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(54) SYSTEMS AND METHODS FOR USING CRYPTOGRAPHY TO PROTECT SECURE AND INSECURE COMPUTING ENVIRONMENTS

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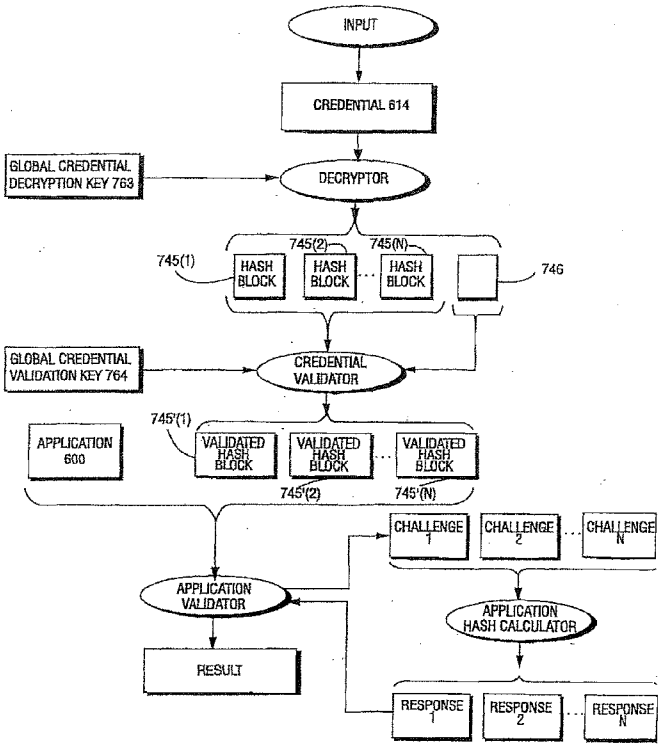
(57) **ABSTRACT**

Computation environments are protected from bogus or rogue load modules, executables, and other data elements through use of digital signatures, seals, and certificates issued by a verifying authority. A verifying authority—which may be a trusted independent third party—tests the load modules and/or other items to verify that their corresponding specifications are accurate and complete, and then digitally signs them based on a tamper resistance work factor classification. Secure computation environments with different tamper resistance work factors use different digital signature authentication techniques (e.g., different signature algorithms and/or signature verification keys), allowing one tamper resistance work factor environment to protect itself against load modules from another tamper resistance work factor environment. The verifying authority can provide an application intended for insecure environments with a credential having multiple elements covering different parts of the application. To verify the application, a trusted element can issue challenges based on different parts of the authenticated credential that the trusted element selects in an unpredictable (e.g., random) way, and deny service (or take other appropriate action) if the responses do not match the authenticated credential.



EXAMPLE CREDENTIAL VALIDATION

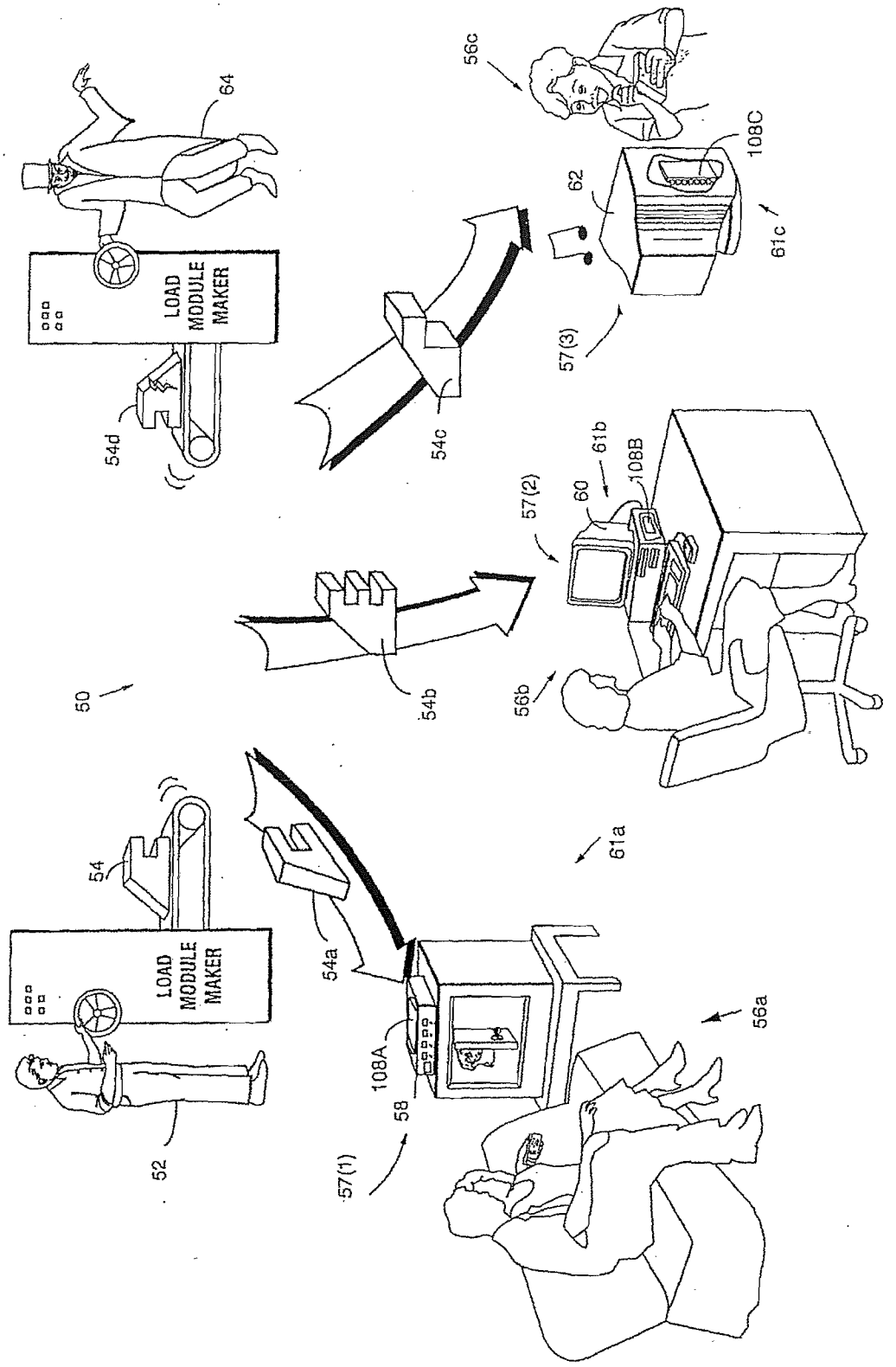


FIG. 1 Defective or "Bogus" Load Modules Can Cause Problems

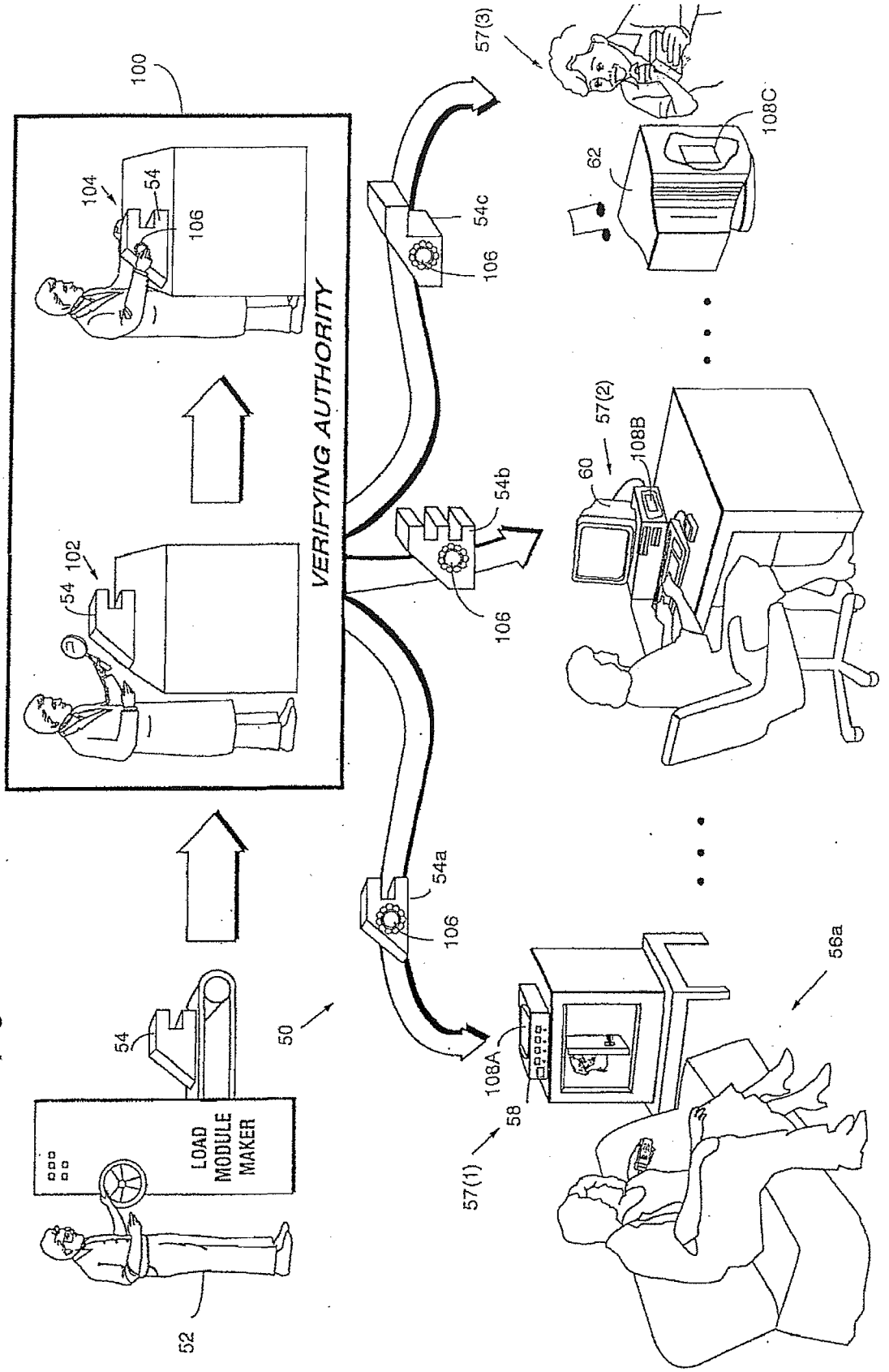
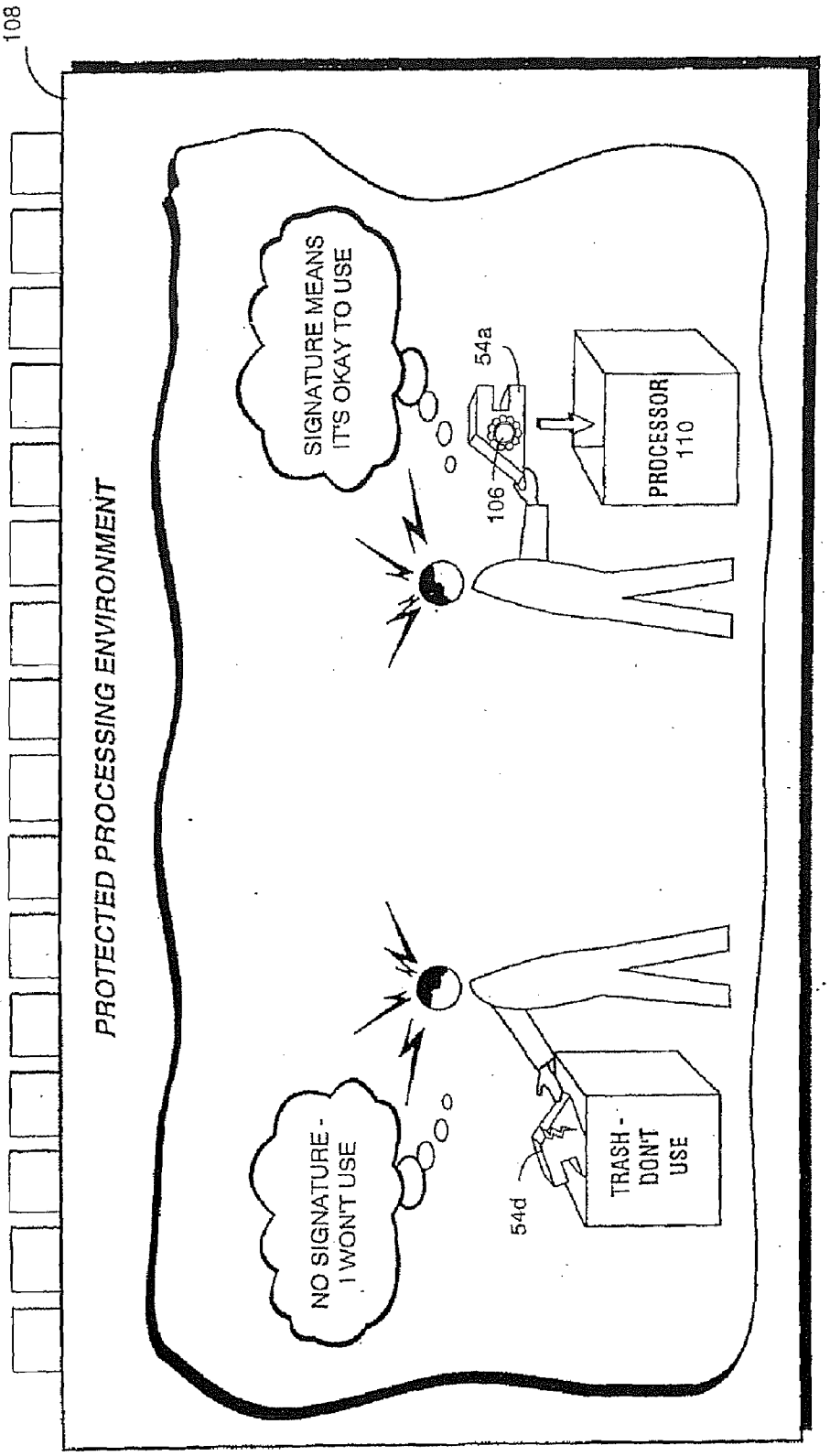


FIG. 2 Verifying Load Modules

FIG. 3 Before Protected Processing Environment Uses A Load Module, It Checks To See If Load Module Has Been Verified



