(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
21 December 2000 (21.12.2000)

PCT

(10) International Publication Number
WO 00/77596 A1

(51) International Patent Classification[7]: G06F 1/00, H04L 9/06, G06F 9/44

(21) International Application Number: PCT/CA00/00677

(22) International Filing Date: 8 June 2000 (08.06.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/329,117 9 June 1999 (09.06.1999) US
60/164,892 10 November 1999 (10.11.1999) US

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(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

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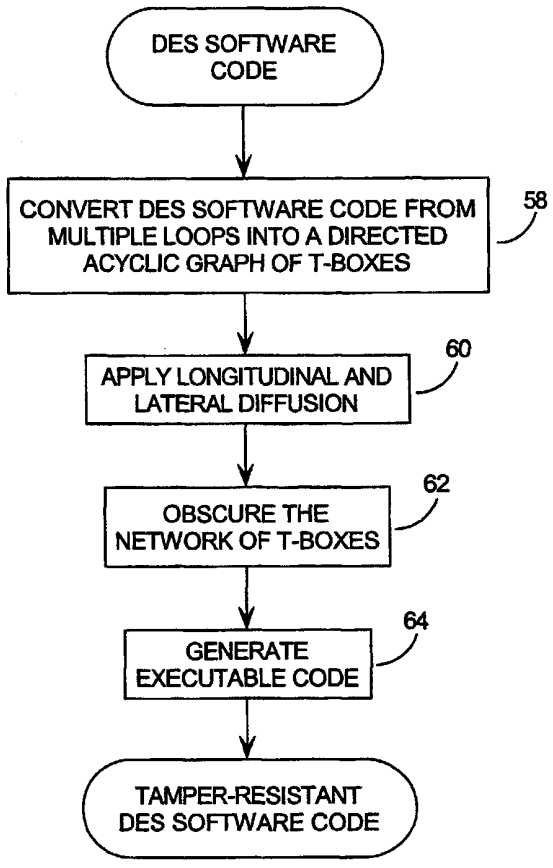
(54) Title: TAMPER RESISTANT SOFTWARE ENCODING



(57) Abstract: The present invention relates generally to computer software and electronic hardware, and more specifically, to a method, apparatus and system resistant to tampering and reverse engineering, including a particular implementation for the Digital Encryption Standard (DES). Cryptographic key-based methodologies have a major weakness in that they require the cryptographic key to be known by both the encrypting and decrypting parties. An attacker who is able to obtain knowledge of both the cryptographic key and the encrypted data is able to decode the message. The invention hides cryptographic keys by increasing the obscurity and temper-resistance of the software program, which is done by randomly generating substantive yet redundant arguments; and inserting those arguments into the data flow of the program.

WO 00/77596 A1

(84) **Designated States** *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *With international search report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

Tamper Resistant Software Encoding

The present invention relates generally to computer software and electronic hardware, and more specifically, to a method, apparatus and system resistant to tampering and reverse engineering, including a particular implementation for the Digital Encryption Standard (DES).

Background of the Invention

The use of computers and computer software in all of their various forms is recognized to be very common and is growing everyday. In industrialized nations, hardly a business exists that does not rely on computers and software either directly or indirectly, in their daily operations. As well, with the expansion of powerful communication networks such as the Internet, the ease with which computer software programs and data files may be accessed, exchanged, copied and distributed is also growing daily.

In order to take advantage of these computer and communication systems and the efficiencies that they offer, there is a need for methods of storing and exchanging computer software and data securely. One such method that has demonstrated widespread use and acceptance is encryption of data using secret cryptographic keys. Such methods are generally accepted as secure, as an attacker must perform an impractically large number of mathematical tests to identify the cryptographic key required to decode a given encrypted data file. Cracking the Data Encryption Standard (DES) for example, would require an average of 2^{55} different keys to be tested, requiring more than 1 million years of testing at a rate of one hundred million key tests per second. DES is a block cipher method which is very fast and is widely used. If the cryptographic key is kept secure, it offers very good security.

The number of tests required to solve triple DES and other related techniques employing cryptographic keys varies correspondingly with the complexity of the method.

However, present cryptographic key-based methodologies have a major weakness in that they require the cryptographic key to be known by both the encrypting and decrypting parties. An attacker who is able to obtain knowledge of

both the cryptographic key and the encrypted data is able to decode the message. The attacker may obtain this information in many ways, including the following:

1. Intercepting data packets while in transit through the Internet. This may be done for example, by the Internet Service Provider (ISP) for the end user, or another party on the End User's local network. Theoretically, this may also be done by any attacker who is able to monitor a node on the Internet which routes the data packets, as the Internet is not a secure network.
2. Reading the cryptographic key and encrypted data file while they are stored on the user's computer or server, which again, may easily be done by another party on the local network. An outside attacker may also be able to read these files by transmitting a software agent to the user's computer programmed to search for the desired files and transmit them back to the attacker.

If the intercepted files are not protected in some other manner, the attacker will have immediate access to what he requires. There are methods of hiding the cryptographic keys and data files, but typically, the attacker need only observe the execution of the decryption algorithm with the target files, to obtain the original cryptographic key and data file.

These vulnerabilities have encouraged many attempts to hide secret cryptographic keys in tamper-resistant, secret-hiding software. Tampering refers to changing computer software in a manner that is against the wishes of the original author. If for example, a cryptographic key is encrypted into a password file with which the user accesses a certain server, one would not want an attacker to obtain the file and modify it to: identify the cryptographic key, obtain access to the server himself, or modify privileges that the file may identify. However, because the attacker has complete access to the software code he has intercepted, there is no way of stopping the attacker from observing its execution and making arbitrary changes.

Attempts to hide secret cryptographic keys in software have been notably ineffective. Therefore, a far more powerful approach to the cryptographic key-hiding, tamper-proofing problem is required. Because of its widespread use, it is particularly desirable to provide such a solution for the Data Encryption Standard (DES), where the software can be stored and may be executed without revealing the cryptographic key.

In addition to the hiding of the cryptographic key, the encrypted data file itself may contain information which must be secured. For example, biometric information may be used for identification purposes, but it is undesirable to use biometric information because it cannot be replaced once it is compromised. Each person has a finite number of biometric identifiers such as two sets of fingerprints, one voice and two retinas. Therefore, the use of biometric data is only practical if it can be implemented in a manner that eliminates risk of compromise due to dissemination of such non-replaceable data.

Previous Approaches Are Either Expensive or Weak

Many attempts have been made to provide secret-hiding and tamper-resistance computer software. Hardware approaches, for example, have been proposed in profusion.

Among hardware-based approaches, "dongles" and smart cards, which move data and code inside a physical device, are the most common. These approaches are costly to administrate and transport compared to software-based approaches, where manufacture is virtually free and transport can be electronic.

A "dongle", for example, is a special piece of plug-in hardware which implements part of the algorithm to be protected. Hence, the software program being protected will not work correctly unless the dongle is physically plugged in. Obviously, this is a high-cost approach and does not work on a standard computer platform. Indeed, it requires the platform to be changed to include the dongle whenever the protected program is to be run.

Due to their structural limitations, smart cards have been far more vulnerable to penetration of their secrets than was hoped, news media describing incidents of smart card penetration on a regular basis. As well, smart card methods require an investment in card reading hardware and the cards themselves, which can be expensive to implement broadly.

A highly elaborate hardware-based approach which is totally inapplicable to the installed base of personal computers is presented by Rafail Ostrovsky and Oded Goldreich in *Comprehensive software protection system,* United States Patent No. 5,123,045. This proposal uses a physically enclosed CPU (Central Processing Unit) which executes code as a "black box", so that execution cannot be observed by an attacker. If external RAM (Random Access Memory) buffers are required, data is

only stored in the RAM in an encrypted form. This method cannot be applied to existing computers, is expensive, and is not mobile.

Hence, existing hardware approaches are generally inapplicable to the installed base of personal computers, and would be, or are, costly to administrate and deploy. Because of these difficulties, a number of attempts have also been made to provide a software solution to tamper-resistance and secret-hiding.

The simplest methods use special-purpose tricks to prevent unauthorized copying of software, including start-up code examining supposedly unused parts of an attached hard-disk, 'fingerprinting' particular personal computer (PC) environments, and querying hardware, operating-system-provided, or network-provided identifiers. These methods have been defeated by attackers on a regular basis. As is well known, special-purpose copy programs which casually remove copy-protection from PC software in transit are available for a fairly modest price.

A software approach for computing with encrypted data is described by Niv Ahituv, Yeheskel Lapid, and Seev Neumann, in *Processing encrypted data,* Communications of the ACM 30(9), Sept. 1987, pp. 777-780. This method hides the actual value of the data from the software doing the computation. However, the computations which are practical using this technique are quite restricted, and as a result, this method is not suitable for DES encryption key hiding.

Christian Collberg, Clark Thomborson, and Douglas Low, in *Manufacturing cheap, resilient, and stealthy opaque constructs,* ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, January, 1998, provide a method for concealing the intent of the control flow in a software program, using basic obfuscation methods. Obfuscation is the process of making the organisation of software code more confusing and hence, more difficult to modify.

The low-level structure of a software program is usually described in terms of its data flow and control flow. Control flow, which is the subject of Collberg et al., is a description of how control is transferred from one location in the software code to another during execution, and the tests that are performed to determine those transfers. In contrast, data flow is a description of the variables together with the operations performed on them.

In particular, Collburg et al. obscure the decision processes in the program, that is, they obscure those computations on which binary or multiway conditional

branches determine their branch targets. Clearly, there are major deficiencies to this approach, including:

1. because only control flow is being addressed, domain transforms are not used and data obfuscation is weak; and
2. there is no effort to provide tamper-resistance. In fact, Collburg *et al.* do not appear to recognize the distinction between tamper-resistance and obfuscation, and as a result, do not provide any tamper-resistance at all.

The approach of Collburg *et al.* is based on the premise that obfuscation can not offer a complete solution to tamper protection. Collburg *et al.* state that: "... code obfuscation can never completely protect an application from malicious reverse-engineering efforts. Given enough time and determination, Bob will always be able to dissect Alice's application to retrieve its important algorithms and data structures."

In *Breaking abstractions and unstructuring data structures,* IEEE International Conference on Computer Languages, 1998, Christian Collberg, Clark Thomborson, and Douglas Low provide more comprehensive proposals on obfuscation, together with methods for obfuscation of structured and object-oriented data.

There remains a weakness, however, even in the methods proposed by Ahituv et al. and Collberg et al. *Obfuscation* and *tamper-resistance* are distinct problems, and while weak obfuscation is provided by Ahituv et al. and Collberg et al., they do not address tamper resistance at all. For example, consider removing password protection from an application by changing one branch from a conditional one to an unconditional one. Plainly, this vulnerability cannot be eliminated effectively by any amount of mere obfuscation. A patient attacker tracing the code will eventually find the "pass, friend" / "begone, foe" branch instruction. Identifying this branch instruction allows the attacker to circumvent a protection routine by simply re-coding it to a non-conditional branch. Therefore, other methods are required to avoid such single points of failure.

Existing general-purpose commercial software obfuscators use a variety of techniques including: removal of debugging information, changing variable names, introducing irreducible flow graphs, and particularly in the case of Java, modifying code structures to avoid stereotyped forms for source control structures. These methods produce superficial changes, but the information exposed by deeper analyses employed by optimizing compilers and similar sophisticated tools is changed very little. The data flow and control flow information exposed by such

analyses is either not affected at all, or is only slightly affected, by the above methods of obfuscation.

Irreducibilities can be handled by well-known compiler techniques. Information present at the 'machine' code level, or equivalent, is not obscured at all, including the data used in computation. For example, information about DES encryption and decryption, and probably any reasonably secure form of encryption or decryption, cannot be hidden effectively using techniques such as these.

An alternative approach is to encrypt the program either as a whole or in parts, and then to decrypt the program or its components temporarily as they are needed. An example of such a strategy is offered by David Aucsmith and Gary Graunke, in *Tamper-resistant software: an implementation,* Proceedings of the First International Workshop on Information Hiding, Cambridge, UK., 1996. This method exposes executable images of the program or its components to logic analysers and the like, permitting recovery of the original program either entirely, or in a piecemeal fashion as its components are exercised. Moreover, unless this paper's subject problem of hiding cryptographic keys is also solved, the cryptographic key can be extracted from the software and used to decrypt the entire program.

