing a tree-formed SML allows to identify a subtree where a manipulation has occurred. Similar considerations hold for diagnostic validation, i.e., the search for components which do not conform to a desired reference configuration of the validated platform (called here failed components). For the linear chained SML this requires comparing each measurement with a reference value and recalculating the complete chain of extend operations up to the PCR to verify the SML’s integrity. Since manipulations in the linear SML cannot be localised, a failure to reproduce the PCR value also means that diagnostic validation becomes impossible, and failed components cannot be distinguished from good ones.

For tree-formed SML, the situation is much better. If a subtree is identified, where manipulation of the SML is suspected, the complement of it in the SML tree can still be validated. Also, for diagnostic validation, one may expect a significant speed-up in determining the set of failed components, and concurrently verifying the root verification data register contents.

A. Tree Traversal Validation

The aim of validation of a tree-formed SML is to find the subset of leaves failing validation, and to detect manipulations of the SML, where possible. We assume there is a reference tree for comparison locally available at the validator. Then, validation can start from the root of the tree, i.e., a verification data element $V$, traversing the tree of SML data. This yields
the leaf set of components for which measurements differ from reference values, called failed components. In traversing the tree, a depth-first search with pruning is applied, and decisions are taken at every branching node. Again we assume that the trees are binary. Then, the SML tree values at a branching node and its two children are compared with the reference tree values of the same node positions, and the results are noted as \( g \) (good) for agreement and \( b \) (bad) for discrepancy. In this notation, the following situations can occur, as shown in Figure 4.

In case (a), the whole subtree below this parent node is validated positively, and traversal ends at this node. In the cases (b), the parent node is recalculated by the validator applying the extend operation to the child node values. If the recalculated value does not match the value at the parent node, this indicates a SML manipulation in one of the subtrees with a root marked as bad. This is handled as an exception. Otherwise, validation can proceed to the next tree level, traversing the subtrees where bad values are found, i.e., left, right, or both subtrees in (b), respectively. In cases (c), a tree manipulation exception is detected. It should be noted that this detection takes place without recalculating an extend operation. The last situation, (d), only occurs when the binary tree is incomplete, and a right branch is null. Then value \( x \) must equal value \( y \), in which case case traversal proceeds to the left, and otherwise a tree manipulation exception occurs.

![Figure 4. Classification of node configurations in a tree-formed SML.](image)

**B. Cost for Tree Validation**

A principal advantage of validating tree-formed SMLs is that subtrees with a correct root can be discarded from further search for failed components. In this section we lay out a simple, probabilistic model to quantitatively assess the performance of tree validation. Assume for simplicity that the SML is a full tree of depth \( d \). The validator has a complete reference tree representing a known, desired platform configuration. We assume that recalculating hash operations is the dominant cost factor to estimate validation complexity, while comparisons are cheap. Assume a random set of failed leaves.

We use an optimistic validation strategy, called diagnostic validation, which traverses the paths from the root to failed components, i.e., components with bad measurement values with respect to the leaves of the reference tree. The unique property of this strategy is that it finds all failed components with authentic measurement values. Diagnostic validation proceeds as follows. When visiting an inner parent node which differs from the corresponding node in the reference tree, i.e., a bad parent node, one of the situations in Figure 4 (b), or the rightmost configuration of (c) is encountered. In the latter case, no recalculation of the parent node needs to be performed since it is an obvious SML integrity failure. The subtree with this root configuration is discarded from further traversal, since it cannot be assumed to yield trustworthy information about failed components. In this case, further steps depend on the validator’s policy. The node configurations (b) are precisely the ones which require re-calculation of the parent hash from the root hash by one extend operation \( \circ \), to confirm that the configuration, which is unknown from the validator’s reference tree, is authentic. The subtrees whose roots are good children of the bad parent node under scrutiny, are discarded from further traversal. Note that this procedure of diagnostic validation implicitly excludes the configuration (a) and the three left configurations of Fig. 4 (c) from diagnostic validation. They may be considered in further forensic evaluation of the SML tree, wherever this makes sense.

