**Chapter 15**

**Nuclear Command and**  
 **Control**

**In Germany and Turkey they viewed scenes that were particularly**

**distressing. On the runway stood a German (or Turkish)**

**quick-reaction alert airplane loaded with nuclear weapons and with**  
 **a foreign pilot in the cockpit. The airplane was ready to take off at**

**the earliest warning, and the nuclear weapons were fully**

**operational. The only evidence of U.S. control was a lonely**

**18-year-old sentry armed with a carbine and standing on the**

**tarmac. When the sentry at the German airﬁeld was asked how he**

**intended to maintain control of the nuclear weapons should the pilot**

**suddenly decide to scramble (either through personal caprice or**

**through an order from the German command circumventing U.S.**

**command), the sentry replied that he would shoot the pilot; Agnew**

**directed him to shoot the bomb.**

– Jerome Wiesner, reporting to President Kennedy on nuclear arms command

and control after the Cuban crisis

**15.1** **Introduction**

The catastrophic harm that could result from the unauthorized use of a nuclear  
 weapon, or from the proliferation of nuclear technology, has led the US and  
 other nuclear powers to spend colossal amounts of money protecting not just  
 nuclear warheads but also the supporting infrastructure, industry and materials.  
 Nuclear arms control is at the heart of international diplomacy: while North  
 Korea now has the bomb, South Africa and Libya were persuaded to give it up,  
 Iran’s program has been stopped (by both diplomatic and cyber means) while  
 Iraq and Syria have had their WMD programs terminated by force.

A surprising amount of nuclear security know-how has been published. In

fact, there are limits on how much could be kept secret even if this was thought  
 desirable. Many countries are capable of producing nuclear weapons but have

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decided not to (Japan, Australia, Switzerland, ...) so maintain controls on

nuclear materials in a civilian context. Much of the real force of nonproliferation  
 is cultural, built over the years through diplomacy and through the restraint  
 of nuclear powers who since 1945 forebore use of these weapons even when  
 facing defeat at the hands of non-nuclear states. This is backed by international  
 agreements, such as the Nonproliferation Treaty and the Convention on the  
 Physical Protection of Nuclear Material [949], enforced by the International  
 Atomic Energy Agency (IAEA).

About ten tons of plutonium are produced by civil reactors each year, and

if the human race is to rely on nuclear power long-term then we’ll be burning it  
 in reactors as well as just making it as a side-effect of burning uranium. So we  
 have to guard the stuff, in ways that inspire international conﬁdence – not just  
 between governments but from an increasingly sceptical public1.

A vast range of security technology has spun off from the nuclear program.

The US Department of Energy weapons laboratories – Sandia, Lawrence Liv-  
 ermore and Los Alamos – have worked for two generations to make nuclear  
 weapons and materials as safe as can be achieved. I’ve already mentioned some  
 of their more pedestrian spin-offs, from the discovery that passwords of more  
 than twelve digits were not usable under battleﬁeld conditions to high-end bur-  
 glar alarm systems. The trick of wrapping an optical ﬁber round the devices to  
 be protected and using interference effects to detect a change in length of less  
 than a micron, is also one of theirs – it was designed to loop round the warheads  
 in an armoury and alarm without fail if any of them are moved.

In later chapters, we’ll see still more technology of nuclear origin. For ex-

ample, iris recognition – the most accurate system known for biometric identi-  
 ﬁcation of individuals, and now used in India’s Aadhar identity system – was  
 developed using US Department of Energy funds to control entry to the pluto-  
 nium store, and much of the expertise in tamper-resistance and tamper-sensing  
 technology originally evolved to prevent the abuse of stolen weapons or control  
 devices. After 9/11, the US and its allies took many aggressive steps to control  
 nuclear proliferation including:

1. the invasion of Iraq in March 2003, for which the casus belli was a claim

that Iraq possessed weapons of mass destruction;

2. an agreement by Libya in December 2003 to abandon an undeclared weapons

program;

3. the disclosure in 2004 that Abdul Qadeer Khan, a senior scientist with

Pakistan’s nuclear program, had helped a number of other countries in-  
 cluding Syria, Libya, Iran and North Korea get hold of weapons technol-  
 ogy, and the dismantling of his network;

4. the Israeli operation ’Outside the Box’ where a suspected Syrian reactor

near Deir-ez-Zor was bombed on September 6th, 2007;

1For example, the British government was seriously embarrassed in 2007 when the safety

of its plutonium stockpile was criticised by eminent scientists [1626], and again in 2018 when  
 parliament’s public accounts committee criticised the weapons program’s crumbling facilities,  
 aging workforce, specialist staff shortages and endemic funding and practical problems [1560].

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5. the 2015 Joint Comprehensive Plan of Action whereby Iran agreed with

the USA, the UK, Russia, China, France, Germany and the EU to halt its  
 weapons program.

Not all of the efforts were successful, the obvious case in point being North

Korea, which had signed a treaty with the USA in 1994 to halt weapons develop-  
 ment in return for oil shipments and help developing civil nuclear energy. This  
 collapsed in 2003, after which Pyongyang withdrew from the Non-Proliferation  
 Treaty and developed weapons. This history makes many people apprehensive of  
 the possible long-term effects of the Trump administration’s 2018 abandonment  
 of the agreement with Iran (even though Iran was abiding by it). And then  
 there’s also its 2019 abandonment of the Intermediate-Range Nuclear Forces  
 Treaty with the Russia (even though that was the result of Russian cheating);  
 and the fact that the New START treaty, signed in 2010 by Barack Obama, will  
 run out in February 2021, unless America elects a president in November 2020  
 who agrees to renew it.