The level of obfuscation obtained using the above techniques is plainly quite weak, since the executed code, control flow and data flow analysed in graph form, is either isomorphic to, or nearly isomorphic to, the unprotected code. That is, although the details of the obfuscated code are different from the original code, the general organisation and structure have not changed.

Attempts have also been made to hide the real code by introducing dummy code, for example, by making every other statement a dummy statement designed to look much like the real code. Along with the higher overhead created, this approach has two fatal weaknesses:

1. It is vulnerable to data flow analysis (DFA) to discover the dummy code.
2. Even if DFA can be rendered ineffective, if x% of the code is dummy code, then 100 - x% of the code is significant. For realistic values of x, a patient attacker can locate which statements matter and which do not, by trial and error.

Attempts have also been made to hide cryptographic keys by a variety of more specific approaches, including:

1. Splitting the cryptographic key into pieces stored in different locations in the software code. This is ineffective as the pieces can be reassembled by tracing execution of the code.
2. Modifying the encryption algorithm to allow use of a disguised key. This is ineffective as human memory capacities limit the amount of disguise to a small number of algorithmic steps.
3. Use of a disguised algorithm. Similar to point 2 above, this is ineffective due to the restrictions imposed by limited human memory capacities.

In addition, a variety of cryptographically weak approaches have been used for encryption and decryption, to avoid the use of any explicit key whatever. These methods are vulnerable either to a cryptographic black-box attack if plain-text can be recognized in an automated way, or to algorithmic analysis with the aid of debugging tools, since the would-be encryption is then a data transformation of quite limited algorithmic complexity.

In general, then, the state of the art has been that programs could not be made effectively secret-hiding and tamper-resistance. In particular, cryptographic keys for reasonably secure ciphers could not be securely hidden in software.

There is therefore a need for a method, apparatus and system for encryption that is tamper-resistant, allowing secret cryptographic keys, biometric data and encrypted data to be transmitted and stored together, without fear that security will be breached.

Summary of the Invention

It is therefore an object of the invention to provide a method and system that improves upon the problems described above.

One aspect of the invention is broadly defined as a method of increasing the obscurity and tamper-resistance of a software program, comprising the steps of: randomly generating substantive yet redundant arguments; and inserting those arguments into the data flow of the software program.

Another aspect of the invention is defined as an apparatus for increasing the obscurity and tamper-resistance of computer software code comprising: randomly generating substantive yet redundant arguments; and inserting those arguments into the data flow of the software program.

A further aspect of the invention is defined as a computer readable memory medium, storing computer software code executable to perform the steps of: randomly generating substantive yet redundant arguments; and inserting those arguments into the data flow of the software program.

An additional aspect of the invention is defined as a computer data signal embodied in a carrier wave, the computer data signal comprising a set of machine executable code being executable by a computer to perform the steps of: randomly generating substantive yet redundant arguments; and inserting those arguments into the data flow of the software program.

Brief Description of the Drawings

These and other features of the invention will become more apparent from the following description in which reference is made to the appended drawings in which:

Figure 1 presents a flow chart of a general algorithm for implementation of the invention;

Figure 2 presents an exemplary computer system in which the invention may be embodied;

Figure 3 presents a data flow diagram of the outer structure of the DES standard;

Figure 4 presents a data flow diagram of a single round of the DES standard;

Figure 5 presents a flow chart of the overall algorithm in a preferred embodiment of the invention;

Figure 6 presents a flow chart of the unrolling routine in a preferred embodiment of the invention;

Figure 7 presents a data flow diagram of the initial connections of one T-box operation, in an embodiment of the invention;

Figure 8 presents a data flow diagram of T-box connections after partial evaluation in an embodiment of the invention;

Figure 9 presents a flow chart of a longitudinal diffusion routine in a preferred embodiment of the invention;

Figure 10 presents a flow chart of a lateral diffusion routine in a preferred embodiment of the invention; and

Figure 11 presents a flow chart of network obscuring in a preferred embodiment of the invention.

Description of the Invention

A method which addresses the objects outlined above, is presented as a flow chart in **Figure 1**. This figure presents a method of increasing the obscurity and tamper-resistance of a software program by:

1. randomly generating substantive yet redundant arguments at step **10**; and
2. inserting those substantive yet redundant arguments into the data flow of the software program at step **12**.

This process obscures the valuations of the original arguments in the software program, making it very difficult to make changes which are useful for perturbation analysis.

As noted above, the low-level structure of a software program is usually described in terms of its data flow and control flow. Data flow is a description of the variables together with the operations performed on them. Control flow is a description of how control jumps from place to place in the program during execution, and the tests that are performed to determine those jumps.

The method of the invention in broad terms, is to add new redundant arguments into the data flow of the program. The simplest example of a pair of redundant arguments is: a first argument which increments the value of a variable in one operation, immediately followed by a second operation which decrements the value of the same variable. Such a pair of operations is redundant in that they do not affect the outcome of the software code. This example is for illustrative purposes only; much more complex examples are described hereinafter.

In the method of the invention, these redundant arguments are substantive in that they are applied to variables used in the software program, and they actually do alter the value of those variables. This is in contrast to "dummy code" used in the art, which does not actually execute and can be identified using data flow analysis techniques. With the method of the invention, it is quite difficult to distinguish which operations are from the original software code, and which have been added.

As these redundant arguments ultimately have no impact on the outcome of the software program, they can be generated randomly. Techniques for generating random numbers, known in the art, can easily be applied to the generation of random equations as explained in greater detail hereinafter.

Hence, a cryptographic key can be incorporated into a software program, without the danger of the cryptographic key being disclosed, or the program being altered to do anything other than what it was originally intended to do. Similarly,

passwords, biometric data and other secure programs and data files can also be securely stored, transferred and executed using the method of the invention.

As described above, cryptographic keys are often used to encrypt data flies to prevent unwanted parties from reading or using the data files. Unfortunately, the cryptographic keys must also be transmitted between the communicating parties, and are generally stored at both locations, leaving many opportunities for discovery by unwanted attackers.

In the invention, the cryptographic key is made secure by obscuring the data flow of the program.

Tamper-resistance, in the sense of creating software which changes behaviour drastically in response to small changes, was thought in the art to be irrelevant to secret-hiding, such as hiding a cryptographic key. Actually, it is quite relevant as it makes perturbation-based analysis (analysis by examination of responses to small changes) much more difficult.

In the application of the invention to encryption using a cryptographic key, it is possible for an attacker to observe the execution and not obtain any useful information. At no time during the execution does the actual key data appear.

In the preferred method described hereinafter, the new arguments are based on multiple inputs and outputs, preferably three or more. This makes the arguments of the software program intimately interconnected with one another, so it is not possible to alter one entry without altering many outputs. This provides even greater tamper resistance and protection against perturbation analysis.

This method is unaffected by a data flow analysis attack, because all of the software code, including the added redundant code, is actually executed. As well, the method of the invention is not vulnerable to black-box or debugging attacks.

Being a software solution, the cost of the invention is very small and can be transported electronically. The invention has none of the costly administrative and physical limitations of hardware solutions.

In terms of obfuscation, the invention is far superior to anything generally available in a commercial obfuscator. Obfuscation may be simply defined as making the organisation of the software code more confusing and hence, more difficult to modify. Obfuscation is inherently provided by the invention, but the invention goes much further by providing a tamper-resistant solution. As noted above, obfuscation merely makes software code more confusing to analyse, while tamper-resistance makes software code resistant to small changes, in the sense that any small code

change produces a massive, unpredictable behavioural change. While obfuscation can ultimately be overcome by patient observation, tamper-resistance requires a great deal of analysis to overcome. The degree of complexity of tamper-resistance is easily scalable, so that the degree of analysis required to overcome it can be made impractically great.

Further, the method of the invention does not require any disguises or personal passwords to be remembered or stored, so there is no dependance on human memory or other human limitations.

An example of a system upon which the invention may be performed is presented as a block diagram in **Figure 2**. This computer system **14** includes a display **16**, keyboard **18**, computer **20** and external devices **22**.

The computer **20** may contain one or more processors or microprocessors, such as a central processing unit (CPU) **24**. The CPU **24** performs arithmetic calculations and control functions to execute software stored in an internal memory **26**, preferably random access memory (RAM) and/or read only memory (ROM), and possibly additional memory **28**. The additional memory **28** may include, for example, mass memory storage, hard disk drives, floppy disk drives, magnetic tape drives, compact disk drives, program cartridges and cartridge interfaces such as those found in video game devices, removable memory chips such as EPROM or PROM, or similar storage media as known in the art. This additional memory **28** may be physically internal to the computer **20**, or external as shown in **Figure 2**.

The computer system **14** may also include other similar means for allowing computer programs or other instructions to be loaded. Such means can include, for example, a communications interface **30** which allows software and data to be transferred between the computer system **14** and external systems. Examples of communications interface **30** can include a modem, a network interface such as an Ethernet card, a serial or parallel communications port. Software and data transferred via communications interface **30** are in the form of signals which can be electronic, electromagnetic, optical or other signals capable of being received by communications interface **30**.

Input and output to and from the computer **20** is administered by the input/output (I/O) interface **32**. This I/O interface **32** administers control of the display **16**, keyboard **18**, external devices **22** and other such components of the computer system **14**.

The invention is described in these terms for convenience purposes only. It would be clear to one skilled in the art that the invention may be applied to other computer or control systems **14**. Such systems would include all manner of appliances having computer or processor control including telephones, cellular telephones, televisions, television set top units, point of sale computers, automatic banking machines, lap top computers, servers, personal digital assistants and automobiles.

The invention will now be described with respect to the particular application to the Digital Encryption Standard (DES) encryption and decryption.

High-Level View of Techniques Used for Tamper-Resistance and Obscuring

The approach of the invention to tamper-resistance, secret-hiding software is based on the following principles. It should be recognized that while the invention provides inherent obscurity, which is a widely-recognized principle in software protection, tamper-resistance is a distinctly different focus:

1. *Targeting:* The approach taken is specifically directed to the operations to be performed and the data to be manipulated. For example, in the case of DES, the techniques used are specially suited to the data and operations employed in DES. It would be clear to one skilled in the art how to tailor the techniques disclosed herein, to other software programs.
2. *Fusion:* Encoded software handles the data in such a way that multiple components are manipulated together, so that separating out individual original (i.e., pre-encoding) data operations is difficult, and tampering with one entity in effect modifies the behaviour of more than one entity.
3. *Diffusion:* Encoded data and computation distribute information among multiple sites, so that no site alone is sufficient for understanding, ambiguity is increased, and tampering at individual sites is made less effective.
4. *Fake robustness:* Presumably, *true* robustness would preserve the *same* computation even after some forms of tampering. The invention 'fakes' such robustness by avoiding failure responses to data in the presence of tampering. Instead, computation proceeds with apparent normalcy, but along nonsensical lines. This is strongly allied to the principle of *anti-holographic behaviour.*
5. *Anti-holographic behaviour:* Tampering with a small part of a hologram causes a slight reduction in resolution. The method of the invention induces

the opposite behaviour, where the effect of any small change is to produce *large*, *wide-spread*, *cascading* changes in behaviour.

6. *Partial evaluation:* Part of the process of hiding constant input data is to partially evaluate the application with respect to that data. In the case of DES key-hiding, for example, the cryptographic key is constant and is eliminated by partial evaluation. This principle is allied to the principle of *diffusion*, where the components of the cryptographic key are then distributed to multiple locations.

Description of DES

The Digital Encryption Standard (DES) is a block cipher, where a piece of software to be encoded is broken down into sixty-four-bit blocks which are operated upon separately. DES inputs a sixty-four-bit block to be encrypted or decrypted and a sixty-four-bit raw key and outputs a sixty-four-bit result. Only fifty-six bits of the raw key are actually used: the low-order bit of each raw key 8-bit byte is discarded, or can be used for parity.

DES will only be described herein with sufficient detail to explain the invention. A more detailed description of (single) DES is provided in FIPS (Federal Information Processing Standards in the United States) publication 46-3. A description and an extensive discussion are also provided by Bruce Schneier, *Applied Cryptography,* ISBN 0-471-11709-9, John Wiley & Sons, 1996, DES receiving particular attention on pp. 265-294.