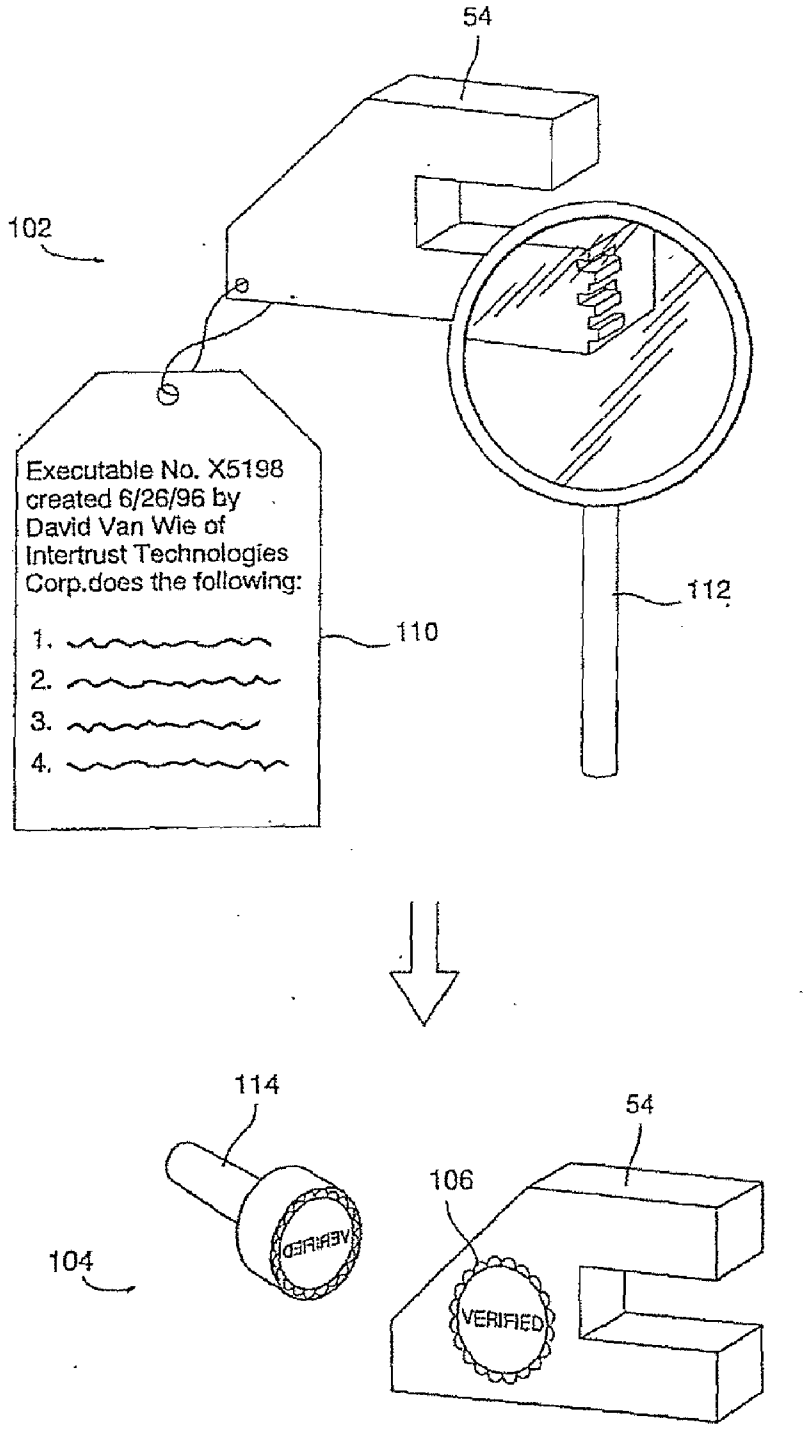


FIG. 4

Certifying Load Module by
Checking it Against its Documentation

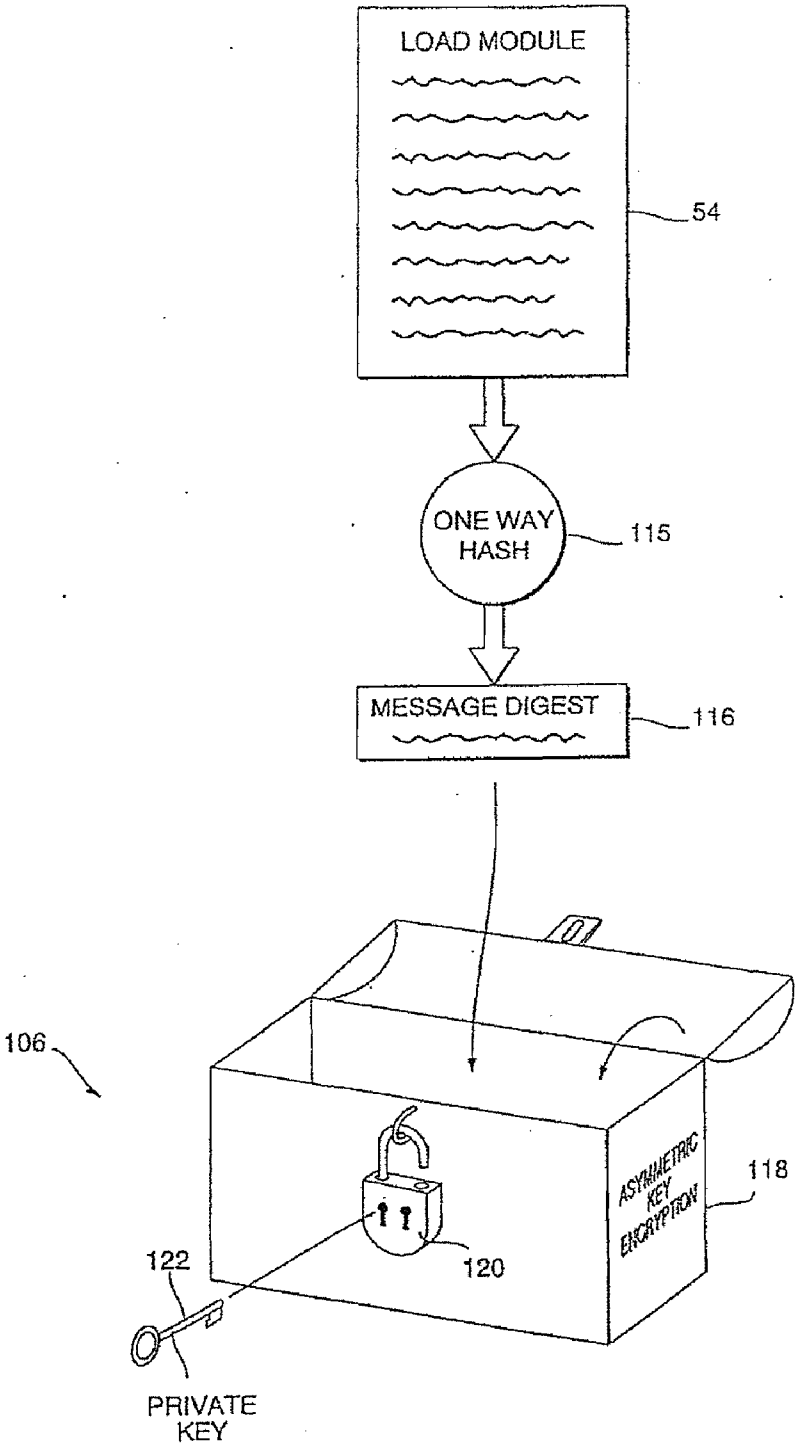


FIG. 5

Creating a Certifying Digital Signature

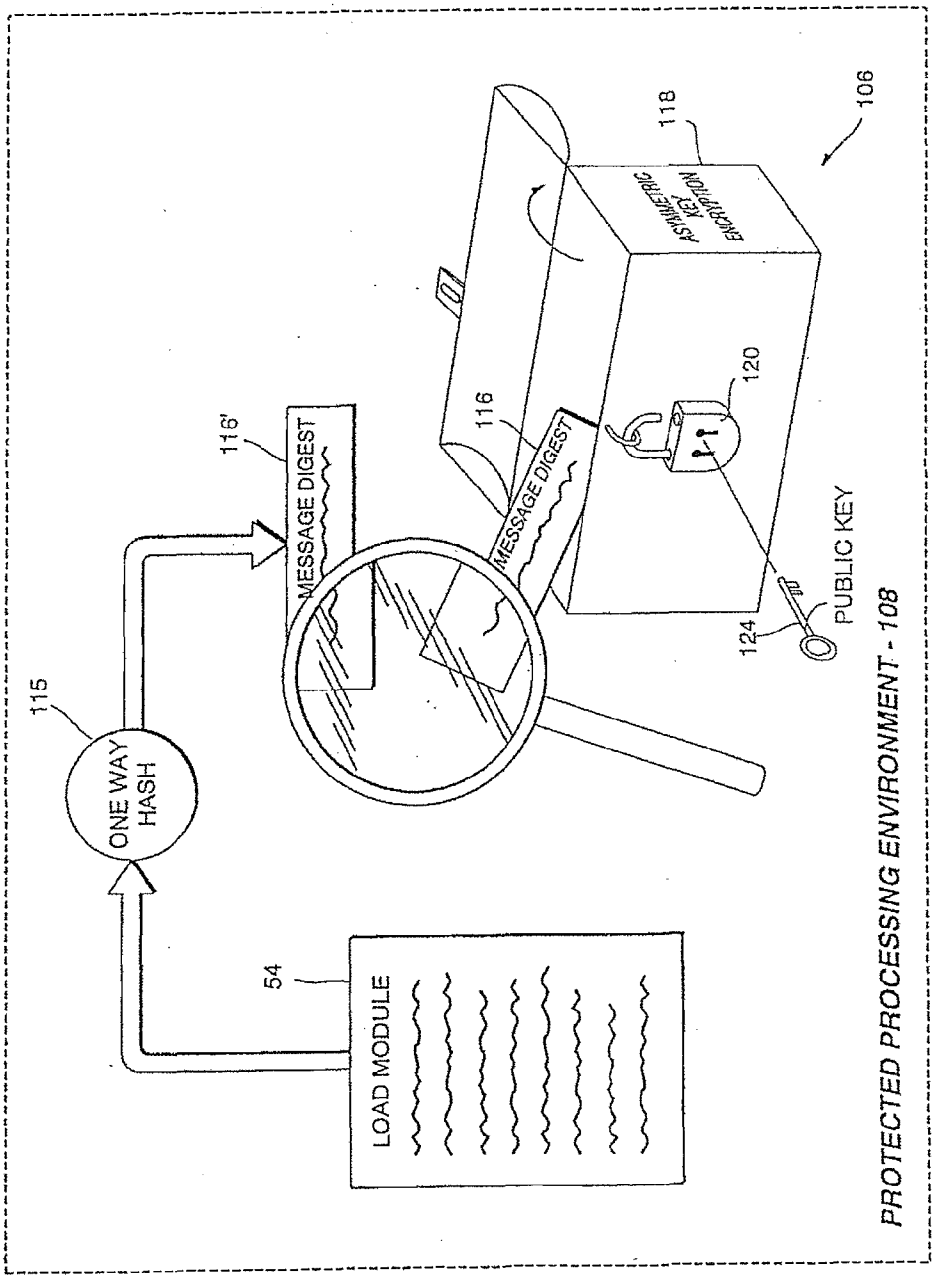


FIG. 6 Authenticating a Digital Signature

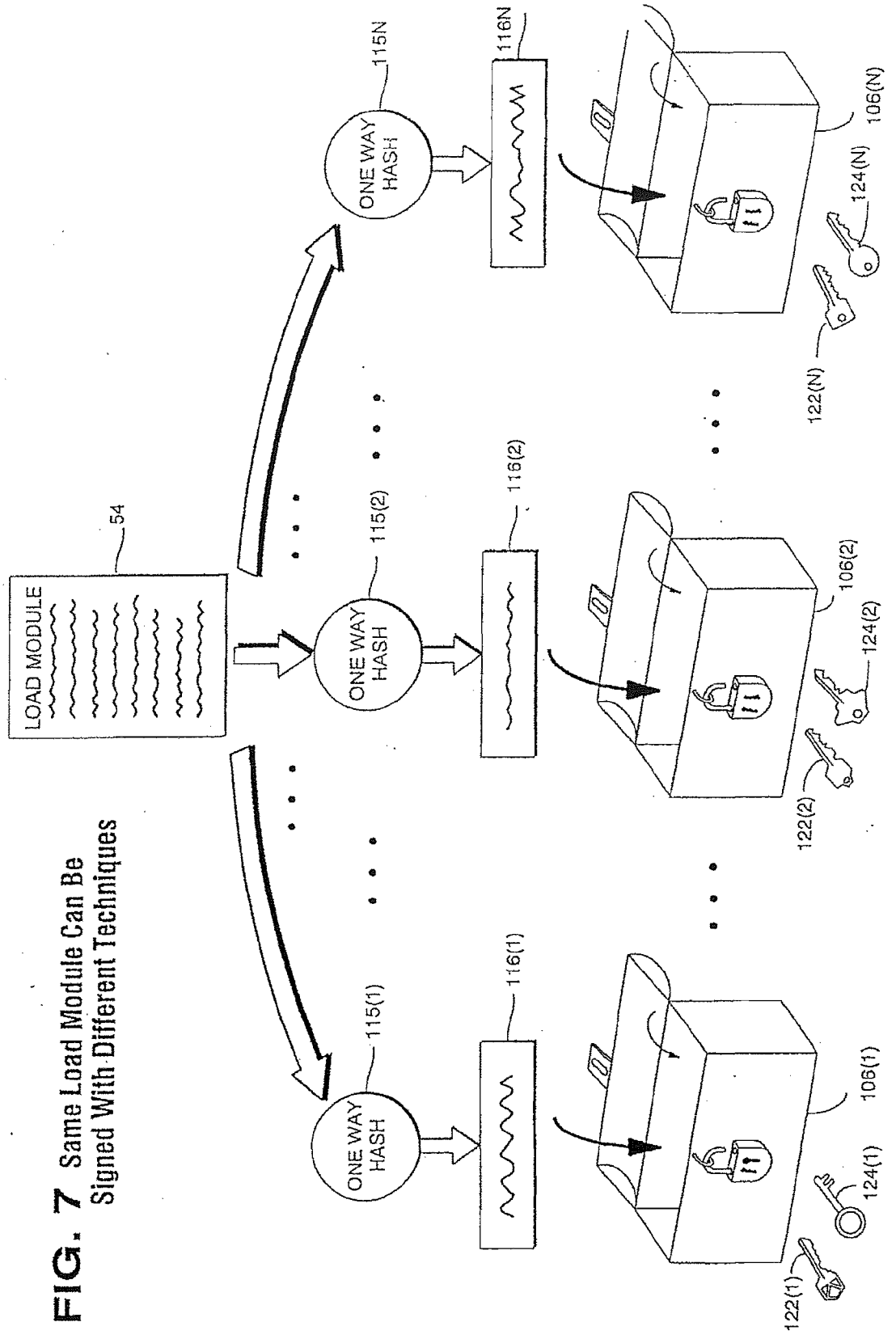


FIG. 7 Same Load Module Can Be Signed With Different Techniques

FIG. 8 Same Load Module Can Be Distributed with Multiple Signatures

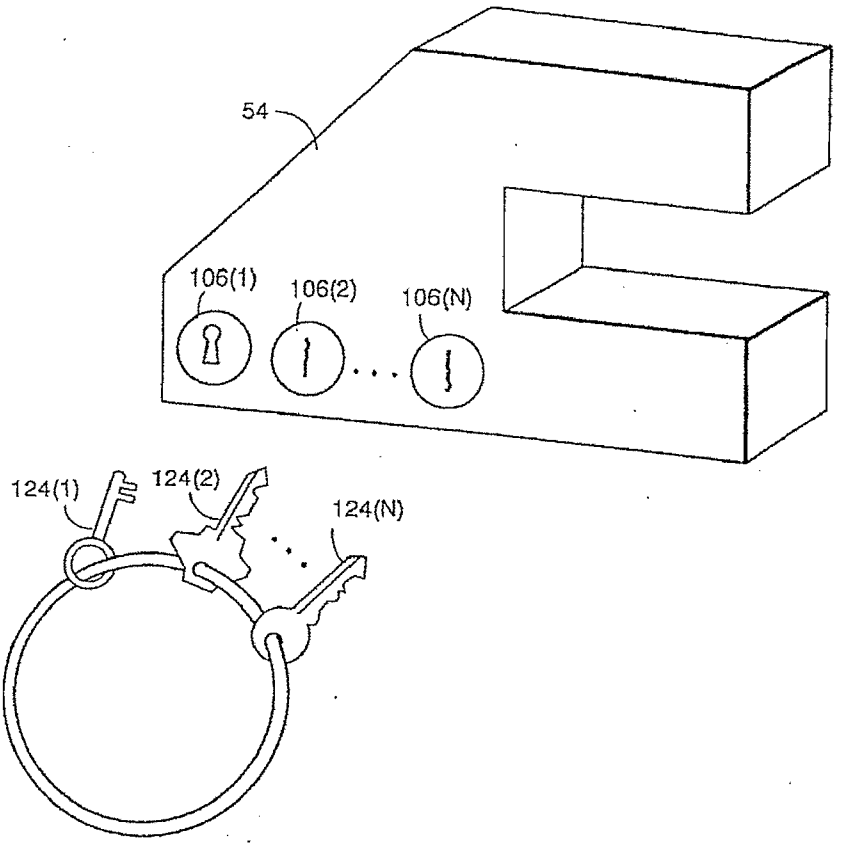


FIG. 8A Different Processing Environments Can Have Different Subsets of Keys

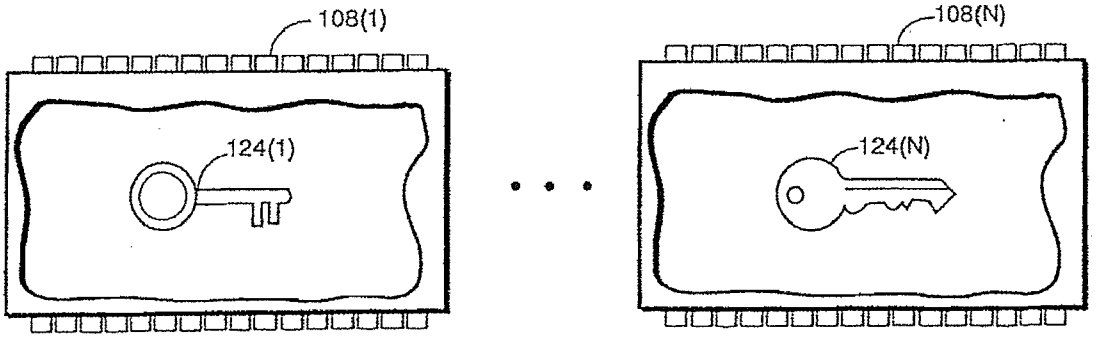
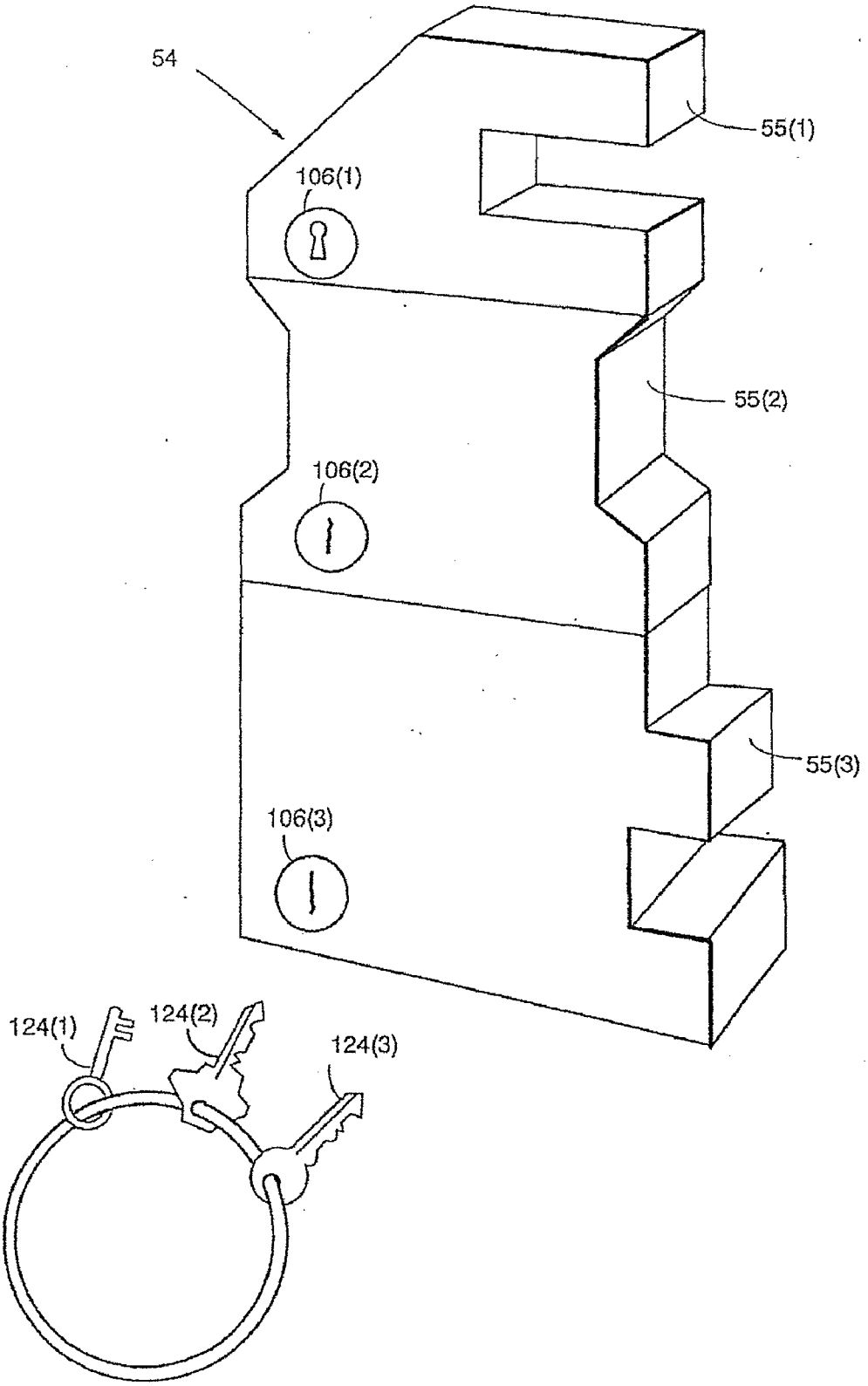


FIG. 9 Load Module Can Have Several Independently Signed Portions



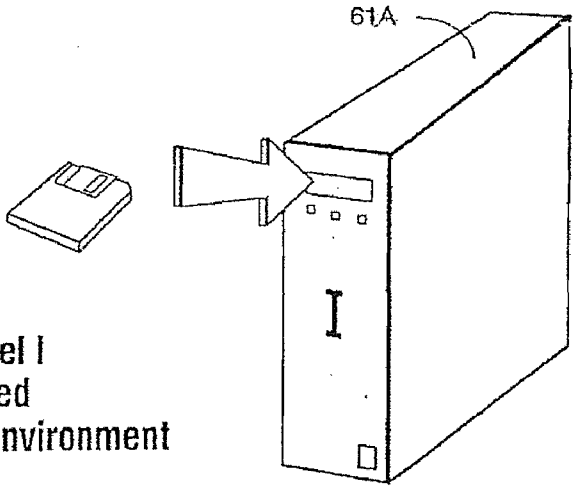


FIG. 10A Assurance Level I
Software-Based
Protected Processing Environment

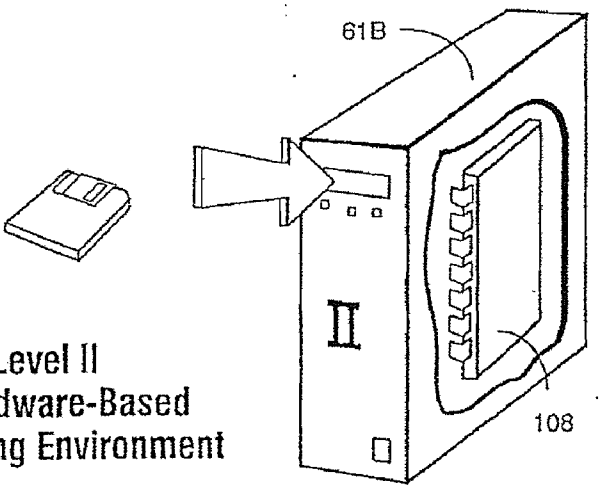


FIG. 10B Assurance Level II
Software and Hardware-Based
Protected Processing Environment

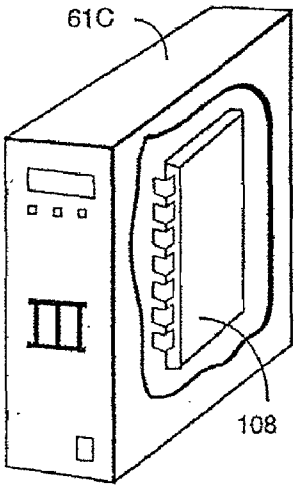


FIG. 10C Assurance Level III
Hardware-Based
Protected Processing Environment

FIG. 11A Level I Digital Signature

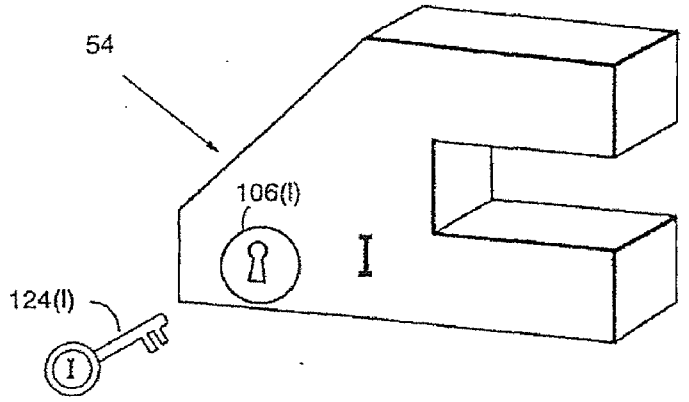


FIG. 11B Level II Digital Signature

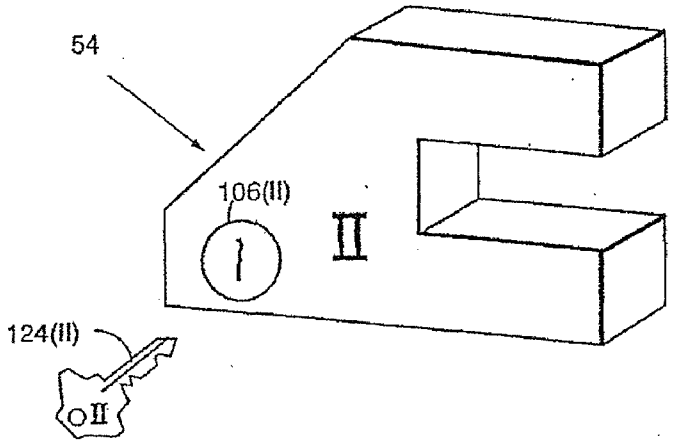
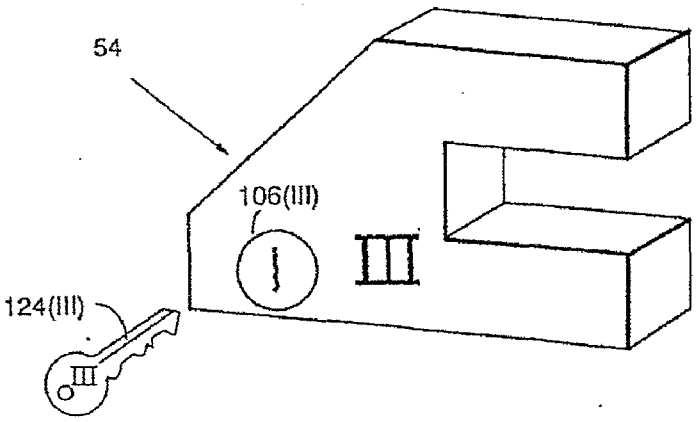


FIG. 11C Level III Digital Signature



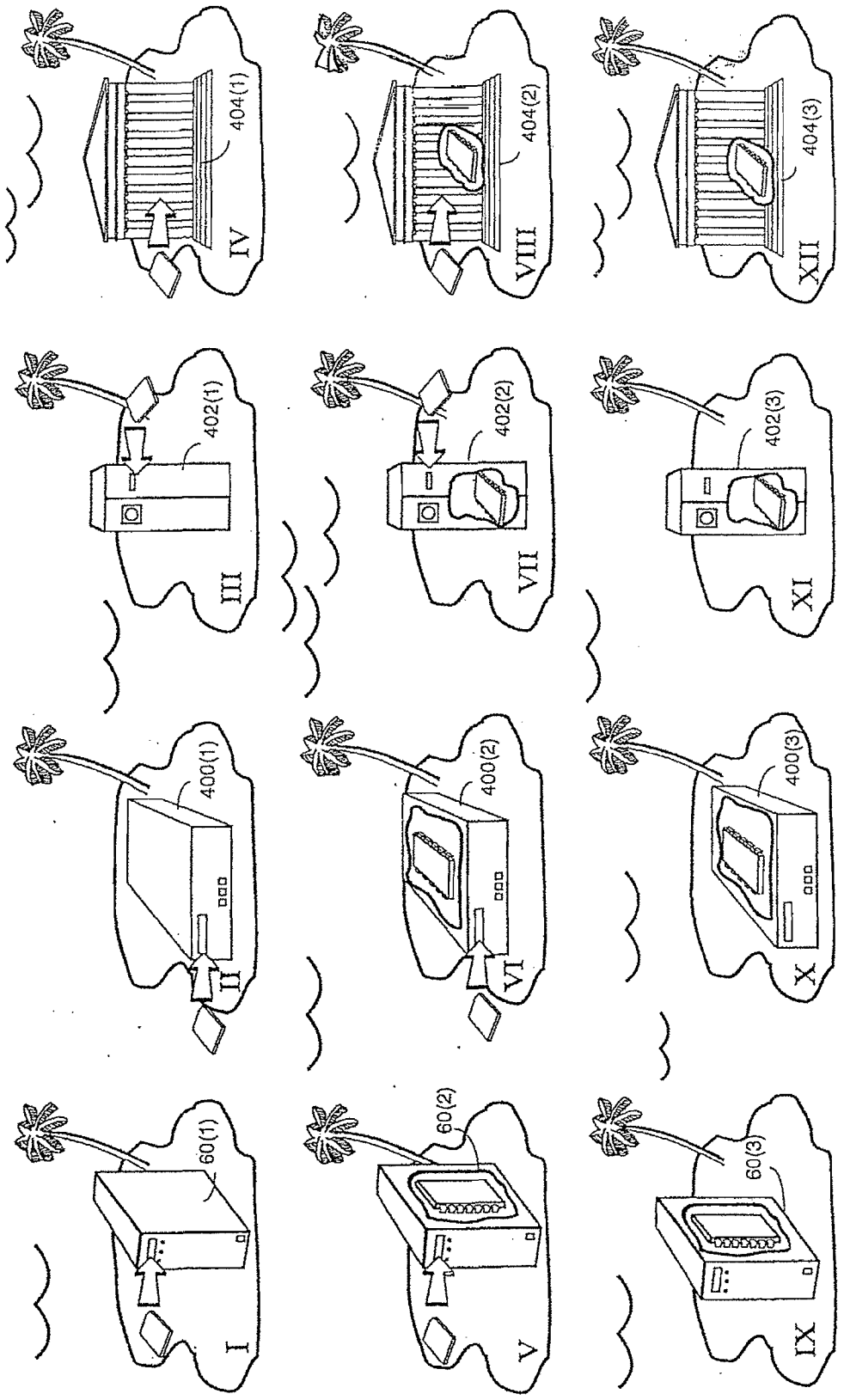


FIG. 12 Using Digital Signatures For Compartmentalizing Different Assurance Levels