Nuclear controls apply to more than just warheads and the ﬁssile materials

required for their construction. Following 9/11, we learned that Al-Qaida had  
 talked about a ‘dirty bomb’ – a device that would disperse radioactive material  
 over a city block – which might not kill anyone but could lead to panic, and  
 in a ﬁnancial center could cause great economic damage. So in 2007, GAO

investigators set up a bogus company and got a license from the Nuclear Reg-  
 ulatory Commission authorizing them to buy isotopes. The license was printed  
 on ordinary paper; the investigators altered it to change the quantity of mate-  
 rial they were allowed to buy, then used it to order dozens of moisture density  
 gauges containing americium-241 and cesium-137, which could have been used  
 in a dirty bomb [1112]. Thanks to the fear of terrorism, the control of nuclear  
 materials has tightened and spread more widely in the economy.

Nuclear safety continually teaches us lessons about the limits of assurance.

For example, it’s tempting to assume that if a certain action that you don’t  
 want to happen has a probability of 1 in 10 of happening through human error,  
 then by getting ﬁve different people to check, you can reduce the probability to  
 1 in 100,000. The US Air Force thought so too. Yet in October 2007, six US  
 hydrogen bombs went missing for 36 hours after a plane taking cruise missiles  
 from Minot Air Force Base in North Dakota to Barksdale in Louisiana was  
 mistakenly loaded with six missiles armed with live warheads. All the missiles  
 were supposed to be inspected by handlers in the storage area and checked  
 against a schedule (which was out of date), by ground crew waiting for the  
 inspection to ﬁnish before moving any missiles, (they didn’t), by ground crew  
 inspecting the missiles (they didn’t look in the glass portholes to see whether  
 the warheads were real or dummy), by the driver calling in the identiﬁcation  
 numbers to a control centre (nobody there bothered to check), and ﬁnally by  
 the navigator during his preﬂight check (he didn’t look at the wing with the live  
 missiles). The plane took off, ﬂew to Louisiana, landed, and sat unguarded on  
 the runway for nine hours before the ground crew arrived to unload the missiles  
 and discovered they were live [187, 549]. This illustrates one of the limits to  
 shared control. People will rely on others and slack off – a lesson also known in  
 the world of medical safety. Indeed, in the USAF case it turned out that the  
 airmen had replaced the official procedures with an ‘informal’ schedule of their

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own. So how can you design systems that don’t fail in this way?

In this chapter I describe the nuclear safety environment and some of the

tricks that might ﬁnd applications (or pose threats) elsewhere. It has been

assembled from public sources – but even so there are useful lessons to be drawn.

**15.2** **The Evolution of Command and Control**

The ﬁrst atomic bomb to be used in combat was the ‘Little Boy’ dropped on  
 Hiroshima. Its safety was somewhat improvised. It came with three detonators,  
 and the weapon officer was supposed to replace green dummy ones with red  
 live ones once the plane was airborne. However, a number of heavily loaded  
 B-29s had crashed on takeoff from Tinian, the base they used. The Enola Gay  
 weapon officer, Navy Captain Deak Parsons, reckoned that if the plane crashed,  
 the primer might explode, detonating the bomb and wiping out the island. So  
 he spent the day before the raid practising removing and reinstalling the primer  
 – a gunpowder charge about the size of a loaf of bread – so he could install it  
 after takeoff instead.

Doctrine has rather moved away from improvisation, and if anything we’re

at the other extreme now, with mechanisms and procedures tested and drilled  
 and exercised and analysed by multiple experts from different agencies. It has  
 been an evolutionary process. When weapons started being carried in single-  
 seat tactical aircraft in the 1950s, and being slung under the wings rather than  
 in a bomb bay, it was no longer possible to insert a bag of gunpowder manually.  
 There was a move to combination locks: the pilot would arm the bomb after  
 takeoff by entering a 6-digit code into a special keypad with a wired-seal lid. This  
 enabled some central control; the pilot might only get the code once airborne.  
 But both the technical and procedural controls in the 1950s were primitive.

**15.2.1** **The Kennedy Memorandum**

The Cuban missile crisis changed all that. The Soviet B-59 was a Foxtrot-

class diesel-electric submarine which came under attack on 27th October 1962  
 when a US battle group consisting of the aircraft carrier USS Randolph and 11  
 destroyers started dropping depth charges nearby. These were practice rounds,  
 dropped in an attempt to force the submarine to the surface for identiﬁcation;  
 but the ship’s captain, Valentin Savitsky, thought he was under attack, that war  
 had started, and so he should ﬁre a nuclear torpedo to destroy the carrier. But  
 this could only be done if the three senior officers on board agreed, and luckily  
 one of them, Vasily Arkhipov, refused. Eventually the submarine surfaced and  
 returned to Russia.

This made the risk that a world war might start by accident salient to US

policymakers, and President Kennedy ordered his science adviser Jerome Wies-  
 ner to investigate. He reported that hundreds of US nuclear weapons were kept  
 in allied countries such as Greece and Turkey, which were not particularly sta-  
 ble and occasionally fought with each other. These weapons were protected by  
 token US custodial forces, so there was no physical reason why the weapons

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couldn’t be seized in time of crisis. There was also some worry about unautho-  
 rized use of nuclear weapons by US officers – for example, if a local commander  
 under pressure felt that ‘if only they knew in Washington how bad things were  
 here, they would let us use the bomb.’ In [1825] we ﬁnd the passage quoted at  
 the head of this chapter.