Summarising, we see that diagnostic validation requires to visit and perform a hash operation at all bad inner nodes in the union of all paths from failed (bad) leaves to the root. In an otherwise untampered tree, this implicitly excludes the right configuration (c) with bad parent node. Assume that a subset of i.i.d. bad leafs constitute a fraction \( f \in [0, 1] \) of all leafs. The number of bad leafs is \( 2^d f \). The expected number \( E^{\text{inner}}(f) \) of bad inner nodes can be calculated as explained in Appendix B.

![Figure 5. Expected fraction of bad inner nodes on random distribution of 2^d f bad leaves for d = 16.](image)
descends along the bad inner nodes which fail comparison with the reference tree’s corresponding inner node. For that, both children of a bad inner node have to be compared in every case, so that the complexity in terms of comparisons is twice the number $E_{\text{inner}}(f)$. The linear SML requires all $2^d$ measurements to be compared with reference values.

If $h$ is the cost of a hash operation at the validator, and $c$ the cost of a comparison of two hash values (160 Bit for SHA-1), then the total validation cost of the linear case is $(2^d + 1)h + 2^dc = 2^d(h + c) + h > 2^d(h + c)$. This is the least effort to obtain the same information from a linear SML, as by diagnostic validation of a tree-formed SML. For the tree-formed SML on the other hand (including the root in the count), the cost is $(E_{\text{inner}}(f) + 1)(2c + h)$. Tree-formed validation is more efficient if

$$\frac{E_{\text{inner}}(f) + 1}{2^d} \leq \frac{h + c}{h + 2c} = \frac{\lambda + 1}{2\lambda + 1}.$$

where $\lambda = c/h \ll 1$. With a very generous margin, $\lambda < 0.01$, which yields a bound of 0.99 for the r.h.s. Then, for $d = 16$, tree-formed validation is expected to be more efficient for fractions $f$ of bad leaves as high as 85%.

We see that diagnostic validation of a tree-formed SML always performs better in terms of hash operations than with a linear SML, and outperforms the linear SML completely even for large fractions of bad components, under reasonable assumptions, and becomes vastly advantageous for small fractions of failed components. It can be expected that tree validation is yet more efficient when the bad leaves are non-uniformly distributed, e.g., exhibit clustering. While we have directly compared linear and diagnostic tree validation, it should be noted that linear validation becomes impossible if the recalulation of the final PCR fails, since then, comparison of single measurements does not yield reliable information — each measurement could be faked in the SML to hide the one which broke the hash chain. In conclusion, the principal, semantic advantage of tree-formed validation data comes about even at decreased computational complexity for the validator.

V. IMPLEMENTATION OPTIONS

With regard to the tree-formation algorithm itself, to achieve the same level of security as TCG standard compliant trusted boot processes, all operations on verification data registers should run inside the hardware-protected TPM environment. Though part of the operations in Most operations of the tree-formation algorithm listed in Section III-B are, however, non-standard TPM functions that can be executed on standard-conforming PCRs. In fact, only the normal extend operation $E_1$ is an internal standard function, and $S_V$ and $S_m$ can be realised by PCR read operations.

We first discuss the minimal modifications that would be necessary to extend a TPM to turn PCRs into tree-formed verification data registers, while the tree-formation algorithm may still run outside the TPM. Then, we propose a new TPM-internal command for tree formation.$^1$

A. Minimal TPM Modifications for Tree-Formation

Let us first take a minimalist approach to implementing tree-formation and carve out the least changes to a standard TPM that would enable PCRs for use with the algorithms [1] and [2]. This regards implementing the elementary operations listed in section III-C by TPM commands or modifications thereof. The core of the algorithm, including the bookkeeping tasks on registers representing inner nodes’ current states, could then be realised as a software root of trust for performing tree-formation in a system integrity measurement process such as authenticated or secure boot.

The operations $S_V$ and $S_m$ pose no problem and can be realised by TPM_PCRRead commands or directly in the tree formation software, respectively. $E_1$ occurs at every right edge at the lowest level of the tree, and extends a $V$ containing already a measurement value which came from the left sibling of the measurement which is extended into $V$. Therefore, $E_1$ is precisely the standard TPM_Extend operation defined [1]. $E_2$ also occurs at right edges inside the tree and, in turn, is straightforwardly modelled by TPM_PCRRead followed by a TPM_Extend.