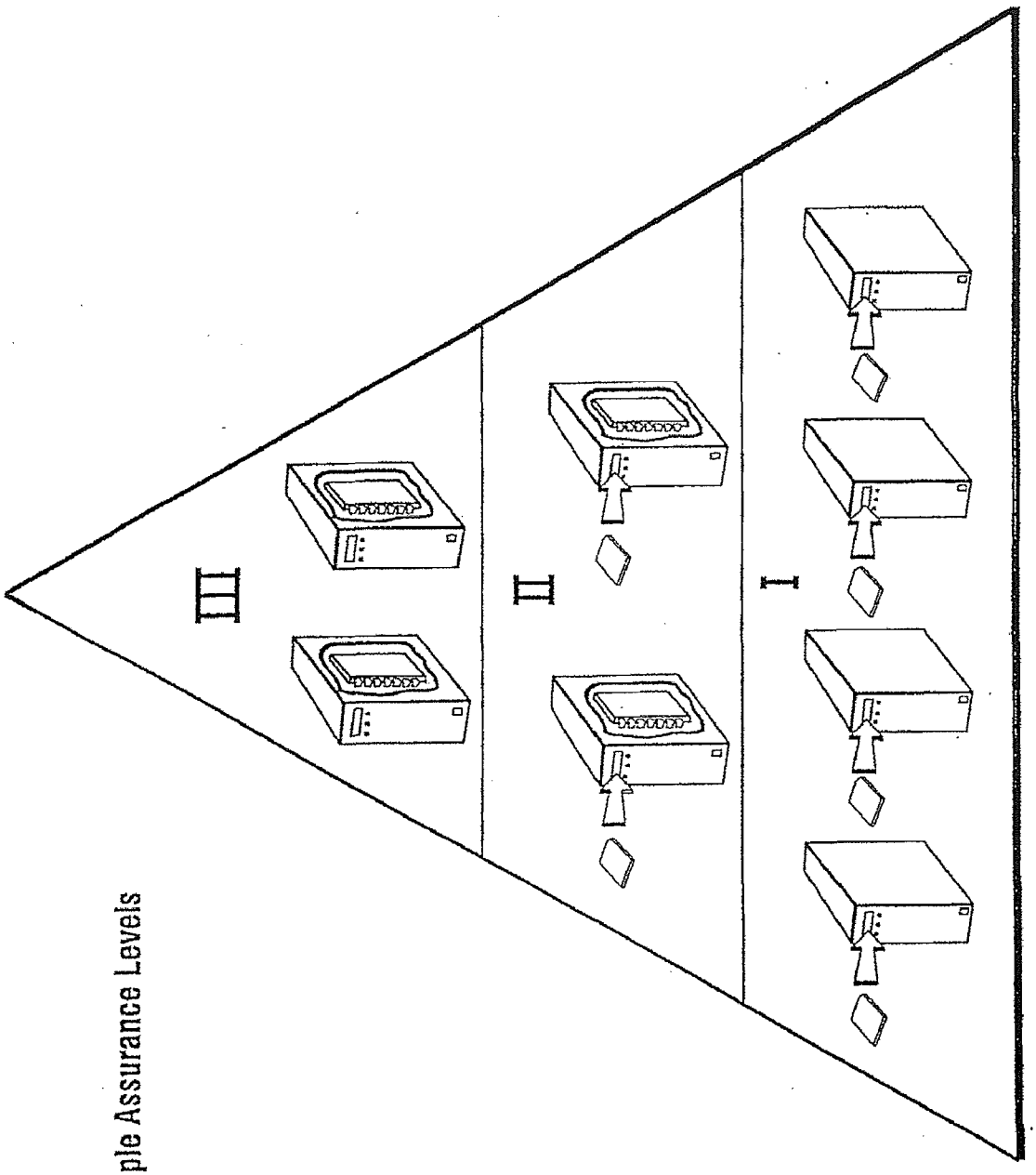


FIG. 13 Multiple Assurance Levels

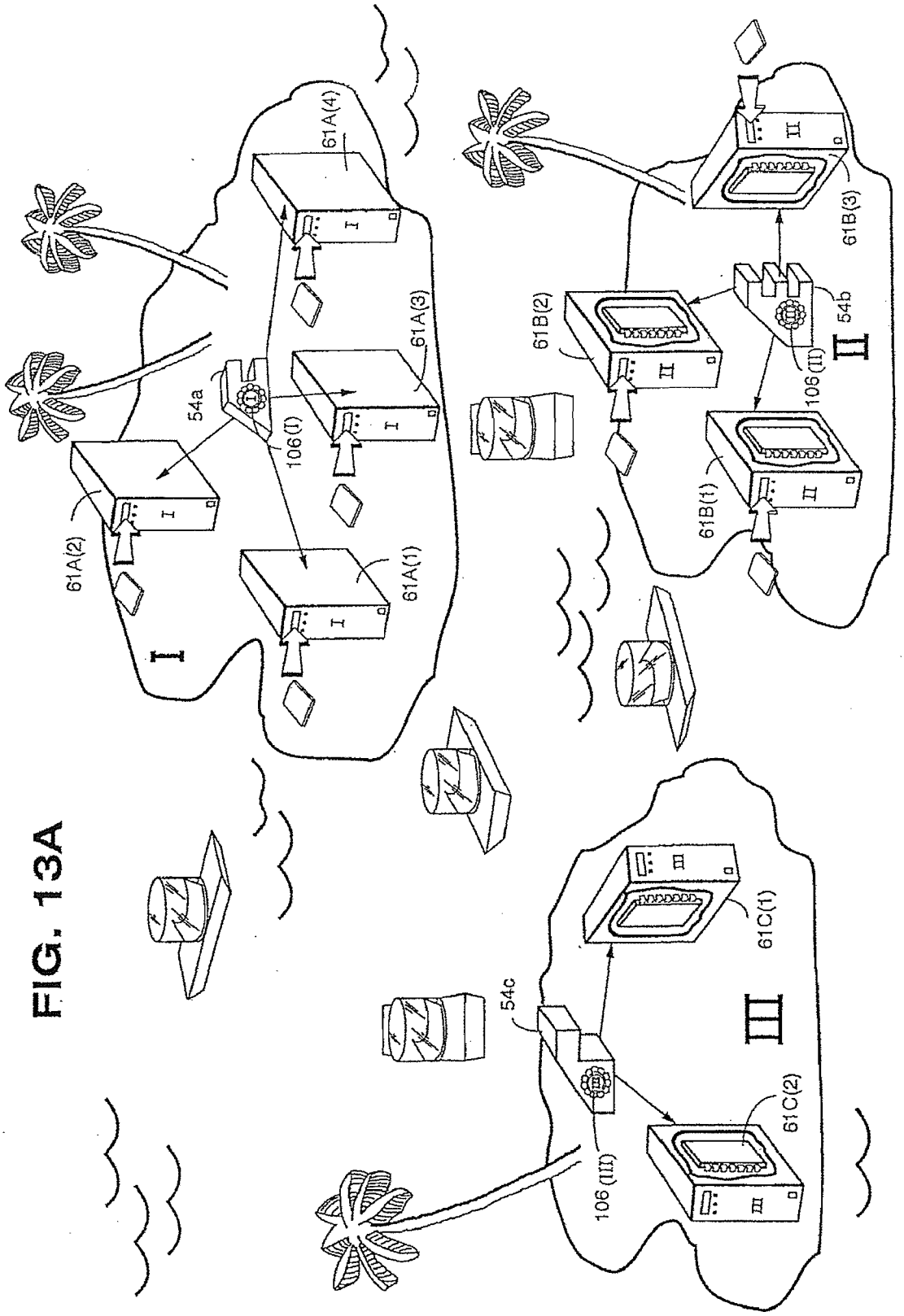
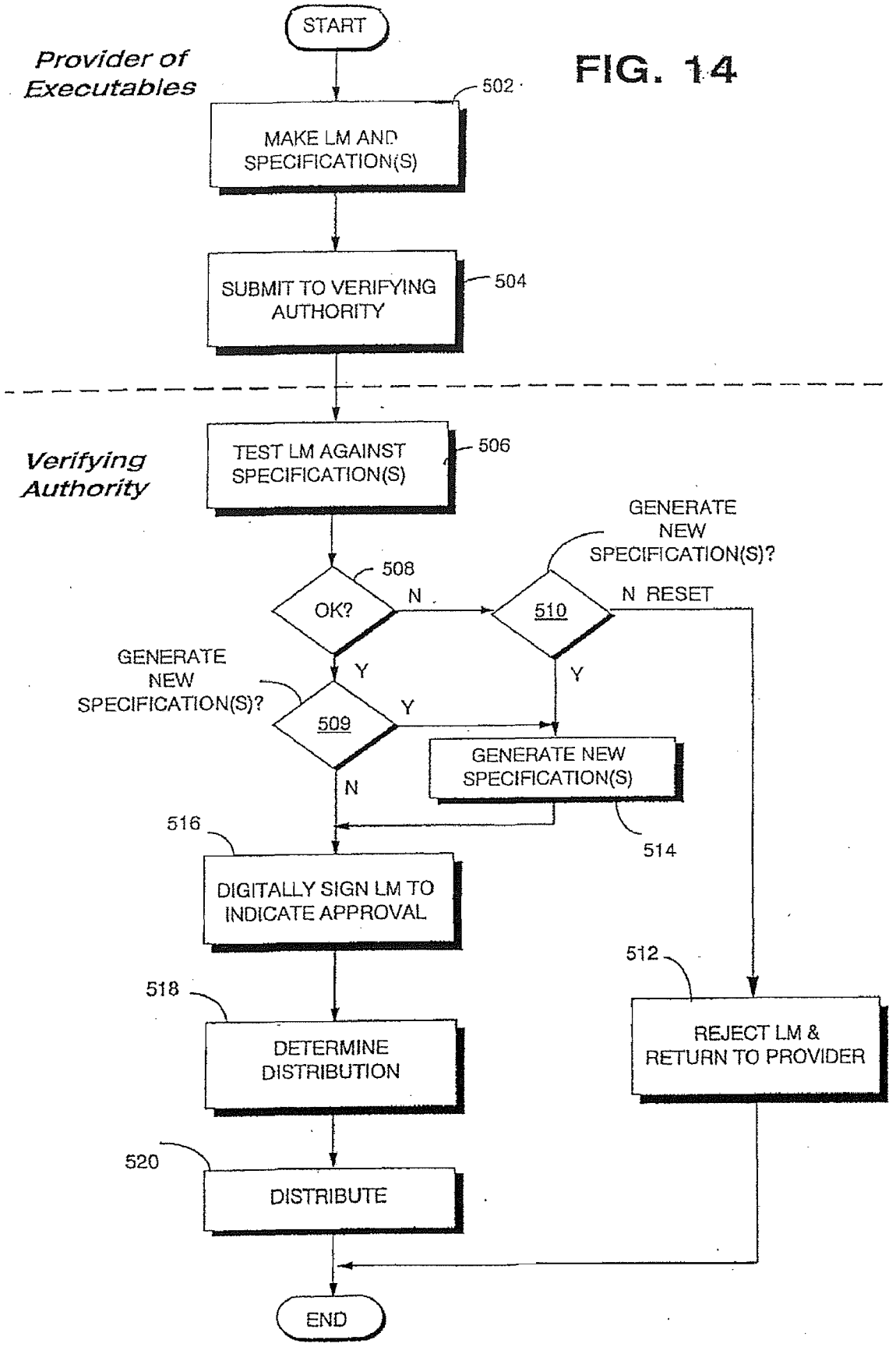

61A(4)
61A(3)
54a
106 (I)
61A(2)
61A(1)
I
61B(3)
61B(2)
54b
106 (II)
61B(1)
II
61C(1)
54c
106 (III)
61C(2)
III

FIG. 13A

FIG. 14


Provider of Executables
START
502
MAKE LM AND SPECIFICATION(S)
SUBMIT TO VERIFYING AUTHORITY
504
Verifying Authority
TEST LM AGAINST SPECIFICATION(S)
506
508
OK?
N
GENERATE NEW SPECIFICATION(S)?
510
N RESET
Y
Y
GENERATE NEW SPECIFICATION(S)?
509
Y
GENERATE NEW SPECIFICATION(S)
N
514
516
DIGITALLY SIGN LM TO INDICATE APPROVAL
512
518
DETERMINE DISTRIBUTION
REJECT LM & RETURN TO PROVIDER
520
DISTRIBUTE
END