Kennedy’s response was National Security Action Memo no. 160 [217]. This

ordered that America’s 7,000 nuclear weapons then dispersed to NATO com-  
 mands should be got under positive US control using technical means, whether  
 they were in the custody of US or allied forces. Although this policy was sold to  
 Congress as protecting US nuclear weapons from foreigners, the worries about  
 a crazy ‘Dr Strangelove’ (or a real-life Captain Savitsky) were actually at the  
 top of Wiesner’s list.

The Department of Energy was already working on weapon safety devices.

The basic principle was that a unique aspect of the environment had to be sensed  
 before the weapon would arm. For example, missile warheads and some free-fall  
 bombs had to experience zero gravity, while artillery shells had to experience  
 an acceleration of thousands of G. There was one exception: atomic demolition  
 munitions. These are designed to be taken to their targets by ground troops  
 and detonated using time fuses. There appears to be no scope for a unique  
 environmental sensor to prevent accidental or malicious detonation.

The solution then under development was a secret arming code that activated

a solenoid safe lock buried deep in the plutonium pit at the heart of the weapon.  
 The main engineering problem was maintenance. When the lock was exposed,  
 for example to replace the power supply, the code might become known. So it  
 was not acceptable to have the same code in every weapon. Group codes were  
 one possibility – ﬁring codes shared by only a small batch of warheads.

Following the Kennedy memo, it was proposed that all nuclear bombs should

be protected using code locks, and that there should be a ‘universal unlock’  
 action message that only the president or his legal successors could give. The  
 problem was to ﬁnd a way to translate this code securely to a large number  
 of individual ﬁring codes, each of which enabled a small batch of weapons.  
 The problem became worse in the 1960s and 1970s when the doctrine changed  
 from massive retaliation to ‘measured response’. Instead of arming all nuclear  
 weapons or none, the President now needed to be able to arm selected batches  
 (such as ‘all nuclear artillery in Germany’). This starts to lead us to a system  
 of some complexity, especially when we realise we need disarming codes too,  
 for maintenance purposes, and some means of navigating the trade-offs between  
 weapons safety and effective command.

**15.2.2** **Authorization, environment, intent**

The deep question was the security policy that nuclear safety systems, and com-  
 mand systems, should enforce. What emerged in the USA was the rule of ‘au-  
 thorization, environment, intent’. For a warhead to detonate, three conditions  
 must be met.

**Authorization:** the use of the weapon in question must have been authorized

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by the *national command authority* (i.e., the President and his lawful  
 successors in office).

**Environment:** the weapon must have sensed the appropriate aspect of the

environment. (With atomic demolition munitions, this requirement is re-  
 placed by the use of a special container.)

**Intent:** the officer commanding the aircraft, ship or other unit must unambigu-

ously command the weapon’s use.

In early systems, ‘authorization’ meant the entry into the device of a four-

digit authorization code.

The means of signalling ‘intent’ depended on the platform. Aircraft typically

use a six-digit arming or ‘use control’ code. The command consoles for inter-  
 continental ballistic missiles are operated by two officers, each of whom must  
 enter and turn a key to launch the rocket. Whatever the implementation, there  
 must be a unique signal; 22 bits derived from a six-digit code are believed to be  
 a good tradeoff between a number of factors from usability to minimising the  
 risk of accidental arming [1349].

**15.3** **Unconditionally Secure Authentication**

Nuclear command and control drove the development of a theory of one-time  
 authentication codes. As I described in Chapter 5, “Cryptography”, these are  
 similar in concept to the test keys invented to protect telegraphic money trans-  
 fers, in that a keyed transformation is applied to the message in order to yield  
 a short authentication code, also known as an *authenticator* or *tag*. As the keys  
 are only used once, authentication codes can be made unconditionally secure,  
 in that the protection they give is independent of the computational resources  
 available to the attacker. So they do for authentication what the one-time pad  
 does for conﬁdentiality.

Recall that we still have to choose the code length to bound the probability

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| of a successful guess; this might be di↵erent depending on whether the opponent  was trying to guess a valid message from scratch (*impersonation*) or modify an  existing valid message so as to get another one (*substitution*). In the GCM mode  of operation discussed in Chapter 5, these are set equal at 2128 but this need  not be the case. |

An example should make this clear. Suppose a commander has agreed an

authentication scheme with a subordinate under which an instruction is to be  
 encoded as a three digit number from 000 to 999. The instruction may have  
 two values: ‘Attack Russia’ and ‘Attack China’. One of these will be encoded  
 as an even number, and the other by an odd number: which is which will be  
 part of the secret key. The authenticity of the message will be vouched for by  
 making its remainder, when divided by 337, equal to a secret number which is  
 the second part of the key.

Suppose the key is that:

*•* ‘Attack Russia’ codes to even numbers, and ‘Attack China’ to odd

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*•* an authentic message has the remainder 12 when divided by 337.

So ‘Attack Russia’ is ‘686’ (or ‘12’) and ‘Attack China’ is ‘349’.

An enemy who has taken over the communications channel between the

commander and the subordinate, and who knows the scheme but not the key,  
 has a probability of only 1 in 337 of successfully impersonating the commander.  
 However, once he sees a valid message (say ‘12’ for ‘Attack Russia’), then he  
 can easily change it to the other by adding 337, and so (provided he understood  
 the commander’s intent) he can send the missiles to the other country. So the  
 probability of a successful substitution attack in this case is 1.

