Distributed Secure Systems: Then and Now

Brian Randell * and John Rushby**

* *School of Computing Science*
Newcastle University
Newcastle upon Tyne
NE1 7RU, UK
Brian.Randell@ncl.ac.uk

** *Computer Science Laboratory,*
SRI International
Menlo Park CA USA
rushby@csl.sri.com

Abstract

The early 1980s saw the development of some rather sophisticated distributed systems. These were not merely networked file systems: rather, using remote procedure calls, hierarchical naming, and what would now be called middleware, they allowed a collection of systems to operate as a coherent whole. One such system in particular was developed at Newcastle that allowed pre-existing applications and (Unix) systems to be used, completely unchanged, as components of an apparently standard large (multi-processor) Unix system.

The Distributed Secure System (DSS) described in our 1983 paper proposed a new way to construct secure systems by exploiting the design freedom created by this form of distributed computing. The DSS separated the security concerns of policy enforcement from those due to resource sharing and used a variety of mechanisms (dedicated components, cryptography, periods processing, separation kernels) to manage resource sharing in ways that were simpler than before.

In this retrospective, we provide the full original text of our DSS paper, prefaced by an introductory discussion of the DSS in the context of its time, and followed by an account of the subsequent implementation and deployment of an industrial prototype of DSS, and a description of its modern interpretation in the form of the MILS architecture. We conclude by outlining current opportunities and challenges presented by this approach to security.

Introduction and Background

The idea of a DSS (Distributed Secure System) was in large part an almost accidental outcome of a long-running and indeed still continuing series of research projects at Newcastle on reliability and in particular fault tolerance, work whose origins can be traced back at least in part to the original 1968 NATO Software Engineering Conference [11]. The discussions at this conference of the major problems of many then-current large software projects were a great spur to research in subsequent years aimed at producing bug-free software. But we at Newcastle, on the other hand, were motivated to wonder whether it might be possible to find means of achieving reasonably reliable service from complex software systems despite the bugs that they would almost certainly still contain.

Our initial work had simply concerned sequential programs. But by 1975 we had moved on to consider the problems of providing structuring for error recovery among sets of co-operating processes. By the late 1970s we were starting to consider the problems of distributed computing systems. In effect, what we had started to do, and in fact continued to do for some years, was gradually extend the range of systems and types of fault for which we tried to provide well-structured error recovery; as a long term research project, as opposed to an urgently-needed real application project, we had the luxury of gradually trying to add complexity to reliability, as opposed to striving to add reliability to immense complexity.

Our reliability research was mainly funded by the SRC (Science Research Council), but we had additional funding from the RSRE (the Royal Signals and Radar Establishment) of the UK Ministry of Defence, which later became part of the Defence Research Agency, and was later still partially privatized as Qinetiq. But then RSRE offered us some further funding to work on security rather than reliability – specifically to undertake a detailed and critical study of the various projects then under way in

the States aimed at providing formal proofs of various would-be highly secure systems.

This enabled Rushby to rejoin Newcastle (where he had been a student), to work alongside the reliability project. Rushby came to realize that the Secure User Executive developed (largely by Derek Barnes) [4] had a much simpler structure than most of the secure operating systems being developed in the USA, and that its formal verification would be best served by a different approach. This led to his formulation of the ideas of a "separation kernel" [13], and of "proof of separability" [14], which were later to influence the conception of DSS.

The reliability project had intended to base its work on the problems of tolerating faults in distributed systems on some suitable pre-existing distributed system. Our efforts to find such a system came to an abrupt halt when in 1982 we came up with a novel scheme for constructing a powerful distributed system from a set of UNIX systems, taking advantage of the hierarchical naming structure used in UNIX. Our scheme involved the insertion of a transparent layer of software (or what would now be called "middleware") at the UNIX system call level, so that neither the UNIX system nor any of the application programs had to be altered – this layer of software we called the "Newcastle Connection", the distributed systems we could build using it we termed "UNIX United" systems [7]. An important characteristic of the Newcastle Connection, the chief designer of which was our colleague Lindsay Marshall, was that it dealt with all of the system calls, not just those involved with files, so that UNIX United was truly a distributed computing system, not merely a distributed file system.

In UNIX United we had come up with what was essentially a recursive approach to system building [12], and we rapidly realized that it would be possible to exploit the recursive characteristics of the Newcastle Connection and UNIX United by the provision of other transparent layers of software, including one for hardware fault tolerance, based on the use of Triple Modular Redundancy (TMR).

It was at this stage that Rushby announced that he was tired of theoretical security research and of critiquing others' such research, and said that he wanted to join in the system-building fun that the rest of us were having. Within a single conversation, against the background of the twin ideas of the Newcastle Connection and of Proofs of Separation, we came to the understanding that the recursive approach to system building could be, so to speak, applied to deconstruct a system as well as to build one. Thus we realized that would be possible, indeed remarkably easy, to implement an apparently-conventional UNIX system that enforced a multi-level security policy by allocating different security domains to different physical machines, and enforcing security constraints on inter-machine communication, rather than by means of the operating system in a single machine.

By the end of the week we had a working demonstration of our DSS scheme, albeit an extremely crude one in which the encryption-based security controls were implemented in software (indeed in shell-script!) rather than in the sort of actual small trusted special-purpose hardware communications devices that we envisaged using. (We initially called these devices Z-boxes, but were later strongly advised, for mysterious reasons that were never explained to us, to instead refer to them as TNIUs, standing for Trusted Network Interface Units.)

A further point that struck us almost immediately was that we could take advantage of complete mutual independence of the TNIUs and the TMR layer. Specifically it would be possible to combine the use of TNIUs, and of groups of three UNIX systems incorporating TMR layers, and so very readily produce a system that was both highly reliable and highly secure, without having to concern ourselves about possible interference between the security and reliability mechanisms.

When we reported our DSS ideas to RSRE, they found them interesting, and sent a small party to Newcastle to see our demonstration system, but raised no objections to our submitting the DSS paper for publication [17]. However, their interest grew, indeed to the point of their planning their own full-scale system building exercise. Thus when – prior to publication of our paper – we discovered a vulnerability in the design of the (virtual) multi-level secure file store that had been missed by the referees, we were forbidden to reveal this vulnerability, leave alone correct the paper by including a solution to it,

What happened afterwards is described in the postscript that follows the original DSS paper, which we reproduce here in full. (The citations in this introduction and in the postscript are to the "Additional References" at the end of this document, and so are kept separate from those in the original DSS paper.)

A distributed general-purpose computing system that enforces a multilevel security policy can be created by properly linking standard Unix systems and small trustworthy security mechanisms.

A Distributed Secure System

John Rushby and Brian Randell
University of Newcastle upon Tyne

A secure system is one that can be trusted to keep secrets, and the important word here is "trusted." Individuals, governments, and institutions such as banks, hospitals, and other commercial enterprises will only consign their secrets to a computer system if they can be absolutely certain of confidentiality.

The problems of maintaining security are compounded because the sharing of secrets is generally desired but only in a tightly controlled manner. In the simplest case, an individual can choose other individuals or groups with whom he wishes to share his private information. This type of controlled sharing is called discretionary security because it is permitted at the discretion of the individual.

When the individuals concerned are members of an organization, however, that organization may circumscribe their discretionary power to grant access to information by imposing a mandatory security policy to safeguard the interests of the organization as a whole. The most widely used scheme of this type is the multilevel security, or MLS, policy employed in military and government environments[1]. Here, each individual is assigned a clearance chosen from the four hierarchically ordered levels, Unclassified, Confidential, Secret, and Top Secret, and each item of information is assigned a classification chosen from the same four levels. The fundamental requirement is that no individual should see information classified above his clearance.

The fewer the people who share a secret, the less the risk of its disclosure through accident or betrayal to unauthorized persons. Consequently, the basic MLS policy is enhanced by the use of compartments or categories designed to enforce "need -to-know" controls on the sharing of sensitive information. Each individual's clearance includes the set of compartments of information to which he is permitted access, and the classification of information is similarly extended to include the set of compartments to which it belongs. The combination of a set of compartments and a clearance or classification is called a security partition. An individual is permitted access to information only if his clearance level equals or exceeds the classification of the information and if his set of compartments includes that of the information. Thus an individual with a Secret-level clearance for the NATO and Atomic compartments, abbreviated as a Secret(NATO, Atomic) clearance, may see information classified as Secret(NATO) or Confidential(NATO, Atomic), but not that classified as Top Secret(NATO) or Confidential(NATO, Crypto).

A multilevel secure system should enforce the policy outlined above; unfortunately, conventional computer systems are quite incapable of doing so. In the first place, they generally have no cognizance of the policy and therefore make no provision for enforcing it; there is usually no way of marking the security classification to which a file, for example, belongs. In the second place, experience shows that conventional systems are vulnerable to outside penetration. Their protection mechanisms can always be broken by sufficiently skilled and determined adversaries. Finally, and most worrisome of all, there is no assurance that the system itself cannot be subverted by the insertion of "trap doors" into its own code or by the infiltration of "Trojan horse" programs. In these cases, the enemy is located "inside the walls" and the system's protection mechanisms may be rendered worthless. This type of attack is particularly insidious and hard to detect or counter because it can compromise security without doing anything so flagrant as directly copying a Top Secret file into an Unclassified one. A Trojan horse program with legitimate access to a Top Secret file can convey the information therein to an Unclassified collaborator by "tapping it out" over clandestine communication channels that depend on the modulation of some apparently innocuous but visible component of the system state, such as the amount of disk space available.