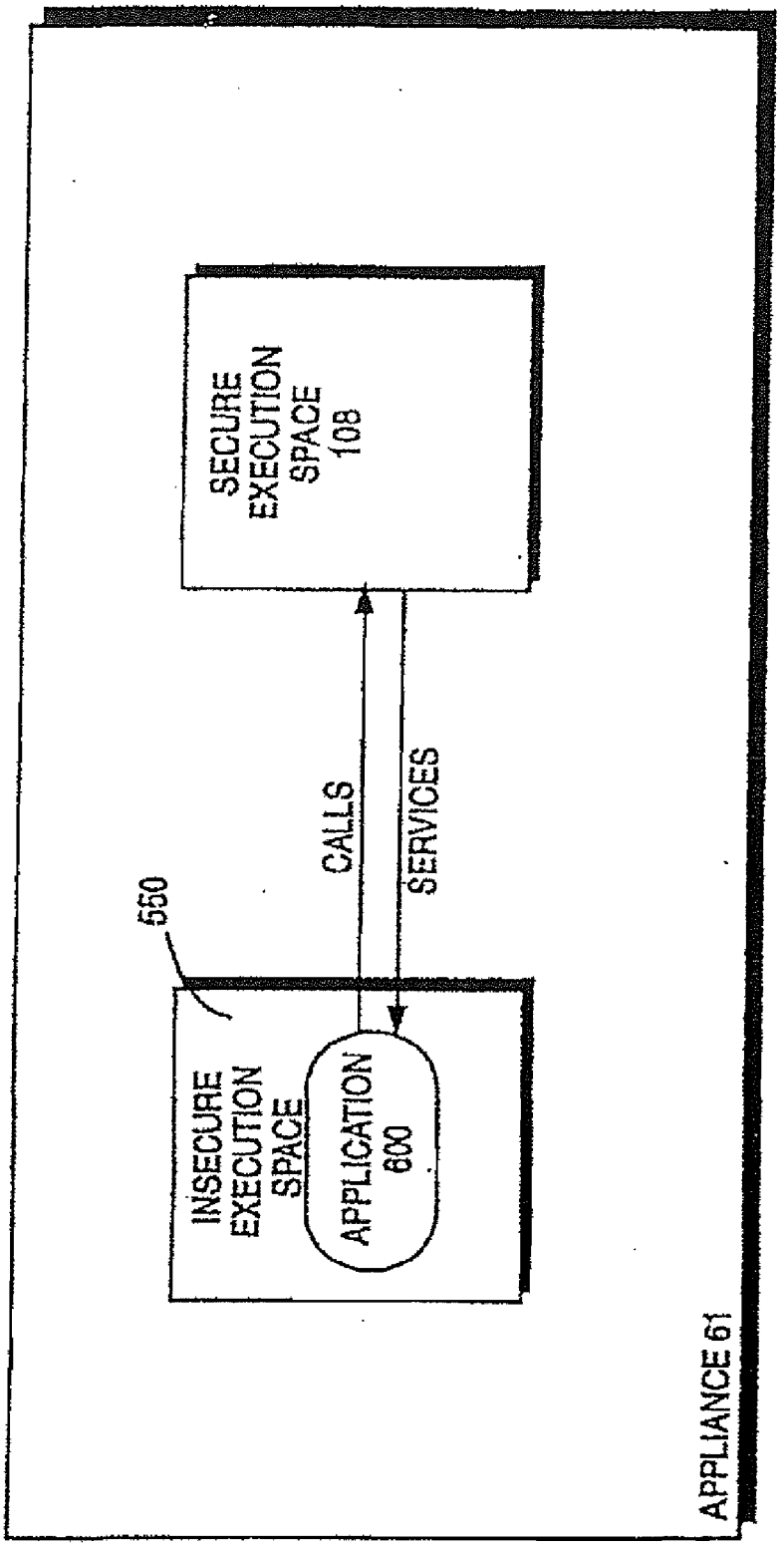


FIG. 15 EXAMPLE APPLIANCE EXECUTING APPLICATION PROGRAM IN INSECURE EXECUTION SPACE

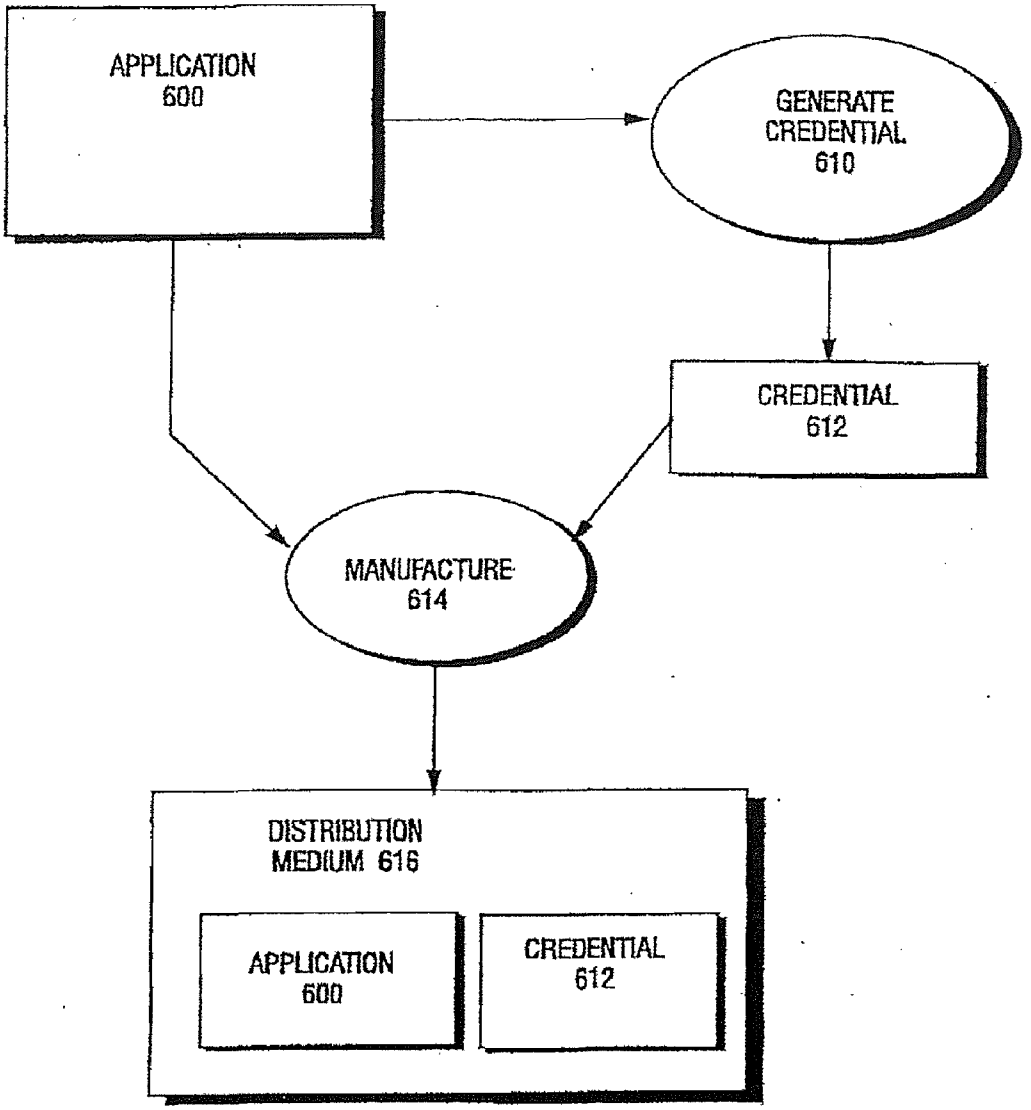


FIG. 16 EXAMPLE APPLICATION CERTIFICATION PROCESS

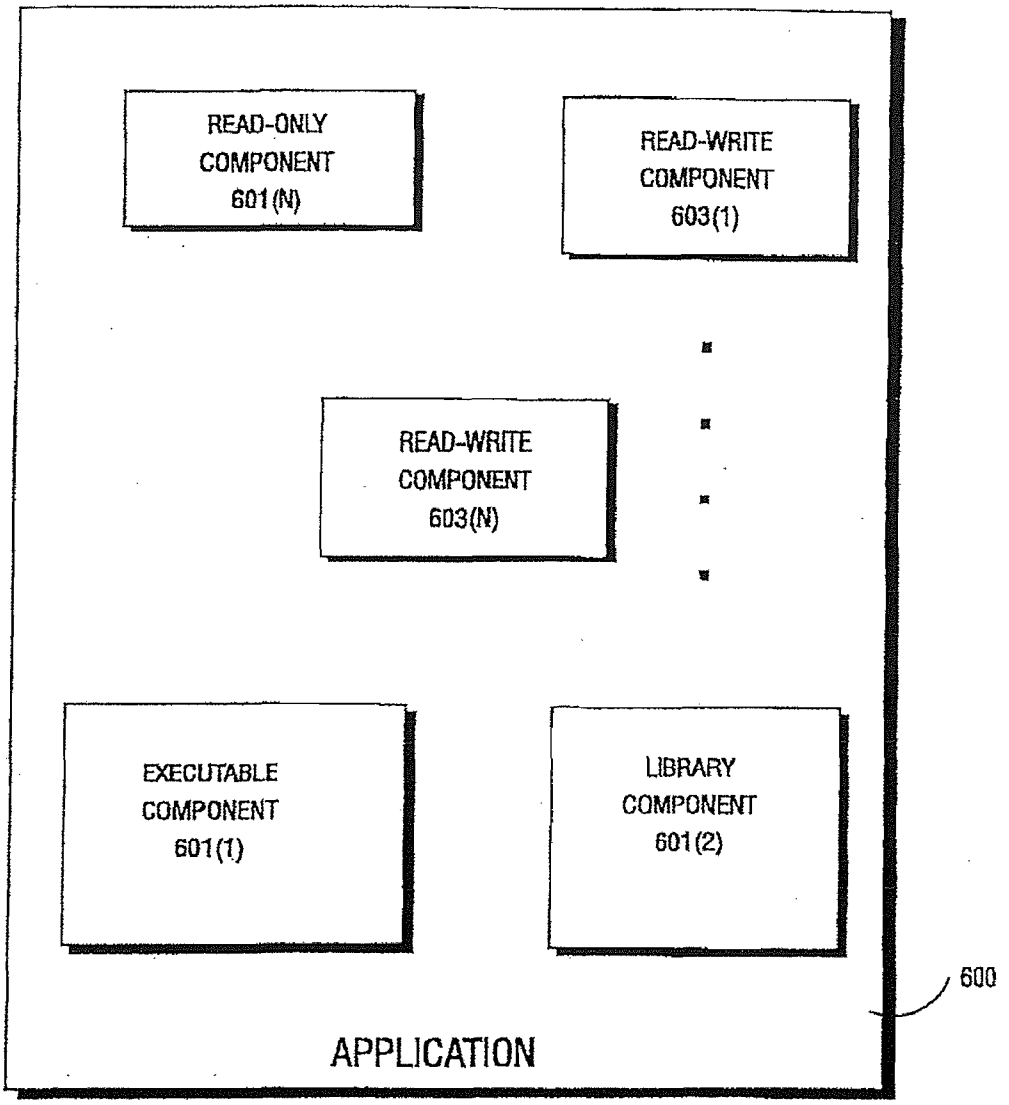


FIG. 16A EXAMPLE APPLICATION PROGRAM AND COMPONENTS

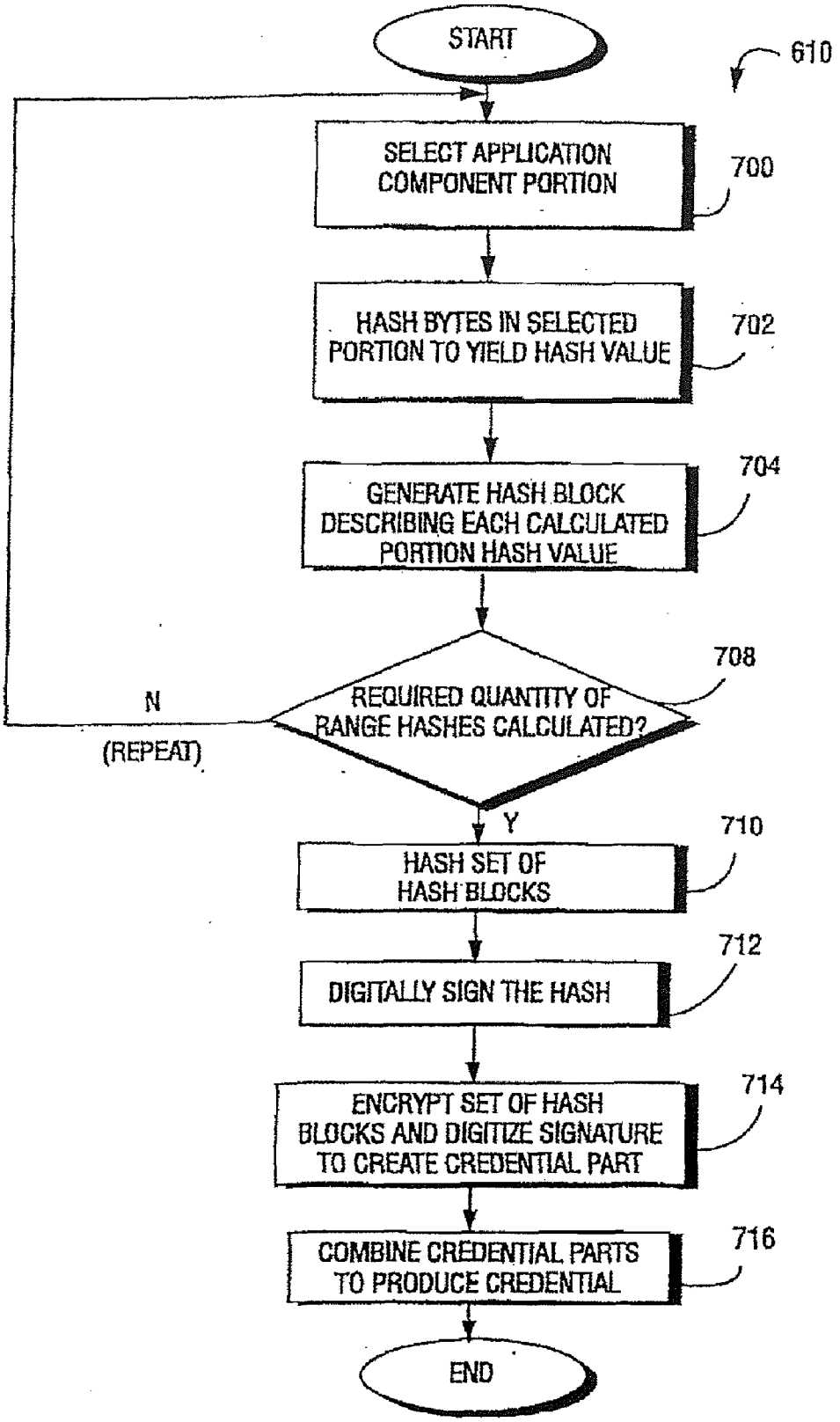


FIG. 17 EXAMPLE CREDENTIAL CREATION PROCESS

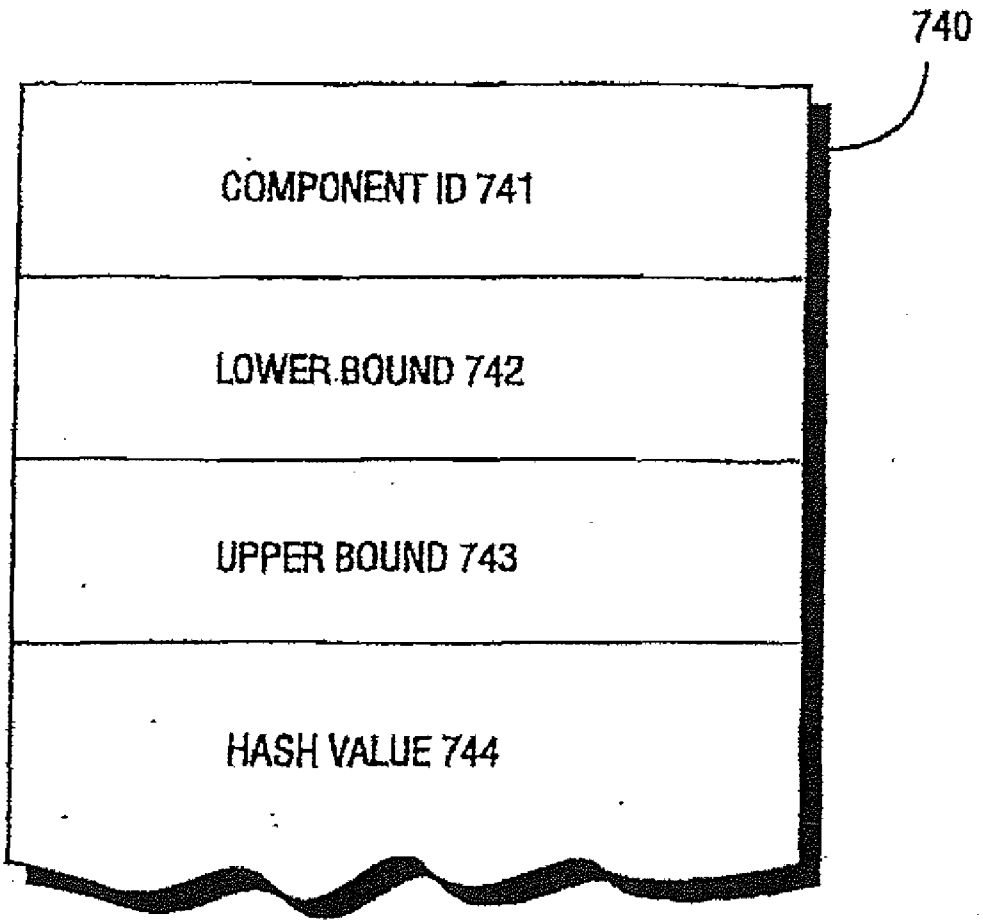


FIG. 18 EXAMPLE HASH BLOCK

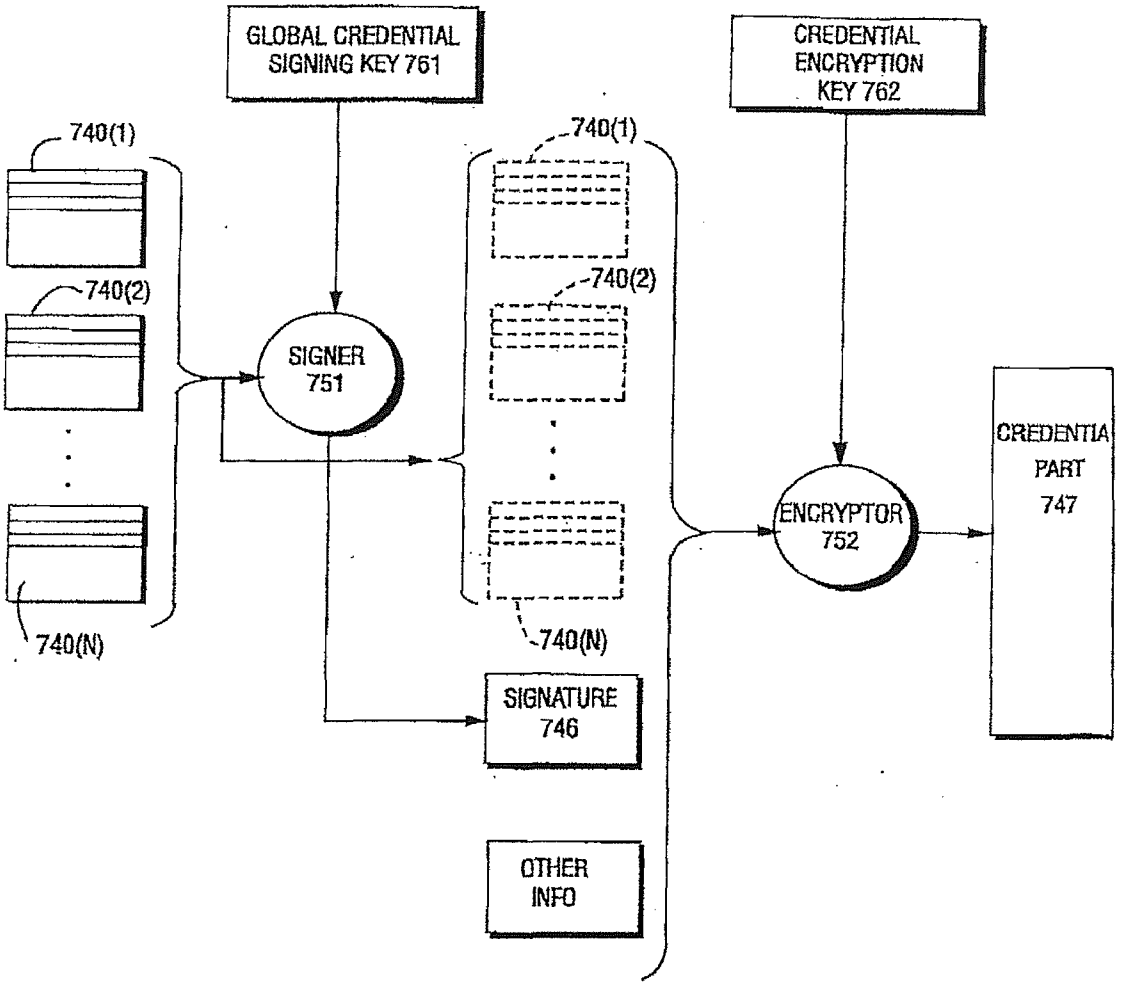


FIG. 19 EXAMPLE CREDENTIAL CREATION

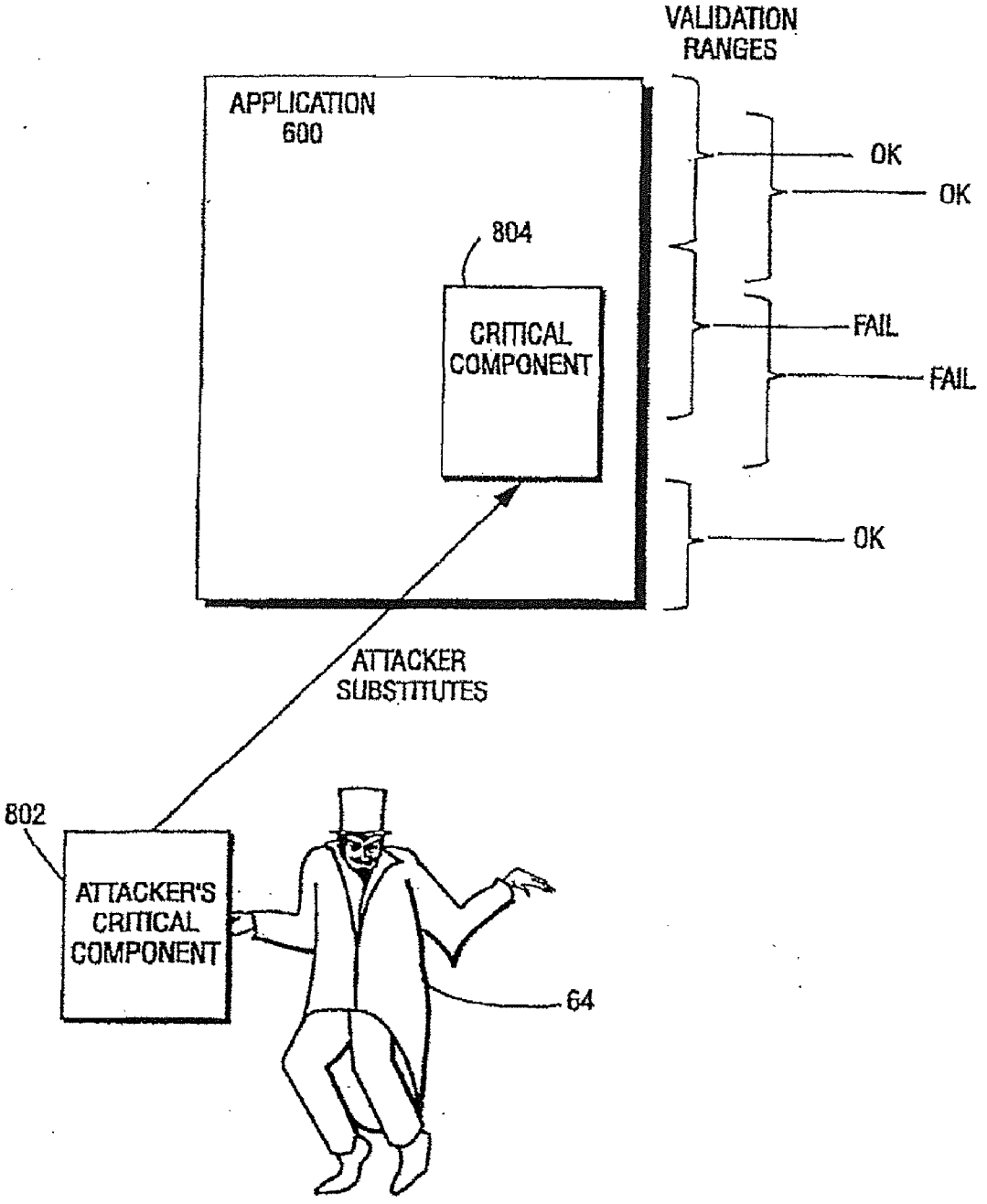


FIG. 20 EXAMPLE ATTACK ON APPLICATION

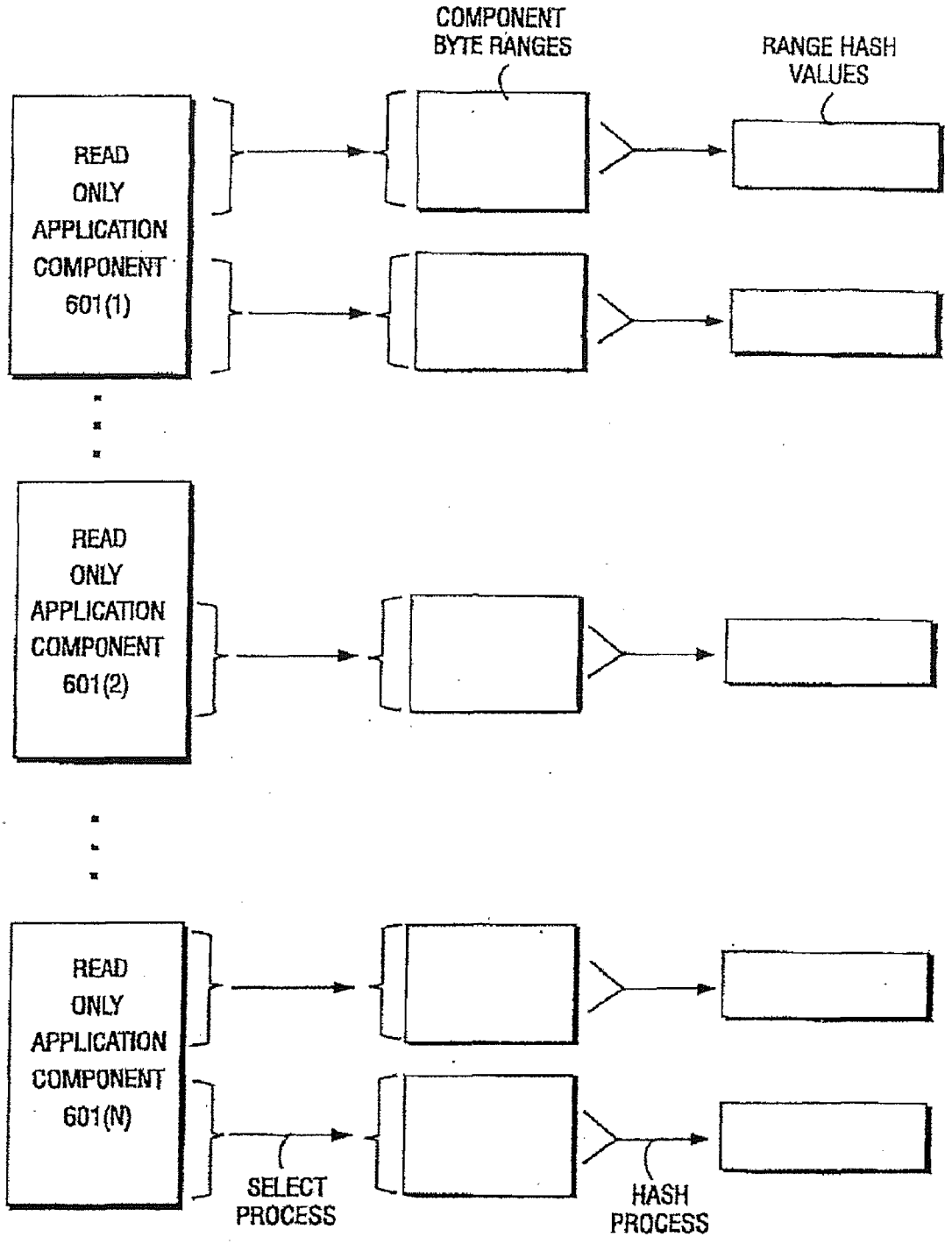


FIG. 20A EXAMPLE NON-OVERLAPPING HASH RANGES

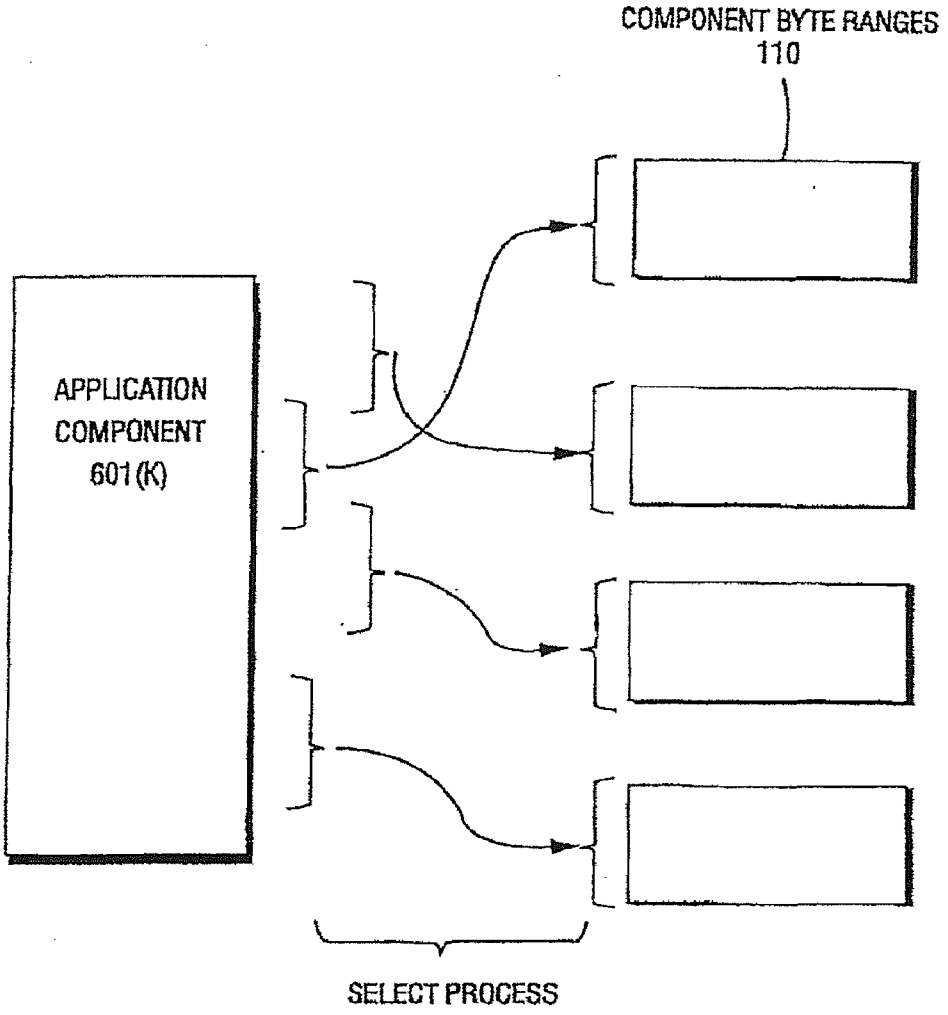


FIG. 20B EXAMPLE OF OVERLAPPING HASH RANGES

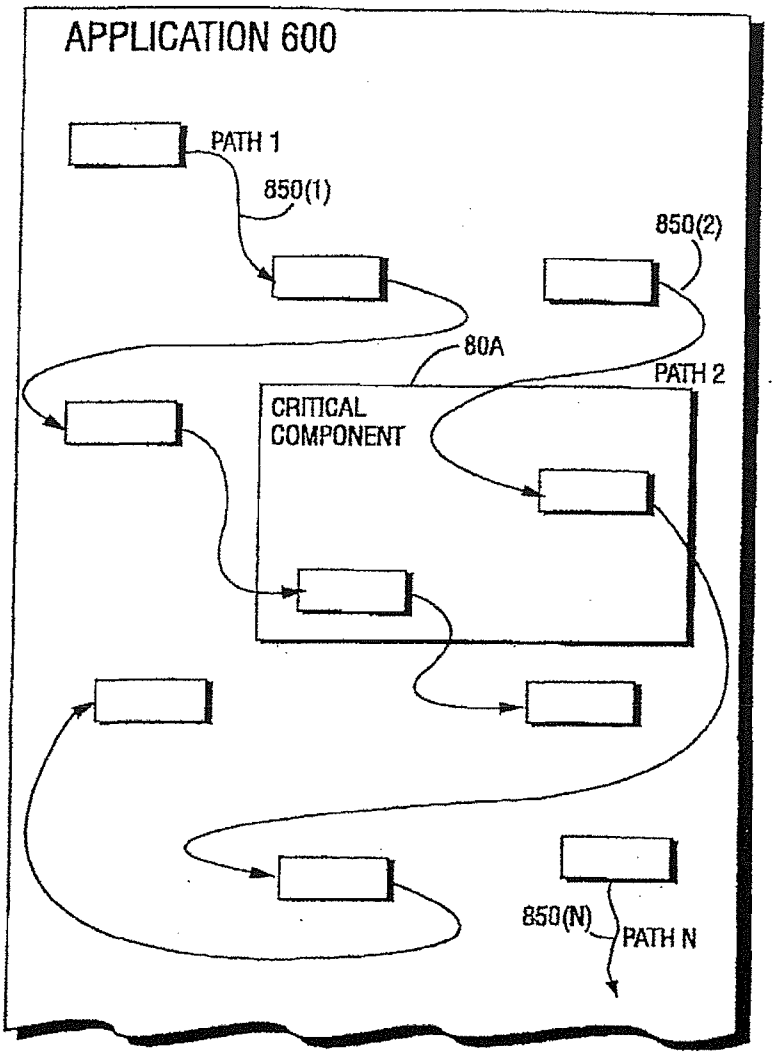


FIG. 20C PSEUDO-RANDOM VALIDATION PATHS IN APPLICATION

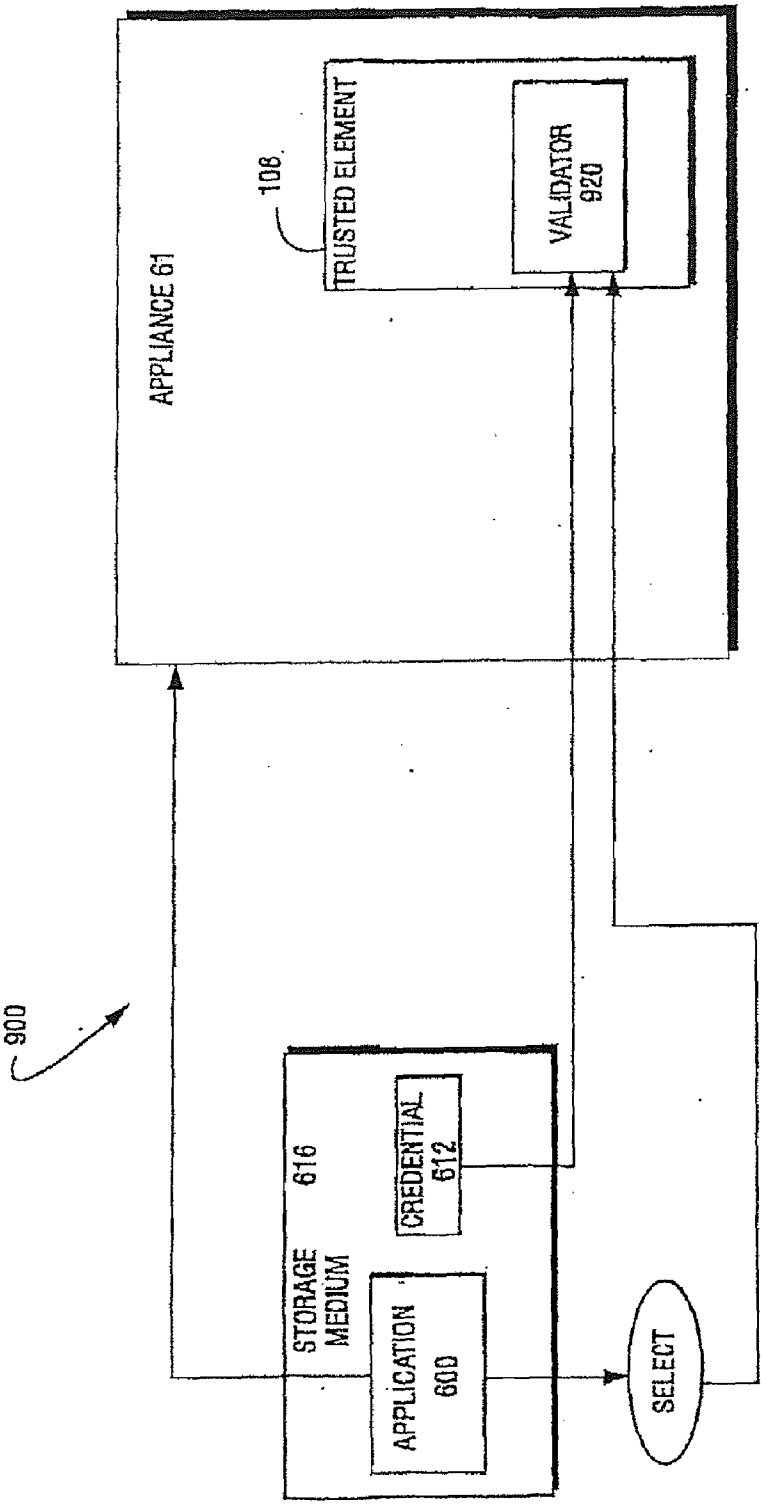
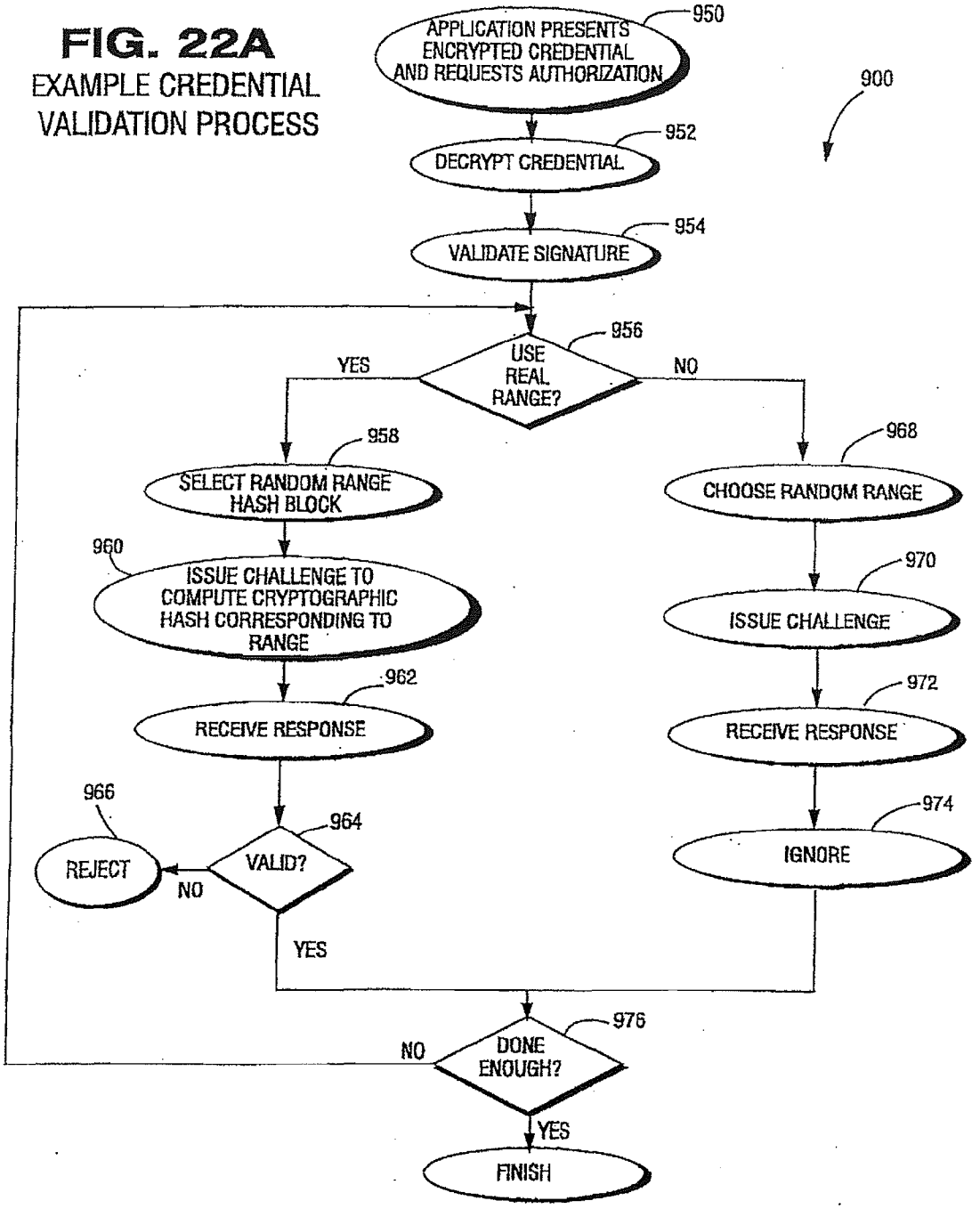


FIG. 21 EXAMPLE CREDENTIAL VALIDATION PROCESS

FIG. 22A
EXAMPLE CREDENTIAL VALIDATION PROCESS



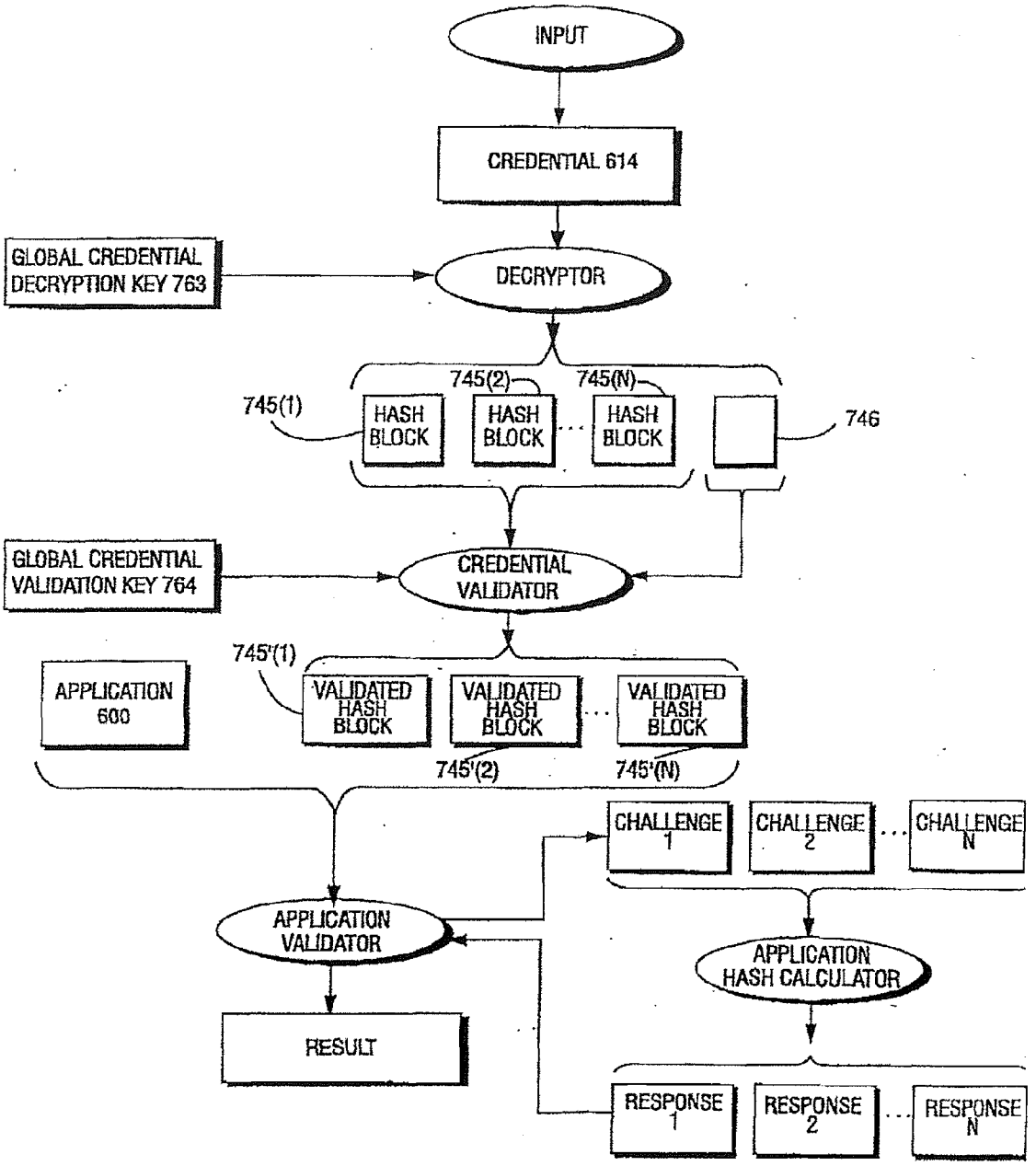


FIG. 22B EXAMPLE CREDENTIAL VALIDATION

SYSTEMS AND METHODS FOR USING CRYPTOGRAPHY TO PROTECT SECURE AND INSECURE COMPUTING ENVIRONMENTS

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 60/146,426, entitled "Systems and Methods for Using Cryptography to Protect Secure and Insecure Computing Environments," filed Jul. 29, 1999, and is related to commonly-assigned U.S. patent application Ser. No. 08/689,754, entitled "Systems and Methods Using Cryptography to Protect Secure Computing Environments," filed Aug. 12, 1996, each of which is hereby incorporated by reference in its entirety.

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FIELD OF THE INVENTION

[0003] The present invention relates to computer security. More specifically, the present invention relates to computer security techniques based at least in part on cryptography, that protect a computer processing environment against potentially harmful computer executables, programs, and/or data; and to techniques for certifying load modules such as executable computer programs or fragments thereof as being authorized for use by secure and/or insecure processing environments.

BACKGROUND OF THE INVENTION

[0004] Computers have become increasingly central to business, finance and other important aspects of our lives. It is now more important than ever to protect computers from "bad" or harmful computer programs. Unfortunately, since many of our most critical business, financial, and governmental tasks now rely heavily on computers, dishonest people have a great incentive to use increasingly sophisticated and ingenious computer attacks.

[0005] Imagine, for example, if a dishonest customer of a major bank could reprogram the bank's computer so it adds to, instead of subtracts from, the customer's account—or diverts a penny to the customer's account from anyone else's bank deposit in excess of $10,000. If successful, such attacks would not only allow dishonest people to steal, but could also undermine society's confidence in the integrity and reliability of the banking system.

[0006] Terrorists can also try to attack us through our computers. We cannot afford to have harmful computer programs destroy the computers driving the greater San Francisco metropolitan air traffic controller network, the New York Stock Exchange, the life support systems of a major hospital, or the Northern Virginia metropolitan area fire and paramedic emergency dispatch service.

[0007] There are many different kinds of "bad" computer programs, including "Trojan horses"—programs that cause a computer to act in a manner not intended by its operator, named after the famous wooden horse of Troy that delivered an attacking army disguised as an attractive gift. Some of the most notorious "bad" computer programs are so-called "computer viruses"—"diseases" that a computer can "catch" from another computer. A computer virus can be a computer program that instructs the computer to do harmful or spurious things instead of useful things—and can replicate itself to spread from one computer to another. Since the computer does whatever its instructions tell it to do, it will carry out the bad intent of a malicious human programmer who wrote the computer virus program, unless the computer is protected from the computer virus program. Special anti-virus protection software exists, but it unfortunately is only partially effective—for example, because new viruses can escape detection until they become widely known and recognized, and because sophisticated viruses can escape detection by masquerading as tasks the computer is supposed to be performing.

[0008] Computer security risks of all sorts—including the risks from computer viruses—have increased dramatically as computers have become increasingly connected to one another over the Internet and by other means. Increased computer connectivity provides increased capabilities, but also creates a host of computer security problems that have not been fully solved. For example, electronic networks are an obvious path for spreading computer viruses. In October 1988, a university student used the Internet (a network of computer networks connected to millions of computers worldwide) to infect thousands of university and business computers with a self-replicating "worm" virus that took over the infected computers and caused them to execute the computer virus instead of performing the tasks they were supposed to perform. This computer virus outbreak (which resulted in a criminal prosecution) caused widespread panic throughout the electronic community.

[0009] Computer viruses are by no means the only computer security risk made even more significant by increased computer connectivity. For example, a significant percentage of the online electronic community has recently become committed to a new "portable" computer language called Java™, developed by Sun Microsystems of Mountain View, Calif. Java was designed to allow computers to interactively and dynamically download computer program code fragments (called "applets") over an electronic network such as the Internet, and to execute the downloaded code fragments locally. The Java programming language's "download and execute" capability is valuable because it allows certain tasks to be performed on local equipment using local resources. For example, a user's computer could run a particularly computationally or data-intensive routine—thus relieving the provider's computer from having to run the task and/or eliminating the need to transmit large amounts of data over the communications path.