As with computationally secure authentication, the unconditional variety

can provide message secrecy or not: it might work like a block cipher, or like a  
 MAC on a plaintext message. Similarly, it can use an arbitrator or not. One  
 might even want multiple arbitrators, so that they don’t have to be trusted indi-  
 vidually. Schemes may also combine unconditional and computational security.  
 For example, an unconditional code without secrecy could have computationally  
 secure secrecy added by simply enciphering the message and the authenticator  
 using a conventional cipher system.

Authentication is in some sense the dual of coding in that in the latter,

given an incorrect message, we want to ﬁnd the nearest correct one efficiently;  
 in the former, we want ﬁnding a correct message to be impossible unless you’ve  
 seen it already or are authorized to construct it. And just as the designer of an  
 error-correcting code wants the shortest length of code for a given error recovery  
 capability, so the designer of an authentication code wants to minimize the key  
 length required to achieve a given bound on the deception probabilities.

Quite a few details have to be ﬁxed before you have a fully-functioning com-

mand and control system. You have to work out ways to build the key control  
 mechanisms into warheads in ways that will resist disarming or dismantling by  
 people without disarming keys. You need mechanisms for generating keys and  
 embedding them in weapons and control devices. You have to think of all the  
 ways an attacker might social-engineer maintenance staff, and what you’ll do  
 to forestall this. And there is one element of cryptographic complexity. How  
 do you introduce an element of one-wayness, so that a maintenance man who  
 disarms a bomb to change the battery doesn’t end up knowing the universal  
 unlock code? You may need to be able to derive the code to unlock this one  
 speciﬁc device from the universal unlock, but not vice-versa. What’s more, you  
 need serviceable mechanisms for recovery and re-keying in the event that a crisis  
 causes you to authorize some weapons, that thankfully are stood down rather  
 than used. US systems now use public-key cryptography to implement this one-  
 wayness, but you could also use one-way functions. In either case, you will end  
 up with an interesting mix of unconditional and computational security.

One interesting spin-off from authentication research was the GCM mode of

operation for block ciphers, described in the chapter on ‘Cryptography’, which  
 has become the most common mode of operation in modern ciphersuites.

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*15.4. SHARED CONTROL SCHEMES*

**15.4** **Shared Control Schemes**

The nuclear command and control business became even more complex with the  
 concern, from the late 1970s, that a Soviet decapitation strike against the US  
 national command authority might leave the arsenal intact but useless. There  
 was also concern that past a certain threshold of readiness, it wasn’t sensible  
 to assume that communications between the authority and ﬁeld commanders  
 could be maintained, because of the likely damage from electromagnetic pulses  
 (and other possible attacks on communications).

The solution was found in another branch of cryptomathematics known as

*secret sharing*, whose development it helped to inspire. The idea is that in

time of tension a backup control system will be activated in which combinations  
 of office holders or ﬁeld commanders can jointly allow a weapon to be armed.  
 Otherwise the problems of maintaining detailed central control of a large num-  
 ber of weapons would likely become insoluble. A particular case of this is in  
 submarine-launched ballistic missiles. These exist to provide a second-strike ca-  
 pability – to take vengeance on a country that has destroyed your country with  
 a ﬁrst strike. The UK government was concerned that, under the US doctrine,  
 it is possible for the submarine commander to be left unable to arm his weapons  
 if the USA is destroyed, and the President and his lawful successors in office are  
 killed. So the British approach is for arming material to be kept in safes under  
 the control of the boat’s officers, along with a letter from the Prime Minister on  
 the circumstances in which weapons are to be used. If the officers agree, then  
 the missiles can be ﬁred.

How can this be generalised? Well, you might just give half of the authen-

tication key to each of two people, but then you need twice the length of key,  
 assuming that the original security parameter must apply even if one of them is  
 suborned. An alternative approach is to give each of them a number and have  
 the two of them add up to the key. This is how keys for automatic teller ma-  
 chines are managed2. But this may not be enough in command applications, as  
 one cannot be sure that the people operating the equipment will consent, with-  
 out discussion or query, to unleash Armageddon. So a more general approach  
 was invented independently by Blakley and Shamir in 1979 [256, 1703]. Their  
 basic idea is illustrated in the following diagram (Figure 15.1).

Suppose the rule Britain wants to enforce is that if the Prime Minister is

assassinated then a weapon can be armed either by any two cabinet ministers, or  
 by any three generals, or by a cabinet minister and two generals. To implement  
 this, let the point *C* on the *z* axis be the unlock code that has to be supplied to  
 the weapon. We now draw a line at random through *C* and give each cabinet  
 minister a random point on the line. Now any two of them together can work  
 out the coordinates of the line and ﬁnd the point *C* where it meets the *z* axis.  
 Similarly, we embed the line in a random plane and give each general a random  
 point on the plane. Now any three generals, or two generals plus a minister, can  
 reconstruct the plane and thence the ﬁring code *C*.

By generalizing this simple construction to geometries of *n* dimensions, or to

2Combining keys using addition or exclusive-or turns out to be a bad idea for ATMs as

it opens up the system to attacks that I’ll discuss later under the rubric of ‘API security’.  
 However in the context of unconditionally-secure authentication codes, addition may be OK.