There are only three kinds of data operations in DES:

1. Selecting some or all bits from a bit-string and re-ordering them into a new bit-string, possibly with multiple appearances of certain bits. Schneier et al. refer to these as *permutations*, though this is not quite accurate since they are not necessarily bijections. Therefore, such transformations will referred to herein as *quasi-permutations* (QPMs), with the true *permutations* being the special case of a QPM being a bijection.

   Each QPM operation is controlled by a table which for each *to*-bit of the output bit-string gives the *from*-bit in the input bit-string whose value it has, except for key-shift QPMs, which are simple rotation permutations, each of which is described by a simple signed shift count.

2. Bit-wise exclusive **or** (XOR).

3. Looking up elements in a table (LKP). In DES, before performing any transformations, these are look-ups in sixty-four-element tables of 4-bit-strings (each of which is called an *S-box* — S for "substitution"), using a 6-bit-string as an index. Initially, each LKP operation is controlled by one of eight *S-box* tables indicating the substitutions it is to perform.

Figure 3 presents a data flow diagram of the outer structure of DES. This presentation is intended to emphasize the three basic kinds of operations making up DES, as described above. Italicized numbers adjacent to the arrows indicate the bit-widths of the indicated values. The outer box **34** represents the entire DES algorithm, whether encryption or decryption. The inner structure of DES comprises sixteen rounds of processing **36**, which are identical except for one minor variation in the final round and the variations in one of the internal QPM operations, namely, the key shift, QPMe, which is explained hereinafter. The initial permutation, QPMa at step **38**, and the final permutation, QPMc at step **40**, are true *permutations*, that is, there are no omissions and no duplicated bits. Note that QPMc at step **40** is the inverse of QPMa at step **38**. The key transformation, QPMb at step **42**, selects fifty-six of sixty-four bits from the raw key, and rearranges the bits.

Figure 4 presents a data flow diagram of the internal structure of one of the sixteen DES rounds at step **36**. Left In and Right In are the left and right halves of the data being encrypted or decrypted as it enters the round, and Left Out and Right Out are these halves after the processing has been performed by the rounds. Key In is the fifty-six-bit key as it enters the round, and Key Out is the fifty-six-bit key as it leaves the round. The expansion permutation, QPMd at step **46**, repeats certain bits, whereas the compression permutation, QPMf at step **48**, which produces the round sub-key as its output, omits certain bits.

The key shift, QPMe at step **44**, consists of rotations of the left and right halves of the fifty-six-bit key by an identical amount, in a direction and with a number of shift positions determined by the round number and by whether encryption or decryption is being performed. LKP *h 1 - h 8* at step **50** (performing *S-box substitution*) are the eight S-box lookup tables performed in the round. In the DES standard, the indices for the LKP operations *h 1 - h 8* at step **50** are each, in effect, preceded by yet another QPM operation, which permutes the six input bits so that the low-order or right-most bit becomes the bit second from the left in the effective index, but this QPM can be eliminated to match what has been shown above by re-ordering the elements of the S-box tables. The P-box permutation, QPMi at step **52**,

permutes the results of LKP *h 1 - h 8* at step **50**, presumably to accelerate diffusion of information across all bits.

The XORg operation at step **54** is a simple Boolean exclusive OR on the outputs of the QPMd at step **46** and the output from the QPMf at step **48**. Similarly, the XORj operation at step **56** is a simple Boolean exclusive OR on the outputs of the Left In and the output from QPMi at step **52**.

Note that all rounds are performed identically except for the previously mentioned differences in the key shift, QPMe, and the swapping of Left Out and Right Out, relative to what is shown in **Figure 3,** in the final round.

Detailed Description of Preferred Embodiments of the Invention

A flow chart of the preferred embodiment method of the invention is presented in **Figure 5**. This flow chart provides an overview of techniques which will be described in greater detail with respect to **Figures 6** through **10**. Briefly, these techniques are:

1. converting the original DES software code from multiple loops to a directed acyclic graph of T-boxes, at step **58**;
2. applying lateral and longitudinal diffusion, at step **60**. Lateral diffusion is the splitting of data flow into separate streams and diffusing data laterally between the separate streams, while longitudinal diffusion is the additional of "padding" into the sequential sequence of the software program;
3. applying additional techniques to obscure the network of T-boxes, at step **62**; and
4. generating executable software code at step **64**.

Due to the abundance of QPM operations, DES operations are handled by the invention at the level of individual Boolean values in accordance with the Targeting principle. At that level, the original QPM operations no longer appear as operations in the data flow; instead, they simply determine connectivity of the LKP **50** and XOR **54**, **56** operations. Note that none of the operations can terminate abnormally, irrespective of their inputs, but changing the inputs or the operation changes the result, hence, the implementation of the invention is completely *fake robust*. Moreover, as with many ciphers, slight changes produce cascading, wide-spread behavioural changes, so that the invention exhibits *anti-holographic behaviour.*

Firstly, the preferred method of effecting step **58**, that of converting the original DES software code from the multiple loops to a directed acyclic graph of T-boxes, is presented as a flow chart in **Figure 6**.

Since the forty-eight bits emitted by the compression permutation, QPMf at step **48**, are entirely determined by the original key and the round number, no information travels from the data-portion to the key-portion of the round of DES. Hence, when the sixteen rounds are unrolled completely, leaving a directed acyclic graph (DAG), that is, a loop-free network of Boolean operations, the key-portion can be eliminated by constant folding. Hence, the network may be partially evaluated for a given key. This will be described in greater detail with respect to steps **66** through **72** of **Figure 6**.

The unrolling of the sixteen DES rounds at step **66** can be effected by duplicating the round network fifteen times and connecting the sixteen blocks of software code end-to-end. Then, the eight S-boxes can be copied fifteen times, so that there are separate copies of the original eight S-boxes for each round. Since there are sixteen rounds, this means that after copying, there are 128 S-boxes.

Next, at step **68**, the lookup tables or S-boxes of the DES can be simplified to avoid multiple-output operations, and to facilitate optimization and other changes. This is done by converting the 4-output S-boxes to 1-output T-boxes, where there is one T-box for each output of an S-box (including each output of an S-box which is a copy of an original S-box). "T" stands for “tiny”, since only one bit is emitted per T-box.

This yields sixteen rounds with thirty-two T-box tables in each round, or 512 independent T-box tables in all, each containing sixty-four Boolean elements since each has six Boolean inputs.

That is, the eight S-box lookup tables, LKP *h 1 - h 8* at step **50**, can be replaced with thirty-two T-box lookup tables, LKP *k 1 - k 32*. If the bits of the S-box elements are regarded as columns in a Boolean or bit matrix, then each T-box is one column of the corresponding S-box. LKP *k 1 - k 4* represent LKP *h 1*, with each output representing one bit of the original *h 1* output; LKP *k 5 - k 8* represent LKP *h 2*, and so on. The T-box lookup tables in different rounds are independent of one another because a separate set of S-boxes were created for each round, therefore, the tables in one round can be modified without affecting the others.

After the above-described targeting of the operations in DES, the initial connections surrounding one T-box operation, LKP *k i* , appear as shown in **Figure 7**. Forty-eight bit round keys are constant in each round as they are entirely determined by the round number and the original cryptographic key. Therefore, at step **70** the forty-eight bit XOR block at the beginning of the round, shown as "XOR g" at step **54** of **Figure 4**, can be eliminated.

Hence, the method is as follows:

1. Note that in **Figure 7**, the right operands of XOR *m 1 - m 6* are constants from the cryptographic key. Hence, the right operands can be deleted and each XOR replaced with a Boolean identity (if the constant is **false**) or a Boolean NOT operation (if it is **true**). Therefore, in each round, replace the initial block of forty-eight bit-wise XORs by forty-eight unary operations, where each unary operation is an identity operation (that is, it returns the input unchanged) if the corresponding forty-eight-bit key bit was 0, and is a NOT operation (that is, it returns the input's complement) if the corresponding forty-eight-bit key bit was 1.

   This step incorporates the secret cryptographic key into the software code.

2. These identities and NOT operations can then be eliminated by connecting the LKP inputs directly to the operations previously providing inputs to the identities and NOTs. To do this, the contents of the LKP table must be adjusted to allow for the effect of any inputs resulting from the elision of a NOT operation. This is easily accomplished by re-ordering the elements of the tables. Therefore, in each round:
   a. eliminate the identity operations created above by connecting their input directly to the destination(s) of their output; and
   b. eliminate the NOT operations created above by connecting their input directly to the destination(s) of their output and modifying the tables of their destination T-boxes so that the output of the T-boxes remains the same as it would have been if the NOTs had not been eliminated.

The operation count is then further reduced and the structure of the DES implementation simplified at step **72** by eliminating the remaining bitwise XOR blocks, shown as "XOR j" in **Figure 4**. This is done by folding the XOR shown as XOR *n* in **Figure 7** together with the LKP shown as LKP *k i* above.

In each round, replace the block of thirty-two T-boxes performing the "QPM i" operation of **Figure 4** and the block of thirty-two XORs performing the "XOR j"

operation of **Figure 4** with thirty-two new T-boxes performing both of those operations. That means each new T-box created by this step has one extra input; that is, instead of six inputs, it has seven. The table is adjusted so the combined function of "QPM i" and "XOR j" is correctly computed.

In other words:

1. a new leftmost input is added to LKP *k i* and connects it to the input to XOR *n*; and then
2. XOR *n* is eliminated, by taking the elements of LKP *k i* 's table, making a copy but with every element inverted, and concatenating that to the end of the original table.

The result is that the new LKP (LKP *k' i* , say) now includes the effect of XOR *n*, thereby increasing the degree of *fusion* in this implementation, and yielding a version of DES consisting of 512 seven-input T-box lookup operations, connected together. The connections of a typical LKP operation, after step **72**, are shown in **Figure 8**. Steps **66** through **72** are referred to herein as "partial evaluation".

Information from the cryptographic key and the manipulations of the cryptographic key has now been *diffused* into the T-box LKP operations, beginning to satisfy the principle of *diffusion* of computations and data. That is, the cryptographic key does not explicitly appear in the software code. Note, however, that the connections of a T-box LKP from the second previous round, created by eliding the XOR operations of XOR *n* (see **Figure 7**) reveal the identities of the T-box LKPs. This problem is addressed in a later transformation.

Next, the optional step of injecting identity T-boxes into the data flow may be performed at step **74**.

Note the connectivity of the look up tables after partial evaluation, shown in **Figure 8**. Six of a T-box's inputs are from T-boxes farther from the source values than the other; that is, six are from a more recent round and one from an earlier round.

In order to obscure the connectivity, the simple connection labelled *from left data* in **Figure 8** can be replaced with a new T-box (the "injected" T- box), which inputs this value and also includes a random set of six other inputs, chosen to make the connectivity of the injected T-box look similar to that of existing T-boxes, that is, injection makes the left and right side connectivity look similar. These six other inputs may be ignored (that is, they act as "*don't care*" inputs). Such T-boxes will be referred to herein as "*identity T-boxes*".

Immediately following this step, the identity T-boxes are easy to identify as data flow analysis of the T-box table for an identity T-box reveals that only one of the inputs is significant. However, after further transformations are applied to them, other bits become significant and the identity T-boxes are harder to identify.

At this point, the original software program is now a DAG with the values of the cryptographic key and lookup tables distributed throughout the software code. The techniques of longitudinal and lateral diffusion are now applied to the partially evaluated software code per step **60** of **Figure 5**.

Longitudinal diffusion injects a diffusing network before, after or between a pair of "real" rounds. As noted above, DES is vulnerable to attacks starting at the beginning and the end of the computation (see Schneier et al.), so to address this vulnerability, the DES implementation of the invention is "padded" with additional code, particularly at the beginning and end. This "padding" has two very significant properties:

1. it is inserted into the longitudinal flow of the program in such a way that the programs outputs are dependent on the code. This is in contrast to "dummy code" as known in the art, where the final outputs are not dependent on the code. Hence it can be identified by data flow analysis (DFA) techniques; and
2. it uses cryptographic identities based on randomly chosen keys, intended to deceive the attacker, so any information that an attacker gleans from analysis of the pads will lead him to incorrect conclusions about the actual cryptographic key.

