**Chapter 9**

**Multilevel security**

**Most high assurance work has been done in the area of kinetic**

**devices and infernal machines that are controlled by stupid**

**robots. As information processing technology becomes more**

**important to society, these concerns spread to**  
 **areas previously thought inherently harmless,**

**like operating systems.**

**– EARL BOEBERT**

**The password on the government phone always seemed to drop, and**

**I couldn’t get into it**

**– US diplomat and former CIA o�cer KURT VOLKER, explaining**

**why he texted from his personal phone**

**I brief;**

**you leak;**

**he/she commits a criminal o↵ence**  
 **by divulging classiﬁed information.**

**– BRITISH CIVIL SERVICE VERB**

**9.1** **Introduction**

In the next few chapters I’m going to explore the concept of a security policy  
 using case studies. A security policy is a succinct description of what we’re trying  
 to achieve; it’s driven by an understanding of the bad outcomes we wish to avoid  
 and in turn drives the engineering. After I’ve ﬂeshed out these ideas a little,  
 I’ll spend the rest of this chapter exploring the *multilevel security* (MLS) policy  
 model used in many military and intelligence systems, which hold information  
 at di↵erent levels of classiﬁcation (Conﬁdential, Secret, Top Secret, ...), and  
 have to ensure that data can be read only by a principal whose clearance level  
 is at least as high. Such policies are increasingly also known as *information ﬂow*  
 *control* (IFC).

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*9.2. WHAT IS A SECURITY POLICY MODEL?*

They are important for a number of reasons, even if you’re never planning

to work for a government contractor:

1. from about 1980 to about 2005, the US Department of Defense spent

several billion dollars funding research into multilevel security. So the

model was worked out in great detail, and we got to understand the second-  
 order e↵ects of pursuing a single policy goal with great zeal;

2. the *mandatory access control* (MAC) systems used to implement it have

now appeared in all major operating systems such as Android, iOS and  
 Windows to protect core components against tampering by malware, as I  
 described in chapter 6;

3. although multilevel security concepts were originally developed to support

conﬁdentiality in military systems, many commercial systems now use  
 multilevel integrity policies. For example, safety-critical systems use a

number of safety integrity levels1.

The poet Archilochus famously noted that a fox knows many little things,

while a hedgehog knows one big thing. Security engineering is usually in fox  
 territory, but multilevel security is an example of the hedgehog approach.

**9.2** **What is a Security Policy Model?**

Where a top-down approach to security engineering is possible, it will typically  
 take the form of *threat model – security policy – security mechanisms*. The

critical, and often neglected, part of this process is the security policy.

By a security policy, we mean a document that expresses clearly and con-

cisely what the protection mechanisms are to achieve. It is driven by our un-  
 derstanding of threats, and in turn drives our system design. It will often take  
 the form of statements about which users may access which data. It plays the  
 same role in specifying the system’s protection requirements, and evaluating  
 whether they have been met, that the system speciﬁcation does for functional-  
 ity and the safety case for safety. Like the speciﬁcation, its primary function is  
 to communicate.

Many organizations use the phrase ‘security policy’ to mean a collection of

vapid statements, as in Figure 9.1:

1Beware though that terminology varies between di↵erent safety-engineering disciplines.

The safety integrity levels in electricity generation are similar to Biba, while automotive safety  
 integrity levels are set in ISO 26262 as a hazard/risk metric that depends on the likelihood  
 that a fault will cause an accident, together with the expected severity and controllability

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*9.2. WHAT IS A SECURITY POLICY MODEL?*

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| **Megacorp Inc security policy**  1. This policy is approved by Management.  2. All sta↵ shall obey this security policy.  3. Data shall be available only to those with a “need-to-know”.  4. All breaches of this policy shall be reported at once to Security. |

Figure 9.1 – typical corporate policy language

This sort of language is common, but useless – at least to the security engi-

neer. It dodges the central issue, namely ‘Who determines “need-to-know” and  
 how?’ Second, it mixes statements at di↵erent levels (organizational approval  
 of a policy should logically not be part of the policy itself). Third, there is a  
 mechanism but it’s implied rather than explicit: ‘sta↵ shall obey’ – but what  
 does this mean they actually have to do? Must the obedience be enforced by the  
 system, or are users ‘on their honour’? Fourth, how are breaches to be detected  
 and who has a speciﬁc duty to report them?

When you think about it, this is political language. A politician’s job is to

resolve the tensions in society, and this often requires vague language on which  
 di↵erent factions can project their own wishes; corporate executives are often  
 operating politically, to balance di↵erent factions within a company2.

Because the term ‘security policy’ is often abused to mean using security for

politics, more precise terms have come into use by security engineers.

A *security policy model* is a succinct statement of the protection properties

that a system must have. Its key points can typically be written down in a  
 page or less. It is the document in which the protection goals of the system are  
 agreed with an entire community, or with the top management of a customer.  
 It may also be the basis of formal mathematical analysis.

A *security target* is a more detailed description of the protection mechanisms

that a speciﬁc implementation provides, and how they relate to a list of con-  
 trol objectives (some but not all of which are typically derived from the policy  
 model). The security target forms the basis for testing and evaluation of a

product.

A *protection proﬁle* is like a security target but expressed in an implementation-

independent way to enable comparable evaluations across products and versions.  
 This can involve the use of a semi-formal language, or at least of suitable se-  
 curity jargon. A protection proﬁle is a requirement for products that are to be  
 evaluated under the *Common Criteria* [1396]. (I discuss the Common Criteria in  
 Part III; they are used by many governments for mutual recognition of security  
 evaluations of defense information systems.)

When I don’t have to be so precise, I may use the phrase ‘security policy’ to

refer to either a security policy model or a security target. I will never use it to  
 refer to a collection of platitudes.

2Big projects often fail in companies when the speciﬁcation becomes political, and they

fail even more often when run by governments – issues I’ll discuss further in Part 3.

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*9.3. MULTILEVEL SECURITY POLICY*

Sometimes, we’re confronted with a completely new application and have

to design a security policy model from scratch. More commonly, there already  
 exists a model; we just have to choose the right one, and develop it into a  
 security target. Neither of these steps is easy. In this section of the book, I  
 provide a number of security policy models, describe them in the context of real  
 systems, and examine the engineering mechanisms (and associated constraints)  
 which a security target can use to meet them.

**9.3** **Multilevel Security Policy**

On March 22, 1940, President Roosevelt signed Executive Order 8381, enabling  
 certain types of information to be classiﬁed Restricted, Conﬁdential or Se-  
 cret [978]. President Truman later added a higher level of Top Secret. This  
 developed into a common protective marking scheme for the sensitivity of doc-  
 uments, and was adopted by NATO governments too in the Cold War. *Classi-*  
 *ﬁcations* are labels, which run upwards from *Unclassiﬁed* through *Conﬁdential*,  
 *Secret* and *Top Secret* (see Figure 9.2). The original idea was that informa-  
 tion whose compromise could cost lives was marked ‘Secret’ while information  
 whose compromise could cost many lives was ‘Top Secret’. Government employ-  
 ees and contractors have *clearances* depending on the care with which they’ve  
 been vetted; in the USA, for example, a ‘Secret’ clearance involves checking FBI  
 ﬁngerprint ﬁles, while ‘Top Secret’ also involves background checks for the pre-  
 vious ﬁve to ﬁfteen years’ employment plus an interview and often a polygraph  
 test [548]. Candidates have to disclose all their sexual partners in recent years  
 and all material that might be used to blackmail them, such as teenage drug  
 use or gay a↵airs3.