Drastic measures have been adopted to overcome these deficiencies in the security mechanisms of conventional systems. One approach is to dedicate the entire system to a single security partition. Thus a system dedicated to Secret(NATO) operations would support only information and users belonging to that single security partition. The principal objection to this method of operation is that it fails to provide one of the main functions required of a secure system – the controlled sharing of information between different security partitions. Another drawback is the cost of providing separate systems for each security partition. This problem can be mitigated to some extent by employing periods processing in which a single system is dedicated to different security partitions at different

times and is cleared of all information belonging to one partition before it is reallocated to a different one.

Another crude method for coping with the security problems of ordinary systems is to require all users to be cleared to the level of the most highly classified information that the system contains. This is called "system high" operation. The rationale is that even if the system has been subverted, it can reveal information only to those who can be trusted with it. The disadvantage to this scheme is that it is very expensive (and counter to normal security doctrines) to clear large numbers of people for highly classified information that they have no real need to know. Furthermore, many excellent people may be unable or unwilling to obtain the necessary clearances. This approach can also lead to the overclassification of information, thereby reducing its availability unnecessarily.

Acronym Definitions

CBC: Cipher block chaining
DES: Data Encryption Standard
FARM: File access reference monitor
FIG: File integrity guarantor
IFS: Isolated file store
LAN: Local area network
MARI: Microelectronics Applications Research Institute
MLS: Multilevel security
RPC: Remote procedure call
RSRS: Royal Signals and Radar Establishment
SFM: Secure file manager
SFS: Secure file store
TNIU: Trustworthy network interface unit
TTIU: Trustworthy terminal interface unit

Several attempts have been made to construct truly secure systems for use in classified and other sensitive environments. However, the builders of such systems face a new problem: They must not only make their systems secure, but also convince those who will rely on them that they are secure. A full general-purpose operating system is far too complex for anyone to be able to guarantee this security. Accordingly, most efforts have focused on partitioning the system into a small and simple trusted portion and a much larger and more complex untrusted one. The system should be structured so that all securityrelevant decisions and operations are performed by the trusted portion in a way that makes the untrusted portion irrelevant to the security of the overall system. It is then necessary to rigorously establish the properties required of the trusted portion and prove that it does indeed possess them. Such proofs constitute security verification; they use the techniques of formal program verification to show that the system implementation (usually its formal specification) is consistent with a mathematical model of the security properties required[1,2].

The trusted portion of a secure system is generally identified with a small operating system nucleus known as a security kernel; the rest of the operating system and all applications and user programs belong to the untrusted component. Certain difficulties attend the use of such kernelized systems, however.

Because it provides an additional level of interpretation beneath the main operating system, a security kernel necessarily imposes some performance degradation. This can be minor when specialized applications are concerned, since the kernel can be tuned to the application, but general-purpose kernelized operating systems are three to ten times slower than their insecure counterparts. Also, the division of a conventional operating system into trusted and untrusted components is a complex and expensive task that cannot easily accommodate changes and enhancements to its base operating system. Consequently, kernelized systems often lag many versions behind the conventional operating systems from which they are derived.

Finally, and as we have argued elsewhere[3], security kernels for general-purpose operating systems tend to be complex, and their interactions with nonkernel trusted processes are also complex. The result is that the verification of their security properties is neither as complete nor as convincing as might be desired. None of these problems are arguments against security kernels per se, which have proved very successful for certain limited and specialized applications such as cryptographic processors and message systems[4]; but they do indicate that security kernels are unlikely to prove satisfactory as the primary security mechanism for general-purpose systems[5].

Our approach is to finesse the problems that have caused difficulty in the past by constructing a distributed secure system instead of a secure operating system. Our system combines a number of different security mechanisms to provide a general-purpose distributed computing system that is not only demonstrably secure but also highly efficient, cost-effective, and convenient to use. The approach involves interconnecting small, specialized, provably trustworthy systems and a number of larger, untrusted host machines. The latter each provide services to a single security partition and continue to run at full speed. The trusted components mediate access to and communications between the untrusted hosts; they also provide specialized services such as a multilevel secure file store and a means for changing the security partition to which a given host belongs.

The most significant benefits of our approach to secure computing are that it requires no modifications to the untrusted host machines and it allows them to

provide their full functionality and performance. Another benefit is that it enables the mechanisms of security enforcement to be isolated, single purpose, and simple. We therefore believe that this approach makes it possible to construct secure systems whose verification is more compelling and whose performance, cost, and functionality are more attractive than in previous approaches.

Principles and mechanisms for secure and distributed systems

The structure of all secure systems constructed or designed recently has been influenced by the concept of a reference monitor. A reference monitor is a small, isolated, trustworthy mechanism that controls the behavior of untrusted system components by mediating their references to such external entities as data and other untrusted components. Each proposed access is checked against a record of the accesses that the security policy authorizes for that component.

It is implicit in the idea of a reference monitor, and utterly fundamental to its appreciation and application, that information, programs in execution, users, and all other entities belonging to different security classifications be kept totally separate from one another. All channels for the flow of information between or among users and data of different security classifications must be mediated by reference monitors. For their own protection, reference monitors must also be kept separate from untrusted system components.

Our approach to the design of secure systems is based on these key notions of separation and mediation. These are distinct logical concerns, and for ease of development and verification, the mechanisms that realize them are best kept distinct also. We consider it a weakness that many previous secure system designs confused these two issues and used a single mechanism – a security kernel – to provide both. Once we recognize that separation is distinct from mediation, we can consider a number of different mechanisms for providing it and use each wherever it is most appropriate. In fact, our system uses four different separation mechanisms: physical, temporal, logical, and cryptographical.

Physical separation is achieved by allocating physically different resources to each security partition and function. Unfortunately, the structure of conventional centralized systems is antithetical to this approach; centralized systems constitute a single resource that must be shared by a number of users and functions. For secure operation, a security kernel is needed to synthesize separate virtual resources from the shared resources actually available. This is not only inimical to the efficiency of the system, but it requires complex mechanisms whose own correctness is difficult to guarantee.

In contrast with traditional centralized systems, modern distributed systems are well suited to the provision of physical separation. They necessarily comprise a number of physically separated components, each with the potential for dedication to a single security level or a single function. To achieve security, then, we must provide trustworthy reference monitors to control communications between the distributed components and to perform other security-critical operations. The real challenge is to find ways of structuring the system so that the separation provided by physical distribution is fully exploited to simplify the mechanisms of security enforcement without destroying the coherence of the overall system.

Because it is costly to provide physically separate systems for each security partition and reference monitor, we use physical separation only for the untrusted computing resources (hosts) of our system and for the security processors that house its trusted components. Temporal separation allows the untrusted host machines to be used for activities in different security partitions by separating those activities in time. The system state is reinitialized between activities belonging to different security partitions.

The real challenge is to find ways of structuring the system so that the separation provided by physical distribution is fully exploited to simplify the mechanisms of security enforcement without destroying the coherence of the overall system.

The security processors can each support a number of different separation and reference monitor functions, and also some untrusted support functions, by using a separation kernel to provide logical separation between those functions. Experience indicates that separation kernels (simple security kernels whose only function is to provide separation) can be relatively small, uncomplicated, and fast, and verification seems simpler and potentially more complete for them than it does for general-purpose security kernels[3].

Our fourth technique, cryptographic separation, uses encryption and related (checksum) techniques to separate different uses of shared communications and storage media.

The four separation techniques provide the basis for our distributed secure system. This is a heterogeneous system comprising both untrusted general-purpose systems and trusted specialized components, and to be useful it must operate as a coherent whole. To this end, our mechanisms for providing security are built on a distributed system called Unix United, developed in

the Computing Laboratory at the University of Newcastle upon Tyne[6]. A Unix United system is composed of a (possibly large) set of interlinked standard Unix systems, or systems that can masquerade as Unix at the kernel interface level, each with its own storage and peripheral devices, accredited set of users, and system administrator. The naming structures (for files, devices, commands, and directories) of each component Unix system are joined into a single naming structure in which each Unix system is, to all intents and purposes, just a directory. The result is that, subject to proper accreditation and appropriate access control, each user on each Unix system can read or write any file, use any device, execute any command, or inspect any directory regardless of which system it belongs to. The directory naming structure of a Unix United system is set up to reflect the desired logical relationships between its various machines and is quite independent of the routing of their physical interconnections.

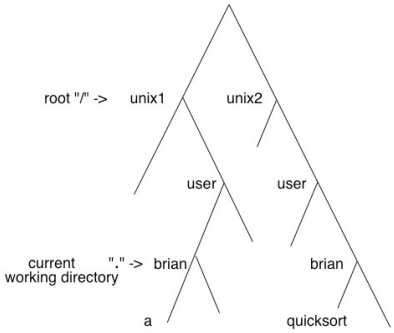

Figure 1: The naming structure of a simple Unix United system.