The method for adding longitudinal diffusion is presented as a flow chart in **Figure 9**. First, at step **76**, cryptographic identities are generated, specifically chosen to permit their implementation by means of T-boxes. A cryptographic identity comprises a T-box sub graph which computes an identity by first encrypting and then decrypting the data, using some key not related to the DES key that is being hidden. Examples of cryptographic identities would be: n-round DES encryption with some randomly chosen key K_r, followed by n-round DES decryption using K_r, where n would typically be some even number less than sixteen. However, any DES variant, or indeed any sufficiently DES-like cipher whatever, can also be used, to further complicate the problem of identifying the S-boxes given the T-boxes. If the cryptographic identities are DES-based, one would typically omit the initial and final permutations from the identities. (See Schneier et al., pp. 294-300, for examples of

DES variants.) Techniques for generating the various randomly chosen keys are well known in the art.

Then, at step **78**, these identities are inserted into the DES implementation, either at the beginning, the end, or in the middle, between any pair of unrolled rounds. For protection against attacks beginning at the ends, it is preferred to place such padding before and after 1 or more initial round pairs, and before and after 1 or more final round pairs.

Since the pads are identities, they have no effect on the output of the software code. At this point, they do not sound like a sensible addition as complementary pairings of sixty-four Boolean equations would stand out during tracing of the software. However, after further techniques have been applied, they no longer have the appearance of identities.

These identities, even after further processing, continue to have the property inherent in DES-like ciphers that interfering with any individual Boolean, or any computation which produces such a Boolean, has a diffuse effect, altering many bits in future computations. Hence, this padding is *not* dummy code. It changes what happens in response to tampering, thereby contributing to *anti-holographic behaviour.* That is, any small change will have an increased tendency to produce a wide-spread, cascading effect over many output bits; even more so than in ordinary DES (with respect to the 'real' rounds). The specific need to protect the beginning and end of the computation is also addressed by the invention. Pads also increase the *obscurity* of the implementation: there is no longer just one key for an attacker to identify in any given hidden-key cryptographic function; there are several.

Further pads may be injected at points in the middle of the computation to increase anti-holographic behaviour as much as one desires. At a minimum, it is preferred to enclose a sequence of initial round pairs (one or more) between two pads, and similarly for a sequence of final round pairs.

Next, lateral diffusion is performed, as presented in **Figure 10**. Lateral diffusion may be described as splitting the data flow of the program into separate streams and then diffusing data laterally between the separate streams. A simple implementation will first be described which employs a two-input Boolean function, then improvements will be described which result in a much stronger implementation:

1. At step **80**, choose an existing T-box (which will be referred to as *original*) and generate two new T-boxes (which will be referred to as *left* and *right*),

with the same dimensions as *original*. Note that the *original* T-box must not be a final output T-box.

2. At step **82**, choose a Boolean function with two inputs and one output. There are sixteen of these, but one should not use Boolean functions for which some input is a '*don't care*'. There are six functions that must therefore be rejected, specifically, those which output constant **true**, constant **false**, the left input, the right input, **not** the left input, and **not** the right input. The remaining ten Boolean functions are substantive and usable, and one of such functions can be chosen at random for any given pair of *left, right* look up tables. The function chosen for any particular *left, right* pair of tables will be identified as "*func*".

3. Fill the tables for *left* and *right* at step **84**, proceeding as follows:

   a. For each element, indexed by *i* in *original*, where *i* ranges from 0 to 127 inclusive (since the T-boxes have seven inputs at the start of this transformation), choose a pair of values *x, y* for the *left* and *right* elements indexed by *i*, respectively, such that *func* (*x, y*) has the same value as element *i* of *original*.

   b. There are often multiple choices of Boolean *x, y* value pairs which achieve the desired output, so one can choose randomly among such choices. Of course, one must be careful not to make selections that cause the new *left* or *right* table to be identical to the *original*.

   c. Insert the chosen *x, y* value pair into the outputs of the left and right look up tables, at the same index location as the *original*.

4. Last, at step **86**, insert the two new tables into the data flow of the software code so that the old index to the original table now indexes both of the new tables. Similarly, insert the random Boolean function into the data flow of the program following the two new tables, so that the outputs of the two tables are directed to the Boolean function.

This process effectively converts seven-input T-boxes into eight-input T-boxes, randomly *diffusing* information from the *original* T-box between *left* and *right* T-boxes, and adding random, redundant information. This process can also be generalized to the case of an *n*-input T-box LKPs, where $n \geq 8$. Initially, $n = 8$, but as additional techniques are applied, *n* may take on higher values with the splitting of more inputs into input pairs. (Note: the T-boxes started with six inputs, folding in the

XOR changed it to seven, and adding one further input increases this from seven to eight.)

The Boolean value stored in the table of a resulting 8-input T-box look up operation for any 8-bit input vector is determined as follows: Let *A* and *B* be bit-strings with a combined length of six bits, and let *u*, *v*, and *w* be individual bits. For any element indexed by some index *AuvB* (variables juxtaposed in this manner represent concatenation of their bit values) in the expanded 8-input table, the value stored is the same as that of the element indexed by *AwB* in the 7-input table from which it is derived, where $w = func\ (u, v)$. The same logic extends to $n > 8$.

By working this transformation backwards from the output T-box LKP operations to the beginning of the DES implementation graph, one can arrange that, in general, T-box LKP operations other than those producing the final outputs and the initial ones whose inputs are not from other T-box LKP operations, have more than seven inputs.

This transformation is quite simple, and contributes greatly to *obscurity*, by diffusing information among T-box LKP operations and thereby making their contents randomly perturbed relative to their original contents. Moreover, it tends to make the injected *pad* identities not quite identities anymore.

However, it can be made combinatorially stronger (that is, increase the number of possible functions above ten), and at the same time address the T-box identification problem mentioned at the end of the section on partial evaluation, with the following refinement: instead of having *func* be a function of only two Boolean inputs, it can be made a function of three Boolean inputs, where one of the inputs is one of the inputs of *original* which comes from the round previous to *original*. Let us call this extra input *p*. Then *func* must be a Boolean function such that:

1. if there is a '*don't care*' input, it is the *p* input; and
2. for each value of *p*, it is possible to make *func* return either **true** or **false** by modifying the other inputs.

This increases the number of choices for *func* from ten to 100. Then LKPs which used to input from *original* input from all of: *left*, *right*, and the LKP, or the original input from the start of DES, which is the source of *p*.

Then, the uses of $func\ (x, y)$ and $func\ (u, v)$ above, are replaced with uses of $func\ (p, x, y)$ and $func\ (p, u, v)$, respectively. Filling in the table for the expanded input set is a straightforward extension of the methods used above. In addition to increasing the combinatorial complexity of determining the contents of the diffused

tables in *left* and *right*, this refinement makes it much harder to identify which T-box LKP corresponds to which column of which S-box, since connections from two rounds back become more frequent, and this plus a later T-box LKP input permutation step make T-box LKP identities ambiguous.

It is important to make suitable choices for *original* and for the source of *p*. Examination of the interconnection pattern for T-box LKP operations will show that in many cases one can make the identity of a T-box LKP with respect to a column in an S-box *ambiguous*, by increasing the number of inputs from two rounds previous from one to two or more, so that it is not clear which input from the second previous round came from eliding an XOR (XOR *j* in **Figure 4**) and which was added by the *diffusion* transformation. When this is combined with the obscuring transformation of step **62**, which permutes the T-box LKP inputs, it makes identification of T-box LKPs with their corresponding S-box columns far more difficult, combinatorially speaking. The details depend on the nature of the *expansion permutation* (QPM *d* in **Figure 4**) and the *P-box permutation* (QPM *i* in **Figure 4**), which together determine the connectivity among rounds.

The above approach, with or without the recommended refinement, easily extends from producing *left, right* pairs of T-box LKP operations to producing triplets — *left, middle, right* — or even quadruplets or larger numbers. The number of inputs in non-initial T-box LKP operations can then be increased, either by producing more pairs, or by producing triplets or quadruplets instead of pairs, or by some combination of these approaches. One can also vary the number of inputs among T-box LKP operations, making the structure of the DES implementation highly irregular.

Next, the network of T-boxes is obscured by encoding the input vectors of non-initial T-boxes, referred to as step **62** in **Figure 5**. As each input vector is encoded, adjust the table of the T-box so its output is not affected. At this point, the T-box operations have 7- or 8-bit input vectors (or, optionally, larger ones). The encoding consists of flipping randomly chosen bits and permuting the positions of the vector elements as shown in the flow chart of **Figure 11**:

1. First, the flipping part of the encoding is performed at step **88**. Inputs are selected for inversion randomly. This is done only where the sources of these inputs are internal to the implementation; that is, do not flip any bits in the input data. When a bit is flipped, the bits of its source T-box's table are inverted. That is, obtaining the NOT of the output of previous outputs.

Inputs to T-boxes may come from shared sources. As a result, when two T-boxes disagree on the encoding of inputs coming from the same other T-box, that source T-box is no longer fully sharable (since its output must be delivered to one client flipped and to another unflipped). As a result, this stage increases the number of T-box LKP operations in the implementation.

2. The second part of the coding at step **90**, is to randomly permute the inputs of each T-box LKP operation. The elements of each T-box LKP table are re-ordered to allow for the new arrangement of the inputs.

These modifications to the T-box LKP tables intermingle elements which previously were widely separated, increasing the degree of *fusion*. They also increase the *obscurity*, as does the presence of multiple T-boxes derived from one T-box, and containing different tables. Moreover, the previously described *pad* rounds injected into the software code have now very definitely ceased to be identities.

The final step is to generate executable code from the network of T-boxes per step **64** of **Figure 5**.

Up to this point, a symbolic Boolean DAG has been described, which is not in a form suitable for execution on any platform. Since the DAG consists entirely of T-box LKP operations, it is preferred to implement DES based on the DAG, as follows:

Each LKP operation can be represented by a call to a utility function. For an n-input LKP, this requires $n + 1$ arguments. The extra argument is a pointer to the table of Boolean functions to be used for that particular LKP operation. The utility function compresses its inputs into an index, indexes into its table to find the result, and returns that result.

The body of the DES function, then, consists of an initial expansion of the sixty-four-bit input data block into sixty-four separate values, followed by a chain of T-box LKP routine calls, plus any needed loads and stores, implementing the desired Boolean DAG's connectivity, followed by a compression of the sixty-four result Booleans into a sixty-four-bit result value, which is returned.

Optionally, one can reduce the number of arguments to each of the above LKP routine calls by one, by taking advantage of the fact that the calls are chained together in a specific sequential order. Therefore, one can sequence through the tables used in the successive calls by having the utility routines index through a sequence of tables stored in just that sequential order. Thus, the tables can be implicit in the calls, instead of being passed as an argument in each call. The body

of the DES function would then begin by setting the appropriate starting state for iterating through these tables.

In summary, one can convert T-boxes into calls to utility routines, with interspersed code to move outputs to inputs as follows:

1. generate T-box utility calls by topologically sorting the T-box network in "connected to" order, and emitting code for this sorted order;
2. insert at the beginning of the software code, operations which separate the sixty-four-bit data input into individual values for arguments to the utility routines; and
3. insert at the end of the software code, operations which combine sixty-four separate values into a single sixty-four bit output.

Alternative Embodiments

1. **Virtual Machine Interpreter**

A variation on the generation of executable code described above, which is somewhat more compact, is to utilize an interpreter for a T-box virtual machine (TVM) with some number (see below) of 1-bit registers. An interpreter is a program that directly executes high-level code, as opposed to a compiler which generates machine language for execution. A virtual machine is a self-contained operating environment which can execute on a computer or similar device. The Java Virtual Machine, for example, will run the same way on any computer.

In addition to the 1-bit registers, the TVM contains a linear table of bits and a counter indicating how many of the bits in this linear table have been consumed. The linear table comprises the concatenation of the tables of all of the T-boxes in their intended execution order. Each TVM instruction comprises a series of fields, namely:

a. bit consumption count, indicating how many bits of the linear table are to be consumed. That is, what the size of the table is for the T-box represented by this instruction;
b. input count, indicating how many inputs this T-box has;
c. series of input register numbers, indicating which 1-bit register corresponds to which T-box input; and
d. output register number, indicating which 1-bit register receives the result of the T-box lookup represented by this instruction.

The TVM's program comprises a sequence of such instructions, followed by an instruction with a bit consumption count of 0, indicating termination of the program.

The number of 1-bit registers needed is the largest number of values computed but not yet consumed at any point during execution of the particular executable T-box ordering chosen for the graph. At start-up, a sixty-four element prefix of the TVM's 1-bit registers are filled with the data to be encrypted or decrypted, and at termination, the sixty-four element prefix contains the encrypted or decrypted result value.