Operations $M$ and $V$ occur at left edges on the lowest level of, respectively, inside the tree. They pose a particular problem for two reasons. First PCRs cannot be directly written to, and a natural approach to reset them via TPM_PCR_Reset as a first step in $M$ or $V$ is problematic, since only PCRs above 16 of a standard TPM can be reset, and only from the correct locality. Thus it is necessary that enough PCRs are resettable and that they respond to the locality in which the tree-formation software is executed as a trusted code. Secondly, even after reset, the only operation which can modify a PCR, TPM_Extend, does not directly copy a value into the register but truly executes $[1]$ with the existing value of the reset PCR, which is 160bit binary 0x00 and the input value, which yields a result different from the input value. One option, which avoids exposing new commands directly writing to, or shifting values between PCRs, would be to augment PCRs with a reset flag which indicates that they are in a pristine state after reset. Then, TPM_Extend can be modified such that it directly writes into the PCR when this flag is true, and then sets it to false.

Realising that $M$ and $V$ consistently occur at left edges of a tree, and only if the right sibling is empty (nil), and then deterministically produce an outcome depending only on the two siblings involved, a third option would be to deviate slightly form the definition of a Merkle hash tree. The correct configuration of values in every elementary triangle in the SML tree would then be as follows.

$$(0 \otimes x) \diamond y$$

$$_x y$$

$^1$A third variant, which is not further discussed here is a software-based implementation of tree-formed verification data, where the root registers are soft registers managed by a trusted application, and where the current state of such registers is protected by a ‘real’ register, e.g., a PCR.
That is, $V$ or $M$ is modelled by TPM\_PCR\_Reset followed by TPM\_Extend to obtain $0 \overset{\circ}{\odot} x = H((0|x)$ in the first step. The right sibling is then normally extended in that register and the result written to the SML. See Appendix A for a consistent treatment of nil node values in intermediate stages and finalisation of a tree.

### B. TPM\_Tree\_Extend

The split TPM/software implementation of tree formation compromises on the security level of the resulting root verification data register values. It is preferable that tree-formed verification data is produced by a TPM-internal implementation of the proposed algorithms. For this, a TPM modification can work as follows. The modified TPM exposes a new command TPM\_Tree\_Extend with the same input parameters as the usual TPM\_Extend command. The TPM maintains flags for PCRs signifying which of them are currently designated tree roots, which are occupied and locked, and which are usable as intermediate $V$s by the algorithm. Furthermore, the TPM maintains the additional data mentioned in Section III-C. In the simplest case, internal logic prevents concurrent use of more than one PCR for tree formation. While TPM\_Extend only updates the target PCR value, TPM\_Tree\_Extend returns a variable number $1, \ldots, d$ of updated verification register data values in sequence such that they produce the natural order described in Section III-A. These return values are the output of the SML write operations of algorithms 1 and 2. When $d$ values are returned, the receiver knows that this tree is exhausted and the corresponding root $V$ locked. Another option not considered here is for TPM\_Tree\_Extend to return all intermediate $V$s on each call.

### VI. Conclusion

Though hash trees are widely used, ours is the first proposal, to the best of our knowledge, to use Merkle hash trees to protect the integrity of the secure start up process of a trusted platform in the same way as is traditionally done with PCRs. We have demonstrated the efficiency and flexibility gains resulting from using tree-formed verification data in platform validation. This may be effective in particular in the remote validation and management of platforms via a network. Given the small size and complexity of the tree-formation algorithm, it seems possible to implement all these operations directly inside the TPM, if specifications are amended accordingly. This may be a feasible approach for future TPM generations.

With regard to generalisations, trees are certainly not the most general structures for which integrity protection using cryptographic digests can be applied. For instance, some researchers have extended hashes to provide identification of directed graphs [48]. Others have applied variant one-way functions, e.g., multi-set hashes [49] to uniquely identify complex data structures such as RDF graphs [50]. Along these lines, generalisation of tree-formed verification data to, for instance, directed acyclic graphs, and dependence graphs [32], [33] can be conceived. While potentially interesting for complex platform management and protection tasks, every such generalisation would incur increased complexity and lose the efficiency of binary trees for validation. Application cases for such generalisations are therefore deferred to further study.