The simplest possible case of such a structure, incorporating just two Unix systems, named unix1 and unix2, is shown in Figure 1. From unixl, and with the root ("/")and current working directory (".") as shown, one could copy the file "a" into the corresponding directory on the other machine with the Unix shell command

cp a /../unix2/user/brian/a

(For those unfamiliar with Unix, the initial "/" symbol indicates that a path name starts at the root directory rather than at the current working directory, and the ".." symbol is used to indicate a parent directory.)

This command is in fact a perfectly conventional use of the standard Unix shell command interpreter and would have exactly the same effect if the naming structure shown had been set up on a single machine and unix I and unix2 had been conventional directories.

All the standard Unix facilities, whether invoked by shell commands or by system calls within user programs, apply unchanged to Unix United, causing intermachine communication as necessary. A user can therefore specify a directory on a remote machine as his current working directory, request execution of a program held in a file on a remote machine, redirect input and/or output, use files and peripheral devices on a remote machine, and set up pipelines that cause parallel execution of communicating processes on different machines. Since these are completely standard Unix facilities, a user need not be concerned that several machines are involved.

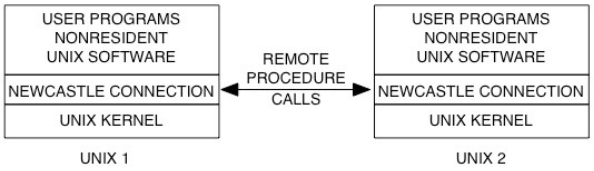

Figure 2: The Newcastle Connection.

Unix United conforms to a design principle for distributed systems that we call the "recursive structuring principle". This requires that each component of a distributed system be functionally equivalent to the entire system. Applying this principle results in a system that automatically provides network transparency and can be extended (or contracted) without requiring any change to its user interface or to its external or internal program interfaces. The principle may seem to preclude systems containing specialized components such as servers, but this is not so. Any system interface must contain provisions for exception conditions to be returned when a requested operation cannot be carried out. Just as the operating system of an ordinary host machine can return an exception when asked to operate on a nonexistent file, so a specialized server that provides no file storage can always return exceptions when asked to perform file operations.

Unix United has been implemented without changing the standard Unix software in any way; neither the Unix kernel nor any of its utility programs – not even the shell command interpreter – have been reprogrammed. This has been accomplished by incorporating an additional layer of software called the Newcastle Connection in each of the component Unix systems. This layer of software sits on top of the resident Unix kernel; from above it is functionally indistinguishable from the kernel, while from below it looks like a normal user process. Its role is to filter out system calls that have to be redirected to another Unix system and to accept system calls that have been directed to it from other systems. Communication between the Newcastle Connection layers on the various systems is based on the use of a remote procedure call protocol and is shown schematically in Figure 2.

All requests for system-supported objects such as files ultimately result in procedure calls on the Unix kernel interface. If the service or object required is remote rather than local, the local procedure call is simply intercepted by the Newcastle Connection and replaced with a remote one. This substitution is completely invisible at the user or program level, providing a powerful yet simple way of putting systems together. Equally important, it provides a means of partitioning what appears to be a single system into a number of distributed components. From our perspective, this partitioning is the crucial property of Unix United, since it enables a large, insecure Unix system to be broken into a number of physically separate components with no visible change at the user level. The following sections will explain how we exploit this physical separation to construct a secure system. We begin with a very simple system that merely isolates different security partitions from one another.

A securely partitioned distributed system

We will describe a secure Unix United system composed of standard Unix systems (and possibly some specialized servers that can masquerade as Unix) interconnected by a local area network, or LAN. We assume that all the component Unix systems are untrustworthy and that the security of the overall system must not depend on assumptions concerning their behavior – except that the LAN provides their only means of intercommunication.

The consequence of not trusting the individual systems is that the unit of protection must be those systems themselves; thus, we will dedicate each to a fixed security partition. We might allocate two systems to the Secret level, one to the Top Secret level, and the rest to Unclassified use. Limited need-to-know controls can be provided by dedicating individual machines to different compartments within a single security level; thus, one of the Secret systems could be dedicated to the Atomic compartment and another to NATO. In a commercial environment, some systems could be dedicated to Finance and others to Personnel and Management. Users are assigned to hosts with the knowledge that no security is guaranteed within those individual systems. Note also that since the hosts are not trusted, they cannot be relied upon to authenticate their users correctly. Therefore, access to each system must be controlled by physical or other external mechanisms.

Although there is no security within an individual Unix system, the key to our proposal is to enforce security on the communication of information between systems. To this end, we place a trustworthy mediation device between each system and its network connection; we call it a trustworthy network interface unit, or TNIU (see Figure 3).

The initial and very restrictive purpose of TNIUs is to permit communication only between machines belonging to the same security partition. The single Unix United system is therefore divided into a number of disjoint subsystems. We will describe later how our system can be extended to move information between partitions securely, thereby providing true multilevel security.

Controlling which hosts can communicate with one another is a reference monitor function, but because the LAN can be subverted or tapped, the TNIUs must also provide a separation function to isolate and protect the legitimate host-to-host communications channels. This separation function is provided cryptographically, with TNIUs encrypting all communications sent over the LAN. Encryption is traditionally used to protect communications between parties who share a common interest in preserving the secrecy of that communication, but this is not the case here. Host machines are untrusted and may attempt to thwart the cryptographic protection provided by their TNIUs. For this reason, the encryption must be managed very carefully to prevent clandestine communication between host machines, or between a host machine and a wiretapping accomplice.

Although the basic principles of encryption management are well established[8], a tutorial outline of the issues and techniques as they affect our system may benefit readers to whom this material is new.

Encryption and the protection of communications. Trustworthy network interface units use the Data Encryption Standard, or DES[8] to protect information sent over the LAN. However, since host machines are untrusted and the LAN can be tapped, the simplest form of DES encryption – the so-called electronic code book mode – is ruled out. In this mode, each 64-bit block of data is encrypted as a separate unit, and even a very powerful encryption algorithm such as the DES cannot prevent the leakage of information from a corrupt host machine under these circumstances. For example, suppose that a corrupt host wishes to communicate the bit pattern 01101 to a wiretapping accomplice. The host constructs a message XYYXY, where X and Y are arbitrary but distinct bit patterns of the same length and alignment as the units of block encryption, and sends it to its TNIU for transmission. The TNIU will encrypt the message to yield, say, PQQPQ before transmitting it over the LAN, but the bit pattern 01101 remains visible in this encrypted message and can easily be extracted by a wiretapper. Notice that the threat here is not due to any

weakness in the encryption algorithm employed, but to the way in which it is used; one need not be able to decrypt messages to extract information planted by a corrupt machine,

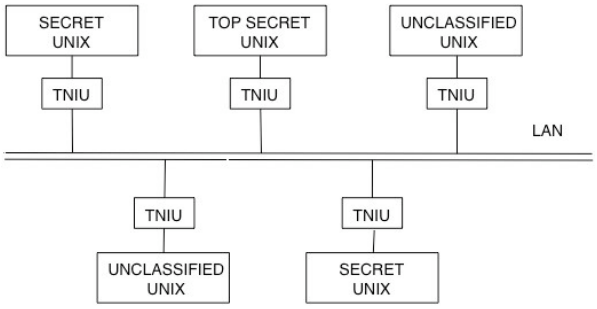

Figure 3: A securely partitioned system.

Clandestine communications channels based on plaintext patterns that persist into the ciphertext can be thwarted by employing a more elaborate mode of encryption called cipher block chaining, or CBC, which uses a feedback technique to mask such patterns by causing the encrypted value of each block to be a complex function of all previous blocks[8]. Of course, identical messages will yield identical ciphertexts, even when CBC-mode encryption is used. More importantly, messages that begin with the same prefix will yield ciphertexts that also share a common prefix. A corrupt host can therefore signal to a wiretapping accomplice by modulating the length of the prefix that successive messages have in common. This channel for clandestine information flow must be closed, and this will be achieved if TNIUs attach a random block of data, different in each case, to the front of each message before encrypting it,

The careful use of CBC-mode encryption prevents information from leaking through channels that modulate message contents, but significant channels for information leakage still remain. These are pattern-of-use channels whereby a corrupt host modulates the visible parameters of messages in a way that can be decoded by a wiretapping accomplice. The properties that can be modulated are the lengths of individual messages, their time and frequency of transmission, and their destination.

All techniques for introducing noise inevitably reduce the bandwidth available for legitimate communications and may increase the latency of message delivery.

(Presumably the source is fixed at the location of the corrupt host.) These properties, of which length and destination are by far the most important, can be modulated to yield clandestine communication channels of surprisingly high bandwidth. Unless link encryption is used to reinforce the end-to-end encryption described here, it will not be possible to completely sever these channels. Since link encryption is infeasible with most LAN technologies, the best approach is to reduce the bandwidth of these pattern-of-use channels to a tolerable level, either directly or through the introduction of noise,

The length channel is the easiest to deal with. TNIUs process message units of a fairly large, fixed size – say 1024 bytes. Long messages must be broken into a number of separate message units; short ones, and the residue of long ones, must be padded to fill a whole unit. (If this technique causes great numbers of largely empty message units to be generated, some of the legitimate bandwidth of the LAN will be wasted; but this is not usually a scarce resource and some tuning of the choice of the unit size is possible in any case.) When this is done, a wiretapper cannot observe the exact length of a message but can only estimate the number of message units that it occupies. This information will be difficult to extract, and the corrupt host will also have to modulate a second parameter (e.g., destination) so that the wiretapper can identify the message units constituting each message.