2. **Bit-Exploded and Bit-Tabulated Coding**

Several means of data flow encoding for tamper-resistance are disclosed in the co-pending patent application "Tamper Resistant Software Encoding", United States Patent Application No. 09/329,117, which is incorporated herein by reference. Two such methods disclosed in this application which are particularly well suited to hiding Data Encryption Standard (DES) Keys are Bit-Exploded coding and Bit-Tabulated coding.

Similar to the above, these methods begin by unrolling the DES algorithm and introducing the tables and encryption key to each round as constants. The sixteen 'rounds' of DES may be unrolled at the source level, or by applying aggressive loop unrolling to unroll the rounds in the code optimizer. The tamper resistance and obfuscation are added to this unrolled code as follows:

a. The principle of the bit-exploded coding technique is to convert *n*-bit variables into *n* Boolean variables. That is, each bit of the original variable is stored in a separate and new Boolean variable.

Each such new Boolean variable may either be unchanged or inverted by interchanging **true** and **false**. For example, this means that for a thirty-two-bit variable, there are 2^{32}, a little over 4 billion, bit-exploded codings to choose from. These variables and their transforms are recorded in a "phantom parallel program", so that the inversions can be rationalised with other equations and operations in the software. At this point, the software code contains excessive bulk, but may be reduced using conventional constant folding. The effect is that the cryptographic key has now completely disappeared, but the code bulk remains large.

b. Further encoding is now performed by bit-exploded to bit-tabular optimization.

Bit-exploded coding may produce data flow networks having subnetworks with the following properties: they have only a reasonably small number of inputs; and they are acyclic; that is, contain no loops.

When this occurs, one can replace the entire network or subnetwork with a table lookup. This results from the fact that an *m*-input, *n*-output Boolean function can be represented by a zero-origin table of 2^m *n*-bit elements. Instead of including the network in the final encoded program, it is simply replaced with a corresponding table lookup, in which one indexes into the table using the integer index formed by combining the *m* inputs into a non-negative integer, obtaining the *n*-bit result, and converting it back into individual bits.

Note that the positions of the bits in the index and the result of the above lookup can be random, and the network can be previously encoded using the bit-exploded coding, so the encoding chosen for the data is not exposed.

A completely different set of look up tables has now been produced which bears no discoverable relation to the originals and correspond only to the encoded data. The positions of the bits, and to some extent even which part of the computation has been assigned to which S-box, is now radically changed. Thereby, this provides an effective means for data-coding small tables used in table lookup operations.

The same process can be used to create a routine which performs the corresponding decryption.

This encoding is highly suitable for code in which bitwise Boolean operations, constant shifts or rotations, fixed bit permutations, field extractions, field insertions, and the like are performed. Shifts, rotations, and other bit rearrangements have no semantic equivalent in high-level code, since they specifically involve determining which bits participate in which Boolean operations. Hence, such changes are a significant impediment to decompiling and reverse-engineering.

As well, variables may be transformed in a bit-wise manner using de Morgan's laws. This encoding results in a substantial increase in the number

of operations relative to the original program, except for operations which can be "factored out" because they can be done by reinterpreting which variables represent which bits or which bits are in the representation are inverted.

Why Is It Hard to Find the Cryptographic Key?

The invention presents a new way to generate an implementation of DES with an implicit, hidden key. It is intended for use where key-hiding is important, but the volume of data to be encrypted or decrypted is modest, so that a much slower implementation can be tolerated in order to achieve a greatly increased level of security. This approach injects a huge amount of random, arbitrary information into the structure of the hidden-key DES implementation.

At present, there are, quite simply, *no* widely accepted, theoretically well founded metrics for estimating the level of security delivered by a technology for the production of secret-hiding, tamper-resistant software. This is a vast unexplored area in the theory of computational complexity.

In the absence of such metrics, the effectiveness of the invention can only be defended on the basis of arguments. In terms of its ability to hide the cryptographic key, for example, the invention is highly effective for the following reasons:

1. The way S-box LKP operations are interconnected when the round loop of DES is unrolled, determines the way the T-box LKP operations are interconnected after converting from S-box LKPs to T-box LKP operations and then partially evaluated with respect to the cryptographic key. The cryptographic key has no effect on connectivity. This would allow one to identify the T-box LKPs. However, after performing the refined version of diffusion of information into pairs of T-box LKP tables, followed by encoding of T-box LKP input vectors, which permutes the inputs, there is no way to coordinate the arrangement of the T-box LKPs. While analysis of the combinatorial complexity of T-box identification is a dauntingly difficult undertaking, it is clear that these transformations make the problem of identifying the effective positions of individual T-box LKP operations, as compared to columns of the original S-boxes, a combinatorially sizable search problem.
2. Even if one could identify all of the T-box LKPs with individual columns in individual original S-boxes, however, one would still not know the cryptographic key. Due to padding, an attacker must contend with multiple

keys and unknown boundaries between pad rounds and 'real' rounds. The difficulty of finding the 'real' key can be increased by using more injected pads, or pads with more rounds, or both. Due to the encoding and diffusing of information among tables, and due the large size of the combinatorial search for ways to coordinate the T-box LKP identities and then recombine diffused pairs of LKPs back into single LKPs, an extremely large combinatorial guessing problem has been created to find the cryptographic key. This problem can be made harder to solve by increasing the number of inputs in the T-boxes, thereby making more and more T-box tables the result of combinatorially hidden diffused information.

Exact computation of the search problem's complexity is difficult, even if most T-box LKPs have only eight or nine inputs, but the combinatorial complexity of the guessing problem is massive, even with a small number of minimal pads surrounding only the initial and final round pairs of an implementation. As well, the complexity will vary with the particulars of the implementation.

The above method for hiding DES keys may be more useful if it is embedded in a larger program, and control flow encoding is used in concert with data flow encoding in a manner of the invention. This makes the above technique highly useful, since it is then no longer possible to extract the encryption and decryption routines in isolation.

Applications

1. **Protection of Biometric Data**

Biometric data stored in the software program could not be decrypted by simply extracting the encryption and decryption components from the software, because subsidiary techniques would be applied to make separation into components an even harder problem. Moreover, one would employ subsidiary tamper-resistant, secret-hiding methods to ensure that comparisons of biometric data do not compromise it, even when the attacker has full debugging access, and that the behaviour of the application performing such operations is not modifiable in any way useful to the attacker. Hence, the biometric information can be well protected both locally and globally.

2. **Encode 'Plain-Text' and 'Ciphertext' and Embed the DES Implementation in a Larger Tamper-Resistance, Obscure Program**

To this point, an implementation has been described in which the DES implementation is standard. In practice, to achieve much greater protection, the following additional methods are proposed:

Use an encoded implementation in which input and output blocks are encrypted or decrypted from, and encrypted and decrypted to, an encoded format with bits permuted and some bits flipped, as described in the section on *Bit-Exploded Encoding* in co-pending patent application "Tamper Resistant Software Encoding", United States Patent Application No. 09/329,117. In many contexts, one can compute with such encoded data using the methods of co-pending patent application "Tamper Resistant Software Encoding", United States Patent Application No. 09/329,117, and using an encoded plain-text form makes the problem of penetrating the DES implementation to find the cryptographic key significantly harder.

Also, deploy the product of the instant process in a larger, tamper-resistant, information-hiding program, such as a program produced by the methods described in co-pending patent application "Tamper Resistant Software Encoding", United States Patent Application No. 09/329,117 and "Tamper Resistant Software - Control Flow Encoding", United States Patent Application No. 09/377,312. If other computations in the vicinity of the DES implementation can be implemented similarly, this makes finding the beginning and end of the DES implementation much harder, rendering discovery of the cryptographic key, or information about the S-boxes, or effective tampering with the implementation, yet more difficult.

While particular embodiments of the present invention have been shown and described, it is clear that changes and modifications may be made to such embodiments without departing from the true scope and spirit of the invention. For example, rather than using the techniques described above, alternate techniques could be developed which diffuse a cryptographic key, biometric or other data throughout a software program.

There are many uses for software applications which embed and employ a secret encryption key without making either the cryptographic key or a substitute for the cryptographic key available to an attacker. The method of the invention can generally be applied to these applications.

The teachings herein are easily modified to apply to a different arrangement of lookup tables, rather than the 4-output S-boxes, or to an application with a number of rounds, or format of the initial and final permutations. These applications would include, for example, the various triple DES algorithms now available. As well, one skilled in the art could apply these obfuscation and tamper-resistance techniques to any manner of other software programs.

It is understood that as de-compiling and debugging tools become more and more powerful, the degree to which the techniques of the invention must be applied to ensure tamper protection, will also rise. As well, the concern for system resources may also be reduced over time as the cost and speed of computer execution and memory storage capacity continue to improve.

These improvements will also increase the attacker's ability to overcome the simpler tamper-resistance techniques included in the scope of the claims. It is understood, therefore, that the utility of some of the simpler encoding techniques that fall within the scope of the claims, may correspondingly decrease over time. That is, just as in the world of cryptography, increasing key-lengths become necessary over time in order to provide a given level of protection, so in the world of the instant invention, increasing complexity of encoding will become necessary to achieve a given level of protection.

The method steps of the invention may be embodiment in sets of executable machine code stored in a variety of formats such as object code or source code. Such code is described generically herein as programming code, or a computer program for simplification. Clearly, the executable machine code may be integrated with the code of other programs, implemented as subroutines, by external program calls or by other techniques as known in the art.

The embodiments of the invention may be executed by a computer processor or similar device programmed in the manner of method steps, or may be executed by an electronic system which is provided with means for executing these steps. Similarly, an electronic memory medium may be programmed to execute such method steps. Suitable memory media would include serial access formats such as magnetic tape, or random access formats such as floppy disks, hard drives, computer diskettes, CD-Roms, bubble memory, EEPROM, Random Access Memory (RAM), Read Only Memory (ROM) or similar computer software storage media known in the art. Furthermore, electronic signals representing these method steps may also be transmitted via a communication network.

It will be obvious to one skilled in these arts that there are many practical embodiments of the DES implementation produced by the instant invention, whether in normal executable machine code, code for a virtual machine, or code for a special purpose interpreter. It would also be possible to directly embed the invention in a net-list for the production of a pure hardware implementation, that is, an ASIC.

It would also be clear to one skilled in the art that this invention need not be limited to the existing scope of computers and computer systems.

Credit, debit, bank and smart cards could be encoded to apply the invention to their respective applications. An electronic commerce system in a manner of the invention could for example, be applied to parking meters, vending machines, pay telephones, inventory control or rental cars and using magnetic strips or electronic circuits to store the software and passwords. Again, such implementations would be clear to one skilled in the art, and do not take away from the invention.

WHAT IS CLAIMED IS:

1. A method of increasing the obscurity and tamper-resistance of a software program, comprising the steps of:

randomly generating substantive yet redundant arguments; and

inserting said arguments into the data flow of said program.

2. A method as claimed in claim 1, wherein said steps of randomly generating and inserting comprise the steps of:

randomly generating substantive yet redundant, lookup tables; and

inserting said lookup tables into the data flow of said program.

3. A method as claimed in claim 2, wherein said steps of randomly generating and inserting comprise the steps of:

introducing longitudinal diffusion by:

randomly generating identity look up tables; and

inserting said identity look up tables into the data flow of said program.

4. A method as claimed in claim 3, wherein said program is a data encryption standard (DES) program and said step of randomly generating comprises the step of randomly generating DES-based identities as networks of T-boxes.

5. A method as claimed in claim 4, wherein said DES-based identities comprise complementary encryption and decryption lookup tables containing a cryptographic key unlike the secret cryptographic key of said DES program.

6. A method as claimed in claim 5, wherein said step of inserting comprises the step of:

placing said DES-based identities before and after one or more initial round pairs of said DES program, and before and after one or more final round pairs, thereby defending against attacks from the ends of said DES program.

7. A method as claimed in claim 2, wherein said steps of randomly generating and inserting comprise the steps of:

splitting the data flow of said program into separate streams; and

diffusing data laterally between said separate streams.

8. A method as claimed in claim 2, wherein said steps of randomly generating and inserting comprise the steps of:

introducing lateral diffusion by:

generating multiple lookup tables for an original lookup table;

generating entries for said multiple lookup tables in accordance with a random Boolean function; and

transposing the output of said multiple lookup tables in accordance with said random Boolean function.