The access control policy was simple: you can read a document only if your

clearance is at least as high as the document’s classiﬁcation. So an o�cial

cleared to ‘Top Secret’ could read a ‘Secret’ document, but not vice versa. So  
 information may only ﬂow upwards, from conﬁdential to secret to top secret,  
 but never downwards – unless an authorized person takes a deliberate decision  
 to declassify it.

|  |  |
| --- | --- |
|  | TOP SECRET |

|  |  |
| --- | --- |
|  | SECRET |
|  | CONFIDENTIAL |

|  |  |
| --- | --- |
|  | UNCLASSIFIED |

Figure 9.2 – multilevel security

The system rapidly became more complicated. The damage criteria for

classifying documents were expanded from possible military consequences to

3In June 2015, the clearance review data of about 20m Americans was stolen from the

O�ce of Personnel Management by the Chinese intelligence services. By then, about a million  
 Americans had a Top Secret clearance; the OPM data also covered former employees and job  
 applicants, as well as their relatives and sexual partners. With hindsight, collecting all the  
 dirt on all the citizens with a sensitive job may not have been a great idea.

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economic harm and even political embarrassment. Information that is neither  
 classiﬁed nor public is known as ‘Controlled Unclassiﬁed Information’ (CUI) in  
 the USA while Britain uses ‘O�cial’4.

There is also a system of codewords whereby information, especially at Se-

cret and above, can be restricted further. For example, information that might  
 reveal intelligence sources or methods – such as the identities of agents or de-  
 cryption capabilities – is typically classiﬁed ‘Top Secret Special Compartmented  
 Intelligence’ or TS/SCI, which means that so-called *need to know* restrictions  
 are imposed as well, with one or more codewords attached to a ﬁle. Some code-  
 words relate to a particular military operation or intelligence source and are  
 available only to a group of named users. To read a document, a user must have  
 all the codewords that are attached to it. A classiﬁcation label, plus a set of  
 codewords, makes up a *security category* or (if there’s at least one codeword)  
 a *compartment*, which is a set of records with the same access control policy.  
 Compartmentation is typically implemented nowadays using discretionary ac-  
 cess control mechanisms; I’ll discuss it in the next chapter.

There are also *descriptors*, *caveats* and *IDO markings*. Descriptors are words

such as ‘Management’, ‘Budget’, and ‘Appointments’: they do not invoke any  
 special handling requirements, so we can deal with a ﬁle marked ‘Conﬁdential –  
 Management’ as if it were simply marked ‘Conﬁdential’. Caveats are warnings  
 such as “UK Eyes Only”, or the US equivalent, “NOFORN”; they do create  
 restrictions. There are also *International Defence Organisation* markings such as  
 *NATO*5. The lack of obvious di↵erences between codewords, descriptors, caveats  
 and IDO marking helps make the system confusing. A more detailed explanation  
 can be found in [1562].

**9.3.1** **The Anderson report**

In the 1960s, when computers started being widely used, the classiﬁcation sys-  
 tem caused serious friction. Paul Karger, who worked for the USAF then,

described having to log o↵ from a Conﬁdential system, walk across the yard  
 to a di↵erent hut, show a pass to an armed guard, then go in and log on to a  
 Secret system – over a dozen times a day. People soon realised they needed a  
 way to deal with information at di↵erent levels at the same desk, but how could  
 this be done without secrets leaking? As soon as one operating system bug was  
 ﬁxed, some other vulnerability would be discovered. The NSA hired an eminent  
 computer scientist, Willis Ware, to its scientiﬁc advisory board, and in 1967  
 he brought the extent of the computer security problem to o�cial and public  
 attention [1985]. There was the constant worry that even unskilled users would

4Prior to adopting the CUI system, the United States had more than 50 di↵erent mark-

ings for data that was controlled but not classiﬁed, including For O�cial Use Only (FOUO),  
 Law Enforcement Sensitive (LES), Proprietary (PROPIN), Federal Tax Information (FTI),  
 Sensitive but Unclassiﬁed (SBU), and many, many others. Some agencies made up their own  
 labels, without any coordination. Further problems arose when civilian documents marked  
 Conﬁdential ended up at the National Archives and Records Administration, where CONFI-  
 DENTIAL was a national security classiﬁcation. Moving from this menagerie of markings to  
 a single centrally-managed government-wide system has taken more than a decade and is still  
 ongoing. The UK has its own post-Cold-War simpliﬁcation story.

5Curiously, in the UK ‘NATO Secret’ is less secret than ‘Secret’, so it’s a kind of anti-

codeword that moves the content down the lattice rather than up.

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discover loopholes and use them opportunistically; there was also a keen and  
 growing awareness of the threat from malicious code. (Viruses were not invented  
 until the 1980s; the 70’s concern was Trojans.) There was then a serious scare  
 when it was discovered that the Pentagon’s World Wide Military Command and  
 Control System (WWMCCS) was vulnerable to Trojan Horse attacks; this had  
 the e↵ect of restricting its use to people with a ‘Top Secret’ clearance, which  
 was inconvenient.

The next step was a 1972 study by James Anderson for the US government

which concluded that a secure system should do one or two things well; and  
 that these protection properties should be enforced by mechanisms which were  
 simple enough to verify and that would change only rarely [51]. It introduced the  
 concept of a *reference monitor* – a component of the operating system which  
 would mediate access control decisions and be small enough to be subject to  
 analysis and tests, the completeness of which could be assured. In modern

parlance, such components – together with their associated operating procedures  
 – make up the *Trusted Computing Base* (TCB). More formally, the TCB is  
 deﬁned as the set of components (hardware, software, human, ...) whose correct  
 functioning is su�cient to ensure that the security policy is enforced, or, more  
 vividly, whose failure could cause a breach of the security policy. The Anderson  
 report’s goal was to make the security policy simple enough for the TCB to be  
 amenable to careful veriﬁcation.

**9.3.2** **The Bell-LaPadula model**

The multilevel security policy model that gained wide acceptance was proposed  
 by Dave Bell and Len LaPadula in 1973 [210]. Its basic property is that infor-  
 mation cannot ﬂow downwards. More formally, the *Bell-LaPadula* (BLP) model  
 enforces two properties:

*•* The *simple security property*: no process may read data at a higher level.

*•* The *\*-property*: no process may write data to a lower level. This is also

The \*-property was Bell and LaPadula’s critical innovation. It was driven

by the WWMCCS debacle and the more general fear of Trojan-horse attacks.  
 An uncleared user might write a Trojan and leave it around where a system  
 administrator cleared to ‘Secret’ might execute it; it could then copy itself into  
 the ‘Secret’ part of the system, read the data there and try to signal it down  
 somehow. It’s also quite possible that an enemy agent could get a job at a com-  
 mercial software house and embed some code in a product that would look for  
 secret documents to copy. If it could then write them down to where its creator  
 could read them, the security policy would have been violated. Information

might also be leaked as a result of a bug, if applications could write down.

Vulnerabilities such as malicious and buggy code are assumed to be given.

It is also assumed that most sta↵ are careless, and some are dishonest; exten-  
 sive operational security measures have long been used, especially in defence

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environments, to prevent people leaking paper documents. So the pre-existing  
 culture assumed that security policy was enforced independently of user actions;  
 Bell-LaPadula sets out to enforce it not just independently of users’ direct ac-  
 tions, but of their indirect actions (such as the actions taken by programs they  
 run).