[0010] While Java's "download and execute" capability has great potential, it raises significant computer security concerns. For example, Java applets could be written to damage hardware, software, or information on the recipient's computer; to make the computer unstable by depleting its resources; and/or to access confidential information on the computer and send it to someone else without first getting the computer owner's permission. People have expended large amounts of time and effort trying to solve Java's security problems. To alleviate some of these concerns, Sun Micro-

systems has developed a Java interpreter providing certain built-in security features such as:

[0011] a Java verifier that will not let an applet execute until the verifier verifies that the applet does not violate certain rules;

[0012] a Java class loader that treats applets originating remotely differently from those originating locally; and

[0013] a Java security manager that controls access to resources such as files and network access.

In addition, Sun has indicated that future Java interpreters may use digital signatures to authenticate applets.

[0014] Numerous security flaws have been found despite the use of these techniques. Moreover, a philosophy underlying this overall security design is that a user will have no incentive to compromise the security of her own locally installed Java interpreter—and that any such compromise is inconsequential from a system security standpoint because only the user's own computer (and its contents) are at risk. This philosophy—which is typical of many security system designs—is seriously flawed in many useful electronic commerce contexts for reasons described below with reference to commonly-assigned U.S. Pat. No. 5,892,900, entitled "Systems and Methods for Secure Transaction Management and Electronic Rights Protection," issued Apr. 6, 1999 ("the '900 patent"), which is hereby incorporated by reference in its entirety.

[0015] The '900 patent describes a "virtual distribution environment" comprehensively providing overall systems and wide arrays of methods, techniques, structures and arrangements that enable secure, efficient electronic commerce and rights management, including on the Internet or other "Information Super Highway."

[0016] The '900 patent describes, among other things, techniques for providing secure, tamper resistant execution spaces within a "protected processing environment" for computer programs and data. The protected processing environment described in the '900 patent may be hardware based, software-based, or a hybrid. It can execute computer code that the '900 patent refers to as "load modules." (See, for example, FIG. 23 of the '900 patent and corresponding text). These load modules—which can be transmitted from remote locations within secure cryptographic wrappers or "containers"—are used to perform the basic operations of the virtual distribution environment. Load modules may contain algorithms, data, cryptographic keys, shared secrets, and/or other information that permits a load module to interact with other system components (e.g., other load modules and/or computer programs operating in the same or different protected processing environment). For a load module to operate and interact as intended, it should execute without unauthorized modification and its contents may need to be protected from disclosure.

[0017] Unlike many other computer security scenarios, there may be a significant incentive for an owner of a protected processing environment to attack his or her own protected processing environment. For example:

[0018] the owner may wish to "turn off" payment mechanisms necessary to ensure that people delivering content and other value receive adequate compensation; or

[0019] the owner may wish to defeat other electronic controls preventing him or her from performing certain tasks (for example, copying content without authorization); or

[0020] the owner may wish to access someone else's confidential information embodied within electronic controls present in the owner's protected processing environment; or

[0021] the owner may wish to change the identity of a payment recipient indicated within controls such that they receive payments themselves, or to interfere with commerce; or

[0022] the owner may wish to defeat the mechanism(s) that disable some or all functions when a budget has been exhausted, or audit trails have not been delivered.

[0023] Security experts can often be heard to say that to competently do their job, they must "think like an attacker." For example, a successful home security system installer must try to put herself in the place of a burglar trying to break in. Only by anticipating how a burglar might try to break into a house can the installer successfully defend the house against burglary. Similarly, computer security experts must try to anticipate the sorts of attacks that might be brought against a presumably secure computer system.

[0024] From this "think like an attacker" viewpoint, introducing a bogus load module is one of the strongest forms of attack (by a protected processing environment user or anyone else) on the virtual distribution environment disclosed in the '900 patent. Because load modules have access to internal protected data structures within protected processing environments and also (at least to an extent) control the results brought about by those protected processing environments, bogus load modules can perform almost any action possible in the virtual distribution environment without being subject to intended electronic controls (putting aside for the moment additional possible local protections such as addressing and/or ring protection, and also putting aside system level fraud and other security related checks). Especially likely attacks may range from straightforward changes to protected data (for example, adding to a budget, billing for nothing instead of the desired amount, etc.) to wholesale compromise (for example, using a load module to expose a protected processing environment's cryptographic keys). For at least these reasons, the methods for validating the origin and soundness of a load module are critically important.