9. A method as claimed in claim 8, wherein said step of generating entries comprises:

choosing a random, substantive, Boolean function;

for each output of said original lookup table:

determining the set of inputs to said Boolean function that will yield said output of said original lookup table;

randomly selecting one of said sets of inputs; and

inserting said selected set of inputs, into the output of said multiple lookup tables;

modifying calls to said original lookup table to call upon said multiple lookup tables; and

inserting said random Boolean function into the data flow of said program following said calls to said multiple lookup tables.

10. A method as claimed in claim 9, wherein said random Boolean function is a two input Boolean function and each said set of inputs comprises two inputs.

11. A method as claimed in claim 9, wherein said random Boolean function is a three input Boolean function and each said set of inputs comprises three inputs.

12. A method as claimed in either of claims 10 or 11, wherein said steps are executed beginning at penultimate lookup tables, and working backwards towards earlier rounds.

13. A method as claimed in either of claims 6 or 12, wherein said software program is an encryption program requiring a cryptographic key, said method comprising the previous step of:

converting said software program into a direct acyclic graph.

14. A method as claimed in claim 13, wherein said encryption program is a Data Encryption Standard (DES) program and said step of converting comprises the steps of:

unrolling the *n* digital encryption software algorithm rounds by:

duplicating the round network *n* times and connecting said *n* rounds end-to-end;

copying the *i* S-boxes explicitly into each round, resulting in *n x i* separate S-boxes; and

converting each said *k*-output S-box into *k* 1-output T-boxes resulting in *n x i x k* separate T-boxes, with *k x i* separate T-boxes per round.

15. A method as claimed in claim 13, wherein said step of converting comprises the step of:

unrolling the sixteen digital encryption software algorithm rounds by:

duplicating the round network sixteen times and connecting said rounds end-to-end;

copying the eight S-boxes explicitly into each round, resulting in 128 separate S-boxes; and

converting each said 4-output S-box into four 1-output T-boxes resulting in 512 separate T-boxes, thirty-two per round.

16. A method as claimed in claim 15, further comprising the step of:

partially evaluating said program to eliminate the cryptographic key as a separate constant or series of constants.

17. A method as claimed in claim 16, further comprising the step of:

where one operand of an XOR operation adjacent to a T-box is a constant,

eliminating said XOR operation by:

modifying the entries of said T-box to effect said XOR accordingly; and

deleting said XOR operation.

18. An apparatus for increasing the obscurity and tamper-resistance of computer software code comprising:

means for modifying said software code by:

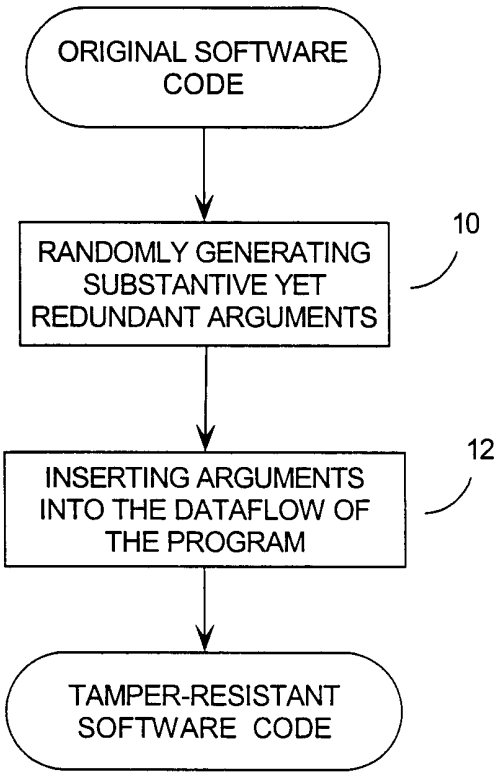
randomly generating substantive yet redundant arguments; and

inserting said arguments into the data flow of said software code.

19. A computer readable memory medium, storing computer software code executable to perform the steps of any one of claims 1 through 17.

20. A computer data signal embodied in a carrier wave, said computer data signal comprising a set of machine executable code being executable by a computer to perform the steps of any one of claims 1 through 17.

FIGURE 1


ORIGINAL SOFTWARE CODE
RANDOMLY GENERATING SUBSTANTIVE YET REDUNDANT ARGUMENTS
10
INSERTING ARGUMENTS INTO THE DATAFLOW OF THE PROGRAM
12
TAMPER-RESISTANT SOFTWARE CODE