So we must prevent programs running at ‘Secret’ from writing to ﬁles at ‘Un-

classiﬁed’. More generally we must prevent any process at High from signalling  
 to any object at Low. Systems that enforce a security policy independently of  
 user actions are described as having *mandatory access control*, as opposed to  
 the *discretionary access control* in systems like Unix where users can take their  
 own access decisions about their ﬁles.

The Bell-LaPadula model enabled designers to prove theorems. Given both

the simple security property (no read up), and the star property (no write down),  
 various results can be proved: in particular, if your starting state is secure, then  
 your system will remain so. To keep things simple, we will generally assume  
 from now on that the system has only two levels, High and Low.

**9.3.3** **The standard criticisms of Bell-LaPadula**

The introduction of BLP caused a lot of excitement: here was a security policy  
 that did what the defence establishment thought it wanted, was intuitively clear,  
 yet still allowed people to prove theorems. Researchers started to beat up on it  
 and reﬁne it.

The ﬁrst big controversy was about John McLean’s *System Z*, which he

deﬁned as a BLP system with the added feature that a user can ask the system  
 administrator to temporarily declassify any ﬁle from High to Low. In this way,  
 Low users can read any High ﬁle without breaking the BLP assumptions. Dave  
 Bell countered that System Z cheats by doing something his model doesn’t allow  
 (changing labels isn’t a valid operation on the state), and John McLean’s retort  
 was that it didn’t explicitly tell him so: so the BLP rules were not in themselves  
 enough. The issue is dealt with by introducing a *tranquility property*. Strong  
 tranquility says that security labels never change during system operation, while  
 weak tranquility says that labels never change in such a way as to violate a  
 deﬁned security policy.

Why weak tranquility? In a real system we often want to observe the prin-

ciple of least privilege and start o↵ a process at the uncleared level, even if  
 the owner of the process were cleared to ‘Top Secret’. If they then access a  
 conﬁdential email, their session is automatically upgraded to ‘Conﬁdential’; in  
 general, a process is upgraded each time it accesses data at a higher level (the  
 *high water mark* principle). As subjects are usually an abstraction of the mem-  
 ory management sub-system and ﬁle handles, rather than processes, this means  
 that state changes when access rights change, rather than when data actually  
 moves.

The practical implication is that a process acquires the security labels of all

the ﬁles it reads, and these become the default label set of every ﬁle that it  
 writes. So a process which has read ﬁles at ‘Secret’ and ‘Crypto’ will thereafter  
 create ﬁles marked ‘Secret Crypto’. This will include temporary copies made of

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other ﬁles. If it then reads a ﬁle at ‘Secret Nuclear’ then all ﬁles it creates after  
 that will be labelled ‘Secret Crypto Nuclear’, and it will not be able to write to  
 any temporary ﬁles at ‘Secret Crypto’.

The e↵ect this has on applications is one of the serious complexities of mul-

tilevel security; most application software needs to be rewritten (or at least  
 modiﬁed) to run on MLS platforms. Real-time changes in security level mean  
 that access to resources can be revoked at any time, including in the middle of  
 a transaction. And as the revocation problem is generally unsolvable in mod-  
 ern operating systems, at least in any complete form, the applications have to  
 cope somehow. Unless you invest some care and e↵ort, you can easily ﬁnd that  
 everything ends up in the highest compartment – or that the system fragments  
 into thousands of tiny compartments that don’t communicate at all with each  
 other. In order to prevent this, labels are now generally taken outside the MLS  
 machinery and dealt with using discretionary access control mechanisms (I’ll  
 discuss this in the next chapter).

Another problem with BLP, and indeed with all mandatory access control

systems, is that separating users and processes is the easy part; the hard part is  
 when some controlled interaction is needed. Most real applications need some  
 kind of *trusted subject* that can break the security policy; the classic example  
 was a trusted word processor that helps an intelligence analyst scrub a Top  
 Secret document when she’s editing it down to Secret [1270]. BLP is silent on  
 how the system should protect such an application. So it becomes part of the  
 Trusted Computing Base, but a part that can’t be veriﬁed using models based  
 solely on BLP.

Finally it’s worth noting that even with the high-water-mark reﬁnement,

BLP still doesn’t deal with the creation or destruction of subjects or objects  
 (which is one of the hard problems of building a real MLS system).

**9.3.4** **The evolution of MLS policies**

Multilevel security policies have evolved in parallel in both the practical and  
 research worlds.

The ﬁrst multilevel security policy was a version of high water mark writ-

ten in 1967–8 for the ADEPT-50, a mandatory access control system developed  
 for the IBM S/360 mainframe [2006]. This used triples of level, compartment  
 and group, with the groups being ﬁles, users, terminals and jobs. As programs  
 (rather than processes) were subjects, it was vulnerable to Trojan horse compro-  
 mises. Nonetheless, it laid the foundation for BLP, and also led to the current  
 IBM S/390 mainframe hardware security architecture [940].

The next big step was Multics. This had started as an MIT project in

1965 and developed into a Honeywell product; it became the template and  
 inspirational example for ‘trusted systems’. The evaluation that was carried  
 out on it by Paul Karger and Roger Schell was hugely inﬂuential and was the  
 ﬁrst appearance of the idea that malware could be hidden in the compiler [1019]  
 – and led to Ken Thompson’s famous paper ‘Reﬂections on Trusting Trust’  
 ten years later [1883]. Multics had a derivative system called SCOMP that I’ll  
 discuss in section 9.4.1 .

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The torrent of research money that poured into multilevel security from the

1980s led to a number of alternative formulations. *Noninterference* was intro-  
 duced by Joseph Goguen and Jose Meseguer in 1982 [773]. In a system with this  
 property, High’s actions have no e↵ect on what Low can see. *Nondeducibility* is  
 less restrictive and was introduced by David Sutherland in 1986 [1847] to model  
 applications such as a LAN on which there are machines at both Low and High,  
 with the High machines encrypting their LAN tra�c6. Nondeducibility turned  
 out to be too weak, as there’s nothing to stop Low making deductions about  
 High input with 99% certainty. Other theoretical models include *Generalized*  
 *Noninterference* and *restrictiveness* [1276]; the *Harrison-Ruzzo-Ullman* model  
 tackles the problem of how to deal with the creation and deletion of ﬁles, on  
 which BLP is silent [868]; and the *Compartmented Mode Workstation* (CMW)  
 policy attempted to model the classiﬁcation of information using ﬂoating labels,  
 as in the high water mark policy [2040, 807].

Out of this wave of innovation, the model with the greatest impact on modern

systems is probably the *type enforcement* (TE) model, due to Earl Boebert  
 and Dick Kain [271], later extended by Lee Badger and others to *Domain and*  
 *Type Enforcement* (DTE) [153]. This assigns subjects to *domains* and objects  
 to *types*, with matrices deﬁning permitted domain-domain and domain-type  
 interactions. This is used in SELinux, now a component of Android, which

simpliﬁes it by putting both subjects and objects in types and having a matrix  
 of allowed type pairs [1187]. In e↵ect this is a second access-control matrix; in  
 addition to having a user ID and group ID, each process has a security ID (SID).  
 The Linux Security Modules framework provides pluggable security where you  
 can set rules that operate on SIDs.