[0025] A variety of techniques can be used to secure protected processing environments against inauthentic load modules introduced by the computer owner, user, or any other party, including for example:

[0026] Encrypting and authenticating load modules whenever they are shared between protected processing environments via a communications path outside of a tamper-resistant barrier and/or passed between different virtual distribution environment participants;

[0027] Using digital signatures to determine if load module executable content is intact and was created by a trusted source (i.e., one with a correct certificate for creating load modules);

[0028] Strictly controlling initiation of load module execution by use of encryption keys, digital signatures, and/or tags;

[0029] Carefully controlling the process of creating, replacing, updating, or deleting load modules; and

[0030] Maintaining shared secrets (e.g., cryptographic keys) within a tamper resistant enclosure that the owner of the electronic appliance cannot easily tamper with.

SUMMARY OF THE INVENTION

[0031] The present invention provides improved techniques for protecting secure computation and/or execution

spaces from unauthorized (and potentially harmful) load modules or other executables or associated data. In accordance with one aspect provided by the present invention, one or more trusted verifying authorities validate load modules or other executables by analyzing and/or testing them. A verifying authority digitally signs and certifies the load modules or other executables that it has verified (using, for example, a public key based digital signature and/or a certificate based thereon).

[0032] Protected execution spaces such as protected processing environments can be programmed or otherwise conditioned to accept only those load modules or other executables bearing a digital signature/certificate of an accredited (or particular) verifying authority. Tamper resistant barriers may be used to protect this programming or other conditioning. The assurance levels described below are a measure or assessment of the effectiveness with which this programming or other conditioning is protected.

[0033] A web of trust may stand behind a verifying authority. For example, a verifying authority may be an independent organization that can be trusted by all electronic value chain participants not to collaborate with any particular participant to the disadvantage of other participants. A given load module or other executable may be independently certified by any number of authorized verifying authority participants. If a load module or other executable is signed, for example, by five different verifying authority participants, a user will have (potentially) a higher likelihood of finding one that they trust. General commercial users may insist on several different certifiers, and government users, large corporations, and international trading partners may each have their own unique "web of trust" requirements. This "web of trust" prevents value chain participants from conspiring to defraud other value chain participants.

[0034] In accordance with another aspect provided by this invention, each load module or other executable has specifications associated with it describing the executable, its operations, content, and functions. Such specifications could be represented by any combination of specifications, formal mathematical descriptions that can be verified in an automated or other well-defined manner, or any other forms of description that can be processed, verified, and/or tested in an automated or other well-defined manner. The load module or other executable is preferably constructed using a programming language (e.g., a language such as Java or Python) and/or design/implementation methodology (e.g., Gypsy, FDM) that can facilitate automated analysis, validation, verification, inspection, and/or testing.

[0035] A verifying authority analyzes, validates, verifies, inspects, and/or tests the load module or other executable, and compares its results with the specifications associated with the load module or other executable. A verifying authority may digitally sign or certify only those load modules or other executables having proper specifications—and may include the specifications as part of the material being signed or certified.

[0036] A verifying authority may instead, or in addition, selectively be given the responsibility for analyzing the load module and generating a specification for it. Such a specification could be reviewed by the load module's originator and/or any potential users of the load module.

[0037] A verifying authority may selectively be given the authority to generate an additional specification for the load module, for example by translating a formal mathematical specification to other kinds of specifications. This authority could be granted, for example, by a load module originator wishing to have a more accessible, but verified (certified), description of the load module for purposes of informing other potential users of the load module.

[0038] Additionally, a verifying authority may selectively be empowered to modify the specifications to make them accurate—but may refuse to sign or certify load modules or other executables that are harmful or dangerous irrespective of the accuracy of their associated specifications. The specifications may in some instances be viewable by ultimate users or other value chain participants—providing a high degree of assurance that load modules or other executables are not subverting the system and/or the legitimate interest of any participant in an electronic value chain the system supports.

[0039] In accordance with another aspect provided by the present invention, an execution environment protects itself by deciding—based on digital signatures, for example—which load modules or other executables it is willing to execute. A digital signature allows the execution environment to test both the authenticity and the integrity of the load module or other executables, as well permitting a user of such executables to determine their correctness with respect to their associated specifications or other descriptions of their behavior, if such descriptions are included in the verification process.

[0040] A hierarchy of assurance levels may be provided for different protected processing environment security levels. Load modules or other executables can be provided with digital signatures associated with particular assurance levels. Appliances assigned to particular assurance levels can protect themselves from executing load modules or other executables associated with different assurance levels. Different digital signatures and/or certificates may be used to distinguish between load modules or other executables intended for different assurance levels. This strict assurance level hierarchy provides a framework to help ensure that a more trusted environment can protect itself from load modules or other executables exposed to environments with different work factors (e.g., less trusted or tamper resistant environments). This can be used to provide a high degree of security compartmentalization that helps protect the remainder of the system should parts of the system become compromised.

[0041] For example, protected processing environments or other secure execution spaces that are more impervious to tampering (such as those providing a higher degree of physical security) may use an assurance level that isolates them from protected processing environments or other secure execution spaces that are relatively more susceptible to tampering (such as those constructed solely by software executing on a general purpose digital computer in a non-secure location).

[0042] A verifying authority may digitally sign load modules or other executables with a digital signature that indicates or implies an assurance level. A verifying authority can use digital signature techniques to distinguish between assurance levels. As one example, each different digital signature may be encrypted using a different verification key and/or fundamentally different encryption, one-way hash, and/or other techniques. A protected processing environment or other secure execution space protects itself by executing only those load modules or other executables that have been digitally signed for its corresponding assurance level.

[0043] The present invention may use a verifying authority and the digital signatures it provides to compartmentalize the different electronic appliances depending on their level of security (e.g., work factor or relative tamper resistance). In particular, a verifying authority and the digital signatures it provides isolate appliances with significantly different work factors, thus preventing the security of high work factor appliances from collapsing into the security of low work factor appliances due to the free exchange of load modules or other executables.

[0044] Encryption can be used in combination with the assurance level scheme discussed above to ensure that load modules or other executables can be executed only in specific environments or types of environments. The secure way to ensure that a load module or other executable cannot execute in a particular environment is to ensure that the environment does not have the key(s) necessary to decrypt it. Encryption can rely on multiple public keys and/or algorithms to transport basic key(s). Such encryption protects the load module or other executable from disclosure to environments (or assurance levels of environments) other than the one(s) it is intended to execute in.

[0045] In accordance with another aspect provided by this invention, a verifying authority can digitally sign a load module or other executable with several different digital signatures and/or signature schemes. A protected processing environment or other secure execution space may require a load module or other executable to present multiple digital signatures before accepting it. An attacker would have to "break" each (all) of the several digital signatures and/or signature schemes to create an unauthorized load module or other executable that would be accepted by the protected processing environment or other secure execution space. Different protected processing environments (secure execution spaces) might examine different subsets of the multiple digital signatures, so that compromising one protected processing environment (secure execution space) will not compromise all of them. As an optimization, a protected processing environment or other secure execution space might verify only one of the several digital signatures (for example, chosen at random each time an executable is used), thereby speeding up the digital signature verification while still maintaining a high degree of security.

[0046] In accordance with yet another aspect provided by the present invention(s), a tamper-resistant mechanism is provided for allowing a trusted element to validate certifications presented by applications intended to be run or otherwise used, at least in part, within an insecure environment. Such techniques can detect whether applications have been certified and/or modified (i.e., tampered with) in a way that makes them no longer trustworthy.

[0047] Briefly, examples of these techniques provide a credential having multiple elements covering corresponding parts of the application—and preferably having a combined overall effect of covering all (or a substantial portion) of the application. For example, the credential can provide verification information for different byte ranges, virtual paths, and/or other portions of the application. Sufficient verification information may be provided to substantially cover the application, or at least those portions of the application deemed to be the most likely to be tampered with.

[0048] To validate the credential, the trusted element first authenticates the credential, and then issue challenges based on different parts of the authenticated credential that the trusted element selects in an unpredictable (e.g., random) way. For example, the trusted element can repeatedly challenge the application or other agent to provide (or can itself generate) a cryptographic hash value corresponding to application portions or ranges that the trusted element randomly selects, The trusted element can compare the responses to its challenges with information the authenticated credential provides, and deny service or take other appropriate action if the comparison fails. The challenges may be repeated on an ongoing basis (e.g., during execution of the application) and/or interleaved with non-predetermined challenges not defined by the credential, to increase the tamper-resistance of the verification process.

[0049] These and other features and advantages of the present invention will be presented in more detail in the following detailed description and the accompanying figures which illustrate by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0050] The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings, wherein like reference numerals designate like structural elements, and in which:

[0051] FIG. **1** illustrates how defective or bogus load modules can wreak havoc in the electronic community;

[0052] FIG. **2** shows an example verification authority that protects the electronic community from unauthorized load modules;

[0053] FIG. **3** shows how a protected processing environment can distinguish between load modules that have been approved by a verifying authority and those that have not been approved;

[0054] FIG. **4** shows an example process a verifying authority may perform to authenticate load modules;

[0055] FIG. **5** shows how a verifying authority can create a certifying digital signature;

[0056] FIG. **6** shows how a protected processing environment can securely authenticate a verifying authority's digital signature to guarantee the integrity of the corresponding load module;

[0057] FIG. **7** shows how several different digital signatures can be applied to the same load module;

[0058] FIG. **8** shows how a load module can be distributed with multiple digital signatures;

[0059] FIG. **8**A shows how key management can be used to compartmentalize protected processing environments;

[0060] FIGS. **9** shows how a load module can be segmented and each segment protected with a different digital signature;

[0061] FIGS. **10**A, **10**B, and **10**C show how different assurance level electronic appliances can be provided with different cryptographic keys for authenticating verifying authority digital signatures;

[0062] FIGS. **11**A, **11**B, and **11**C show how a verifying authority can use different digital signatures to designate the same or different load modules as being appropriate for execution by different assurance level electronic appliances;

[0063] FIGS. **12**, **13**, and **13**A show how assurance level digital signatures can be used to isolate electronic appliances or appliance types based on work factor and/or tamper resistance to reduce overall security risks;

[0064] FIG. **14** shows example overall steps that may be performed within an electronic system (such as, for example, a virtual distribution environment) to test, certify, distribute and use executables;

[0065] FIG. **15** shows an example appliance having both secure and insecure execution spaces;

[0066] FIG. **16** shows an example process for certifying applications intended to be run in insecure execution spaces;

[0067] FIG. **16**A shows an example application including multiple components;

[0068] FIG. **17** shows an example overall credential creation process;

[0069] FIG. **18** shows an example range hash block;

[0070] FIG. **19** shows example credential creation from a set of range hash blocks;

[0071] FIG. **20** shows an example threat model;

[0072] FIG. **20**A shows an example of non-overlapping hash ranges;

[0073] FIG. **20**B shows an example of overlapping hash ranges;

[0074] FIG. **20**C shows an example use of pseudo-random validation paths within an application;

[0075] FIG. **21** shows an example simplified credential validation process; and

[0076] FIGS. **22**A and **22**B show an example more detailed credential validation process.

DETAILED DESCRIPTION

[0077] A detailed description of the present invention is provided below. While the invention is described in conjunction with several embodiments, it should be understood that the invention is not limited to any one embodiment, and encompasses instead, numerous alternatives, modifications and equivalents. While numerous specific details are set forth in the following description in order to provide a thorough understanding of the present invention, the present invention may be practiced without some or all of these details. Moreover, for the purpose of clarity, certain specifics relating to technical material that is known in the art related to the invention have not been described in detail in order to avoid unnecessarily obscuring the present invention.

[0078] FIG. **1** shows how defective, bogus, and/or unauthorized computer information can wreak havoc within an electronic system **50**. In this example, provider **52** is authorized to produce and distribute load modules **54** for use by different users or consumers **56**. FIG. **1** shows load module **54** as a complicated looking machine part for purposes of illustration only; the load module preferably comprises one or more computer instructions and/or data elements used to assist, allow, prohibit, direct, control or facilitate at least one task performed at least in part by an electronic appliance such as a computer. For example, load module **54** may comprise all or part of an executable computer program and/or associated data ("executable"), and may constitute a sequence of instructions or steps that bring about a certain result within a computer or other computation element.

[0079] FIG. **1** shows a number of electronic appliances **61** such as, for example, a set top box or home media player **58**, a personal computer **60**, and a multi-media player **62**. Each of appliances **58**, **60**, **62** may include a secure execution space. One particular example of a secure execution space is a protected processing environment **108**, such as that described in the '900 patent. Protected processing environments **108** provide a secure execution environment in which appliances **58**, **60**, **62** may securely execute load modules **54** to perform useful tasks. For example:

[0080] Provider **52** might produce a load module **54***a* for use by the protected processing environment **108**A within set top box or home media player **58**. Load module **54***a* could, for example, enable the set top box/home media player **58** to play a movie, concert or other interesting program, charge users **56***a* a "pay per view" fee, and ensure that the fee is paid to the appropriate rights holder (for example, the film studio, concert promoter, or other organization that produced the program material).

[0081] Provider **52** might produce another load module **54***b* for delivery to personal computer **60**'s protected processing environment **108**B. The load module **54***b* might enable personal computer **60** to perform a financial transaction, such as, for example, home banking, a stock trade, or an income tax payment or reporting.

[0082] Provider **52** could produce a load module **54***c* for delivery to multi-media player **62**'s protected processing environment **108***c*. This load module **54***c* might allow user **56***c* to view a particular multi-media presentation while preventing the user from making a copy of the presentation-or it could control a portion of a transaction (e.g. a meter that records usage, and is incorporated into a larger transaction involving other load modules associated with interacting with a multi-media piece). (Load modules associated with the financial portion of a transaction, for example, may often be self-contained and independent).

[0083] FIG. **1** also shows an unauthorized and/or disreputable load module provider **64**. Unauthorized provider **64** knows how to make load modules that look a lot like the load modules produced by authorized load module provider **52**, but are defective or even destructive. Unless precautions are taken, the unauthorized load module **54***d* made by unauthorized producer **64** will be able to run on protected processing environments **108** within appliances **58**, **60** and **62**, and may cause serious harm to users **56** and/or to the integrity of system **50**. For example:

[0084] unauthorized provider **64** could produce a load module **54***d* that is quite similar to authorized load module **54***a* intended to be used by set top box or home media player **58**. The unauthorized load module **54***d* might allow protected processing environment **108**A within set top box/home media player **58** to present the very same program material, but divert some or all of the user's payment to unauthorized producer **64**, thereby defrauding the rights holders in the program material that the users watch.

[0085] Unauthorized provider **64** might produce an unauthorized version of load module **54***b* that could, if run by personal computer **60**'s protected processing environment **108**B, disclose the user **56***b*'s bank and credit card account numbers to unauthorized provider **64** and/or divert electronic or other funds to the unauthorized provider.

[0086] Unauthorized provider **64** could produce an unauthorized version of load module **54***c* that could damage the protected processing environment **108**C within multi media player **62**—erasing data it needs for its operation and making it unusable. Alternatively, an unauthorized version of load module **54***c* could defeat

the copy protection provided by multi-media player **62**'s protected processing environment, causing the makers of multi media programs to lose substantial revenues through unauthorized copying—or could defeat or alter the part of the transaction provided by the load module (e.g., billing, metering, maintaining an audit trail, etc.).

[0087] FIG. **2** shows how a verifying authority **100** can prevent the problems shown in FIG. **1**. In this example, authorized provider **52** submits load modules **54** to verifying authority **100**. Verifying authority **100** carefully analyzes the load modules **54** (see **102**), testing them to make sure they do what they are supposed to do and do not compromise or harm system **50**. If a load module **54** passes the tests verifying authority **100** subjects it to, a verifying authority may affix a digital "seal of approval" (see **104**) to the load module.

[0088] Protected processing environments **108** can use this digital seal of approval **106** (which may comprise one or more digital signatures) to distinguish between authorized and unauthorized load modules **54**. FIG. **3** illustrates how an electronic protected processing environment **108** can use and rely on a verifying authority's digital seal of approval **106**. In this example, the protected processing environment **108** can distinguish between authorized and unauthorized load modules **54** by examining the load module to see whether it bears the seal of verifying authority **100**. Protected processing environment **108** will execute the load module **54***a* with its processor **110** only if the load module bears a verifying authority's seal **106**. Protected processing environment **108** discards and does not use any load module **54** that does not bear this seal **106**. In this way, protected processing environment **108** securely protects itself against unauthorized load modules **54** such as, for example, the defective load module **54***d* made by disreputable load module provider **64**.

[0089] FIG. **4** shows the analysis and digital signing steps **102**, **104** performed by verifying authority **100** in this example. Provider **52** may provide, with each load module **54**, associated specifications **110** identifying the load module and describing the functions the load module performs. In this example, these specifications **110** are illustrated as a manufacturing tag, but preferably comprise a data file associated with and/or attached to the load module **54**.

[0090] Verifying authority **100** uses an analyzing tool(s) **112** to analyze and test load module **54** and determine whether it performs as specified by its associated specifications **110**—that is, whether the specifications are both accurate and complete. FIG. **4** illustrates an analysis tool **112** as a magnifying glass; verifying authority **100** may not rely on visual inspection only, but instead preferably uses one or more computer-based software testing techniques and/or tools to verify that the load module performs as expected, matches specifications **110**, is not a "virus," and includes no significant detectable "bugs" or other harmful functionality. (See, for example, Pressman, "Software Engineering: A Practitioner's Approach," 3d ed., chapters 18 and 19, pages 595-661 (McGraw-Hill 1992), and the various books and papers referenced therein). Although it has been said that "testing can show only the presence of bugs, not their absence," such testing (in addition to ensuring that the load module **54** satisfies its specifications **110**) can provide added degrees of assurance that the load module isn't harmful and will work as it is supposed to.

[0091] Verifying authority **100** is preferably a trusted, independent third party such as an impartial, well respected independent testing laboratory. Therefore, all participants in an electronic transaction involving load module **54** can trust a verifying authority **100** as performing its testing and analysis functions competently and completely objectively and impartially. As described above, there may be several different verifying authorities **100** that together provide a "web of trust." Several different verifying authorities may each verify and digitally sign the same load module, thus increasing the likelihood that a particular value chain participant will trust one of them, and decreasing the likelihood of collusion or fraud. Electronic value chain participants may rely upon different verifying authorities **100** to certify different types of load modules. For example, one verifying authority **100** trusted by and known to financial participants might verify load modules relating to financial aspects of a transaction (e.g., billing), whereas another verifying authority **100'** trusted by and known to participants involved in using the "information exhaust" provided by an electronic transaction might be used to verify load modules relating to usage metering aspects of the same transaction.

[0092] Once verifying authority **100** is satisfied with load module **54**, it affixes its digital seal of approval **106** to the load module. FIG. **4** illustrates the digital sealing process as being performed by a stamp **114**, but in a preferred embodiment the digital sealing process is actually performed by creating a digital signature using a well-known process, such as one or more of the techniques described in Schneier, "Applied Cryptography," 2d ed., chapter 20, pages 483-502 (John Wiley & Sons 1996), which is hereby incorporated by reference. This digital signature, certificate, or seal creation process is illustrated in FIG. **5**. For convenience, information on suitable digital signature techniques has also been set forth in Appendix A hereto.

[0093] In the FIG. **5** process, load module **54** (along with specifications **110** if desired) is processed to yield a message digest **116** using one or more one-way hash functions selected to provide an appropriate resistance to algorithmic attack. For example, use could be made of the well-known transformation processes discussed in the Schneier text at chapter 18, pages 429-455, which is hereby incorporated by reference. A one-way hash function 115 provides a "fingerprint" (message digest **116**) that is effectively unique to load module **54**. The one-way hash function transforms the contents of load module **54** into message digest **116** based on a mathematical function. This one-way hash mathematical function has the characteristic that it is easy to calculate message digest **116** from load module **54**, but it is hard (computationally infeasible) to calculate load module **54** starting from message digest **116** and it is also hard (computationally infeasible) to find another load module **54'** that will transform to the same message digest **116**. There are many potential candidate functions (e.g., MD5, SHA, MAC), families of functions (e.g., MD5, or SHA with different internal constants), and keyed functions (e.g., message authentication codes based on block ciphers such as DES) that may be employed as one-way hash functions in this scheme. Different functions may have different cryptographic strengths and weaknesses so that techniques which may be developed to defeat one of them are not necessarily applicable to others.

[0094] Message digest **116** may then be encrypted using asymmetric key cryptography. FIG. **5** illustrates this encryption operation using the metaphor of a strong box **118**. The message digest **116** is placed into strong box **118**, and the strongbox is locked with a lock **120** having two key slots opened by different ("asymmetrical") keys. A first key **122**

(sometimes called the "private" key) is used to lock the lock. A second (different) key **124** (sometimes called the "public" key) must be used to open the lock once the lock has been locked with the first key. The encryption algorithm and key length are selected so that it is computationally infeasible to calculate first key **122** given access to second key **124**, the public key encryption algorithm, the clear text message digest **116**, and the encrypted digital signature **106**. There are many potential candidate algorithms for this type of asymmetric key cryptography (e.g., RSA, DSA, El Gamal, Elliptic Curve Encryption). Different algorithms may have different cryptographic strengths and weaknesses so that techniques which may be developed to defeat one of them are not necessarily applicable to others.

[0095] In this case the first key is owned by verifying authority **100** and is kept highly secure (for example, using standard physical and procedural measures typically employed to keep an important private key secret while preventing it from being lost). Once message digest **116** is locked into strong box **118** using the first key **122**, the strong box can be opened only by using the corresponding second key **124**. Note that other items (e.g., further identification information, a time/date stamp, etc.) can also be placed within strong box **106**.

[0096] FIG. **6** shows how a protected processing environment **108** authenticates the digital signature **106** created by the FIG. **5** process. Second key **124** and the one-way hash algorithm are first securely provided to the protected processing environment. For example, a secure key exchange protocol can be used as described in connection with FIG. 64 of the '900 patent. Public key cryptography allows second key **124** to be made public without compromising first key **122**. However, in this example, protected processing environment **108** preferably keeps the second key **124** (and, if desired, also the one-way hash algorithm and/or its associated key) secret to further increase security.

[0097] Maintaining public verification key **124** as a secret within tamper resistant protected processing environment **108** greatly complicates the job of generating bogus digital signatures, If the attacker does not possess second key **124**, the difficulty of an algorithmic attack or cryptanalytic attack on the verification digital signature algorithm is significantly increased, and the attacker might be reduced to exhaustive search (brute force) type attacks which would be even less practical because the search trials would require attempting to present a bogus load module **54** to protected processing environment **108**, which, after a few such attempts, is likely to refuse all further attempts. Keeping second key **124** secret also necessitates a multi-disciplinary attack: an attacker must both (A) extract the secret from protected processing environment **108**, and (B) attack the algorithm. It may be substantially less likely that a single attacker may have expertise in each of these two specialized disciplines.