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Figure 15.1: – Shared control using geometry

general algebraic structures rather than lines and planes, this technique enables  
 weapons, commanders and options to be linked together with a complexity  
 limited only by the available bandwidth. An introduction to secret sharing

can be found in [1829] and a more detailed exposition in [1750]. This inspired  
 the development of threshold signature schemes, as described in Chapter 5,  
 ‘Cryptography’, and can be used in products that enforce a rule such as ‘Any  
 two vice-presidents of the exchange may activate a cold bitcoin wallet’.

In the typical military application, two-out-of-*n* control is used; *n* must be

large enough that at least two of the keyholders will be ready and able to do  
 the job, despite combat losses. Many details need attention. For example, the  
 death of a commander shouldn’t give his deputy both halves of the key, and  
 there are all sorts of nitty-gritty issues such as who shoots whom when (on the  
 same side). Banking is much the same; it may take two officers to release a large  
 payment, and you need to take care that delegation rules don’t allow both keys  
 to fall into the one pair of hands.

In some civilian applications, a number of insiders may conspire to break your

system. The classic example is pay-TV where a pirate may buy several dozen  
 subscriber cards and reverse engineer them for their secrets. So the pay-TV  
 operator wants a system that’s robust against multiple compromised subscribers.  
 I’ll talk about this *traitor tracing* problem more in the chapter on copyright.

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*15.5. TAMPER RESISTANCE AND PALS*

**15.5** **Tamper Resistance and PALs**

In modern weapons the solenoid safe locks have been superseded by *permissive*  
 *action links* (PALs), which are used to protect most US nuclear devices. A

summary of the published information about PALs can be found in [217]. PAL  
 development started in about 1961, but deployment was slow. Even twenty years  
 later, about half the US nuclear warheads in Europe still used four-digit code  
 locks 3. As more complex arming options were introduced, the codes increased  
 in length from 4 to 6 and ﬁnally to 12 digits. Devices started to have multiple  
 codes, with separate ‘enable’ and ‘authorize’ commands and also the ability to  
 change codes in the ﬁeld (to recover from false alarms).

The PAL system is supplemented by various coded switch systems and op-

erational procedures, and in the case of weapons such as atomic demolition  
 munitions, which are not big and complex enough for the PAL to be made inac-  
 cessible, the weapon is also stored in tamper sensing containers called PAPS (for  
 *prescribed action protective system*). Other mechanisms used to prevent acciden-  
 tal detonation include the deliberate weakening of critical parts of the detonator  
 system, so that they will fail if exposed to certain abnormal environments.

Whatever combination of systems is used, there are penalty mechanisms

to deny a thief the ability to obtain a nuclear yield from a stolen weapon.  
 These mechanisms vary from one weapon type to another but include gas bottles  
 to deform the pit and hydride the plutonium in it, shaped charges to destroy  
 components such as neutron generators and the tritium boost, and asymmetric  
 detonation that results in plutonium dispersal rather than yield. This self-

destruct procedure will render them permanently inoperative, without yield, if  
 enemy capture is threatened. It is always a priority to destroy the code. It is  
 assumed that a renegade government prepared to deploy “terrorists” to steal a  
 shipment of bombs would be prepared to sacriﬁce some of the bombs (and some  
 technical personnel) to obtain a single serviceable weapon.

To perform authorized maintenance, the tamper protection must be disabled,

and this requires a separate unlock code. The devices that hold the various  
 unlock codes – for servicing and ﬁring – are themselves protected in similar  
 ways to the weapons.

The assurance target is summarized in [1825]:

It is currently believed that even someone who gained possession  
 of such a weapon, had a set of drawings, and enjoyed the technical  
 capability of one of the national laboratories would be unable to  
 successfully cause a detonation without knowing the code.

Meeting such an ambitious goal requires a very substantial effort. There are

several examples of the level of care needed:

*•* after tests showed that 1 mm chip fragments survived the protective det-

3Bruce Blair says that Strategic Air Command resisted the new doctrine and kept Min-

uteman authorization codes at ’00000000’ until 1977, lying to a succession of Presidents and  
 Defense Secretaries [255]. Others said that this was just the use control code.

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software was rewritten so that all key material was stored as two separate  
 components, which were kept at addresses more than 1 mm apart on the  
 chip surface;

*•* the ‘football’, the command device carried around behind the President,  
 disable its protective mechanisms. Shaped charges can generate a plasma  
 jet with a velocity of 8000m/s, which could in theory be used to disable  
 tamper sensing circuitry. So some distance may be needed to give the  
 alarm circuit enough time to zeroize the code memory.

This care must extend to many details of implementation and operation. The

weapons testing process includes not just independent veriﬁcation and valida-  
 tion, but hostile ‘black hat’ penetration attempts by competing agencies. Even  
 then, all practical measures are taken to prevent access by possible opponents.  
 The devices (both munition and control) are defended in depth by armed forces;  
 there are frequent zero-notice challenge inspections; and staff may be made to  
 re-sit the relevant examinations at any time of the day or night.

I discuss tamper resistance in much more detail in its own chapter, as it’s

widely used in applications such as bank cards and phones. However, tamper re-  
 sistance, secret sharing and one-time authenticators aren’t the only technologies  
 to have beneﬁted from the nuclear industry’s interest. There are more subtle  
 system lessons too.

**15.6** **Treaty Veriﬁcation**

A variety of veriﬁcation systems are used to monitor compliance with nuclear  
 nonproliferation treaties. For example, the IAEA and the US Nuclear Regu-  
 latory Commission (NRC) monitor ﬁssile materials in licensed civilian power  
 reactors and other facilities.