DTE introduced a language for conﬁguration (DTEL), and implicit typing of

ﬁles based on pathname; so all objects in a given subdirectory may be declared  
 to be in a given domain. DTE is more general than BLP, as it starts to deal with  
 integrity as well as conﬁdentiality concerns. One of the early uses was to enforce  
 trusted pipelines: the idea is to conﬁne a set of processes in a pipeline so that  
 each can only talk to the previous stage and the next stage. This can be used  
 to assemble guards and ﬁrewalls which cannot be bypassed unless at least two  
 stages are compromised [1430]. Type-enforcement mechanisms can be aware  
 of code versus data, and privileges can be bound to code; in consequence the  
 tranquility problem can be dealt with at execute time rather than as data are  
 read. This can make things much more tractable. They are used, for example,  
 in the Sidewinder ﬁrewall.

The downside of the greater ﬂexibility and expressiveness of TE/DTE is

that it is not always straightforward to implement policies like BLP, because  
 of state explosion; when writing a security policy you have to consider all the  
 possible interactions between di↵erent types. Other mechanisms may be used  
 to manage policy complexity, such as running a prototype for a while to observe  
 what counts as normal behaviour; you can then turn on DTE and block all the  
 information ﬂows not seen to date. But this doesn’t give much assurance that

6Quite a lot else is needed to do this right, such as padding the High tra�c with nulls so

that Low users can’t do tra�c analysis – see [1632] for an early example of such a system. You  
 may also need to think about Low tra�c over a High network, such as facilities for soldiers to  
 phone home.

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the policy you’ve derived is the right one.

In 1992, *role-based access control* (RBAC) was introduced by David Ferraiolo

and Richard Kuhn to manage policy complexity. It formalises rules that attach  
 primarily to roles rather than to individual users or machines [678, 679]. Trans-  
 actions that may be performed by holders of a given role are speciﬁed, then  
 mechanisms for granting membership of a role (including delegation). Roles, or  
 groups, had for years been the mechanism used in practice in organizations such  
 as banks to manage access control; the RBAC model started to formalize this.  
 It can be used to give ﬁner-grained control, for example by granting di↵erent  
 access rights to ‘Ross as Professor’, ‘Ross as member of the Admissions Com-  
 mittee’ and ‘Ross reading private email’. A variant of it, aspect-based access  
 control (ABAC), adds context, so you can distinguish ‘Ross at his workstation  
 in the lab’ from ‘Ross on his phone somewhere on Earth’. Both have been

supported by Windows since Windows 8.

SELinux builds it on top of TE, so that users are mapped to roles at login

time, roles are authorized for domains and domains are given permissions to  
 types. On such a platform, RBAC can usefully deal with integrity issues as  
 well as conﬁdentiality, by allowing role membership to be revised when certain  
 programs are invoked. Thus, for example, a process calling untrusted software  
 that had been downloaded from the net might lose the role membership required  
 to write to sensitive system ﬁles. I discuss SELinux in more detail at 9.5.2.

**9.3.5** **The Biba model**

The incorporation into Windows 7 of a multilevel integrity model revived interest  
 in a security model devised in 1975 by Ken Biba [237], which deals with integrity  
 alone and ignores conﬁdentiality. Biba’s observation was that conﬁdentiality and  
 integrity are in some sense dual concepts – conﬁdentiality is a constraint on who  
 can read a message, while integrity is a constraint on who can write or alter it.  
 So you can recycle BLP into an integrity policy by turning it upside down.

As a concrete application, an electronic medical device such as an ECG

may have two separate modes: calibration and use. Calibration data must be  
 protected from corruption, so normal users should be able to read it but not  
 write to it; when a normal user resets the device, it will lose its current user state  
 (i.e., any patient data in memory) but the calibration must remain unchanged.  
 Only an authorised technician should be able to redo the calibration.

To model such a system, we can use a multilevel integrity policy with the

rules that we can read data at higher levels (i.e., a user process can read the  
 calibration data) and write to lower levels (i.e., a calibration process can write  
 to a bu↵er in a user process); but we must never read down or write up, as  
 either could allow High integrity objects to become contaminated with Low –  
 i.e. potentially unreliable – data. The Biba model is often formulated in terms of  
 the *low water mark* principle, which is the dual of the high water mark principle  
 discussed above: the integrity of an object is the lowest level of all the objects  
 that contributed to its creation.

This was the ﬁrst formal model of integrity. A surprisingly large number

of real systems work along Biba lines. For example, the passenger informa-

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tion system in a railroad may get information from the signalling system, but  
 shouldn’t be able to a↵ect it; and an electricity utility’s power dispatching sys-  
 tem will be able to see the safety systems’ state but not interfere with them.  
 The safety-critical systems community talks in terms of *safety integrity levels*,  
 which relate to the probability that a safety mechanism will fail and to the level  
 of risk reduction it is designed to give.

Windows, since version 6 (Vista), marks ﬁle objects with an integrity level,

which can be Low, Medium, High or System, and implements a default policy  
 of NoWriteUp. Critical ﬁles are at System and other objects are at Medium by  
 default – except for the browser which is at Low. So things downloaded using  
 IE can read most ﬁles in a Windows system, but cannot write to them. The  
 goal is to limit the damage that can be done by malware.

As you might expect, Biba has the same fundamental problems as Bell-

LaPadula. It cannot accommodate real-world operation very well without nu-  
 merous exceptions. For example, a real system will usually require trusted sub-  
 jects that can override the security model, but Biba on its own cannot protect  
 and conﬁne them, any more than BLP can. For example, a car’s airbag is on a  
 less critical bus than the engine, but when it deploys you assume there’s a risk  
 of a fuel ﬁre and switch the engine o↵. There are other real integrity goals that  
 Biba also cannot express, such as assured pipelines. In the case of Windows,  
 Microsoft even dropped the NoReadDown restriction and did not end up using  
 its integrity model to protect the base system from users, as this would have  
 required even more frequent user conﬁrmation. In fact, the Type Enforcement  
 model was introduced by Boebert and Kain as an alternative to Biba. It is  
 unfortunate that Windows didn’t incorporate TE.

**9.4** **Historical Examples of MLS Systems**

The second edition of this book had a much fuller history of MLS systems; since  
 these have largely gone out of fashion, and the MLS research programme has  
 been wound down, I give a shorter version here.

**9.4.1** **SCOMP**

A key product was the *secure communications processor* (SCOMP), a derivative  
 of Multics launched in 1983 [710]. This was a no-expense-spared implementation  
 of what the US Department of Defense believed it wanted for handling messaging  
 at multiple levels of classiﬁcation. It had formally veriﬁed hardware and soft-  
 ware, with a minimal kernel to keep things simple. Its operating system, STOP,  
 used Multics’ system of rings to maintain up to 32 separate compartments, and  
 to allow appropriate one-way information ﬂows between them.

SCOMP was used in applications such as military *mail guards*. These are ﬁre-

walls that allow mail to pass from Low to High but not vice versa [538]. (In gen-  
 eral, a device which supports one-way ﬂow is known as a *data diode*.) SCOMP’s  
 successor, XTS-300, supported C2G, the Command and Control Guard. This  
 was used in the time phased force deployment data (TPFDD) system whose

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function was to plan US troop movements and associated logistics. SCOMP’s  
 most signiﬁcant contribution was to serve as a model for the *Orange Book* [544]  
 – the US Trusted Computer Systems Evaluation Criteria. This was the ﬁrst  
 systematic set of standards for secure computer systems, being introduced in  
 1985 and ﬁnally retired in December 2000. The Orange Book was enormously  
 inﬂuential not just in the USA but among allied powers; countries such as the  
 UK, Germany, and Canada based their own national standards on it, until these  
 national standards were ﬁnally subsumed into the Common Criteria [1396].