[0098] In addition, maintaining the public key within a tamper-resistant environment forecloses the significant threat that the owner of protected processing environment **108** may himself attack the environment. For example, if the owner could replace the appropriate public key **124** with his own substitute public key, the owner could force the protected processing environment **108** to execute load modules **54** of his own design, thereby compromising the interests of others in enforcing their own controls within the owner's protected processing environment. For example, the owner could turn off the control that required him to pay for watching, or the control that prohibited him from copying content. Since protected processing environment **108** can support a "virtual business presence" by parties other than the owner, it is important for the protected processing environment to be protected against attacks from the owner.

[0099] The load module **54** and its associated digital signature **106** are then delivered to the protected processing environment **108**. (These items can be provided together at the same time, independently, or at different times.) Protected processing environment **108** applies the same one way hash transformation on load module **54** that a verifying authority **100** applied. Since protected processing environment **108** starts with the same load module **54** and uses the same one-way hash function **115**, it should generate the same message digest **116'**.

[0100] Protected processing environment **108** then decrypts digital signature **106** using the second key **124**—i.e., it opens strongbox **118** to retrieve the message digest **116** that a verifying authority **100** placed therein. Protected processing environment **108** compares the version of message digest **116** it obtains from the digital signature **106** with the version of message digest **116'** it calculates itself from load module **54** using the one way hash transformation **115**. The message digests **116**, **116'** should be identical. If they do not match, digital signature **106** is not authentic or load module **54** has been changed, and protected processing environment **108** rejects load module **54**.

[0101] FIG. **7** shows that multiple digital signatures **106(1)**, **106(2)**, . . . **106**(N) can be created for the same load module **54**. For example:

- **[0102]** one digital signature **106(1)** can be created by encrypting message digest **116(1)** with a private key **122(1)**;
- **[0103]** another (different) digital signature **106(2)** can be created by encrypting the message digest **116(2)** with a different private key **122(2)**, possibly employing a different signature algorithm; and
- **[0104]** a still different digital signature **106**(N) can be generated by encrypting the message digest **116**(N) using a still different private key **122**(N), possibly employing yet another signature algorithm.

[0105] The public key **124(1)** corresponding to private key **122(1)** acts only to decrypt (authenticate) digital signature **106(1)**. Similarly, digital signature **106(2)** can only be decrypted (authenticated) using public key **124(2)** corresponding to the private key **122(2)**. Public key **124(1)** will not "unlock" digital signature **106(2)** and public key **124(2)** will not unlock digital signature **106(1)**.

[0106] Different digital signatures **106(1)**, **106**(N) can also be made by using different one way hash functions **115** and/or different encryption algorithms. As shown in FIG. **8**, a load module **54** may have multiple different types of digital signatures **106** associated with it. Requiring a load module **54** to present, to a protected processing environment **108**, multiple digital signatures **106** generated using fundamentally different techniques decreases the risk that an attacker can successfully manufacture a bogus load module **54**.

[0107] For example, as shown in FIG. **8**, the same load module **54** might be digitally signed using three different private keys **122**, cryptographic algorithms, and/or hash algorithms. If a given load module **54** has multiple distinct digital signatures **106** each computed using a fundamentally different technique, the risk of compromise is substantially lowered. A single algorithmic advance is unlikely to result in

simultaneous success against both (or multiple) cryptographic algorithms. The two digital signature algorithms in widespread use today (RSA and DSA) are based on distinct mathematical problems (factoring in the case of RSA, discrete logs for DSA). The most currently popular one-way hash functions (MD4/MD5 and SHA) have similar internal structures, possibly increasing the likelihood that a successful attack against one would lead to a success against another. However, hash functions can be derived from any number of different block ciphers (e.g., SEAL, IDEA, triple-DES) with different internal structures; one of these might be a good candidate to complement MD5 or SHA.

[0108] Multiple signatures as shown in FIG. **8** impose a cost of additional storage for the signatures **106** in each protected load module **54**, additional code in the protected processing environment **108** to implement additional algorithms, and additional time to verify the digital signatures (as well as to generate them at verification time). As an optimization to the use of multiple keys or algorithms, an appliance **61** might verify only a subset of several signatures associated with a load module **54** (chosen at random) each time the load module is used. This would speed up signature verification while maintaining a high probability of detection. For example, suppose there are one hundred private verification keys, and each load module **54** carries one hundred digital signatures. Suppose each protected processing environment **108**, on the other hand, knows only a few (e.g., ten) of the corresponding public verification keys randomly selected from the set. A successful attack on that particular protected processing environment **108** would permit it to be compromised and would also compromise any other protected processing environment possessing and using precisely that same set of ten keys. However, it would not compromise most other protected processing environments, since they would employ a different subset of the keys used by verifying authority **100**.

[0109] FIG. **8**A shows a simplified example of different processing environments **108**(**1**), . . . **108**(N) possessing different subsets of public keys used for digital signature authentication, thereby compartmentalizing the protected processing environments based on key management and availability. The FIG. **8**A illustration shows each protected processing environment **108** having only one public key **124** that corresponds to one of the digital signatures **106** used to sign load module **54**. As explained above, any number of digital signatures **106** may be used to sign the load module **54**, and different protected processing environments **108** may possess any subset of the corresponding public keys.

[0110] FIG. **9** shows that a load module **54** may comprise multiple segments **55**(**1**), **55**(**2**), **55**(**3**) signed using different digital signatures **106**. For example:

[0111] a first load module segment **55**(**1**) might be signed using a digital signature **106**(**1**);

[0112] a second load module segment **55**(**2**) might be digitally signed using a second digital signature **106**(**2**); and

[0113] a third load module segment **55**(**3**) might be signed using a third digital signature **106**(**3**).

[0114] These three signatures **106**(**1**), **106**(**2**), **106**(**3**) could all be affixed by the same verifying authority **100**, or they could be affixed by three different verifying authorities (providing a "web of trust"). (In another model, a load module is verified in its entirety by multiple parties—if a user trusts any of them, she can trust the load module.) A protected processing environment **108** would need to have all three corresponding public keys **124**(**1**), **124**(**2**), **124**(**3**) to authenticate the entire load module **54**—or the different load module segments could be used by different protected processing environments possessing the corresponding different keys **124**(**1**), **124**(**2**), **124**(**3**). Different signatures **106**(**1**), **106**(**2**), **106**(**3**) could be calculated using different signature and/or one-way hash algorithms to increase the difficulty of defeating them by cryptanalytic attack.

Assurance Levels

[0115] Verifying authority **100** can use different digital signing techniques to provide different "assurance levels" for different kinds of electronic appliances **61** having different "work factors" or levels of tamper resistance. FIGS. **10**A-**10**C show an example assurance level hierarchy providing three different assurance levels for different electronic appliance types:

[0116] Assurance level I might be used for an electronic appliance(s) **61** whose protected processing environment **108** is based on software techniques that may be somewhat resistant to tampering. An example of an assurance level I electronic appliance **61**A might be a general purpose personal computer that executes software to create protected processing environment **108**.

[0117] An assurance level II electronic appliance **61**B may provide a protected processing environment **108** based on a hybrid of software security techniques and hardware- based security techniques. An example of an assurance level II electronic appliance **61**B might be a general purpose personal computer equipped with a hardware integrated circuit secure processing unit ("SPU") that performs some secure processing outside of the SPU. (See FIG. 10 of the '900 patent and associated text), Such a hybrid arrangement might be relatively more resistant to tampering than a software-only implementation.

[0118] The assurance level III appliance **61**C shown is a general purpose personal computer equipped with a hardware-based secure processing unit providing and completely containing protected processing environment **108**. (See, for example, FIGS. 6 and 9 of the '900 patent). A silicon-based special purpose integrated circuit security chip is relatively more tamper-resistant than implementations relying on software techniques for some or all of their tamper-resistance.

[0119] In this example, verifying authority **100** digitally signs load modules **54** using different digital signature techniques (for example, different private keys **122**) based on assurance level, The digital signatures **106** applied by verifying authority **100** thus securely encode the same (or different) load module **54** for use by appropriate corresponding assurance level electronic appliances **61**.

[0120] The assurance level in this example may be assigned to a particular protected processing environment **108** at initialization (e.g., at the factory in the case of hardware-based secure processing units). Assigning the assurance level at initialization time facilitates the use of key management (e.g., secure key exchange protocols) to enforce isolation based on assurance level, For example, since establishment of assurance level is done at initialization time, rather than in the field in this example, the key exchange mechanism can be used to provide new keys (assuming an assurance level has been established correctly).

[0121] Within a protected processing environment **108**, as shown in FIGS. **10**A-**10**C, different assurance levels may be assigned to each separate instance of a channel (see, e.g., the '900 patent, FIG. 15) contained therein. In this way, each secure processing environment and host event processing environment (see, e.g., the '900 patent, FIG. 10 and associated description) contained within an instance of a protected processing environment **108** may contain multiple instances of a channel, each with independent and different assurance levels. The nature of this feature of the invention permits the separation of different channels within a protected processing environment **108** from each other, each channel possibly having identical, shared, or independent sets of load modules for each specific channel limited solely to the resources and services authorized for use by that specific channel. In this way, the security of the entire protected processing environment is enhanced and the effect of security breaches within each channel is compartmentalized solely to that channel.

[0122] As shown in FIGS. **11**A-**11**C, different digital signatures and/or signature algorithms corresponding to different assurance levels may be used to allow a particular execution environment to protect itself from particular load modules **54** that are accessible to other classes or assurance levels of electronic appliances. As shown in FIGS. **11**A-**11**C:

[0123] A protected processing environment(s) of assurance level I protects itself (themselves) by executing only load modules **54** sealed with an assurance level digital signature **106**(I). Protected processing environment(s) **108** having an associated assurance level I is (are) securely issued a public key **124**(I) that can "unlock" the level I digital signature.

[0124] Similarly, a protected processing environment(s) of assurance level II protects itself (themselves) by executing only the same (or different) load modules **54** sealed with a level II digital signature **106**(II). Such a protected processing environment **108** having an associated corresponding assurance level II possesses a public key **124**(II) used to unlock the level II digital signature.

[0125] A protected processing environment(s) **108** of assurance level III protects itself (themselves) by executing only load modules **54** having a digital signature **106**(III) for assurance level III. Such an assurance level III protected processing environment **108** possesses a corresponding assurance level III public key **124**(III). Key management encryption (not signature) keys can allow this protection to work securely.

[0126] In this example, electronic appliances **61** of different assurance levels can communicate with one another and pass load modules **54** between one another—an important feature providing a scaleable virtual distribution environment involving all sorts of different appliances (e.g., personal computers, laptop computers, handheld computers, television sets, media players, set top boxes, internet browser appliances, smart cards, mainframe computers, etc.). The present invention uses verifying authority **100** and the digital signatures it provides to compartmentalize the different electronic appliances depending on their level of security (e.g., work factor or relative tamper resistance). In particular, verifying authority **100** and the digital signatures it provides isolate appliances with significantly different work factors, thus preventing the security of high work factor appliances from collapsing into the security of low work factor appliances due to the free exchange of load modules **54**.

[0127] In one example, verifying authority **100** may digitally sign identical copies of a load module **54** for use by different classes or assurance levels of electronic appliances **61**. If the sharing of a load module **54** between different electronic appliances is regarded as an open communications channel between the protected processing environments **108** of the two appliances, it becomes apparent that there is a high degree of risk in permitting such sharing to occur. In particular, the extra security assurances and precautions of the more trusted environment are collapsed into those of the less trusted environment because an attacker who compromises a load module within a less trusted environment is then able to launch the same load module to attack the more trusted environment. Hence, although compartmentalization based on encryption and key management can be used to restrict certain kinds of load modules **54** to execute only on certain types of electronic appliances **61**, a significant application in this context is to compartmentalize the different types of electronic appliances and thereby allow an electronic appliance to protect itself against load modules **54** of different assurance levels.

[0128] FIG. **12** emphasizes this isolation using the illustrative metaphor of desert islands. It shows how assurance levels can be used to isolate and compartmentalize any number of different types of electronic appliances **61**. In this example:

[0129] Personal computer **60**(**1**) providing a software-only protected processing environment **108** may be at assurance level I;

[0130] Media player **400**(**1**) providing a software-only based protected processing environment may be at assurance level II;

[0131] Server **402**(**1**) providing a software-only based protected processing environment may be at assurance level III;

[0132] Support service **404**(**1**) providing a software-only based protected processing environment may be at assurance level IV;

[0133] Personal computer **60**(**2**) providing a hybrid software and hardware protected processing environment **108** may be at assurance level V;

[0134] Media player **400**(**2**) providing a hybrid software and hardware protected processing environment may be at assurance level VI;

[0135] Server **402**(**2**) providing a software and hardware hybrid protected processing environment may be at assurance level VII;

[0136] Support service **404**(**2**) providing a software and hardware hybrid protected processing environment may be at assurance level VIII; and

[0137] Personal computer **60**(**3**) providing a hardware-only protected processing environment **108** may be at assurance level IX;

[0138] Media player **400**(**3**) providing a hardware-only protected processing environment may be at assurance level X;

[0139] Server **402**(**3**) providing a hardware-only based protected processing environment may be at assurance level XI;

[0140] Support service **404**(**3**) providing a hardware-only based protected processing environment may be at assurance level XII.

[0141] In accordance with this feature of the invention, verifying authority **100** supports all of these various categories of digital signatures, and system **50** uses key management

to distribute the appropriate verification keys to different assurance level devices. For example, verifying authority **100** may digitally sign a particular load module **54** such that only hardware-only based server(s) **402**(**3**) at assurance level XI may authenticate it. This compartmentalization prevents any load module executable on hardware-only servers **402**(**3**) from executing on any other assurance level appliance (for example, support service **404**(**1**) with a software-only based protected processing environment).

[0142] To simplify key management and distribution, execution environments having significantly similar work factors can be classified in the same assurance level. FIG. **13** shows one example of a hierarchical assurance level arrangement. In this example, less secure, software-only protected processing environment **108** devices are categorized as assurance level I, somewhat more secure, software-and-hardware-hybrid protected processing environment appliances are categorized as assurance level II, and more trusted, hardware-only protected processing environment devices are categorized as assurance level III.

[0143] To show this type of isolation, FIG. **13** A shows three example corresponding "desert islands." Desert island I is "inhabited" by personal computers **61**A providing a software-only protected processing environment. The software-only protected processing environment based personal computers **61**A that inhabit desert island I are all of the same assurance level—and thus will each authenticate (and may thus each use) an assurance level I load module **54***a*. Desert island II is inhabited by assurance level II hybrid software and hardware protected processing environment personal computers **61**B. These assurance level II personal computers will each authenticate (and may thus each execute) an assurance level II load module **54***b*. Similarly, desert island III is inhabited by assurance level III personal computers **61**C providing hardware-only protected processing environments. These assurance level III devices **61**C may each authenticate and execute an assurance level III load module **54***c*.

[0144] The desert islands are created by the use of different digital signatures on each of load modules **54***a*, **54***b*, **54***c*. In this example, all of the appliances **61** may freely communicate with one another (as indicated by the barges—which represent electronic or other communications between the various devices). However, because particular assurance level load modules **54** will be authenticated only by appliances **61** having corresponding assurance levels, the load modules cannot leave their associated desert island, providing isolation between the different assurance level execution environments. More specifically, a particular assurance level appliance **61** thus protects itself from using a load module **54** of a different assurance level. Digital signatures (and/or signature algorithms) **106** in this sense create the isolated desert islands shown, since they allow execution environments to protect themselves from "off island" load modules **54** of different assurance levels.

[0145] A load module or other executable may be certified for multiple assurance levels. Different digital signatures may be used to certify the same load module or other executable for different respective assurance levels. The load module or other executable could also be encrypted differently (e.g. using different keys to encrypt the load module) based on assurance level. If a load module is encrypted differently for different assurance levels, and the keys and/or algorithms that are used to decrypt such load modules are only distributed to environments of the same assurance level, an additional measure of security is provided. The risk associated with disclosing the load module or other executable contents (e.g., by decrypting encrypted code before execution) in a lower assurance environment does not compromise the security of higher assurance level systems directly, but it may help the attacker learn how the load module or other executable works and how to encrypt them—which can be important in making bogus load modules or other executables (although not in certifying them—since certification requires keys that would only become available to an attacker who has compromised the keys of a corresponding appropriate assurance level environment). Commercially, it may be important for administrative ease and consistency to take this risk. In other cases, it will not be (e.g. provider sensitivities, government uses, custom functions, etc.).

[0146] FIG. **14** shows an example sequence of steps that may be performed in an overall process provided by these inventions. To begin the overall process, a load module provider **52** may manufacture a load module and associated specifications (FIG. **14**, block **502**). Provider **52** may then submit the load module and associated specifications to verifying authority **100** for verification (FIG. **14**, block **504**). Verifying authority **100** may analyze, test, and/or otherwise validate the load module against the specifications (FIG. **14**, block **506**), and determine whether the load module satisfies the specifications.

[0147] If the load module is found to satisfy its specifications, a verifying authority **100** determines whether it is authorized to generate one or more new specifications for the load module (FIG. **14**, block **509**). If it is authorized and this function has been requested ("Y" exit from decision block **509**), a verifying authority generates specifications and associates them with the load module (FIG. **14**, block **514**).

[0148] If the load module fails the test ("N" exit from decision block **508**), verifying authority **100** determines whether it is authorized and able to create new specifications corresponding to the actual load module performance, and whether it is desirable to create the conforming specifications (FIG. **14**, decision block **510**). If verifying authority **100** decides not to make new specifications ("N" exit from decision block **510**), verifying authority returns the load module to provider **52** (block **512**) and the process ends. On the other hand, if verifying authority **100** determines that it is desirable to make new specifications and it is able and authorized to do so, a verifying authority **100** may make new specifications that conform to the load module ("Y" exit from decision block **510**; block **514**).

[0149] A verifying authority **100** may then digitally sign the load module **54** to indicate approval (FIG. **14**, block **516**). This step **516** may involve applying multiple digital signatures and/or a selection of the appropriate digital signatures to use in order to restrict the load module to particular assurance levels of electronic appliances as discussed above. Verifying authority **100** may then determine the distribution of the load module (FIG. **14**, block **518**). This "determine distribution" step may involve, for example, determining who the load module should be distributed to (e.g., provider **52**, support services **404**, a load module repository operated by a verifying authority, etc.) and/or what should be distributed (e.g., the load module plus corresponding digital signatures, digital signatures only, digital signatures and associated description, etc.). Verifying authority **100** may then distribute the appro-

priate information to a value chain using the appropriate distribution techniques (FIG. **14**, block **520**).

Certifying Applications Intended For Insecure Environments

[0150] Truly secure certification validation is performed in a secure environment such as within a protected processing environment **108** or other secure, tamper-resistant space. The secure environment's tamper-resistance prevents an attacker from defeating the validation process. However, not all applications are intended to be run within a secure environment.

[0151] For example, some arrangements use a trusted element to perform certain secure functions, but perform other tasks within an insecure environment. FIG. **15** shows an example electronic appliance **61** including a trusted element such as a secure execution space **108** and an insecure execution space **550**. Appliance **61** might, for example, be a personal computer providing trusted element **108** in the form of a hardware or software tamper-resistant protected processing environment; and insecure execution space **550** in the form of the personal computer processor's typical execution space. It may be desirable to permit an application (e.g., a program) **600** executing within insecure execution space **550** to request services from trusted element **108**. In this scenario, it would be desirable to allow a validation authority **100** to certify the application (e.g., to ensure that the application follows rules for good application behavior) and allow the trusted element **108** to validate the application's certification before providing any services to it. For example, trusted element **108** can refuse to provide a requested service if application **600** has not been certified or if application **600** has been tampered with.

[0152] Since insecure execution space **550** does not provide the tamper-resistance necessary to support truly secure validation of application **600**, it would be desirable to provide a tamper-resistant mechanism for allowing trusted element **108** to validate certifications presented by applications intended to be run or otherwise used, at least in part, within an insecure environment.

[0153] In accordance with a further presently preferred example embodiment, tamper-resistant techniques are provided for certifying and validating applications **600** intended to be executed or otherwise used at least in part within insecure environments **550**. Such techniques can detect whether applications **600** have been certified and/or whether they have been modified (i.e., tampered with) in a way that makes them no longer trustworthy.

[0154] Briefly, examples of these techniques provide a credential having multiple elements covering corresponding parts of the application—and preferably having a combined overall effect of covering all (or a substantial portion) of the application **600**. For example, the credential can provide verification information for different byte ranges, virtual paths, and/or other portions of application **600**. Sufficient verification information may be provided to substantially cover the application or at least the portions of the application most likely to be tampered with.

[0155] To validate the credential, the trusted element **108** may authenticate the credential, and then issue challenges based on different parts of the authenticated credential that the trusted element selects in an unpredictable (e.g., random) way. For example, the trusted element **108** can repeatedly challenge application **600** or other agent to provide (or it can itself generate) a cryptographic hash value corresponding to application portions the trusted element **108** randomly selects. The trusted element **108** can compare the responses to its challenges with information the authenticated credential provides, and deny service to application **600** or take other appropriate action if the comparison fails. The challenges may be repeated on an ongoing basis (e.g., during execution of application **600**) and/or interleaved with non-predetermined challenges not defined by the credential, to increase the tamper-resistance of the verification process.

[0156] FIG. **16** shows an example process for certifying an application **600**. In this example, verifying authority **100** takes application program **600** and performs a credential generating process **610** to yield a credential **612**. As part of a software manufacturing process **614**, the application program **600** and credential **612** are packaged on a distribution medium **616** and made available for use.

[0157] As shown in FIG. **16**A, application **600** may include different components. For example application **600** may include one or more read-only application components such as executable component **601**(**1**), library component **601**(**2**), and/or other read-only component **601**(N). Application program **600** may also include one or more modifiable (read-write) components **603**(**1**), . . . , **603**(N). The modifiable components **603** are typically not certified because of their modifiability; however, it may be desirable to certify any or all of the read-only components **601** irrespective of whether they are executable code, data, or a combination or hybrid. The credential **612** created by credential generating process **610** can provide verification information corresponding to each of these read-only components **601**(**1**), . . . **601** (N).

[0158] FIG. **17** shows an example credential generating process **610**. In this example, application **600** is certified by taking each read-only application component **601** and repeatedly applying to it, the overall process **610** shown in FIG. **17**.