An interesting example comes from the tamper-resistant seismic sensor de-

vices designed to monitor the Comprehensive Test Ban Treaty [1747]. The goal  
 in this application was to have sufficiently sensitive sensors in each signatory’s  
 test sites that any violation of the treaty (such as by testing too large a de-  
 vice) can be detected with high probability. The tamper sensing here is fairly  
 straightforward: the seismic sensors are ﬁtted in a steel tube and inserted into  
 a drill hole that is backﬁlled with concrete. The whole assembly is so solid that  
 the seismometers themselves can be relied upon to detect tampering events  
 with a fairly high probability. This physical protection is reinforced by random  
 challenge inspections.

The authentication process becomes somewhat more complex because of the

assumption of pervasive deceit. Because there is no third party trusted by

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| both sides, and because the quantity of seismic data being transmitted is of the  order of 108 bits per day, a digital signature scheme (RSA) was used instead of  one-time authentication tags. But this is only part of the answer. One party  might always disavow a signed message by saying that the o�cial responsible  for generating it had defected, and so the signature was forged. So the keys | | |
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had to be generated within the seismic package itself once it had been sealed  
 by both sides. Also, if one side builds the equipment, the other will suspect  
 it of having hidden functionality. Several protocols were proposed of the *cut*  
 *and choose* variety, in which one party would produce several devices of which  
 the other party would dismantle a sample for inspection. A number of these  
 issues have since resurfaced in electronic commerce. (Many system designers  
 since could have saved themselves a lot of grief if they’d read the account of  
 these treaty monitoring systems by Sandia’s former crypto chief Gus Simmons  
 in [1747].)

**15.7** **What Goes Wrong**

Despite the huge amounts of money invested in developing high-tech protection  
 mechanisms, nuclear control and safety systems appear to suffer from just the  
 same kind of design bugs, implementation blunders and careless operations as  
 any others.

**15.7.1** **Nuclear accidents**

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| The main risk may be just an accident. We’ve already had two nuclear accidents  rated at 74 on the International Nuclear and Radiological Event Scale, namely  those at Chernobyl and Fukushima, and quite a few less serious ones. Britain’s  main waste reprocessing plant at Sellaﬁeld, which stores 160 tonnes of plutonium  – the world’s largest stockpile – has been plagued with scandals for decades.  Waste documentation has been forged; radiation leaks have been covered up;  workers altered entry passes so they could bring their cars into restricted areas;  there have been reports of sabotage; and the nuclear police force only manage  to clear up 10–20% of cases of theft or criminal damage [1131]. The task of  cleaning it all up could take a century and cost over $100bn; meanwhile it has  to be guarded [1867]. There are signiﬁcant and pervasive problems elsewhere in  the defence nuclear enterprise, including at the nuclear weapons factories and the  submarine bases, ranging from dilapidated facilities, incompetent contractors,  poor morale, project delays, spiralling costs, and 20 old submarines awaiting  disposal – nine of which still contain fuel [1560]. The situation in Russia appears  to be even worse. A survey of nuclear safekeeping described how dilapidated  their security mechanisms became following the collapse of the USSR, with ﬁssile  materials occasionally appearing on the black market and whistleblowers being  prosecuted [953]. |

**15.7.2** **Interaction with cyberwar**

A second, and growing, concern is that nuclear safety might be undermined  
 by the possibility of cyber-attack. Even if the command and control channel  
 itself has been made invulnerable to manipulation using the cryptographic and

4The deﬁnition is ‘Major release of radioactive material with widespread health and envi-

ronmental effects requiring implementation of planned and extended countermeasures’

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tamper-resistance mechanisms described here, it might be subject to service-  
 denial attack; and in 2018, the Trump administration changed doctrine to allow  
 the ﬁrst use of nuclear weapons in response to such an attack. Another vital  
 question is whether commanders can believe what they see on their screens. In  
 1983, a new Soviet early-warning system malfunctioned at a time of international  
 tension, reporting that the USA had launched ﬁve Minuteman missiles at Russia.  
 The commander in the Moscow bunker, lieutenant-colonel Stanislav Petrov,  
 decided it was probably a false alarm, as launching only ﬁve missiles would have  
 been illogical, and held ﬁre until satellites conﬁrmed it was indeed a false alarm.  
 That was probably the closest that the world got to accidental nuclear war  
 (there had also been a US false alarm three years previously). How would such  
 a system failure play out today, now that we have much more complex systems,  
 with AI creeping into the command chain in all sorts of places without our even  
 realising it? And never mind failures – what about attacks on our intelligence,  
 surveillance and reconnaissance (ISR) capability, including the satellites that  
 watch for missile launches, detect nuclear detonations and pass on orders?

A 2018 report from the Nuclear Threat Initiative describes the concerns in

some detail [1833]. It’s not enough to protect the weapons themselves, as a  
 cyber attack on the planning, early-warning or communications systems could  
 also have catastrophic consequences. The main risk is of use because of false  
 warnings or miscalculation; there are also external dependencies, from networks  
 to the electricity grid. Attacks on conventional command-and-control networks  
 could be seen as strategic threats if these networks are also used for nuclear  
 forces. Such issues have been acknowledged in the Trump administration’s 2018  
 Nuclear Posture Review. Technical cybersecurity measures alone are unlikely to  
 be enough, as there are signiﬁcant soft issues, such as whether key people can  
 be undermined by making them look incompetent.