The Orange Book allowed systems to be evaluated at a number of levels

with A1 being the highest, and moving downwards through B3, B2, B1 and C2  
 to C1. SCOMP was the ﬁrst system to be rated A1. It was also extensively  
 documented in the open literature. Being ﬁrst, and being fairly public, it set a  
 target for the next generation of military systems.

MLS versions of Unix started to appear in the late 1980s, such as AT&T’s

System V/MLS [47]. This added security levels and labels, showing that MLS  
 properties could be introduced to a commercial operating system with minimal  
 changes to the system kernel. By this book’s second edition (2007), Sun’s Solaris  
 had emerged as the platform of choice for high-assurance server systems and for  
 many clients as well. *Comparted Mode Workstations* (CMWs) were an example  
 of the latter, allowing data at di↵erent levels to be viewed and modiﬁed at the  
 same time, so an intelligence analyst could read ‘Top Secret’ data in one window  
 and write reports at ‘Secret’ in another, without being able to accidentally copy  
 and paste text downwards [932]. For the engineering, see [635, 636].

**9.4.2** **Data diodes**

It was soon realised that simple mail guards and crypto boxes were too restric-  
 tive, as more complex networked services were developed besides mail. First-  
 generation MLS mechanisms were ine�cient for real-time services.

|  |
| --- |
| HIGH  PUMP  LOW |

Figure 9.3: – the NRL pump

The US Naval Research Laboratory (NRL) therefore developed the *Pump* –

a one-way data transfer device (a data diode) to allow secure one-way informa-  
 tion ﬂow (Figure 9.3. The main problem is that while sending data from Low to  
 High is easy, the need for assured transmission reliability means that acknowl-

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edgement messages must be sent back from High to Low. The Pump limits the  
 bandwidth of possible backward leakage using a number of mechanisms such  
 as bu↵ering and random timing of acknowledgements [1012, 1013, 1014]. The  
 attraction of this approach is that one can build MLS systems by using data  
 diodes to connect separate systems at di↵erent security levels. As these systems  
 don’t process data at more than one level – an architecture called *system high*  
 – they can be built from cheap *commercial-o↵-the-shelf* (COTS) components.  
 You don’t need to worry about applying MLS internally, merely protecting them  
 from external attack, whether physical or network-based. As the cost of hard-  
 ware has fallen, this has become the preferred option, and the world’s military  
 bases are now full of KVM switches (which let people switch their keyboard,  
 video display and mouse between Low and High systems) and data diodes (to  
 link Low and High networks). The pump’s story is told in [1015].

An early application was logistics. Some signals intelligence equipment is

‘Top Secret’, while things like jet fuel and bootlaces are not; but even such  
 simple commodities may become ‘Secret’ when their quantities or movements  
 might leak information about tactical intentions. The systems needed to manage  
 all this can be hard to build; MLS logistics projects in both the USA and UK  
 have ended up as expensive disasters. In the UK, the Royal Air Force’s Logistics  
 Information Technology System (LITS) was a 10 year (1989–99), £500m project  
 to provide a single stores management system for the RAF’s 80 bases [1386].  
 It was designed to operate on two levels: ‘Restricted’ for the jet fuel and boot  
 polish, and ‘Secret’ for special stores such as nuclear bombs. It was initially  
 implemented as two separate database systems connected by a pump to enforce  
 the MLS property. The project became a classic tale of escalating costs driven  
 by creeping changes in requirements. One of these changes was the easing of  
 classiﬁcation rules with the end of the Cold War. As a result, it was found that  
 almost all the ‘Secret’ information was now static (e.g., operating manuals for  
 air-drop nuclear bombs that are now kept in strategic stockpiles rather than at  
 airbases). To save money, the ‘Secret’ information is now kept on a CD and  
 locked up in a safe.

Another major application of MLS is in wiretapping. The target of inves-

tigation should not know they are being wiretapped, so the third party must  
 be silent – and when phone companies started implementing wiretaps as silent  
 conference calls, the charge for the conference call had to go to the wiretapper,  
 not to the target. The modern requirement is a multilevel one: multiple agen-  
 cies at di↵erent levels may want to monitor a target, and each other, with the  
 police tapping a drug dealer, an anti-corruption unit watching the police, and  
 so on. Eliminating covert channels is harder than it looks; for a survey from  
 the mid-2000s, see [1707]; a pure MLS security policy is insu�cient, as suspects  
 can try to hack or confuse wiretapping equipment, which therefore needs to re-  
 sist online tampering. In one notorious case, a wiretap was discovered on the  
 mobile phones of the Greek Prime Minister and his senior colleagues during the  
 Athens olympics; the lawful intercept facility in the mobile phone company’s  
 switchgear was abused by unauthorised software, and was detected when the  
 buggers’ modiﬁcations caused some text messages not to be delivered [1550].  
 The phone company was ﬁned 76 million Euros (almost $100m). The clean way  
 to manage wiretaps nowadays with modern VOIP systems may just be to write  
 everything to disk and extract what you need later.

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*9.5. MAC: FROM MLS TO IFC AND INTEGRITY*

There are many military embedded systems too. In submarines, speed, reac-

tor output and RPM are all Top Secret, as a history of these three measurements  
 would reveal the vessel’s performance – and that’s among the few pieces of in-  
 formation that even the USA and the UK don’t share. The engineering is made  
 more complex by the need for the instruments not to be Top Secret when the  
 vessel is in port, as that would complicate maintenance. And as for air combat,  
 some US radars won’t display the velocity of a US aircraft whose performance  
 is classiﬁed, unless the operator has the appropriate clearance. When you read  
 stories about F-16 pilots seeing an insanely fast UFO whose speed on their radar  
 didn’t make any sense, you can put two and two together. It will be interesting  
 to see what sort of other side-e↵ects follow when powerful actors try to bake  
 MAC policies into IoT infrastructure, and what sort of superstitious beliefs they  
 give rise to.

**9.5** **MAC: from MLS to IFC and integrity**

In the ﬁrst edition of this book, I noted a trend to use mandatory access controls  
 to prevent tampering and provide real-time performance guarantees [1313, 1018],  
 and ventured that “perhaps the real future of multilevel systems is not in conﬁ-  
 dentiality, but integrity.” Government agencies had learned that MAC was what  
 it took to stop malware. By the second edition, multilevel integrity had hit the  
 mass market in Windows, which essentially uses the Biba model.

**9.5.1** **Windows**

In Windows, all processes do, and all securable objects (including directories,  
 ﬁles and registry keys) may, have an integrity-level label. File objects are la-  
 belled ’Medium’ by default, while Internet Explorer (and everything downloaded  
 using it) is labelled ’Low’. User action is therefore needed to upgrade down-  
 loaded content before it can modify existing ﬁles. It’s also possible to implement  
 a crude BLP policy using Windows, as you can also set ‘NoReadUp’ and ‘NoEx-  
 ecuteUp’ policies. These are not installed as default; Microsoft was concerned  
 about malware installing itself in the system and then hiding. Keeping the

browser ‘Low’ makes installation harder, and allowing all processes (even Low  
 ones) to inspect the rest of the system makes hiding harder. But this integrity-  
 only approach to MAC does mean that malware running at Low can steal all  
 your data; so some users might care to set ‘NoReadUp’ for sensitive directories.  
 This is all discussed by Joanna Rutkowska in [1634]; she also describes some  
 interesting potential attacks based on virtualization.