The single command extension of the TPM integrity measurement functionality, TPM\_Tree\_Extend proposed above is, however, only the starting point of a flexible, TPM-based tree verification data management architecture. In particular it would be desirable to enable secure updates of subtree roots, for instance for dynamic platform management, and ultimately to quote an inner node of a tree-formed SML with the same security assertions as TPM\_Quote provides to a remote validator for a PCR value. This shall be discussed elsewhere.

### APPENDIX A

#### A Useful Convention

In many cases, the hash tree stored in the SML will be incomplete, i.e., contain empty leaves and inner nodes. In the continuous measurement process, such nodes, with value denoted nil, are treated procedurally by the operations $M$ and $V$ (see Section III-C) which means that right nil siblings are ignored. This happens in lines 18 and 19 of Algorithm 1 for intermediate stages of tree formation, and in line 27 of Algorithm 2 at completion of the tree after the last measurement. Generally, i.e., transgressing the restrictions of a standard TPM, it may be useful to assume that nil is a two-sided unit for the operation $\odot$, i.e.,

$$x \odot \text{nil} = \text{nil}, x = x, \text{and} \text{nil} \odot \text{nil} = \text{nil}.$$  \hfill (3)

This convention manifests rule (d) of Section IV-A. It is a reinterpretation of the usual extend operation and can also be used to eliminate the operations $M$ and $V$ in the algorithms’ formulations. Namely, $M$ and $V$ can be replaced by a reset of a register $V$ to nil followed by the operation $V \leftarrow V \odot m$, respectively $V \leftarrow V \odot V'$. For the implementation of this convention, we may assume that nil is to be represented as an additional flag of PCR registers, and the inputs and output of $\odot$. For a PCR, the nil flag is set by a particular reset command. When nil is encountered as the input of an extend operation to a PCR, then logic of the TSS, or a TPM modification, may prevent execution of the hash operation (1) and write to the PCR directly.

### APPENDIX B

#### The Expected Number of Bad Inner Nodes

The problem under consideration is that of bi-colouring (bad vs. good inner nodes) of a binary tree generated by a random, i.i.d. choice of leaves and colouring of the path connecting it to the root. Random choices of such leaves and paths is equivalent to random choices of i.i.d. bit strings of length $d$. We first calculate the expected number $E_k^{N}$ of coloured leaves after $k$ choices from the set of $N = 2^d$ leaves. Recursively, $E_0^N = 0$, and

$$E_{k+1}^N = E_k^N \cdot E_k^N \cdot \frac{E_k^N}{N} + (E_k^N + 1) \frac{1 - E_k^N}{N} = 1 + E_k^N - \frac{E_k^N}{N}.$$
Solving this obtains

\[ E_N^k = N \left(1 - \left(1 - \frac{1}{N}\right)^k\right). \]

Since all substrings of the chosen bit-strings are statistically independent the same argument applies to inner nodes at all levels \(d = 1, \ldots, \). Thus, the expected number of coloured inner nodes is obtained by summation

\[
E_{k}^{\text{inner}} = \sum_{d=0}^{d-1} E_d^k.
\]

It remains to find the expected number of choices \(k\) which corresponds to a certain expected number \(E_N^k = fN\) of coloured leaves, where \(0 \leq f \leq 1\) is a target fraction of leaves. Solving this equation for \(k\) yields

\[
k = \frac{\ln(1 - f)}{\ln(1 - 2^{-d})},
\]

where \(N = 2^d\) was inserted. From this, the expected number of bad inner nodes in dependency of \(f, E_{f}^{\text{inner}}(f)\), can be calculated.

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**References**

[1] A. U. Schmidt, I. Cha, and A. Leicher, “Scaling concepts between trust and enforcement,” in Trust Modeling and Management in Digital Environments: From Social Concept to System Development, Z. Yan, Ed. IGI Global Publishing, 2010, pp. 20–57.