The bandwidth of the channel that modulates message destinations can only be reduced by introducing noise, thereby complicating traffic patterns so that the wiretapper finds it hard to detect and extract any deliberate modulation. The obvious way to do this is for each TNIU to generate a steady stream of spurious messages to all other TNIUs in its own security partition. Spurious messages are marked as such (under encryption, of course) and are discarded by TNIUs that receive them. More refined strategies, such as routing messages indirectly through a number of intermediate TNIUs before delivering them to their final destination, are clearly possible, but all techniques for introducing noise inevitably reduce the bandwidth available for legitimate communications and may increase the latency of message delivery. Each installation must choose its priorities in such a trade-off.

The techniques described so far enforce separation between the outside world and communications internal to the distributed secure system. They do not, however, provide separation between the different internal communications channels of the system. Thus, the reference monitor component of a Secret-level TNIU can determine that its host is attempting to communicate with another Secret-level host and that this communication accords with the security policy and may therefore proceed; however, it cannot prevent the LAN messages that constitute the communication from being delivered, either through error or malice, to the TNIU of, say, an Unclassified host. Furthermore,

unless additional mechanisms are introduced, the receiving TNIU will not necessarily be able to detect that the messages have been sent to it in error.

Incorrect delivery can occur because the LAN hardware, by accident or intent, misinterprets message destination fields, or because those fields are modified by an active wiretapper. (Remember that these fields must be in the clear so that the LAN hardware can interpret them.) TNIUs may attempt to overcome this threat by embedding the true source, destination, and security partition of each message unit inside the data portion of the message unit itself, where it will be protected by encryption, However, this technique can be defeated by an active wiretapper who splices the identification portion of a genuinely Unclassified message onto the body of a Secret one.

It might appear that CBC-mode encryption automatically protects against this type of attack and that because the encrypted value of each block within a message unit is a complex function of all previous blocks, messages formed by splicing parts of different messages together will decrypt unintelligibly, In fact, this is not so. Although the encrypted value of each block produced by CBC-mode encryption depends implicitly on all prior plaintext blocks, it depends explicitly on only the immediately preceding ciphertext block[8]. Thus, damage to the contents or sequencing of ciphertext blocks affects only the decryption of the block immediately following the damaged or misplaced block; in other words, CBC-mode decryption is "self-healing."

Two methods are available for securely separating the communications channels belonging to different security partitions. The first uses a high-quality checksum to guarantee the integrity of each message unit, including its identification fields. TNIUs must calculate the checksum of each message unit before they encrypt it, and they must encrypt the message unit and its checksum as a single unit so that the checksum will be protected by encryption. Whenever a TNIU receives a message unit, it must first decrypt it and recompute its checksum. Only if the recomputed checksum matches the one sent with the message unit should the unit be accepted by the TNIU for further processing. The integrity of all message units accepted is thereby guaranteed because they cannot be forged, modified, or formed by splicing parts of different units together during transmission over the LAN, Consequently, TNIUs can trust the value of the security partition identifier embedded in each message unit, then they can (and must) reject those bearing a different identifier.

The second method for distinguishing the communications belonging to different security partitions is to use a different encryption key for each partition. (Until now, we have implicitly assumed that the same key is used for all communications.) Each TNIU will be provided with only the single key associated with its own security partition and will therefore have no way of communicating with TNIUs belonging to different partitions. If a message unit is delivered to a TNIU belonging to a different security partition from its sender, it will be encrypted using one key and decrypted using another, making it unintelligible to the host attached to the receiving TNIU. It is unwise, however, to allow the untrusted host machines to see even such unintelligible transmissions from another security partition, so we propose to combine the use of different encryption keys with the checksum technique described earlier. A message delivered to a TNIU in a different security partition from its sender, and therefore encrypted and decrypted with different keys, will certainly fail to checksum correctly.

The use of both checksums and different encryption keys is not strictly necessary, since either technique is sufficient to separate the communications channels belonging to different security partitions. The two techniques are complementary, however, and provide worthwhile redundancy. Checksums guarantee the integrity of message contents, a very desirable property in its own right, while the use of different encryption keys provides failsafe separation.

Any system using encryption must contain mechanisms for generating and distributing keys securely. But unlike connection-oriented (virtual circuit) schemes in which a unique key must be manufactured and distributed every time a new circuit is opened, our system imposes no requirement for frequent or rapid key distribution. The key allocated to a TNIU is a function of the (fixed) security partition to which its host belongs. This, combined with the presumption that a LAN-based system is geographically compact, makes manual key distribution perfectly viable. Because of its evident simplicity and security, this is the mechanism we employ. If the fear of cryptanalysis calls for more frequent key changes than is convenient for manual distribution, a set of keys can be installed on each occasion or a single master key can be installed from which the TNIU can manufacture a whole set of communications keys. In either case, the TNIUs must contain mechanisms for synchronizing their current encryption keys.

Although not strictly necessary, it is highly desirable to be able to detect and counter the activity of an active wiretapper who attempts to "spoof" the system by replaying recordings of genuine LAN messages. (Consider, for example, a banking system that carries messages such as "move $100 from account A to

account B. “) Spoofs can be detected if sequence numbers or time stamps are embedded in each message unit. Of course, it is perfectly feasible for hosts to do this themselves, but it seems more appropriate for TNIUs to provide this function. The sequence number or time stamp of each message unit can constitute the unique material that should be attached to the front of each message prior to encryption to mask the similarity between messages that share a common prefix. Synchronizing the sequence numbers or time stamps used between each pair of TNIUs requires a special TNIU-to-TNIU protocol. This protocol must be resistant to spoofs, but it obviously cannot use sequence numbers or time stamps itself for this purpose. A challenge-response technique first proposed by Needham and Schroeder[9] can be used instead.

The integration and construction of TNIUs. The interposition of a TNIU between a host and its LAN station raises interesting questions concerning the location of various protocol functions. The whole issue of assigning function to layers in a protocol hierarchy can become quite complex in the presence of encryption because standard functions such as checksums and sequence numbering, for example, are duplicated – though in a different and more sophisticated way – by the protection and security mechanisms. For this reason, TNIUs should not operate below the normal protocol layering hierarchy but must be integrated with it. In fact, we propose that TNIUs take over all protocol functions, except those at the highest level. The benefit of this approach is that the TNIUs act as network front ends, relieving their hosts of the low-level network load and thereby boosting overall performance.

The top-level protocol of the Newcastle Connection provides a remote procedure call, or RPC, service and requires a fairly reliable datagram service from the lower levels of its protocol hierarchy. We use this datagram service as the interface between host machines and their TNIUs; individual datagrams form the message units that are encrypted and protected by the TNIUs. Most RPCs and their results can be encoded into a single datagram, but those concerned with file reads and writes, which can transfer arbitrarily large amounts of data, are broken into as many separate datagrams as necessary by a subprotocol of the host machines’ RPC protocol.

The cryptographic techniques employed by TNIUs counter the threat of information disclosure. The remaining danger is denial of service caused by the destruction of genuine LAN traffic or the injection of large quantities of garbage. Although they can do nothing to prevent or defeat such attacks, TNIUs must, as a correctness requirement, continue to provide reliable (though necessarily degraded) service in spite of such occurrences. It is also a correctness requirement of TNIUs that they recover from crashes safely. (Of course, verified software does not crash, but we must allow for the possibility of a power failure.)

TNIUs that perform all the functions described certainly present a challenge in both construction and verification. We argue, however, that they are very similar to the cryptographic front ends of wide-area networks, and examples of these have already been built and, in some cases, verified,4 Modern 16-bit microprocessors provide a suitable hardware base for the construction of TNIUs, and single-chip implementations of the DES algorithm are available that can perform CBC-mode encryption at LAN speeds. A separation kernel must be used to enforce cleartext/ciphertext (so-called red/black) separation within each TNIU, with the basic physical protection provided by the memory management chips appropriate to the chosen processor. Since no disks are needed (the software can be held in ROM), a complete TNIU should fit on a single board and cost less than a thousand dollars.

Unclassified hosts can generally be considered to belong to the same security partition as the outside world. They need not be separated from it, and therefore their TNIUs need not use encryption to protect their communications. In this case, there is no need to provide TNIUs to Unclassified hosts, and this provides a worthwhile economy in systems where the majority of hosts are Unclassified. It also permits a standard, unpartitioned Unix United system to be smoothly upgraded to a securely partitioned one by the addition of a limited number of TNIUs.

A multilevel secure file store

The design introduced so far imposes a very restrictive security policy. The security partitions are isolated from one another with no flow of information possible across different levels or compartments. We will now explain how to extend this design to permit information to cross security partitions in a multilevel secure manner. This will allow information to flow from the Secret to the Top Secret levels, for example, but not vice versa.