[0159] In this FIG. **17** example, the verifying authority **100** performs a selection process to select a portion of application **600**—for example, a random byte range, virtual path, or other subset of the information contained in the application component being certified (FIG. **17**, block **700**). The verifying authority **100** applies a cryptographic hash function to the selected portion to yield a portion hash value associated with that subset and that component (FIG. **17**, block **702**). Verifying authority **100** then generates a portion hash block describing that portion (FIG. **17**, block **704**).

[0160] FIG. **18** shows an example hash block **740** generated by FIG. **17**, block **704**. In this particular example, portion hash block **740** has the following elements:

[0161] a component ID **741** that designates the application (and/or component) from which the hash value is calculated;

[0162] a lower bound field **742** and upper bound field **743** together specifying the byte range used in the hash calculation; and

[0163] a hash value **744** that is the result of the hash calculation process of FIG. **17**, block **702**.

[0164] Referring once again to FIG. **17**, blocks **700**, **702**, **704** are repeated enough times to generate the required quantity of portion hash values. Preferably, enough hash values are calculated to ensure that every byte in each application component is represented by more than one hash value. That is, every byte is contained in more than one hashed portion and thus in more than one associated hash block **740**. As mentioned above, in one example the portions to be hashed are randomly selected to provide a high degree of unpredictability.

[0165] To help explain how many different portions of application **600** to select and hash, FIG. **20** shows an example "threat model" that the disclosed credential creation process **610** is designed to counter. In this threat model, an attacker tampers with application **600** by static modification (e.g., patching) by, for example, substituting the attacker's critical component **802** for a corresponding critical component **804** within the application. To counter this threat, the credential creation process **610** selects a sufficient quantity of different application portion hashes to provide "coverage" for critical component **804**. Preferably, enough hash values are calculated to ensure that critical component **804** is represented by more than one hash value. Since it may be desirable to protect substantial portions (or the entire) application **600**, not all hash ranges will necessarily cover any given critical component **804**.

[0166] The hash ranges selected by FIG. **17**, block **700** may be disjoint (see FIG. **20**A), or they may overlap arbitrarily (see FIG. **20**B). It is even possible that a selection process of FIG. **17**, block **700** will randomly select precisely the same portion of application **600** twice.

[0167] Although a straightforward way to specify portions of application **600** is in terms of byte ranges defined between upper and lower bounds (see FIG. **18**), other ways to specify portions are also possible. For example, FIG. **20**C shows application portion selection based on pseudo-random validation paths within application **600**. In this example, the FIG. **17**, block **700** "select application component portion" step selects application **600** portions to be hashed based on execution or other data traversal access paths defined within application **600**. FIG. **20**C shows two such paths **850**(**1**) and **850**(**2**). Each of paths **850**(**1**), **850**(**2**) in this example passes through critical component **804**—and the resulting hash values thus each protect the critical component. Any number of such paths **850**(N) can be selected.

[0168] Once the required quantity of hash values has been calculated (FIG. **17**, block **708**), the resulting hash blocks **740**(**1**), . . . **740**(N) are organized in one or more groups **745** (see FIG. **19**). Each group **745** may contain one or more range block **740**. A digital signature process **751** is then performed on the information in each group, yielding a digital signature **746** (FIG. **17**, block **712**; see FIG. **19**). In one example, these steps may be performed, for example, by cryptographically hashing the hash block set **745**, and then digitally signing the resulting hash with a global credential signing key **761** (FIG. **17**, blocks **710**, **712**).

[0169] The digital signature process **751** may be performed with a public key (asymmetrical) algorithm using global credential signing key **761**. As is typical for digital signatures, the digital signature process **751** may involve first calculating a cryptographic hash function over the set **745**, and then creating a digital signature representing the hash. A secret key authentication (Message Authentication Code) process may be used in place of signature process **751**—although this may reduce resistance to attacks during the certification generation process.

[0170] The global credential signing key **761** may be chosen from a set of global signing keys, such that the corresponding credential validation key is guaranteed to be available to the validator where application **600** will be used. The identity of signing key **761** is preferably incorporated within credential **612**. Different signing keys **761** can be used to distinguish among applications **600** suitable for different types or classes of electronic appliances **61** distinguished by different validators. Multiple signatures **746** can be calculated using different credential signing keys **761** to permit an application **600** to be validated with different credential validation keys.

[0171] In this particular example, an encryption process **752** is then applied to the combination of set **745** and its digital signature **746** to yield a credential part **747** (FIG. **17**, block **714**; see FIG. **19**). Encryption process **752** may be performed using an asymmetric (public key) algorithm employing a global credential encryption key **762**. The encryption process **752** may involve first generating a random key for a symmetric (secret key) algorithm, using the symmetric algorithm for encryption of the credential data, and using the symmetric algorithm for encrypting the random key. A secret key encryption process may be substituted for encryption process **752** (such substitution may reduce the resistance against attacks on the credential creation process).

[0172] Encryption key **762** may be chosen from a set of global credential encryption keys, such that the corresponding decryption key is guaranteed to be present at the trusted element **108** where the application **600** will be used. Different encryption keys **762** can be used to distinguish among applications suitable for different environments, as described above. The signature process **751** and encryption process **752** may be applied in any order and to any arbitrary selection or subsets **745** of hash blocks **740** such that the result protects the contents of hash blocks from disclosure and/or modification.

[0173] In this example, all resulting encrypted credential parts **747** are combined to produce credential **612** (FIG. **17**, block **716**). Credential **612** may also include (in signed encrypted form) additional information about application **600** including, for example, the number of components in the application, the size and location of each component, information about the identity of the application and/or its manufacturer, information allowing verifying authority **100** to specify a set or subset of secure operations that the application is permitted to access, and/or other information.

[0174] FIG. **21** shows an overall example credential validation process **900** performed by appliance **61**. In this example, appliance **61** includes a trusted element **108** (e.g., a protected processing environment) providing a validator function **920**. In this example, validation process **900** takes information from distribution medium **616** (which may have been copied to other media) and presents it to appliance **61** for validation by validator **920** within trusted element **108**. Thus, in this example, it is trusted element **108**, not application **600**, that is trusted—and the trusted element is responsible for validating the application before the trusted element will provide any services to the application.

[0175] In this particular example, when appliance **61** begins to use or execute application **600**, trusted element **108** performs a validation process in which credential **612** is presented to validator **920** along with data calculated by a "select" process based on application **600**. The validator **920** determines whether credential **612** is a valid representation of application **600**.

[0176] FIGS. **22**A and **22**B show a more detailed example validation process **900**. In this example, application **600** presents its encrypted credential **612** and requests authorization (FIG. **22**A, block **950**). Validation process **900** decrypts the credential **612** using the global credential decryption key **763** corresponding to the global credential encryption key **762** used at creation time (FIG. **22**A, block **952**; see FIG. **22**B). Validation process **900** then validates the digital signature **746**

for any credential part **747** that it uses, using global signature validation key **764** that corresponds to the credential signing key **761** used when the credential **612** was created (FIG. **22**A, block **954**). Steps **952**, **954** may be performed on individual table entries, or sets **745**, or they may be performed on the entire credential **612**.

[0177] Assuming the digital signature **746** is valid, validation process **900** validates the application **600** by repeatedly selecting or choosing portions of application **600**, issuing challenges to compute cryptographic hashes corresponding to the selected portions, and checking responses to ensure they correctly correspond to information within credential **612**. In more detail, validation process **900** in this example initially chooses whether or not to select, for its next iteration, a portion of application **600** predetermined by credential **612** (e.g., a portion for which there is a corresponding hash block **745** within the credential) (FIG. **22**A, decision block **956**). If validation process **900** chooses to use a predetermined portion (i.e., a "yes" exit from decision block **956**), it randomly selects one of the hash blocks **745** from credential **612** and determines the component ID **741** and portion definition (e.g., address lower bound **742** and upper bound **743**) from the selected range hash block (FIG. **22**A, block **958**). The validation process **900** then issues a challenge to compute the cryptographic hash corresponding to the selected address range in the selected component (FIG. **22**A, block **960**).

[0178] In one example, the validation process **900** challenges the application **600** itself to compute the cryptographic hash. In this example, application **600** thus includes an executable routine that accepts a component ID/portion definition as an input parameter, and returns the corresponding cryptographic hash of that conponent ID/portion. Application **600** calculates a cryptographic hash of the selected address range in response to the challenge, and returns the response for receipt by validating process **900** (FIG. **22**A, block **962**).

[0179] The cryptographic hash can be computed in alternate ways that do not require application **600** itself to respond to the challenge. For example, when running under an operating system that supports shared memory (e.g., Microsoft Windows NT or Windows 95), validation process **900** may map one or more regions of its own address space to correspond to the application's read only components **601**(**1**), . . . **601**(N), and make the required checksum (hash) calculation itself. Alternatively, validation process **900** can employ and request an agent, surrogate, or service process to make the necessary mapping(s) to share the address space of application **600** and enable and perform the checksum calculation. Some operating systems may require the cooperation of application **600** to allow regions of its memory to be shared with validation process **900** and/or its agent—but failure of an attempt to establish such sharing can be considered clear evidence that application **600** is not certified.

[0180] Using shared memory to allow the validator **920** or its trusted agent to calculate cryptographic hashes directly significantly increases the difficulty of a "copy" or "substitution" attack. Thus, using shared memory mapping in this manner increases tamper-resistance because it becomes less feasible for the application **600** to provide known answers to the challenge. Further, using shared memory to facilitate process **900** allows the challenge-response process to be performed without any interference with or effect on application **600**. Because application **600** is not even aware of the challenges and corresponding response in the shared-memory scenario, it is not able to intercept them in order to supply misleading answers. This makes it possible to perform validation **900** at arbitrary instants during the operation of application **600**, as well as making it infeasible for application **600** to detect the challenge actions and substitute its own misleading responses.

[0181] Validating process **900** then determines whether the computed hash value equals the hash value **744** from the hash block **745** supplied by credential **612** (FIG. **22**A, decision block **964**). If the returned value does not match, validating process **900** refuses to accept application **600**, returning a "false" result (FIG. **22**A, block **966**).

[0182] One purpose of blocks **968**-**974** shown in FIG. **22** A is to conceal the portions of application **600** that are actually predefined by credential **612**. Thus, if validating process **900** chooses to use a portion that is not predefined (i.e., a "no" exit from decision block **956**), the process randomly chooses a component ID and address lower bound and upper bound (or other suitable portion definition) and then issues a challenge to compute the corresponding cryptographic hash (FIG. **22**A, blocks **968**, **970**). As before, application **600** or another agent returns the calculated corresponding hash value (FIG. **22**A, block **972**). In this case, however, validating process **900** has nothing to compare the response to, and in this example, it simply ignores it (FIG. **22**A, block **974**). If the "no" exit from decision block **956** is chosen often, most challenges will not be meaningful, and it will be difficult for an adversary to collect a table of all the necessary responses in order to falsify an application's response.

[0183] In this example, blocks **956**-**976** are repeated a random number of times sufficient to provide a reasonable probability that the application **600** is providing correct answers and has not been modified (as tested for by FIG. **22**A, decision block **976**). Preferably, blocks **956**-**976** should be repeated until all bytes in the application **600** have been checked at least once against a real hash value supplied by a credential **612** hash block **745**. Complete coverage is desirable because tampering may require modifying only a few bytes in application **600**.

[0184] The validation process **900** shown in FIG. **22**A may be performed repeatedly at initialization and/or during operation of application **600**. Validation challenges occurring during normal operation may be more difficult to tamper with than those that occur at the well-defined point of initialization.

Attacks on Validation Process

[0185] The forms of tampering countered by validation process **900** include:

[0186] (1) static substitution of an entire program for a certified application;

[0187] (2) static modification (e.g., patching) of a certified application; and

[0188] (3) use of a modified credential corresponding to a different or modified application.

[0189] Any of these forms of tampering would require that the application **600** be able to construct, interpret, or simulate credentials **612**. Construction and interpretation is countered by the secrecy of keys. Simulation is countered by the use of many different ranges, and by false ranges; if a malicious program wanted to provide the "correct" response in order to appear as if it were a different "certified" program, it would have to record all the possible challenges and responses. Because the challenges for any one validation are a small,

randomly selected subset of all those in the credential, collecting them all would be time-consuming and expensive.

[0190] A "correct" response can be simulated by calculating it from a complete copy of a certified program, while running a malicious program. That is probably the simplest technical attack that will defeat this arrangement. Other simulation attacks are significantly more difficult, requiring that challenges and responses be recorded and replayed. As described above, use of shared memory increases the difficulty of a "copy" or "substitution" attack.

[0191] Although the foregoing invention has been described in some detail for purposes of clarity, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. It should be noted that there are many alternative ways of implementing both the processes and apparatuses of the present invention. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

Appendix A

[0192] There exist many well-known processes for creating digital signatures. One example is the Digital Signature Algorithm (DSA). DSA uses a public-key signature scheme that performs a pair of transformations to generate and verify a digital value called a "signature." DSA uses the parameters, p, q, g, x, and y, such that:

[0193] p=a prime number L bits long, wherein L ranges from 512 to 1024 and is a multiple of 64;

[0194] q=a 160-bit prime factor of p−1;

[0195] $g=h^{(P-1)/q} \bmod p$, where h is any number less than p−1 such that $h^{(P-1)/q} \bmod p$ is greater than 1;

[0196] x=a number less than q; and

[0197] $y=g^x \bmod p$.

[0198] The algorithm also makes use of a one-way hash function, H(m), such as, for example, the Secure Hash Algorithm. The first three parameters, p, q, and g, are public and may be shared across a network of users. The private key is x; the public key is y. To sign a message, m, using DSA, a signer generates a random number, k, less than q. The signer also generates:

[0199] $r=(g^k \bmod p) \bmod q$; and

[0200] $s=(k^{-1}(H(m)+xr)) \bmod q$

[0201] The parameters r and s comprise the signer's signature, which may be sent to a recipient or distributed across a network. A recipient verifies the signature by computing:

[0202] $w=s^{-1} \bmod q$;

[0203] $u_1=(H(m)*w) \bmod q$;

[0204] $u_2=(rw) \bmod q$; and

[0205] $v=((g^{u1}*y^{u2}) \bmod p) \bmod q$.

[0206] If v=r, the signature is verified.

[0207] There exist multiple variations of DSA. In one such variant, for example, the signer does not compute k−1. Instead, using the same parameters as in DSA, the signer generates two random numbers, k and d, both less than q. The signature comprises:

[0208] $r=(g^k \bmod p) \bmod q$;

[0209] s=(H(m)+xr)−d mod q; and

[0210] t=kd mod q.

[0211] A recipient verifies the signature by computing:

[0212] w=t/s mod q;

[0213] $u_1=(H(m)*w) \bmod q$; and

[0214] $u_2=(rw) \bmod q$.

[0215] If $r=((g^{u}{}_1-y^{u}{}_2) \bmod p) \bmod q$, then the signature is verified.

[0216] In other variants, the signer may generate a random number, k, less than q. The signature then comprises:

[0217] $r=(g^k \bmod p) \bmod q$; and

[0218] $s=k*(H(m)+xr)^{-1} \bmod q$

[0219] A recipient verifies the signature by computing u_1 and u_2, such that:

[0220] $u_1=(H(/m)*s) \bmod q$

[0221] $u_2=(sr) \bmod q$

[0222] If $r=((g^{u}{}_1-y^{u}{}_2) \bmod p) \bmod q$, then the signature is verified.

[0223] Yet another variant of DSA uses a prime number generation scheme that embeds q and the parameters used to generate the primes within p. Using this method, the values of C and S used to generate p and q are embedded within p and do not need to be stored, thereby minimizing the amount of memory used. This variant may be described as follows:

[0224] (1) Choose, S, arbitrary sequence of at least 160 bits; g is the length of S in bits;

[0225] (2) Compute U=SHA(S)+SHA ((S+1) mod 2^g), where SHA is the Secure Hash Algorithm;

[0226] (3) Let q=U with the most significant bit and the least significant bit of U set to 1;

[0227] (4) Check whether q is prime;

[0228] (5) Let p be the concatenation of q, S, C, and SHA(S), C is set to 32 zero bits;

[0229] (6) p=p−(p mod q)+1;

[0230] (7) p=p+q;

[0231] (8) If the C in p is 0×7 fffffff, go to step (1);

[0232] (9) Check whether p is prime; and

[0233] (10) If p is composite, go to step (7).

[0234] Still another variant of DSA is the Russian digital signature standard, officially known as GOST R 34-10-94. The algorithm is very similar to DSA, and uses the following parameters:

[0235] p=a prime number, either between 509 and 512 bits long, or between 1020 and 1024 bits long;

[0236] q=a 254- to 256-bit prime factor of p−1;

[0237] a=any number less than p−1 such that $a^q \bmod p=1$;

[0238] x=a number less than q; and

[0239] $y=a^x \bmod p$.

[0240] This algorithm also uses a one-way hash function, H(x), such as, for example, GOST R 34.11-94, a function based on the GOST symmetric algorithm. The first three parameters, p, q, and a, are public and may be distributed across a network of users. The private key is x, the public key is y.

[0241] To sign a message, m, using GOST DSA, a signer generates a random number, k, less than q, and generates $r=(a^k \bmod p) \bmod q$ and s=(xr+k(H(m))) mod q. If H(m) mod q=0, then set it equal to 1. If r=0, then choose another k and start again. The signature is comprised of two numbers: r mod $2^{256}$and s mod 2^{256}. A sender transmits these two numbers to a recipient, who verifies the signature by computing:

[0242] $v=H(m)^{q-2} \bmod q$;

[0243] $z^1=(sv) \bmod q$;

[0244] $z^2=((q-r)*v) \bmod q$; and

[0245] $u=((a^{Z1}*y^{Z2}) \bmod p) \bmod q$.

[0246] If u=r, then the signature is verified.

[0247] Many signature schemes are very similar. In fact, there are thousands of general digital signature schemes based on the Discrete Logarithm Problem, like DSA. Addi-

tional information on the digital signature standard can be found in National Institute of Standards and Technology (NIST) FIPS Pub. 186, "Digital Signature Standard," U.S. Dept. of Commerce, May 1994.

1-27. (canceled)

28. A trusted element for use with a computer system including an insecure arrangement for using an application, the trusted element comprising:

a challenge generator that selects, based at least in part on a credential associated with the application, at least one predetermined portion of the application, the predetermined portion of the application including at least some executable software code, and issues a challenge requesting a response from the application, the response providing a computation of at least one value based on the selected predetermined portion of the application; and

a response checker that checks the response against the credential.

29. A trusted element as in claim **28**, wherein the credential corresponds to a digital signature.

30. A trusted element as in claim **29**, wherein the trusted element further includes a validator that validates the digital signature.

31. A trusted element as in claim **28**, wherein the challenge generator randomly selects the predetermined portion from plural predetermined portions defined by the credential.

32. A trusted element as in claim **28**, wherein the challenge generator issues the challenge during execution of the application by the insecure arrangement.

33. A trusted element as in claim **28**, wherein the challenge generator requests the application to compute a cryptographic hash of the selected portion.

34. A trusted element as in claim **28**, wherein the challenge generator selects a virtual path within the application.

35. A trusted element as in claim **28**, wherein the challenge generator selects a byte range within the application.

36. In an electronic appliance including a secure execution space and an insecure execution space, a method for permitting an application executing within the insecure execution space to request one or more services from a trusted element executing in the secure execution space, the method comprising:

issuing a challenge from the trusted element to the application executing within the insecure execution space, the challenge being based at least in part on randomly selected parts of an authenticated credential, the challenge requesting the application to compute at least one value based on one or more portions of the application, the one or more portions of the application including at least some executable software code;

sending, from the application to the trusted element, the at least one value;

comparing, at the trusted element, information provided by the authenticated credential with said at least one value; and

denying the application access to said one or more services if the at least one value does not correspond with the information provided by the authenticated credential.

37. A method as in claim **36**, wherein the at least one value is computed by computing one or more cryptographic hashes of the one or more portions of the application.

38. A method as in claim **36**, in which the issuing, sending, and comparing steps are performed multiple times during execution of the application.

39. A method as in claim **36**, in which the authenticated credential is digitally signed.

40. A method as in claim **36**, in which the authenticated credential is at least in part encrypted.

41. A method as in claim **36**, in which at least one of the portions of the application overlaps another of the portions of the application.

42. A method as in claim **36**, in which at least one of the one or more portions of the application corresponds to a predetermined byte range or virtual path in the application.

43. A computer readable medium storing a computer program, the computer program including instructions that, when executed by a processor of an electronic appliance, are operable to cause the electronic appliance to take actions comprising:

issuing a challenge from a trusted element executing in a secure execution space to an application executing in an insecure execution space, the challenge being based at least in part on randomly selected parts of an authenticated credential, the challenge requesting the application to compute at least one value based on one or more portions of the application, the one or more portions of the application including at least some executable software code;

receiving, from the application, the at least one value;

comparing information provided by the authenticated credential with the at least one value; and

denying the application access to said one or more services if the at least one value does not correspond with the information provided by the authenticated credential.

44. A computer readable medium as in claim **43**, wherein the at least one value is computed by computing one or more cryptographic hashes of the one or more portions of the application.

45. A computer readable medium **43**, in which the issuing, sending, and comparing steps are performed multiple times during execution of the application.

46. A computer readable medium as in claim **43**, in which the authenticated credential is digitally signed.

47. A computer readable medium as in claim **43**, in which the authenticated credential is at least in part encrypted.

48. A computer readable medium as in claim **43**, in which at least one of the portions of the application overlaps another of the portions of the application.

49. A computer readable medium as in claim **43**, in which at least one of the one or more portions of the application corresponds to a predetermined byte range or virtual path in the application.

50. An electronic appliance comprising:

a secure execution space;

an insecure execution space; and

a trusted element operable to execute within the secure execution space, the trusted element being operable to:

issue a challenge to an application executing in the insecure execution space, the challenge being based at least in part on randomly selected parts of an authenticated credential, the challenge requesting the application to computer at least one value based on one or more portions of the application, the one or more portions of the application including at least some executable software code;

receive, from the application or agent, said at least one value;

compare information provided by the authenticated credential with said at least one value; and

deny the application access to one or more services provided by an application executing in the secure execution space if the at least one value does not correspond with the information provided by the authenticated credential.

51. An electronic appliance as in claim **50**, wherein the at least one value is computed by computing one or more cryptographic hashes of the one or more portions of the application.

52. An electronic appliance as in claim **50**, in which the secure execution space comprises a protected processing environment.

53. An electronic appliance as in claim **50**, in which the authenticated credential is digitally signed and at least in part encrypted.

54. An electronic appliance as in claim **50**, in which at least one of the portions of the application overlaps another of the portions of the application.

55. An electronic appliance as in claim **50**, in which at least one of the one or more portions of the application corresponds to a predetermined byte range or virtual path in the application.

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