[2] Trusted Computing Group, “TCG PC Client Specific Implementation Specification For Conventional BIOS,” Ver. 1.20 FINAL Rev. 1.00, July 2005, for TPF Family 1.2; Lvl. 2.

[3] ——, “TCG Mobile Reference Architecture,” Ver. 1.0 Rev. 5, June 2008.

[4] ——, “TPM Main,” Ver. 1.2 Lvl. 2 Rev. 103, July 2007.

[5] ——, “TCG Mobile Trusted Module,” Ver. 1.0 Rev. 6, June 2008.

[6] ——, “TCG Infrastructure Working Group Reference Architecture for Interoperability (Part 1),” Ver. 1.0 Rev. 1, June 2005.

[7] ——, “Trusted Network Connect (TNC) Architecture for Interoperability,” Ver. 1.4 Rev. 4, May 2005.

[8] R. C. Merkel, “A certified digital signature,” in Advances in Cryptology (CRYPTO ’89), ser. LNCS, G. Brassard, Ed., no. 435. Springer-Verlag, 1989, pp. 218–238, republication of the 1979 original.

[9] ——, “Protocols for public key cryptosystems,” in Proceedings of the IEEE Symposium on Security and Privacy, Los Alamitos, CA, USA: IEEE Computer Society, 1980, p. 122.

[10] B. Schneider and J. Kelsey, “Cryptographic support for secure logs on untrusted machines,” in SSYM’98: Proc. 7th USENIX Security Symposium, Berkeley, CA, USA: USENIX Association, 1998, pp. 53–62.

[11] ——, “Secure audit logs to support computer forensics,” ACM Trans. Inf. Syst. Secur., vol. 2, no. 2, pp. 159–176, 1999.

[12] R. Sailer, X. Zhang, T. Jaeger, and L. Van Doorn, “Design and implementation of a TCG-based integrity measurement architecture,” in Proc. 13th USENIX Security Symposium, 2004, pp. 223–238.

[13] I. Cha, Y. Shah, A. U. Schmidt, A. Leicher, and M. V. Meyerstein, “Trust in M2M communication,” IEEE Vehicular Technology Magazine, vol. 4, no. 3, pp. 69–75, September 2009.

[14] Detailed information on the industry’s agenda for M2M communications may be found on the web site of the first ETSI Workshop on Machine to Machine (M2M) Standardization Sophia Antipolis 4-5 June 2008. [Online]. Available: http://www.etsi.org/Worksite/NewsandEvents/PastEvents/2008_M2MWORKSHOP.aspx

[15] S. Lo Presti, “A Tree of Trust rooted in Extended Trusted Computing,” in Proceedings of the Second Conference on Advances in Computer Security and Forensics Programme (ACSP), 2007, pp. 13–20.

[16] D. Plaquin, S. Cabuk, C. Dalton, D. Kuhlmann, P. Grete, C. Weinhold, A. Böttcher, D. Murray, T. Hong, and M. Winandy, (2009, 5) TPM Virtualisation Architecture document. IST-027655 J/064.7 FINAL/0.15Update. OpenTC project consortium. [Online]. Available: http://www.opentc.net/deliverables/2008_2009/OpenTC_D04_TPM_Virtualisation_Architecture_document_v2_M42.pdf

[17] B. Lampson, M. Abadi, M. Burrows, and E. Wobber, “Authentication in distributed systems: theory and practice,” ACM Transactions on Computer Systems (TOCS), vol. 10, no. 4, pp. 265–310, 1992.

[18] P. England, B. Lampson, J. Manferdelli, M. Pennado, and B. Willman, “A completed open platform,” CompleteWorld, 2000.

[19] J. Stanley R. Arms, “Security kernels: A solution or a problem?” in Proceedings of the IEEE Symposium on Security and Privacy. Los Alamitos, CA, USA: IEEE Computer Society, 1981, p. 141.

[20] P. S. Tasker, “Trusted computer systems,” in Proceedings of the IEEE Symposium on Security and Privacy. Los Alamitos, CA, USA: IEEE Computer Society, 1981, p. 99.