It might seem that multilevel secure information flow could be provided by simply modifying the policy enforced at the TNIUs so that, for example, Top Secret machines could receive communications from Secret machines as well as Top Secret ones. Top Secret TNUIS would be provided with the Secret as well as the Top Secret encryption keys and would permit incoming but not outgoing communications with Secret-level machines. The flaw in this scheme is that

the communication could not be truly one way; a Secret machine cannot reliably send information to a Top Secret one without first obtaining confirmation that the Top Secret machine is able to accept it and, later, that it has received it correctly. The Secret machine must therefore be able to receive information from the Top Secret machine as well as send to it. This conflicts with the multilevel security policy.

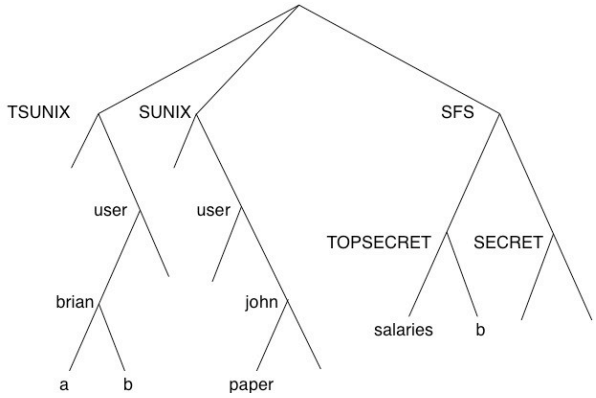

Figure 4. The naming structure of a simple Unix United system incorporating a secure file store.

Certainly the trustworthy TNIUs in the system could be enhanced to undertake reliable delivery of data across security partitions, but this misses the point. If one host sends a file to another, the sender needs to know that the receiver has been able to store the file correctly, not merely that its TNIU received it correctly. Notice, too, that this scheme would only provide for unsolicited communications; a Secret machine could send information to a Top Secret machine of its own volition, but the Top Secret machine could not request that the information be sent because its request would constitute an insecure information flow.

The best way to provide secure information flow across security boundaries is through a trustworthy intermediary that provides an independent and useful service. The complexity of such an intermediary will depend on the generality of that service. Combining simplicity with the most useful function, we have selected files as the only objects allowed to cross security boundaries, and we have chosen the multilevel secure storage and retrieval of files as the service provided by the trustworthy intermediary. This is achieved by adding to the system a secure file store with the ability to communicate with hosts of all security classifications. The idea is that when a Secret-level host wishes to make one of its files available to higher levels, it "publishes" it by sending it to the secure file store. A Top Secret host can subsequently acquire a copy of this file from the secure file store.

Before describing the mechanism of the secure file store, we need to outline its logical position and role within the overall Unix United system. Conceptually, the secure file store is just an ordinary Unix system that returns exceptions to all system calls except certain ones concerned with files. As with any other component, it will be associated with a directory, say SFS, in the Unix United directory structure. The SFS directory will contain subdirectories for each security partition in the overall system. A simple Unix United directory structure containing just the secure file store and two ordinary hosts is shown in Figure 4.

The ordinary hosts are associated with the directories TSUnix and SUnix and are allocated to the Top Secret and Secret security partitions, respectively. Of course, from within SUnix, the TSUnix branch of the directory tree is invisible, and vice versa. Even if the Newcastle Connections within TSUnix and SUnix are aware of each other's existence, any attempted intercommunication will be stopped by their TNIUs. If the Secret-level user John of SUnix wishes to make his "paper" file available to the Top Secret user Brian, he does so by simply copying it into a directory that is subordinate to the SFS directory. For example:

publish <paper/ ../SFS/SECRET/john/paper.

(We explain later why this command uses "publish" and a later one uses "acquire" instead of the standard Unix command "cp.") This command will cause the secure file store machine to receive a remote procedure call from SUnix requesting it to create and write a file called paper located as a sibling of the file "c. " The secure file store will consult its record of the security policy to determine whether such a machine is allowed to create Secret-level files. Assuming that it is, the requested file operation will be allowed to proceed and the copy of the file will be created. Similarly, when the Top Secret user Brian attempts to print a copy of the paper by issuing the command

acquire /../SFS/SECRET/john/paper|lpr

the secure file store will receive a remote procedure call from the machine TSUnix requesting a copy of the file. Once again, it can consult the security policy, where it will see that the request should be allowed to proceed. The secure file store will, however, refuse requests from TSUnix to write into this "paper" file, or to delete it, since these contravene the requirements of multilevel security. Similarly, John will not be allowed to read the "salaries" file held under the TOPSECRET directory.

We now move from the services provided by the secure file store to its construction. A multilevel secure Unix file system might seem to demand a substantial number of provably trustworthy mechanisms – virtually a secure Unix. With careful design, however,

we can reduce the number of trusted mechanisms considerably.

The basic idea is to partition the secure file store into trusted and untrusted components housed in physically separate machines. The trusted component, called the secure file manager, or SFM, is a reference monitor concerned with enforcing the security policy; its file storage is provided by the untrusted components. These untrusted components can be thought of as separate, standard Unix systems connected directly to the SFM. Each untrusted file storage machine is dedicated to a single security partition and is identified with one of the subdirectories of the SFS directory (see Figure 5).

Communicating with hosts in different security partitions requires an enhanced TNIU for the SFM, one that contains the encryption keys of all security partitions. The internal structure of a TNIU with multiple encryption keys will be slightly more complex than that of one with just a single key, particularly if communications using different keys can be in progress simultaneously. Cleartext belonging to logically separate channels should be managed by separate virtual machines, and temporal separation must be provided for different uses of its single DES chip. These are not significant complications, however, and the responsibility for correctly managing more than one encryption key is a small additional burden for the trusted mechanism of a TNIU.

Host machines requiring access to secure files send remote procedure calls, or RPCs, to the SFM. The TNIU of the SFM determines the sender's security partition and passes this information to the SFM along with the decrypted RPC. The SFM can then inspect the RPC to check if the requested operation complies with its security policy. If it does, the SFM simply forwards the RPC to the appropriate file storage machine for processing and relays the results (suitably encrypted) back to the original caller.

There is an obvious flaw in this scheme, however. Because the Unix file storage machines cannot be trusted, they constitute a security weakness – even though each holds files belonging to only a single security partition. A host machine in the Top Secret partition could modulate its legitimate requests for reading secure files belonging to the Secret partition to convey Top Secret information to the Secret-level file storage machine. For example, suppose the secret file storage machine contains a group of 26 files, each a different length. If a corrupt Top Secret host requests, as it may legitimately do, copies of the fifth, fourteenth, ninth, seventh, thirteenth, and first shortest files in that order, then the Top Secret string E-N-I-G-M-A will have been communicated to the Secret file storage machine. This machine could then encode the information received into a file that could subsequently and legitimately be retrieved by a Secret-level host.

Although we cannot prevent Top Secret information from getting into the Secret-level file store, we can prevent it from getting back out again. Once we recognize this, the solution to the above problem is at hand.

The only objects that leave file storage machines are files retrieved in response to external requests. Consequently, any clandestine information that is to reach the outside world must be encoded into those files. Since all movement of files into and out of the file storage machines is mediated by the SFM, security will be maintained if the SFM prevents the file storage machines from encoding information into (i.e., modifying) outgoing files. In other words, security depends on the SFM being able to guarantee the integrity of files retrieved from the file storage machines.

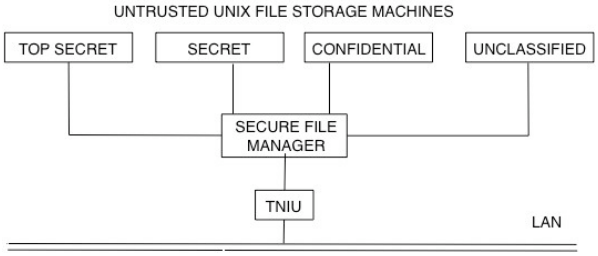

Figure 5. Conceptual structure of the secure file store.

This can be achieved if a checksum is added to each file by the SFM before it is stored in one of the untrusted file storage machines. Any attempt by a file storage machine to modify a file will be detected on its subsequent retrieval by the SFM when the recomputed checksum fails to match the one stored with the file. Of course, this only works so long as the file storage machines are unable to forge the checksums. This can be ensured in two ways (other than by keeping the checksums in the SFM). The first is to use a conventional checksum (i.e., one computed by an algorithm that may be known to the file storage machines) but to protect it by encrypting the file and the checksum as a single unit. The second technique is to use a crypto-checksum that depends on a secret key for its computation. An example of a crypto-checksum is the final block of ciphertext produced during CBC-mode encryption, an alternative is to simply encrypt a conventional checksum. The advantage of crypto-check sums is that they cannot be forged by those who do not possess the key; they can therefore be used with information stored in the clear.

Either technique can be used to guarantee the integrity of files retrieved from the untrusted file

storage machines. We prefer the crypto-checksum approach because it requires only a single operation. Intermediate checksums can be included at intervals within the file if the SFM has insufficient space to buffer an entire file. If part of a file has already been delivered to a host when modification to a later part is detected by the SFM, then some clandestine information may have been conveyed to the host through the position at which the modification began and file transfer was aborted by the SFM. This channel has very limited bandwidth, and as long as all checksum failures raise a security alarm and are logged by the SFM, it is not considered a serious security risk.