**9.5.2** **SELinux**

The case of SELinux is somewhat similar to Windows in that the immediate  
 goal of mandatory access control mechanisms was also to limit the e↵ects of a  
 compromise. SELinux [1187] was implemented by the NSA, based on the Flask  
 security architecture [1811], which separates the policy from the enforcement  
 mechanism; a security context contains all of the security attributes associated

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with a subject or object in Flask, where one of those attributes includes the  
 Type Enforcement type attribute. A security identiﬁer is a handle to a security  
 context, mapped by the security server. This is where policy decisions are made  
 and resides in the kernel for performance [819]. It has been mainstream since  
 Linux 2.6. The server provides a security API to the rest of the kernel, behind  
 which the security model is hidden. The server internally implements a general  
 constraints engine that can express RBAC, TE, and MLS. In typical Linux  
 distributions from the mid-2000s, it was used to separate various services, so  
 an attacker who takes over your web server does not thereby acquire your DNS  
 server as well. Its adoption by Android has made it part of the world’s most  
 popular operating system, as described in chapter 6.

**9.5.3** **Embedded systems**

There are many ﬁelded systems that implement some variant of the Biba model.  
 As well as the medical-device and railroad signalling applications I already men-  
 tioned, there are utilities. In an electricity utility, for example, there is typically  
 a hierarchy of safety systems, which operate completely independently at the  
 highest safety integrity level; these are visible to, but cannot be inﬂuenced by,  
 operational systems such as power dispatching; retail-level metering systems can  
 be observed by, but not inﬂuenced by, the billing system. Both retail meters  
 and the substation-level meters in the power-dispatching system feed informa-  
 tion into fraud detection, and ﬁnally there are the executive information sys-  
 tems, which can observe everything while having no direct e↵ect on operations.  
 In cars, most makes have separate CAN buses for the powertrain and for the  
 cabin, as you don’t want a malicious app on your radio to be able to operate  
 your brakes (though in 2010, security researchers found that the separation was  
 completely inadequate [1085]).

It’s also worth bearing in mind that simple integrity controls merely stop

malware taking over the machine – they don’t stop it infecting a Low compart-  
 ment and using that as a springboard from which to spread elsewhere, or to  
 issue instructions to other machines.

To sum up, many of the lessons learned in the early multilevel systems go

across to a number of applications of wider interest. So do a number of the  
 failure modes, which I’ll now discuss.

**9.6** **What Goes Wrong**

Engineers learn more from the systems that fail than from those that succeed,  
 and here MLS systems have been an e↵ective teacher. The billions of dollars  
 spent on building systems to follow a simple policy with a high level of assurance  
 have clariﬁed many second-order and third-order consequences of information  
 ﬂow controls. I’ll start with the more theoretical and work through to the

business and engineering end.

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**9.6.1** **Composability**

Consider a simple device that accepts two ‘High’ inputs *H*1 and *H*2; multiplexes  
 them; encrypts them by xor’ing them with a one-time pad (i.e., a random gen-  
 erator); outputs the other copy of the pad on *H*3; and outputs the ciphertext,  
 which being encrypted with a cipher system giving perfect secrecy, is considered  
 to be low (output *L*), as in Figure 9.4.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| RAND | *~~•~~* | - | XOR | -*H*3 |
| - *L* |
| - |
|  |  |  |  |  |

*H*2  
 *H*1 - XOR

*Figure 9.4 – insecure composition of secure systems with feedback*

In isolation, this device is provably secure. However, if feedback is permit-

ted, then the output from *H*3 can be fed back into *H*2, with the result that  
 the high input *H*1 now appears at the low output *L*. Timing inconsistencies  
 can also break the composition of two secure systems (noted by Daryl McCul-  
 lough [1260]).

In general, the *composition problem* – how to compose two or more secure

components into a secure system – is hard, even at the relatively uncluttered  
 level of proving results about ideal components [1430]. (Simple information ﬂow  
 doesn’t compose; neither does noninterference or nondeducibility.) Most of the  
 low-level problems arise when some sort of feedback is introduced; without it,  
 composition can be achieved under a number of formal models [1277]. However,  
 in real life, feedback is pervasive, and composition of security properties can  
 be made even harder by interface issues, feature interactions and so on. For  
 example, one system might produce data at such a rate as to perform a service-  
 denial attack on another. And the composition of secure components is often  
 frustrated by higher-level incompatibilities. Components might have been de-  
 signed in accordance with two di↵erent security policies, or designed according  
 to inconsistent requirements.

**9.6.2** **The cascade problem**

An example of the composition problem is given by the *cascade problem* (Fig-  
 ure 9.5). After the Orange book introduced a series of evaluation levels, this  
 led to span-limit rules about the number of levels at which a system can op-  
 erate [548]. For example, a system evaluated to B3 was in general allowed to

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process information at Unclassiﬁed, Conﬁdential and Secret, or at Conﬁdential,  
 Secret and Top Secret; there was no system permitted to process Unclassiﬁed  
 and Top Secret data simultaneously [548].

|  |
| --- |
| Top Secret  Secret Secret  Unclassified |

Figure 9.5: – the cascade problem

As the diagram shows, it is straightforward to connect together two B3

systems in such a way that this policy is broken. The ﬁrst system connects  
 together Unclassiﬁed and Secret, and its Secret level communicates with the  
 second system – which also processes Top Secret information [923]. This defeats  
 the span limit.

**9.6.3** **Covert channels**

One of the reasons why span limits are imposed on multilevel systems emerges  
 from a famous – and extensively studied – problem: the *covert channel*. First  
 pointed out by Lampson in 1973 [1125], a covert channel is a mechanism that  
 was not designed for communication but which can nonetheless be abused to  
 allow information to be communicated down from High to Low.

A typical covert channel arises when a high process can signal to a low one

by a↵ecting some shared resource. In a modern multicore CPU, it could increase  
 the clock frequency of the CPU core it’s using at time *ti* to signal that the *i*-th  
 bit in a Top Secret ﬁle was a 1, and let it scale back to signal that the bit was a 0.  
 This gives a covert channel capacity of several tens of bits per second [35]. Since  
 2018, CPU designers have been struggling with a series of cover channels that  
 exploit the CPU microarchitecture; with names like Meltdown, Spectre, and  
 Foreshadow, they have provided not just ways for High to signal to Low but for  
 Low to circumvent access control and read memory at High. I will discuss these  
 in detail in the chapter on side channels.

The best that developers have been able to do consistently with conﬁdential-

ity protection in regular operating systems is to limit it to 1 bit per second or  
 so. (That is a DoD target [545], and techniques for doing a systematic analysis  
 may be found in Kemmerer [1036].) One bit per second may be tolerable in  
 an environment where we wish to prevent large TS/SCI ﬁles – such as satellite

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photographs – leaking down from TS/SCI users to ‘Secret’ users. However, it’s  
 potentially a lethal threat to high-value cryptographic keys. This is one of the  
 reasons for the military and banking doctrine of doing crypto in special purpose  
 hardware.