There may also be fears that an opponent’s capability at cyber operations

may render one’s own deterrent less effective or overconﬁdence that one’s own  
 capability might make attacking a rival less risky. I was personally told by a se-  
 nior official in the signals intelligence agency of a non-NATO nuclear power that  
 in a confrontation they ‘had the drop on’ a regional rival. Regardless of whether  
 this was actually true or not, such sentiments, when expressed in the corridors of  
 power, can undermine deterrence and make nuclear conﬂict more likely. More re-  
 cently, the U.S. National Security Commission on Artiﬁcial Intelligence warned  
 in 2019 that nuclear deterrence could be undermined if AI-equipped systems  
 succeed in tracking and targeting previously invulnerable military assets [1415].

And it’s not just the declared nuclear states. There are currently 22 countries

with ﬁssile materials in sufficient quantity and quality to be useful in weapons,  
 and 44 with civil nuclear programs (45 once the UAE goes critical). Of these  
 countries, 15 don’t even have cybersecurity laws; energy companies generally  
 won’t invest in cybersecurity unless their regulators tell them to, while some  
 companies (and countries) have no real capability.

This has all been made highly salient to governments by the US / Israeli

attack on Iran’s uranium enrichment capability at Natanz using the Stuxnet  
 virus. In 2009 their output of enriched uranium fell by 30% and in 2010 the  
 virus came to light. It had infected the centrifuge controllers, causing them to  
 spin up and then slow down in such a way as to destroy about 1000 of Iran’s

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ﬂeet of 4,700. US government involvement was ﬁnally admitted in 2012 [1028].

**15.7.3** **Technical failures**

There have also been a number of interesting high-tech security failures. One  
 example is a possible attack discovered on a nuclear arms reduction treaty which  
 led to the development of a new branch of cryptomathematics – the study of  
 subliminal channels – and is relevant to later work on copyright marking and  
 steganography.

The story is told in [1753]. During the Carter administration, the USA

proposed a deal with the USSR under which each side would cooperate with  
 the other to verify the number of intercontinental ballistic missiles. In order  
 to protect US Minuteman missiles against a Soviet ﬁrst strike, it was proposed  
 that 100 missiles be moved randomly around a ﬁeld of 1000 silos by giant trucks,  
 which were designed so that observers couldn’t determine whether they were  
 moving a missile or not. So the Soviets would have had to destroy all 1,000 silos  
 to make a successful ﬁrst strike, which was thought impractical.

But how could the USA assure the Soviets that there were at most 100

missiles in the silo ﬁeld, but without letting them ﬁnd out where? The proposed  
 solution was that the silos would have a Russian sensor package that would  
 detect the presence or absence of a missile, sign this single bit of information,  
 and send it via a US monitoring facility to Moscow. The catch was that only  
 this single bit of information could be sent; if the Russians could smuggle any  
 more information into the message, they could locate the full silos – as it would  
 take only ten bits of address information to specify a single silo in the ﬁeld.  
 (There were many other security requirements to prevent either side cheating,  
 or falsely accusing the other of cheating: for more details, see [1752].)

To see how subliminal channels work, consider the Digital Signature Algo-

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| rithm described in the chapter on cryptography. The system-wide values are a |
| prime number *p*, a prime number *q* dividing *p �* 1, and a generator *g* of a sub-  group of *F ⇤p* of order *q*. The signature on the message *M* is *r, s* where *r* = (*gk*  (mod *p*)) (mod *q*), and *k* is a random session key. The mapping from *k* to *r* |

is fairly random, so a signer who wishes to hide ten bits of information in this  
 signature for covert transmission to an accomplice can ﬁrst agree a convention  
 about how the bits will be hidden (such as ‘bits 72–81’) and second, try out one  
 value of *k* after another until the resulting value *r* has the desired substring.

This could have caused a disastrous failure of the security protocol. But

in the end, the “missile shell game”, as it had become known in the press,  
 wasn’t used. Eventually the medium range ballistic missile treaty (MRBM) used  
 statistical methods. The Russians could say ‘we’d like to look at the following  
 20 silos’ and they would be uncapped for their satellites to take a look. With  
 the end of the Cold War, inspections have become much more intimate with  
 inspection ﬂights in manned aircraft, with observers from both sides, rather  
 than satellites.

Still, the discovery of subliminal channels was signiﬁcant. Ways in which they

might be abused include putting HIV status, or the fact of a felony conviction,  
 into a digital passport or identity card. Where this is unacceptable, the remedy

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is to use a completely deterministic signature scheme such as RSA instead of  
 one that uses a random session key like DSA.

**15.8** **Secrecy or Openness?**

Finally, the nuclear industry provides a nice case history of secrecy. In the

1930s, physicists from many countries had freely shared the scientiﬁc ideas that  
 led to the bomb, but after the ‘atomic spies’ (Fuchs, the Rosenbergs and others)  
 had leaked the designs of the Hiroshima and Nagasaki devices to the Soviet  
 Union, things swung to the other extreme. The US adopted a policy that

atomic knowledge was born classiﬁed. That meant that if you were within US  
 jurisdiction and had an idea relevant to nuclear weapons, you had to keep it  
 secret regardless of whether you held a security clearance or even worked in  
 the nuclear industry. This was in tension with the Constitution. Things have  
 greatly relaxed since then, as the protection issues were thought through in  
 detail.