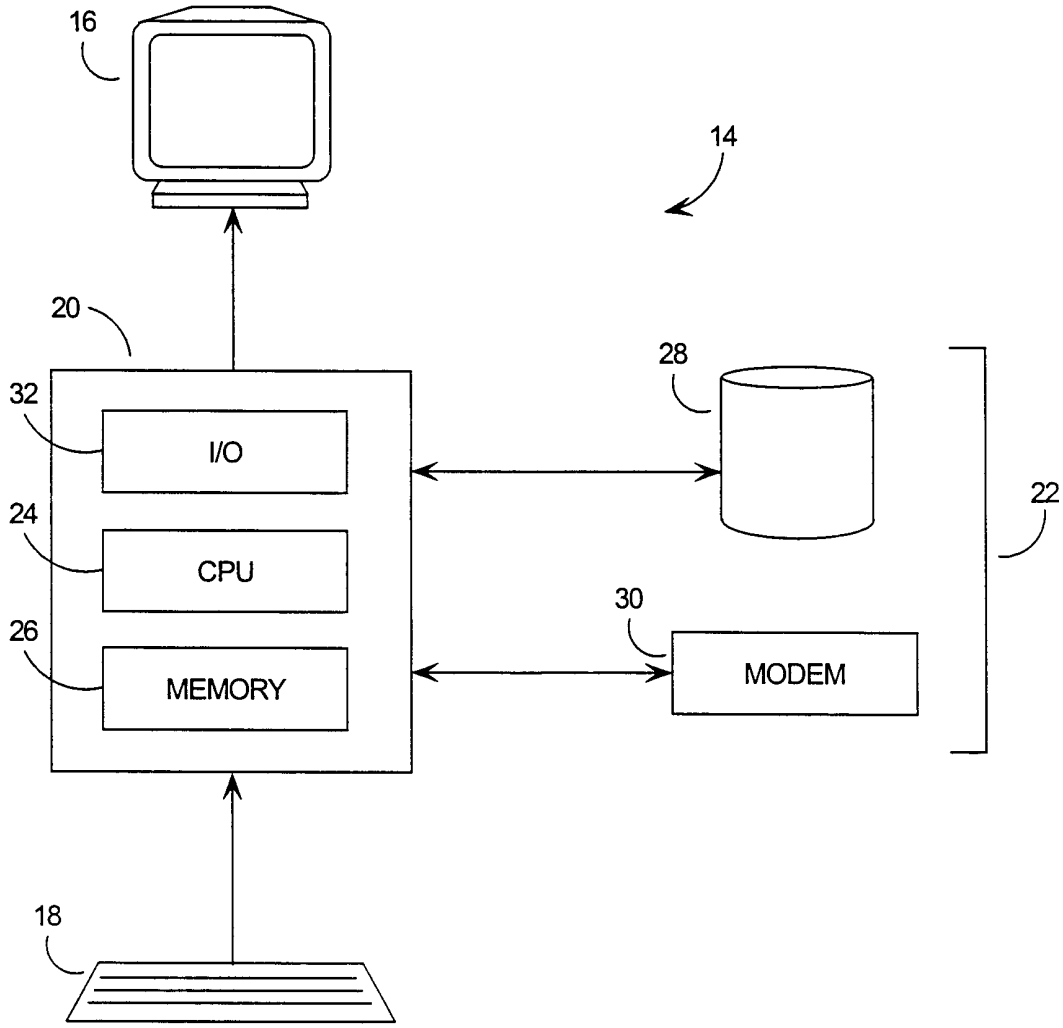


FIGURE 2

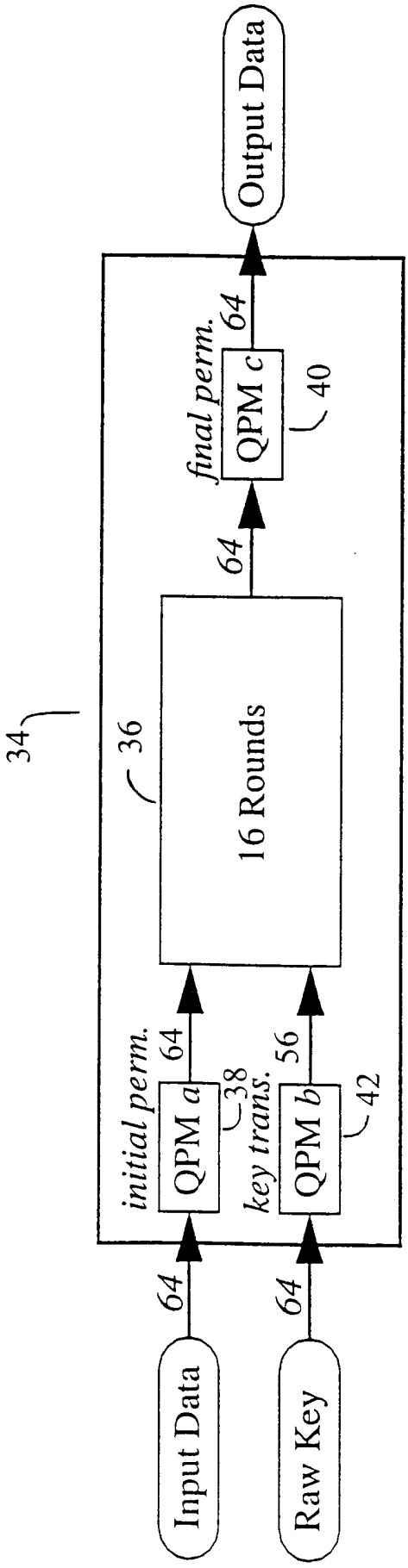


Figure 3: Outer Structure of DES

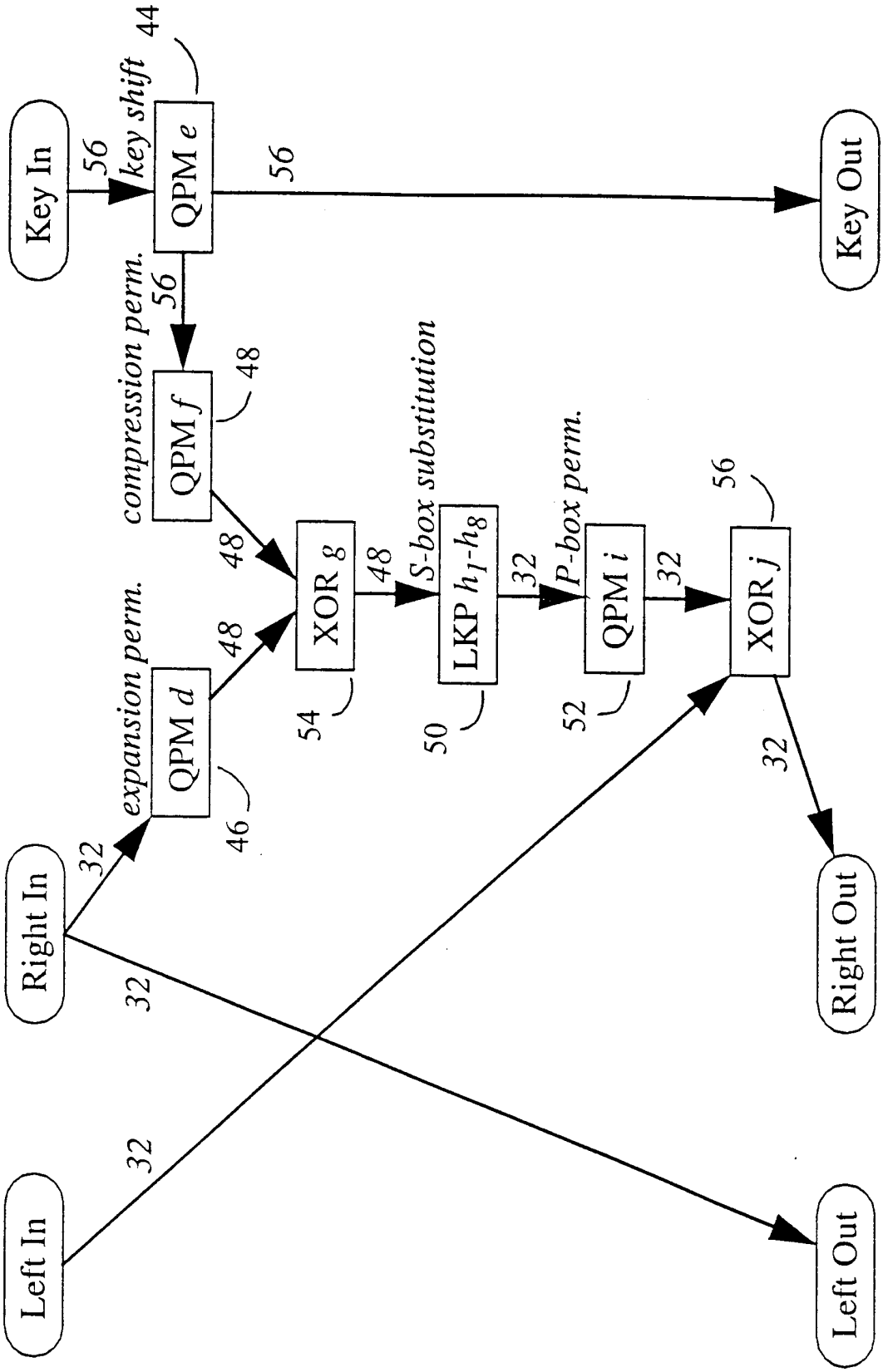


Figure 4: Structure of One DES Round

FIGURE 5

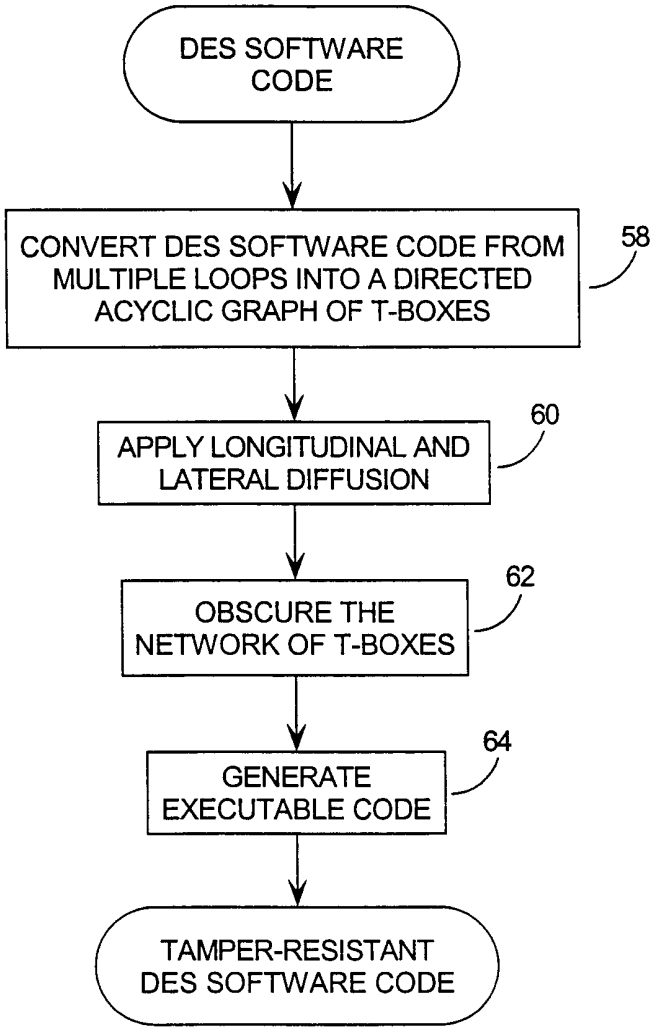
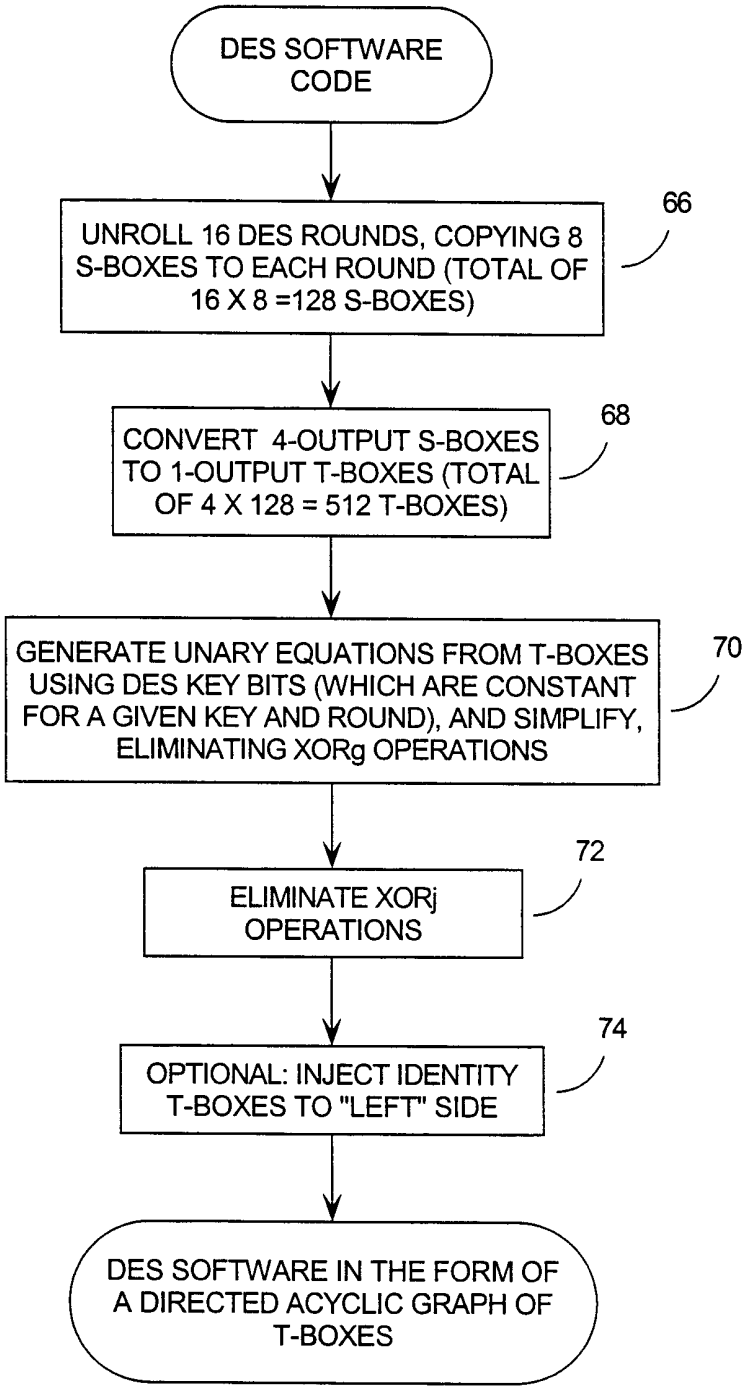

DES SOFTWARE CODE
CONVERT DES SOFTWARE CODE FROM MULTIPLE LOOPS INTO A DIRECTED ACYCLIC GRAPH OF T-BOXES
58
APPLY LONGITUDINAL AND LATERAL DIFFUSION
60
OBSCURE THE NETWORK OF T-BOXES
62
GENERATE EXECUTABLE CODE
64
TAMPER-RESISTANT DES SOFTWARE CODE

FIGURE 6


DES SOFTWARE CODE
UNROLL 16 DES ROUNDS, COPYING 8 S-BOXES TO EACH ROUND (TOTAL OF 16 X 8 =128 S-BOXES)
66
CONVERT 4-OUTPUT S-BOXES TO 1-OUTPUT T-BOXES (TOTAL OF 4 X 128 = 512 T-BOXES)
68
GENERATE UNARY EQUATIONS FROM T-BOXES USING DES KEY BITS (WHICH ARE CONSTANT FOR A GIVEN KEY AND ROUND), AND SIMPLIFY, ELIMINATING XORg OPERATIONS
70
ELIMINATE XORj OPERATIONS
72
OPTIONAL: INJECT IDENTITY T-BOXES TO "LEFT" SIDE
74
DES SOFTWARE IN THE FORM OF A DIRECTED ACYCLIC GRAPH OF T-BOXES