The highest-bandwidth covert channel of which I’m aware occurs in large

early-warning radar systems, where High – the radar processor – controls hun-  
 dreds of antenna elements that illuminate Low – the target – with high speed  
 pulse trains, which are modulated with pseudorandom noise to make jamming  
 harder. In this case, the radar code must be trusted as the covert channel

bandwidth is many megabits per second.

**9.6.4** **The threat from malware**

The defense computer community was shocked when Fred Cohen wrote the ﬁrst  
 thesis on computer viruses, and used a virus to penetrate multilevel secure sys-  
 tems easily in 1983. In his ﬁrst experiment, a ﬁle virus that took only eight  
 hours to write managed to penetrate a system previously believed to be multi-  
 level secure [450]. People had been thinking about malware since the 1960s and  
 had done various things to mitigate it, but their focus had been on Trojans.

There are many ways in which malicious code can be used to break access

controls. If the reference monitor (or other TCB components) can be corrupted,  
 then malware can deliver the entire system to the attacker, for example by  
 issuing an unauthorised clearance. For this reason, slightly looser rules apply  
 to so-called *closed security environments* which are deﬁned to be those where  
 ‘system applications are adequately protected against the insertion of malicious  
 logic’ [548], and this in turn created an incentive for vendors to tamper-proof  
 the TCB, using techniques such as TPMs. But even if the TCB remains intact,  
 malware could still copy itself up from Low to High (which BLP doesn’t prevent)  
 and use a covert channel to signal information down.

**9.6.5** **Polyinstantiation**

Another problem that exercised the research community is *polyinstantiation*.  
 Suppose our High user has created a ﬁle named agents, and our Low user now  
 tries to do the same. If the MLS operating system prohibits him, it will have  
 leaked information – namely that there is a ﬁle called agents at High. But if it  
 lets him, it will now have two ﬁles with the same name.

Often we can solve the problem by a naming convention, such as giving Low

and High users di↵erent directories. But the problem remains a hard one for  
 databases [1649]. Suppose that a High user allocates a classiﬁed cargo to a ship.  
 The system will not divulge this information to a Low user, who might think  
 the ship is empty, and try to allocate it another cargo or even to change its  
 destination.

Here the US and UK practices diverge. The solution favoured in the USA

is that the High user allocates a Low cover story at the same time as the real  
 High cargo. Thus the underlying data will look something like Figure 9.6.

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|  |  |  |
| --- | --- | --- |
| Level | Cargo | Destination |

|  |  |  |
| --- | --- | --- |
| Secret | Missiles | Iran |
| Restricted | – | – |
| Unclassiﬁed | Engine spares | Cyprus |

*Figure 9.6 – how the USA deals with classiﬁed data*

In the UK, the theory is simpler – the system will automatically reply ‘clas-

siﬁed’ to a Low user who tries to see or alter a High record. The two available  
 views would be as in Figure 9.7.

|  |  |  |
| --- | --- | --- |
| Level | Cargo | Destination |

|  |  |  |
| --- | --- | --- |
| Secret | Missiles | Iran |
| Restricted | Classiﬁed | Classiﬁed |
| Unclassiﬁed | – | – |

*Figure 9.7 – how the UK deals with classiﬁed data*

This makes the system engineering simpler. It also prevents the mistakes

and covert channels that can still arise with cover stories (e.g., a Low user tries  
 to add a container of ammunition for Cyprus). The drawback is that everyone  
 tends to need the highest available clearance in order to get their work done.  
 (In practice, cover stories still get used in order not to advertise the existence  
 of a covert mission any more than need be.)

**9.6.6** **Practical problems with MLS**

Multilevel secure systems are surprisingly expensive and di�cult to build and  
 deploy. There are many sources of cost and confusion.

1. They are built in small volumes, and often to high standards of physi-

cal robustness, using elaborate documentation, testing and other quality  
 control measures driven by military purchasing bureaucracies.

2. MLS systems have idiosyncratic administration tools and procedures. A

trained Unix administrator can’t just take on an MLS installation without  
 signiﬁcant further training; so many MLS systems are installed without  
 their features being used.

3. Many applications need to be rewritten or at least greatly modiﬁed to run

under MLS operating systems [1629].

4. Because processes are automatically upgraded as they see new labels, the

ﬁles they use have to be too. New ﬁles default to the highest label belong-  
 ing to any possible input. The result of all this is a chronic tendency for  
 things to be overclassiﬁed. There’s a particular problem when system com-  
 ponents accumulate all the labels they’ve seen, leading to *label explosion*

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where they acquire such a collection that no single principal can access  
 them any more. So they get put in the trusted computing base, which  
 ends up containing a quite uncomfortably large part of the operating sys-  
 tem (plus utilities, plus windowing system software, plus middleware such  
 as database software). This ‘TCB bloat’ constantly pushes up the cost of  
 evaluation and reduces assurance.

5. The classiﬁcation of data can get complex:

*•* in the run-up to a conﬂict, the location of ‘innocuous’ stores such  
 graded;

*•* classiﬁcations are not always monotone. Equipment classiﬁed at ‘con-  
 ﬂip side it’s hard to grant access at ‘secret’ to secret information in  
 a ‘top secret’ database;

*•* information may need to be downgraded. An intelligence analyst  
 might need to take a satellite photo classiﬁed at TS/SCI, and paste  
 it into an assessment for ﬁeld commanders at ‘secret‘. In case infor-  
 mation was covertly hidden in the image by a virus, this may involve  
 special ﬁlters, lossy compression of images and so on. One option is  
 a ‘print-and-fax’ mechanism that turns a document into a bitmap,  
 and logs it for traceability.

*•* we may need to worry about the volume of information available  
 single satellite photo, but declassifying the whole collection would  
 reveal our surveillance capability and the history of our intelligence  
 priorities. (I will look at this *aggregation problem* in more detail in  
 section 11.2.)

*•* Similarly, the output of an unclassiﬁed program acting on unclas-  
 techniques applied to an online forum throw up a list of terror sus-  
 pects.

6. Although MLS systems can prevent undesired things (such as information

leakage), they also prevent desired things too (such as building a search  
 engine to operate across all an agency’s Top Secret compartmented data).  
 So even in military environments, the beneﬁts can be questionable. After  
 9/11, many of the rules were relaxed, and access controls above Top Secret  
 are typically discretionary, to allow information sharing. The cost of that,  
 of course, was the Snowden disclosures.

7. Finally, obsessive government secrecy is a chronic burden. The late Sen-

ator Daniel Moynihan wrote a critical study of its real purposes, and its  
 huge costs in US foreign and military a↵airs [1346]. For example, Presi-  
 dent Truman was never told of the Venona decrypts because the material  
 was considered ‘Army Property’. As he put it: “Departments and agen-  
 cies hoard information, and the government becomes a kind of market.  
 Secrets become organizational assets, never to be shared save in exchange  
 for another organization’s assets.”

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More recent examples of MLS doctrine impairing operational e↵ectiveness  
 include the use of unencrypted communications to drones in the Afghan  
 war (as the armed forces feared that if they got the NSA bureaucracy  
 involved, the drones would be unusable), and the use of the notoriously  
 insecure Zoom videoconferencing system for British government cabinet  
 meetings during the coronavirus crisis (the government’s encrypted video-  
 conferencing terminals are classiﬁed, so ministers aren’t allowed to take  
 them home). This brings to mind a quip from an exasperated British

general: “What’s the di↵erence between Jurassic Park and the Ministry of  
 Defence? One’s a theme park full of dinosaurs, and the other’s a movie!”