[21] J. D. Tygar and B. Yee, “Dyad: A system for using physically secure coprocessors,” in Proceedings of the Joint Harvard-MIT Workshop on Technological Strategies for the Protection of Intellectual Property in the Information Multimedia Environment, 1991.

[22] D. Lie, C. Thekkath, M. Mitchell, P. Lincoln, D. Boneh, J. Mitchell, and M. Horowitz, “Architectural support for copy and tamper resistant software,” SIGPLAN Not., vol. 35, no. 11, pp. 168–177, 2000.

[23] D. Lie, C. A. Thekkath, and M. Horowitz, “Implementing an untrusted operating system on trusted hardware,” in SOSP ’03: Proceedings of the nineteenth ACM symposium on Operating systems principles. New York, NY, USA: ACM, 2003, pp. 178–192.

[24] W. Arbaugh, D. Farber, and J. Smith, “A secure and reliable bootstrap architecture,” in Proceedings of the IEEE/IISS Symposium on Security and Privacy, vol. 0. Los Alamitos, CA, USA: IEEE Computer Society, 1997, p. 0065.

[25] T. Garfinkel, B. Pfaff, J. Chow, M. Rosenblum, and D. Boneh, “Terra: a virtual machine-based platform for trusted computing,” in SOSP ’03: Proceedings of the nineteenth ACM symposium on Operating systems principles. New York, NY, USA: ACM, 2003, pp. 193–206.

[26] J. Poritz, M. Schunter, E. V. Herreweghen, and M. Waidner, “Property Attestation–Scalable and Privacy-Friendly Security Assessment of Peer Computers,” IBM Zurich Research Laboratory, Rüschlikon, Switzerland, 2004.

[27] A. Sadeghi and C. Stüble, “Property-based attestation for computing platforms: caring about properties, not mechanisms,” in Proceedings of the 2004 workshop on New security paradigms. ACM New York, NY, USA, 2004, pp. 67–77.

[28] L. Linn, R. Landfermann, H. Lühr, M. Rohe, A. Sadeghi, and C. Stüble, “A protocol for property-based attestation,” in Proceedings of the first ACM workshop on Scalable trusted computing. ACM New York, NY, USA, 2006, pp. 7–16.

[29] A. Shieh, D. Williams, E. G. Sirer, and F. B. Schneider, “Nexus: a new operating system for trustworthy computing,” in SOSP ’05: Proceedings of the twentieth ACM symposium on Operating systems principles. New York, NY, USA: ACM, 2005, pp. 1–9.

[30] D. Williams, P. Reynolds, K. Walsh, F. B. Schneider, and E. G. Sirer, “Device Driver Safety Through a Reference Validation Mechanism,” in Proceedings of the 8th USENIX Symposium on Operating Systems Design and Implementation (OSDI 2008), R. Draves and R. V. Renesse, Eds., San Diego, California: USENIX Association, 2008, pp. 241–254. [Online]. Available: http://www.usenix.org/events/oisd08/tech/full_papers/williams/williams.pdf

[31] S. Cabuk, D. Plaquin, T. Hong, and D. Murray, “Improving policy verification capabilities of trusted platforms,” HP Laboratories, Tech. Rep. HPL-2008-71, 2008.

[32] D. J. Kuck, R. H. Kuhn, D. A. Padua, B. Leasure, and M. Wolfé, “Dependence graphs and compiler optimizations,” in POPL ’81: Proc. 8th ACM SIGPLAN-SIGACT symposium on Principles of programming languages. New York, NY, USA: ACM, 1981, pp. 207–218.

[33] J. Ferrante, K. J. Ottenstein, and J. D. Warren, “The program dependence graph and its use in optimization,” ACM Trans. Program. Lang. Syst., vol. 9, no. 3, pp. 319–349, 1987.

[34] A. Bults, P. Lauw, and H. Lipman, “Accountable certificate management using undeniable attestations,” in CCS ’00: Proceedings of the
[35] ———. “Eliminating counterevidence with applications to accountable certificate management.” I. Comp. Secur., vol. 10, pp. 273–296, 2002.