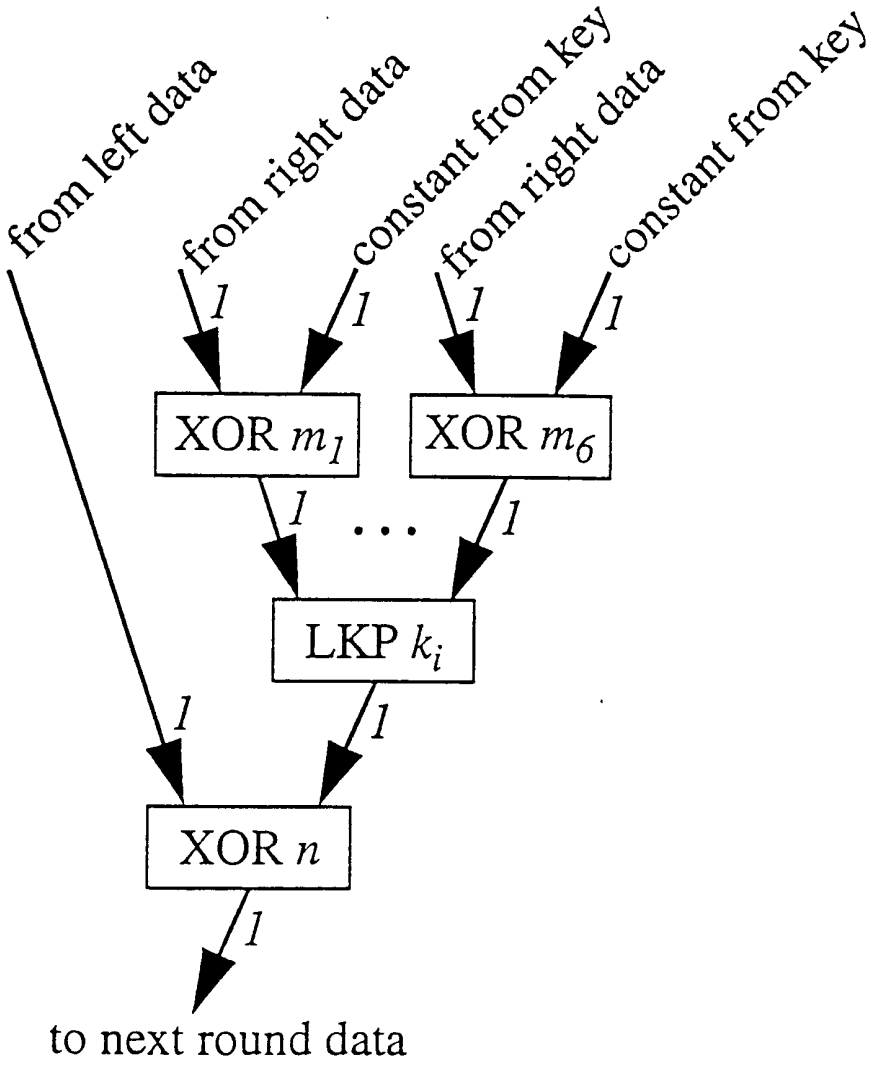


Figure 7: Initial Connections of One T-box Operation

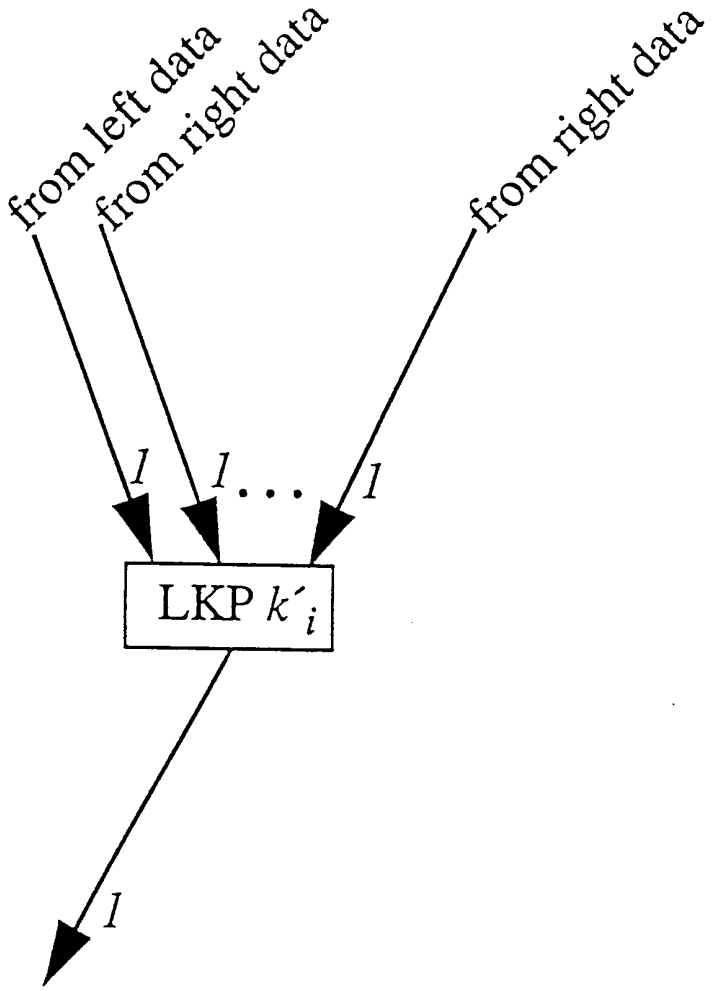


Figure 8: T-box Connections After Partial Evaluation

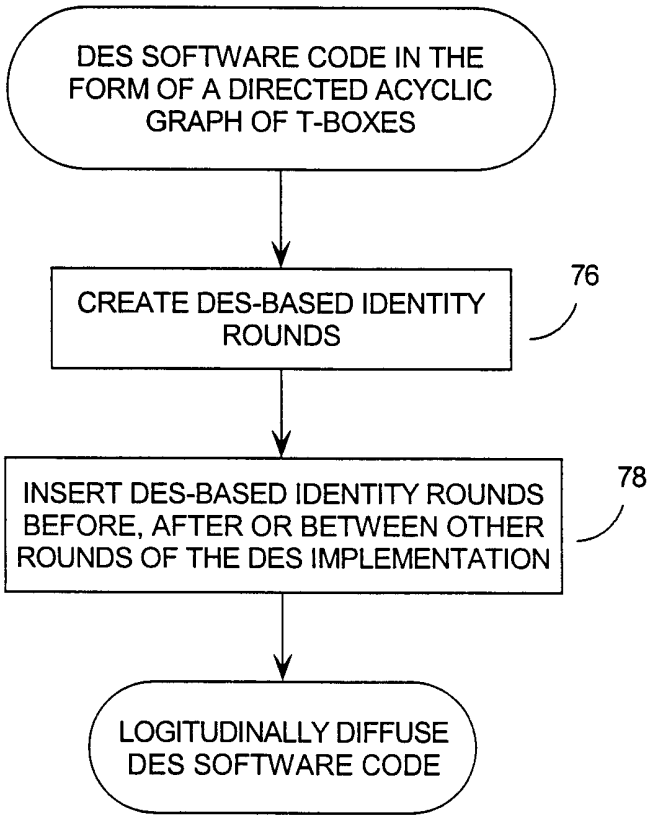

DES SOFTWARE CODE IN THE FORM OF A DIRECTED ACYCLIC GRAPH OF T-BOXES
CREATE DES-BASED IDENTITY ROUNDS
76
INSERT DES-BASED IDENTITY ROUNDS BEFORE, AFTER OR BETWEEN OTHER ROUNDS OF THE DES IMPLEMENTATION
78
LOGITUDINALLY DIFFUSE DES SOFTWARE CODE

FIGURE 9

FIGURE 10

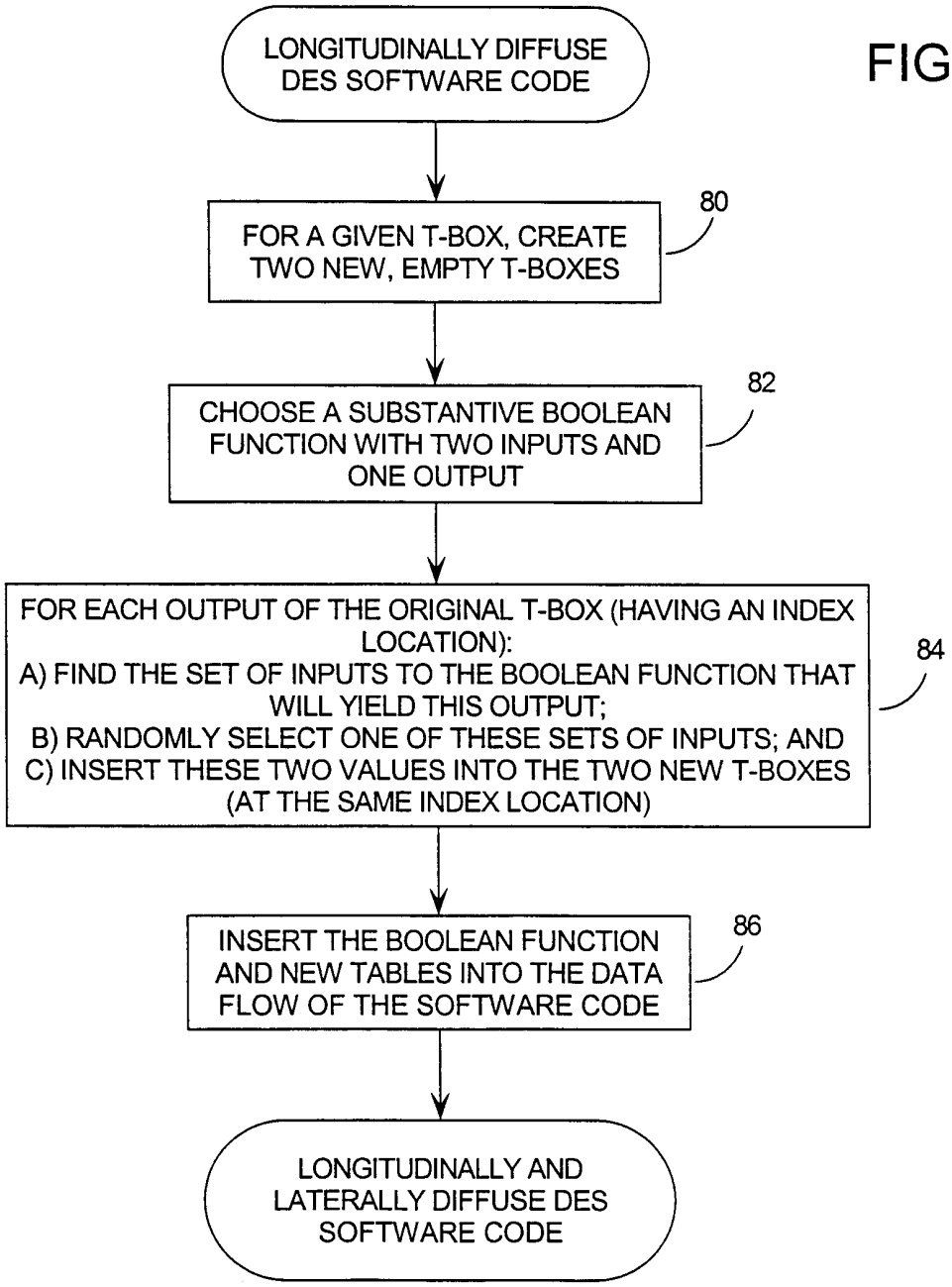
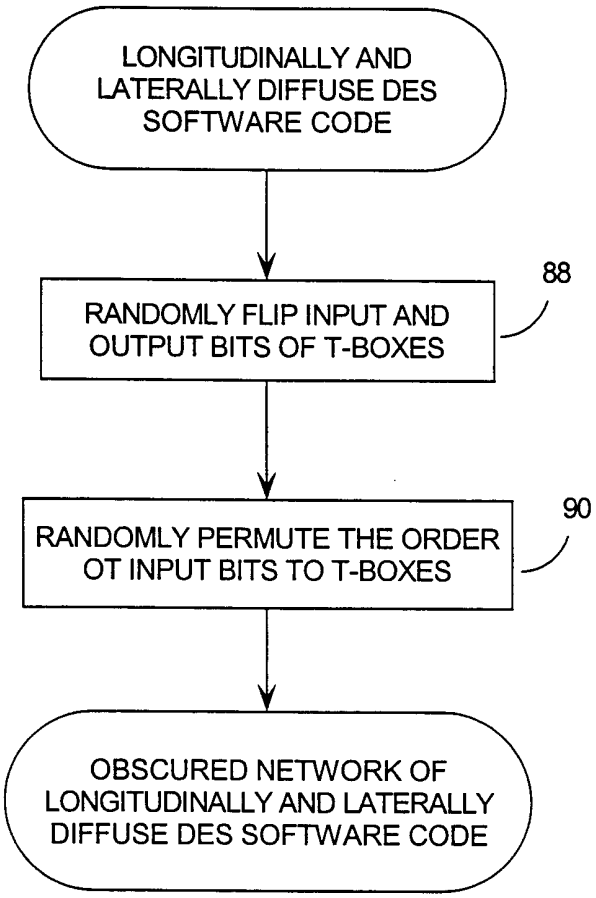

LONGITUDINALLY DIFFUSE DES SOFTWARE CODE
FOR A GIVEN T-BOX, CREATE TWO NEW, EMPTY T-BOXES
80
CHOOSE A SUBSTANTIVE BOOLEAN FUNCTION WITH TWO INPUTS AND ONE OUTPUT
82
FOR EACH OUTPUT OF THE ORIGINAL T-BOX (HAVING AN INDEX LOCATION):
A) FIND THE SET OF INPUTS TO THE BOOLEAN FUNCTION THAT WILL YIELD THIS OUTPUT;
B) RANDOMLY SELECT ONE OF THESE SETS OF INPUTS; AND
C) INSERT THESE TWO VALUES INTO THE TWO NEW T-BOXES (AT THE SAME INDEX LOCATION)
84
INSERT THE BOOLEAN FUNCTION AND NEW TABLES INTO THE DATA FLOW OF THE SOFTWARE CODE
86
LONGITUDINALLY AND LATERALLY DIFFUSE DES SOFTWARE CODE

FIGURE 11


LONGITUDINALLY AND LATERALLY DIFFUSE DES SOFTWARE CODE
RANDOMLY FLIP INPUT AND OUTPUT BITS OF T-BOXES
88
RANDOMLY PERMUTE THE ORDER OT INPUT BITS TO T-BOXES
90
OBSCURED NETWORK OF LONGITUDINALLY AND LATERALLY DIFFUSE DES SOFTWARE CODE

INTERNATIONAL SEARCH REPORT

Inter ›nal Application No
PCT/CA 00/00677

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G06F1/00 H04L9/06 G06F9/44

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G06F H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99 01815 A (COLLBERG CHRISTIAN SVEN; LOW DOUGLAS WAI KOK (NZ); THOMBORSON CLARK) 14 January 1999 (1999-01-14)	1-3, 18-20
Y	abstract; figures 2C-2F,20B page 47, line 5 -page 49, line 12 page 52, line 27 -page 53, line 1 page 59, line 17 -page 61, line 15	7
A	---	4,8
Y	US 5 892 899 A (AUCSMITH DAVID ET AL) 6 April 1999 (1999-04-06) abstract; figures 1,6 column 1, line 46 -column 2, line 11 column 5, line 17 - line 52	7
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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 September 2000	06/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Sigolo, A

2

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Inter nal Application No
PCT/CA 00/00677

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WO 99 03246 A (LUCENT TECHNOLOGIES INC) 21 January 1999 (1999-01-21) abstract page 6, line 23 -page 7, line 27	5

2

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

.ormation on patent family members

Inter ›nal Application No
PCT/CA 00/00677

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9901815 A	14-01-1999	AU 7957998 A	25-01-1999
		CN 1260055 T	12-07-2000
		EP 0988591 A	29-03-2000
US 5892899 A	06-04-1999	AU 723556 B	31-08-2000
		AU 3488397 A	07-01-1998
		CA 2258087 A	18-12-1997
		EP 0900488 A	10-03-1999
		WO 9748203 A	18-12-1997
WO 9903246 A	21-01-1999	NONE	