There has been no shortage of internal strategic critique. A 2004 report by

Mitre’s JASON programme of the US system of classiﬁcation concluded that it  
 was no longer ﬁt for purpose [978]. There are many interesting reasons, including  
 the widely di↵erent risk/beneﬁt calculations of the producer and consumer com-  
 munities; classiﬁcation comes to be dominated by distribution channels rather  
 than by actual risk. The relative ease of attack has led government systems to be  
 too conservative and risk-averse. It noted many perverse outcomes; for example,  
 Predator imagery in Iraq is Unclassiﬁed, and was for some time transmitted in  
 clear, as the Army feared that crypto would involve the NSA bureaucracy in  
 key management and inhibit warﬁghting.

Mitre proposed instead that ﬂexible compartments be set up for speciﬁc

purposes, particularly when getting perishable information to tactical compart-  
 ments; that intelligent use be made of technologies such as rights management  
 and virtualisation; and that lifetime trust in cleared individuals be replaced with  
 a system focused on transaction risk.

Anyway, one of the big changes since the second edition of this book is that

the huge DoD research programme on MLS has disappeared, MLS equipment  
 is no longer very actively promoted on the government-systems market, and  
 systems have remained fairly static for a decade. Most government systems

now operate system high – that is, entirely at O�cial, or at Secret, or at Top  
 Secret. The di�culties discussed in the above section, plus the falling cost of  
 hardware and the arrival of virtualisation, have undermined the incentive to  
 have di↵erent levels on the same machine. The deployed MLS systems thus  
 tend to be ﬁrewalls or mail guards between the di↵erent levels, and are often  
 referred to by a new acronym, MILS (for multiple independent levels of secu-  
 rity). The real separation is at the network level, between unclassiﬁed networks,  
 the Secret Internet Protocol Router Network (SIPRNet) which handles secret  
 data using essentially standard equipment behind crypto, and the Joint World-  
 wide Intelligence Communications System (JWICS) which handles Top Secret  
 material and whose systems are kept in Secure Compartmentalized Information  
 Facilities (SCIFs) – rooms shielded to prevent electronic eavesdropping, which  
 I’ll discuss later in the chapter on side channels.

There are occasional horrible workarounds such as ‘browse-down’ systems

that will let someone at High view a website at Low; they’re allowed to click on  
 buttons and links to navigate, just not to enter any text. Such ugly hacks have  
 clear potential for abuse; at best they can help keep honest people from careless  
 mistakes.

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**9.7** **Summary**

Mandatory access control was initially developed for military applications, where  
 it is still used in specialized ﬁrewalls (guards and data diodes). The main use of  
 MAC mechanisms nowadays, however, is in platforms such as Android, iOS and  
 Windows, where they protect the operating systems themselves from malware.  
 MAC mechanisms have been a major subject of computer security research since  
 the mid-1970’s, and the lessons learned in trying to use them for military mul-  
 tilevel security underlie many of the schemes used for security evaluation. It  
 is important for the practitioner to understand both their strengths and limi-  
 tations, so that you can draw on the research literature when it’s appropriate,  
 and avoid being dragged into overdesign when it’s not.

There are many problems which we need to be a ‘fox’ rather than a ‘hedge-

hog’ to solve. By trying to cast all security problems as hedgehog problems,  
 MLS often leads to inappropriate security goals, policies and mechanisms.

**Research Problems**

A standing challenge, sketched out by Earl Boebert in 2001 after the NSA  
 launched SELinux, is to adapt mandatory access control mechanisms to safety-  
 critical systems (see the quote at the head of this chapter, and [270]). As a tool  
 for building high-assurance, special-purpose devices where the consequences of  
 errors and failures can be limited, mechanisms such as type enforcement and  
 role-based access control should be useful outside the world of security. Will  
 we see them widely used in the Internet of Things? We’ve mentioned Biba-  
 type mechanisms in applications such as cars and electricity distribution; will  
 the MAC mechanisms in products such as SELinux, Windows and Android  
 enable designers to lock down information ﬂows and reduce the likelihood of  
 unanticipated interactions?

The NSA continues to fund research on MLS, now under the label of IFC,

albeit at a lower level than in the past. Doing it properly in a modern smart-  
 phone is hard; for an example of such work, see the Weir system by Adwait  
 Nadkarni and colleagues [1372]. In addition to the greater intrinsic complexity  
 of modern operating systems, phones have a plethora of side-channels and their  
 apps are often useful only in communication with cloud services, where the real  
 heavy lifting has to be done. The commercial o↵ering for separate ‘low’ and  
 ‘high’ phones consists of products such as Samsung’s Knox.

A separate set of research issues surround actual military opsec, where reality

falls far short of policy. All armed forces involved in recent conﬂicts, including  
 US and UK forces in Iraq and Afghanistan, have had security issues around their  
 personal mobile phones, with insurgents in some cases tracing their families back  
 home and harassing them with threats. The Royal Navy tried to ban phones in  
 2009, but too many sailors left. Tracking ships via Instagram is easy; a warship  
 consists of a few hundred young men and women, aged 18-24, with nothing much  
 else to do but put snaps on social media. Discipline tends to focus on immediate  
 operational threats, such as when a sailor is seen snapchatting on mine disposal:  
 there the issue is the risk of using a radio near a mine! Di↵erent navies have

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tried di↵erent things: the Norwegians have their own special network for sailors  
 and the USA is trying phones with MLS features. But NATO exercises have  
 shown that for one navy to hack another’s navigation is shockingly easy. And  
 even the Israelis have had issues with their soldiers using mobiles on the West  
 Bank and the Golan Heights.

**Further Reading**

The unclassiﬁed manuals for the UK government’s system of information clas-  
 siﬁcation, and the physical, logical and other protection mechanisms required  
 at the di↵erent levels, have been available publicly since 2013, with the latest  
 documents (at the time of writing) having been released in November 2018 on  
 the Government Security web page [802]. The report on the Walker spy ring is a  
 detailed account of a spectacular failure, and brings home the sheer complexity  
 of running a system in which maybe three million people have a clearance at  
 any one time, with a million applications being processed each year [876]. And  
 the classic on the abuse of the classiﬁcation process to cover up waste, fraud  
 and mismanagement in the public sector is by Chapman [407].

On the technical side, textbooks such as Dieter Gollmann’s *Computer Se-*

*curity* [779] give an introduction to MLS systems, while many of the published  
 papers on actual MLS systems can be found in the proceedings of two confer-  
 ences: academics’ conference is the *IEEE Symposium on Security & Privacy*  
 (known in the trade as ‘Oakland’ as that’s where it used to be held), while the  
 NSA supplier community’s unclassiﬁed bash is the *Computer Security Appli-*  
 *cations Conference* (ACSAC) whose proceedings are (like Oakland’s) published  
 by the IEEE. Fred Cohen’s experiments on breaking MLS systems using viruses  
 are described in his book, *‘A Short Course on Computer Viruses’* [450]. Many  
 of the classic early papers in the ﬁeld can be found at the NIST archive [1395];  
 NIST ran a conference series on multilevel security up till 1999. Finally, a his-  
 tory of the Orange Book was written by Steve Lipner [1171]; this also tells the  
 story of the USAF’s early involvement and what was learned from systems like  
 WWMCCS.

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