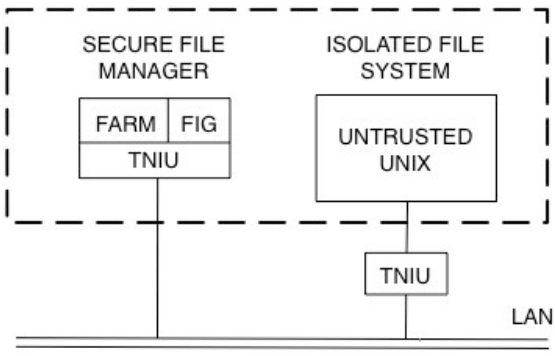

Figure 6. Actual structure of the secure file store.

Checksums prevent the untrusted file storage machines from modifying the files consigned to them and from manufacturing forgeries, but they do not prevent them from signaling to a collaborator by choosing which legitimate files they return in response to requests. For example, a Secret host could send a steady stream of requests for file X, but the files actually returned by the Secret file storage machine could be quite different. In particular, they could be files selected on the basis of length, say, to convey information in the manner of the E-N-I-G-M-A example given earlier, To close this channel, the SFM must be able to verify that the correct file is returned in response to each request. This is easily accomplished by including the name of each file in the checksum calculation.

A variation on this method of covert communication is not so easily countered, however. A file storage machine can keep several old copies of a legitimate file and signal to an outside collaborator by choosing which version of the file to return in response to each request. This type of attack can be countered by recording a time stamp with each file and keeping a separate record of the time stamp that identifies the current version of the file. The problem here is to find a safe place to keep the record of each file's current time stamp. It cannot be entrusted to the file storage machines without additional mechanisms for safeguarding its own integrity, and keeping it in the SFNI will impose a substantial storage requirement on a machine that is intended to have no disks of its own.

To keep the trusted mechanism of the SFM simple, we prefer to reduce the bandwidth of this channel rather than attempt to close it completely. The SFM embeds a time stamp into each file before calculating its checksum and consigning it to an untrusted file storage machine. In addition, the SFM maintains. in its own private storage, a cache of the names and time stamps of all files read from or written to an untrusted file storage machine during, say, the last five minutes. Any attempt to return different versions of the same file within a shorter period will be detected by the SFM and will raise a security alarm. Attacks that operate over a longer period will go undetected, but their bandwidth will then be so low that they can be discounted as serious threats.

Once clandestine information has been prevented from leaving a file storage machine, there is no longer any need to provide separate file storage machines for each security partition; the integrity checks performed by the SFM constitute the required separation mechanism. Accordingly, the file storage machines can all be replaced by a single Unix system called the isolated file store, or IFS. Rather than connect the IFS directly to the SFM, we prefer to connect it to the LAN via a TNIU in the standard way. For it to be truly isolated from the rest of the system, however, the TNIU of the IFS must be loaded with a special encryption key that is shared only with the TNIU of the SFM (see Figure 6).

The revised SFM is required to perform two security-critical tasks and is therefore split into two logically separate components: the file access reference monitor, or FARM, and the file integrity guarantor, or FIG. The task of the FARM is to ensure that all file access requests comply with the security policy. the FIG is responsible for computing and checking the checksums and time stamps on files sent to or received from the IFS.

The FIG achieves its purpose by employing checksum techniques very similar to those used for LAN messages by the TNIUs. We therefore suggest constructing the FIG by making minor modifications and extensions to an ordinary TNIU. The FARM function of the SFM is also straightforward, requiring only the imposition of simple access control rules determined by a security policy. This function can be performed inside a separate virtual machine provided by the separation kernel of the machine that supports the TNIU/SFM functions.

We therefore conclude that all the functions of a complete SFM can be easily integrated into the TNIU that connects it to the LAN. The development and

verification costs of an integrated TNIU/SFM should be little more than those for a TNIU alone, and production costs should be about the same – approximately a thousand dollars.

The FIG checksum mechanism allows files to be read or written only in their entirety. This is different from the standard Unix file system interface, which permits incremental reading and writing, and the repositioning of the file pointer. For this reason, secure files cannot be accessed through the normal Unix file system interface but must use a special extension to that interface provided by the Newcastle Connection. This extension adds new system calls to publish, acquire, and delete secure files, and to list the names of the secure files belonging to a given security partition, (The list operation must be implemented very carefully so as not to provide the IFS with a clandestine information channel.) The minor inconvenience caused for users by this nonstandard interface is certainly no worse than that imposed by the file transfer programs used in conventional network architectures and is more than outweighed by the simplicity of the trusted mechanisms needed to implement it. Extensions to this scheme that do provide the full, standard Unix file system interface are described in a technical report[10], but the difficulties of providing secure access to Unix i-node information and to directories tend to compromise the attractive simplicity of the basic scheme. Completely different mechanisms are known and are probably preferable in this case.

The accessing and allocation of security partitions

A system in which terminals are attached to machines of fixed security level can be somewhat inconvenient to use. A Secret-level user can send mail to a Top Secret user via the secure file system, but the recipient can only reply by leaving his Top Secret machine and logging in to one at the Secret level, or lower. We can avoid this inconvenience and make additional services possible by connecting terminals to trustworthy terminal interface units, or TTIUs, rather than to hosts directly. Moreover, we can then include provisions for dynamically changing the allocation of machines to security partitions.

Accessing different security partitions. What we term a trustworthy terminal interface unit is basically a TNIU enhanced with some additional trusted functions, including a terminal driver, some very limited Newcastle Connection software, and an authentication mechanism. Each of these logically separate mechanisms runs in an individual virtual machine provided by the separation kernel supporting the TTIU.

A TTIU in the "idle" state simply ignores all characters reaching it from the LAN or from its terminal until a special character sequence is typed at the keyboard. This will cause the TTIU to connect the terminal to its authentication mechanism, which will then interrogate the user to determine his identity. Once the user has been authenticated, he can be asked for the security partition to which he wishes to be connected. If the requested partition is within his clearance and all other requirements of the security policy are satisfied (for example, a terminal located in a public place is not permitted a Top Secret connection even if its user is authorized to that level), then the TTIU will load the encryption key of the partition concerned into its DES chip. The Newcastle Connection software in the TTIU will then be able to contact its counterpart in a host machine belonging to the appropriate security partition, and the user will thereafter interact with that remote machine exactly as if he were connected to it directly.

The Newcastle Connection component in the TTIU must be able to respond to remote procedure calls directed to it by the Newcastle Connection of the remote machine. The only calls that require a nonerror response are those appropriate to terminals, namely "read from the keyboard", "write to the screen," and a couple of others concerned with status information. Thus, only a fraction of the full Newcastle Connection software is required for a TTIU, and just like the similar software in a conventional host, it need not be trusted.

A system in which terminals are attached to machines of fixed security level can be somewhat inconvenient to use.

None of the additional trusted mechanisms required to upgrade a TNIU to a TTIU should present an undue challenge in either construction or verification, Nor should the presence of these additional mechanisms affect the construction or verification of the TNIU components themselves, since TNIUs are constructed on top of a separation kernel. In fact, the presence of a separation kernel makes it perfectly feasible to support multiple terminals, each with a separate set of TTIU and TNIU components, on a single processor.

Changing security partitions dynamically. TTIUs enable users to connect to machines in different security partitions, thereby allowing them to perform each of their activities at the most appropriate level within their clearance. If a security policy with a large number of need-to-know compartments is supported, however, the number of different security partitions

can well exceed the number of physical hosts available. Even when the number of distinct security partitions is small, the demand for resources within each partition can vary with time. Furthermore, some users might prefer to use personal workstations for their activities in many different security partitions. All these cases require some provision for reallocating host machines to different security partitions.

With untrusted hosts, this can only be accomplished by temporal separation, which in its simplest form is periods processing. This requires manual intervention to exchange all demountable storage and the reinitialization of all fixed storage to remove every trace of information from the old security partition before the machine can be brought up again at its new level, either "clean" or reloaded with the suspended state of some previous activation at that level.

Manual periods processing requires very rigid administrative controls, and it is slow and expensive, We therefore propose mechanisms for automating the process, making it both rapid and secure. The mechanisms required include one that causes a host's TNIU to load the encryption key of a new security partition, and another that provides temporal separation for different uses of the host machine,

A project to develop an implementation of the system described here has a sponsor and is being carried out.

The system state of a host machine is contained in its writable storage: CPU registers, RAM, and disks, The disks of a Unix system provide swap space and contain the local file system. With the exception of the file system, the local storage available to a host is all used for strictly temporary purposes and can simply be erased and reinitialized when the host changes security partitions. This is achieved by causing the host to boot-load a trusted stand-alone purge program from ROM on power-up, or on command from its TNIU. This program systematically clears and reinitializes all temporary storage available to its host processor.

Unlike temporary storage, the local file system cannot just be erased when the host changes security partitions; it must be retained (inaccessibly) for later activations of the host in the same partition. Since Unix United provides convenient access to remote files, this requirement can be satisfied by holding files remotely, either in file servers dedicated to particular security partitions, or in the secure file store.