“We’ve a database in New Mexico that records the physical and chemical

properties of plutonium at very high temperatures and pressures”, a former  
 head of US nuclear security once told me. “At what level should I classify that?  
 Who’s going to steal it, and will it do them any good? The Russians, they’ve  
 got that data for themselves. The Israelis can ﬁgure it out. Gaddaﬁ? What the  
 hell will he do with it?”

As issues like this got worked through, a lot of the technology has been

declassiﬁed and published, at least in outline. Starting from early publication at  
 scientiﬁc conferences of results on authentication codes and subliminal channels  
 in the early 1980s, the beneﬁts of public design review have been found to  
 outweigh the advantage to an opponent of knowing broadly the system in use.

Many implementation details are kept secret, including information that

could facilitate sabotage, such as which of a facility’s ﬁfty buildings contains  
 the alarm response force. Yet the big picture is fairly open, with command

and control technologies on offer at times to other states, including potentially  
 hostile ones. The beneﬁts of reducing the likelihood of an accidental war were  
 considered to outweigh the possible beneﬁts of secrecy. Post-9/11, we’d rather  
 have decent command and control systems in Pakistan than risk having one of  
 their weapons used against us by some mid-level officer suffering from an attack  
 of religious zealotry. This is a modern reincarnation of Kerckhoffs’ doctrine, the  
 nineteenth-century maxim that the security of a system must depend on its key,  
 not on its design remaining obscure [1042].

The nuclear lessons could be learned more widely. Post-9/11, a number of

governments talked up the possibility of terrorists using biological weapons, and  
 imposed controls on research and teaching in bacteriology, virology, toxicology  
 and indeed medicine. My faculty colleagues in these disciplines were deeply

unimpressed. “You just shouldn’t worry about anthrax,” one of the UK’s top  
 virologists told me. “The real nasties are the things Mother Nature dreams up  
 like HIV and SARS and bird ﬂu. If these policies mean that there aren’t any  
 capable public health people in Khartoum next time a virus comes down the

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Nile, we’ll be sorry.” Sadly, the events of 2020 conﬁrm this wisdom.

**15.9** **Summary**

The control of nuclear weapons, and subsidiary activities from protecting the  
 integrity of the national command system through physical security of nuclear  
 facilities to monitoring international arms control treaties, has made a huge  
 contribution to the development of security technology.

The rational decision that weapons and ﬁssile material had to be protected

almost regardless of the cost drove the development of a lot of mathematics and  
 science that has found application elsewhere. The particular examples we’ve  
 looked at in this chapter are authentication codes, shared control schemes and  
 subliminal channels. There are other examples scattered through the rest of  
 this book, from alarms to iris biometrics and from tamper-resistant electronic  
 devices to seals.

Yet even though we can protect the command and control channel that au-

thorises the use of nuclear weapons, that is by no means the whole story. If  
 cyber attacks can undermine conﬁdence in deterrence by targeting a country’s  
 intelligence, surveillance and reconnaissance capabilities, they can still be seri-  
 ously destabilising. At a time of nuclear brinkmanship, each side could think  
 they have an advantage because of an undeclared cyber capability. And given  
 that US presidents have used nuclear threats about a dozen times since 1945  
 (Cuba, Vietnam and Iraq being merely the more obvious examples), we might  
 expect several such crises each generation.

**Research Problems**

The research problem I set at the end of this chapter in the ﬁrst edition in 2001  
 was ‘Find interesting applications for technologies developed in this area, such  
 as authentication codes.’ By the second edition the Galois Counter mode of  
 operation of block ciphers had been standardised, and by now it’s pervasive.  
 What else might there be?

The most serious research problem now might be the interaction between

silicon and plutonium. The US/Israeli attack on Iran’s uranium enrichment

program in 2009-10 gave the world an example of cyber-attacks being used in  
 the nuclear world. In what ways might the threat of such attacks increase the  
 risk of nuclear conﬂict, and what can we do about it? Given that we can’t

harden everything the way we harden the command and control channel, what  
 can we do to maintain trust in the supporting systems such as surveillance, or  
 at least ensure that they degrade in ways that don’t lead to lethal false alarms?

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**Further Reading**

As my own direct experience of nuclear weapons is rather dated – consisting of  
 working in the 1970s on the avionics of nuclear-capable aircraft – this chapter  
 has been assembled from published sources and conversations with insiders. One  
 of the best sources of public information on nuclear weapons is the Federation of  
 American Scientists, who discuss everything from bomb design to the rationale  
 for the declassiﬁcation of many nuclear arms technologies [672]. Declassiﬁcation  
 issues are also discussed in [2045], and the publicly available material on PALs  
 has been assembled by Steve Bellovin [217].

Gus Simmons was the guy at Sandia who designed the football; he was a

pioneer of authentication codes, shared control schemes and subliminal channels.  
 His book [1749] remains the best reference for most of the technical material  
 discussed in this chapter. A more concise introduction to both authentication  
 and secret sharing can be found in Doug Stinson’s textbook [1829].

Control failures in nuclear installations are documented in many places. The

problems with Russian installations are discussed in [953]; US nuclear safety is  
 overseen by the Nuclear Regulatory Commission [1455]; and shortcomings with  
 UK installations are documented in the quarterly reports posted by the Health  
 and Safety Executive [874]. The best and most up-to-date survey of problems  
 can be found in the Public Accounts Committee’s 2018 report *‘Ministry of*  
 *Defence nuclear programme’* [1560]. As for the interaction ‘between silicon and  
 plutonium’, there’s a recent report on the subject from Chatham House [27].

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