[36] P. Maniatis and M. Baker. “Enabling the archival storage of signed documents,” in FAST ’02: Proceedings of the 1st USENIX Conference on File and Storage Technologies. Berkeley, CA, USA: USENIX Association, 2002, p. 3.

[37] T. Kunz, S. Okunick, and U. Viebeg. “Long-term security for signed documents: services, protocols, and data structures,” in Long-Term and Dynamical Aspects of Information Security: Emerging Trends in Information and Communication Security, A. U. Schmidt, M. Kreutzer, and R. Accorsi, Eds. Hauppauge, New York: Nova, 2007.

[38] T. Vondr, R. Brandner, and U. Pordesch. “Evidence Record Syntax (ERS).” RFC 4998 (Proposed Standard), IETF, Aug. 2007. [Online]. Available: http://www.ietf.org/rfc/rfc4998.txt

[39] R. Elbaz, D. Champagne, C. Gebolys, K. B. Lee, N. Potlapally, and L. Torres. “Hardware mechanisms for memory authentication: A survey of existing techniques and engines,” in Transactions on Computational Science IV, ser. Lecture Notes in Computer Science (LNCS), vol. 5430, M. L. Gavrilova, C. K. Tan, and E. D. Moreno, Eds. Springer-Verlag, 2009, ch. 1, pp. 1–22.

[40] Y. Hu, G. Hammouri, and B. Sunar. “A Fast Real-time Memory Authentication Protocol,” in Proc. 3rd ACM workshop on Scalable trusted computing. New York, NY, USA: ACM, 2008, pp. 31–40.

[41] U. Maheshwari, R. Vingralek, and W. Shapiro. “How to build a trusted database system on untrusted storage,” in OSDI’00: Proc. 4th conference on Symposium on Operating System Design & Implementation. Berkeley, CA: USENIX Association, 2000, p. 10.

[42] B. Gassend, G. E. Suh, D. Clarke, M. van Dijk, and S. Devadas. “Caches and hash trees for efficient memory integrity verification.” in Proc. 9th Intl. Symp. on High Performance Computer Architecture, 2003, p. 295.

[43] T. Williams and E. G. Sirer. “Optimal parameter selection for efficient memory integrity verification using merkle hash trees,” in Proc. IEEE International Symposium on Network Computing and Applications. Los Alamitos, CA, USA: IEEE Computer Society, 2004, pp. 383–388.

[44] L. Sarmenta, M. van Dijk, C. O’Donnell, J. Rhodes, and S. Devadas. “Virtual monotonic counters and count-limited objects using a TPM without a trusted OS,” in Proceedings of the first ACM workshop on scalable trusted computing. ACM, 2006, p. 42.

[45] J. Deng, R. Han, and S. Mishra. “Secure code distribution in dynamically programmable wireless sensor networks,” in Proceedings of the 5th international conference on Information processing in sensor networks. ACM, 2006, p. 300.

[46] H. Chan, A. Perrig, B. Przydatek, and D. Song. “SIA: secure information aggregation in sensor networks,” J. Comput. Secur., vol. 15, no. 1, pp. 69–102, 2007.

[47] P. Maniatis. “Historic integrity in distributed systems,” Ph.D. dissertation, Stanford University, August 2003.

[48] T. E. Portegys. “General graph identification with hashing.” School of Information Technology, Illinois State University, Normal, Illinois, 61790, USA, Tech. Rep., 2007. [Online]. Available: http://www.itkilstu.edu/faculty/portegys/research/graph/graph-hash.pdf

[49] D. Clarke, S. Devadas, M. van Dijk, B. Gassend, and G. E. Suh. “Incremental multiset hash functions and their application to memory integrity checking,” in In Advances in Cryptology - Asiacrypt 2003 Proc., ser. LNCS, vol. 2894. Springer-Verlag, 2003, pp. 188–207.

[50] C. Sayers and A. H. Karp. “Computing the digest of an rdf graph,” Mobile and Media Systems Laboratory, HP Laboratories, Palo Alto, USA, Tech. Rep. HPL-2003-235(R.1), 2004. [Online]. Available: http://www.hpl.hp.com/techreports/2003/HPL-2003-235R1.pdf