Operating host machines without local file store is inefficient. Accordingly, the purge program creates a local file system on its host's disk and initializes it to contain the standard utility programs. (These can be obtained from a local read-only floppy disk, or from a "boot server" accessed over the LAN.) Each reference to an apparently local file is intercepted by a local file relocation process added to the Newcastle Connection. This process checks to see if the requested file is already present in the local file system. If it is, the access is allowed to proceed normally. If it is not, the relocation process first obtains a local copy of the file from the machine that maintains the permanent version of the host's file system for the security partition concerned. For example, if the host is known as PW5 (personal workstation number 5) and is currently operating in the Secret(NATO) partition, then a reference to the local file /user /john /paper might cause the local file relocation process to obtain a copy of the file /../SNSERVER/PW5/user/john/paper, where SNSERVER is the name of the machine that maintains the Secret(NATO) file system. This process is perfectly straightforward and need not be trusted, since an attempt to name a machine in the wrong security partition will be caught by the standard TNIU mechanisms (the local and remote machines will have incompatible encryption keys). Files modified or created during a session must, of course, be written back to their permanent file system by the local file relocation process at or before the end of the session,

In outline, the complete scenario for automatically changing the security partition in which a host operates is as follows. A user at a terminal attached to a TTIU is authenticated and asked for the security partition in which he wishes to work. If this partition is within his clearance, a signal is sent to the TNIU of a vacant host machine (or to the user's personal workstation) instructing it to switch to the indicated security partition. This signal is protected against forgery or spoofing by the standard encryption techniques employed between TNIUs. Upon receipt of the signal, the host's TNIU loads the encryption key appropriate to the new security partition, initiates the purging and reinitialization of its host machine, and informs the host's local file relocation process of the identity of its new security partition,

We have described a distributed system that provides a limited but useful form of multilevel secure operation. Four distinct methods for achieving separation (physical, temporal, cryptographical, and logical) have been illustrated. When used judiciously, they can provide security without inefficiency and with only a limited number of trusted mechanisms. Moreover, our trusted mechanisms are relatively simple and within the current state of the art. Indeed, a number of them have previously been proposed (and some implemented) by others, though usually as stand-alone systems. A more extensive treatment of the topics covered in this article is available as a technical report[10]. It describes our mechanisms in more detail,

relates them to their precursors, and discusses some enhancements to the basic system (the inclusion of downgraders or guards, and support for multilevel objects, for instance). Readers who wish to learn more about issues and techniques relating to computer security should consult the excellent book by D. E. Denning[8].

A project to develop an implementation of the system described here is being sponsored by the Royal Signals and Radar Establishment, or RSRE, of the UK Ministry of Defence, and is being carried out by System Designers Ltd, of Camberley in conjunction with the Microelectronics Applications Research Institute, or MARI, and the Computing Laboratory of the University of Newcastle upon Tyne. The first stage of this project will result in the delivery of a prototype to RSRE in mid-1983. The security mechanisms of the prototype will be provided by ordinary user processes in a standard Unix United system. This will not, of course, be secure, but it will allow the operation of the various mechanisms to be studied in practice, enable the overall performance of the system to be evaluated, and most importantly, permit the impact of a mechanically enforced security policy to be observed in a realistic environment. If this stage is judged a success, a prototype implementation of the real system will follow. We hope that before long we will be able to report on the progress of this project and, in due course, on how well it achieves its security, usability, and performance goals.

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Two anonymous referees directed our attention to a number of vexatious technical problems with some of our mechanisms and led us to make several improvements. The final form of this article benefited considerably from the careful reading, criticism, and advice of Pete Tasker of the Mitre Corporation. Sarah Rolph, also of the Mitre Corporation, suggested many improvements in the presentation of this material.

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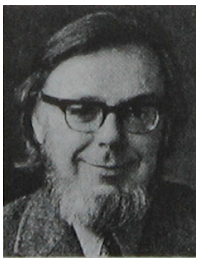
John M. Rushby is a computer scientist with the Computer Science Laboratory of SRI International. His research interests include the design, specification, and verification of secure systems and other computer systems that must satisfy stringent requirements. From 1979 to 1982, he was a research associate with the Computing Laboratory of the University of Newcastle upon Tyne, England, and from 1975 to 1978 he was a lecturer in the Department of Computer Science at Manchester University, England. Rushby received BSc and PhD degrees in Computer Science, both from the University of Newcastle upon Tyne, in 1971 and 1977, respectively.



Brian Randell is a professor of computing science at the University of Newcastle upon Tyne, where in 1971 he initiated a program of research on computing systems that now encompasses several major projects. From 1964 to 1969, he was with IBM, primarily at the IBM Research Center in the US, working on operating systems, the design of ultra high speed computers, and system design methodology. Before that, he worked for the English Electric Company, where he led a team that implemented a number of compilers, including the Whetstone KDF9 Algol compiler. Randell graduated in mathematics from Imperial College, London, in 1957.

Subsequent Developments

For some years after the publication of the DSS paper we had little knowledge of how RSRE's work was progressing. However by about 1985 the RSRE DSS prototype had been completed and partially declassified, and we had been brought back into the picture somewhat. We then belatedly realized that, though the DSS scheme directly exploited one of our system design concepts, that relating to the use of recursion, it had applied only one of Newcastle's ideas about system structuring to security, and that there was an opportunity to apply another, that of "ideal fault-tolerant computing components" [3]. The resulting work led to the paper "Building Reliable Secure Computing Systems out of Unreliable Insecure Components", which was published in the 1986 Oakland conference [8] – and which was reprised in ACSAC's Classic Papers track in 2001.

But the invitation from ACSAC to provide a retrospective on our original DSS paper has prompted us to attempt to discover more about the subsequent implementation and deployment of the industrial prototype of DSS, and also to provide a description of DSS's modern interpretation in the form of the MILS architecture.

The UK DSS Technology Demonstrator Programme

Prompted by our initial work on DSS, RSRE started a "Technology Demonstrator Programme" (DSS TDP) to develop and deploy prototypes of DSS – such TDPs were typical for large physical systems, such as tanks and ships, but this was the Ministry of Defence's first-ever Information Technology TDP. The present authors were not involved in the demonstrator programme, which was conducted by RSRE with private contractors whose identities changed several times owing to acquisitions and reorganizations, and knew nothing of how it was developing other than through publications describing promising progress.

Barnes and Macdonald [5] describe an apparently successful emulation of DSS that "demonstrated the full internal functionality of the DSS." As an emulation, "the TNIU functions are implemented as sub-systems within the untrusted host machines, rather than as separate front-end processors . . . however, in all other respects the emulation is functionally complete." The demonstration was "provided with applications software which is aimed at an office automation type of environment." Its purpose was to "prove the concept and improve the design." The cited paper was based on one presented at a conference in September 1985, so that stage of the project was presumably largely complete by that date. The next stage was "to realize a full, practical DSS prototype" and it seems this was already under way in 1986 (the date of the cited paper).

Bates [6] describes progress on the full DSS TDP five years later and states that it was being developed to Level 5 of the "computer security confidence scale" then in use by the UK (roughly B3 on the contemporaneous US "Orange Book" scheme [9]). It is stated that the programme was "on target to complete in 1991 . . . evaluation and certification is expected to be completed in late 1991 and commercially supported DSS products are also expected in late 1991." Furthermore, "it is intended that the DSS TDP products will be commercially exploited by several UK suppliers . . . the first licence to commercially exploit the DSS technology has already been signed by a major UK IT company."

When we received the invitation to present this retrospective, we inquired after the later history of the DSS TDP. We were fortunate to obtain a final report on the "Phase 2 Insertion Trials" [23]. This reports that the DSS TDP was awarded a UK Level 4 Certificate (not 5 as anticipated earlier) in April 1993 and was licensed to British Telecommunications PLC and GEC-Marconi Secure Systems. The trials were

intended to deploy DSS TDP installations at three sites: "HQ PTC Innsworth," "DRA Fort Halstead," and "HM Treasury." The first used a version running OSI protocols and the other two used TCP/IP. The initial HQ PTC Innsworth trial in December 1993 failed due to "an error in the key material supplied by CESG." A later attempt in June 1994 was hampered by network problems suggesting "the Black Network Ethernet interface might not be fully within IEEE 802.3 specification." These were finally resolved and the system worked but "was considered too slow for day-to-day use." Furthermore, "the DSS system proved too unreliable to leave in place." Improving performance and reliability "would involve significant reengineering of the DSS kernel."

The DRA Fort Halstead trial was conducted in February 1994. Again, network problems intervened so that "a liaison could not be established between the TNIU and the TNIU/TMC." It seems that heavy loads (due to other traffic) on a certain network segment caused the TMC/TNIU to miss the liaison request packets. The DSS software was modified to operate better under high network loads but the trial was not continued. Owing to the problems at the first two trials, the trial at HM Treasury was canceled.

The report concludes: "it is unlikely that MOD or DRA will provide further funding for DSS development . . . its future therefore depends on the licensees being convinced that the necessary substantial investment will be worthwhile." We may be confident the licensees were not convinced and that the DSS project was promptly dropped.

From DSS to MILS

After a decade of development effort, the DSS Technology Demonstration Programme ended in disappointing failure. Naturally, we tend to attribute this to the technological limitations of the time (a topic we will return to later) and to UK development and management practices, and we remain serene and confident in the rightness of the DSS ideas. To describe the subsequent history and evolution of those ideas, we first need to set the context.

The period from the 1970s through the 90s saw many efforts to construct secure computer systems. These systems were of two broad categories: components for network security (end-to-end encryption devices, downgraders, filters, etc.), and general purpose systems supporting Multi-Level Secure (MLS) applications. However, both categories used a similar architecture, in which most of the Trusted Computing Base (TCB) was identified with the operating system kernel. These monolithic "security kernels" had a dual responsibility: they had to provide the basic protection mechanisms of an operating system (address space isolation, controlled access to privileged mode and so on) and they had to enforce the system's security policy.

Rushby's 1981 paper [13] argued that this dual responsibility inevitably leads to complex implementations that are hard to verify and, instead, proposed that secure network components would be better served by a specialized operating system core (a "separation kernel") that focuses solely on the provision of isolated address spaces with controlled communications between them, while policy is enforced by trusted applications running in some of those address spaces.

The paper that is the subject of this retrospective extended this idea to general purpose systems and multilevel security. It argues that "separation" is the essential foundation for any kind of secure architecture, and that it can be achieved by several mechanisms: logical (a separation kernel), physical (separate machines), cryptographic (encryption or digital signatures), and temporal (periods processing). Separation creates an architecture of encapsulated subjects (computational entities with state, often portrayed diagrammatically as circles or boxes) and known communication channels between them (generally portrayed as arrows). Various security policies can be achieved by a suitable geography of subjects and channels, and the allocation of trusted functions to certain subjects, which mediate the services provided or information allowed to flow to their outgoing channels. The DSS paper illustrated this approach with the conceptual design of a system able to provide limited MLS functionality using all four kinds of separation mechanisms and relatively simple trusted functions. The trusted functions were simple because we used the design freedom afforded by the Newcastle Connection to "deconstruct" complex functions (such as the multilevel filestore) into simpler, separated components. The functionality of the full filestore was then reconstructed as a distributed computation over these simpler components. It is for this reason that we refer to our system as a "Distributed Secure System," rather than a "Secure Distributed System," the implication being that it is a secure system that exploits distribution, rather than a distributed system that happens to be secure.

While approaches based on monolithic security kernels can deliver cost-effective and functional secure systems (see, for example, the fervent advocacy of Schell [20]), it seems there were some disappointments. Reviews at NSA in the early 1990s led to reexamination of the separation kernel idea ([10] states "in 1993 an informal separation kernel working

group was established") and to prototype implementations.

Rather later, an architecture for embedded applications emerged called MILS. The earliest references seem to be NSA internal papers by Mark Vanfleet and others dated 1996 and 2003, which are cited in [2]. MILS originally stood for Multiple Independent Levels of Security, but is now best understood as simply a name. Papers on MILS [22], [1] always credit [13] as their inspiration, and cite DSS in passing, but we would like to suggest that MILS is best seen as the modern realization of DSS.

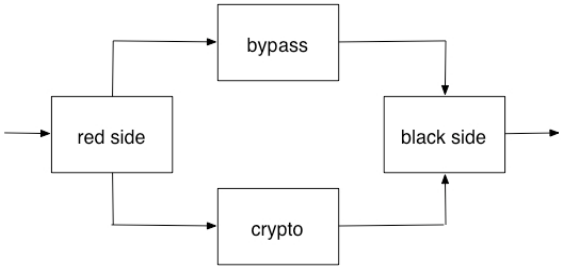


Figure: Encryption Device Composed of Four Subjects

Like DSS, MILS is a two-level architecture that considers the issues and mechanisms of policy enforcement separately from those of resource sharing. Security policy is the concern of the upper level of the architecture and is understood in terms of isolated subjects interacting over known channels (i.e., a "boxes and arrows" picture). Some subjects will be trusted, others untrusted, and the goal is to design the system in such a way that the complexity of trusted subjects is minimized: this may be achieved by splitting large trusted functions into smaller and simpler sub-functions that are allocated to dedicated subjects with carefully configured communications channels. For example, in the elementary end-to-end encryption unit considered in [13], the concern is that plaintext from the secret "red" side might escape to the public network on the "black" side. By splitting the encryption device into four subjects – **red**, **black**, **bypass**, and **crypto** – as shown in the above figure, we simplify this problem. The **crypto** is trusted to encrypt everything that passes across its input and output channels, the **bypass** is trusted to check that the plaintext that passes across its input to output channels looks like packet headers and has limited bandwidth, and there are no other channels connecting the **red** to **black** sides. With this architecture, the black side (which will contain the protocol stack, network drivers, and other complex software) can be completely untrusted (and similarly for the red side).

To derive maximum benefit from this approach, we should assume that the resources required for subjects and their communication channels are cheap, and we should create subjects and channels freely whenever this can minimize the complexity of trusted subjects (where complexity refers to the difficulty of the associated assurance task, which will generally depend on both the function provided by the subject, and the property to be trusted of it). Papers on MILS often show a more elaborate encryption device with 12 subjects (e.g., Figure12 in [1], and MILS architectures for the F22 and other complex platforms have hundreds or thousands of subjects.

We are able to design on the assumption that subjects and communication channels are cheap because the lower level of the MILS architecture makes them so – through the provision of efficient and secure resource sharing. The MILS lower level comprises several interoperable components that each "partition," "virtualize", or otherwise separate individual physical or logical resources into many separated instances that communicate only through controlled channels. These components are specialized to the kind of resource they manage: a separation kernel supports subjects directly, partitioned communication systems and networks, and virtualized NICs provide securely multiplexed communications with various levels of functionality (roughly, CORBA, TCP/IP, and bare metal, respectively), a partitioned file system provides storage functions similar to that proposed for the DSS filestore, while a console subsystem securely partitions display area.

Whereas DSS was conceived as a single system, MILS is conceived as an architecture and a collection of components that integrators can use to build many systems. Indeed, part of the aim of MILS is to foster an infrastructure of commercial off the shelf (COTS) security components. To this end, Common Criteria Protection Profiles are being developed for separation kernels (SKPP), partitioned communications systems (PCSPP), network subsystems (MNSPP) and other MILS elements. The idea is that vendors will develop a COTS marketplace for MILS-compliant components. The SKPP has been approved [21] and one commercial separation kernel has been evaluated against it (to approximately EAL7) and others are planned.

No complete system has been fielded yet, so what are the reasons for believing MILS will be more successful than the DSS TDP? First, the basic technology has evolved and improved greatly over the years. Separation kernels are similar to the partitioning real-time kernels used routinely in modern avionics (indeed some vendors base their separation kernel on their avionics offering) and to hypervisors such as Xen (one project aims to develop a separation kernel by slicing Xen to a minimal subset). Improved hardware support such as the Intel VT architecture, and improved understanding of kernel APIs (such as

paravirtualization), all simplify the task of developing a separation kernel, and improve its performance. It is entirely feasible to contemplate 100,000 partition switches per second at a performance cost in single percentage digits. (On the other hand, modern cache architectures make it difficult and costly to reduce covert channel bandwidth as they introduce wide variation into execution time.) Similarly, avionics buses such as AFDX and TTA demonstrate the feasibility of partitioned communications, while integrated modular avionics (IMA) architectures used successfully in modern commercial airplanes such as the Boeing 777 and 787 and Airbus A380 have much in common with MILS.

Second, the use of distributed computation in DSS was advanced for its time and there was little intellectual or infrastructural support for developing distributed systems. The prevalent thinking was of networks, rather than systems (hence [15]). Now, we have middleware and rich infrastructure for developing distributed applications.

Finally, there is improved understanding of system development and system integration processes and their management. The devolved, component-based approach used in IMA and MILS seems more robust than the central planning used for DSS TDP.

Looking Forward

Twenty-five years is often cited as the time lag from research to deployment. The 25th anniversary of the publication of the DSS paper is approaching (the extended abstract [19] must have been submitted to the conference around December 1982, and the technical report [18] would have been completed about the same time), so we are hopeful that successful realization of these ideas is imminent.

As described above, our hope currently rests on the MILS architecture (and a similar program called HAP, which is developing a specific platform, rather than a set of components). However, a successful system based around MILS would initially establish only the pragmatic viability of the DSS approach; the bigger challenge is to develop a certifiably secure system this way.

As noted, DSS was conceived as a system, and its components were designed for their specific role within the system; MILS, in contrast, is conceived as a set of components that can be integrated with bespoke and glue components, to realize many systems. Roughly, DSS was top-down while MILS is bottom-up. What is the assurance argument for certifiable security of a system assembled this way? That is the role of the MILS architecture, and the MILS Integration Protection Profile (MIPP) being developed by Rushby and Rance DeLong. The MILS architecture has two levels of components; the MIPP specifies that the upper (circles and arrows) level must be compositional, and the lower (resource sharing) level must be additively composable. Intuitively, *compositionality* means that there must be a way to calculate the collective security properties of the upper level components given the security properties of the components; *composable* means that the security properties of a collection of upper level components are unchanged when these run in the environment provided by a lower level component (even if faulty or malicious upper-level components are also present); and *additive* means that a collection of composable lower level components is itself composable.

We believe these ideas can be developed to provide a formal foundation for compositional certification in security and other critical fields, including safety [16]. Compositional assurance and certification seem a worthwhile research challenge for the next twenty-five years and a logical continuation of the design vision that inspired DSS.

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