**Chapter 4**

**Protocols**

**It is impossible to foresee the consequences of being clever.**

– CHRISTOPHER STRACHEY

**If it’s provably secure, it probably isn’t.**

– LARS KNUDSEN

**4.1** **Introduction**

Passwords are just one example of a more general concept, the security protocol.  
 If security engineering has a core theme, it may be the study of security proto-  
 cols. They specify the steps that principals use to establish trust relationships.  
 They are where the cryptography and the access controls meet; they are the  
 tools we use to link up human users with remote machines, to synchronise se-  
 curity contexts, and to regulate key applications such as payment. We’ve come  
 across a few protocols already, including challenge-response authentication and  
 Kerberos. In this chapter, I’ll dig down into the details, and give many examples  
 of how protocols fail.

A typical security system consists of a number of principals such as people,

companies, phones, computers and card readers, which communicate using a  
 variety of channels including ﬁbre, wiﬁ, the cellular network, bluetooth, infrared,  
 and by carrying data on physical devices such as bank cards and transport  
 tickets. The security protocols are the rules that govern these communications.  
 They are designed so that the system will survive malicious acts such as people  
 telling lies on the phone, hostile governments jamming radio, or forgers altering  
 the data on train tickets. Protection against all possible attacks is often too  
 expensive, so protocol designs make assumptions about threats. For example,  
 when we get a user to log on by entering a password into a machine, we implicitly  
 assume that she can enter it into the right machine. In the old days of hard-  
 wired terminals in the workplace, this was reasonable; now that people log on  
 to websites over the Internet, it is much less obvious. Evaluating a protocol  
 thus involves two questions: ﬁrst, is the threat model realistic? Second, does  
 the protocol deal with it?

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*4.2. PASSWORD EAVESDROPPING RISKS*

Protocols may be very simple, such as swiping a badge through a reader

to enter a building. They often involve interaction, and are not necessarily

technical. For example, when we order a bottle of ﬁne wine in a restaurant, the  
 standard protocol is that the wine waiter o↵ers us the menu (so that we see the  
 prices but our guests don’t); they bring the bottle, so we can check the label,  
 the seal and the temperature; they open it so we can taste it; and then serve  
 it. This has evolved to provide some privacy (our guests don’t learn the price),  
 some integrity (we can be sure we got the right bottle and that it wasn’t reﬁlled  
 with cheap plonk) and non-repudiation (we can’t complain afterwards that the  
 wine was o↵). Matt Blaze gives other non-technical protocol examples from  
 ticket inspection, aviation security and voting in [260]. Traditional protocols  
 like these often evolved over decades or centuries to meet social expectations as  
 well as technical threats.

At the technical end of things, protocols get a lot more complex, and they

don’t always get better. As the car industry moved from metal keys to electronic  
 keys with buttons you press, theft fell, since the new keys were harder to copy.  
 But the move to keyless entry has seen car crime rise again, as the bad guys  
 ﬁgured out how to build relay devices that would make a key seem closer to  
 the car than it actually was. Another security upgrade that’s turned out to be  
 tricky is the move from magnetic-strip cards to smartcards. Europe made this  
 move in the late 2000s while the USA is only catching up in the late 2010s.  
 Fraud against cards issued in Europe actually went up for several years; clones  
 of European cards were used in magnetic-strip cash machines in the USA, as  
 the two systems’ protection mechanisms didn’t quite mesh. And there was a  
 protocol failure that let a thief use a stolen chipcard in a store even if he didn’t  
 know the PIN, which took the banks several years to ﬁx.

So we need to look systematically at security protocols and how they fail.

**4.2** **Password Eavesdropping Risks**

Passwords and PINs are still the foundation for much of computer security, as  
 the main mechanism used to authenticate humans to machines. We discussed  
 their usability in the last chapter; now let’s consider the kinds of technical attack  
 we have to block when designing protocols that operate between one machine  
 and another.

Remote key entry is a good place to start. The early systems, such as the

remote control used to open your garage or to unlock cars manufactured up to  
 the mid-1990’s, just broadcast a serial number. The attack that killed them was  
 the ‘grabber’, a device that would record a code and replay it later. The ﬁrst  
 grabbers, seemingly from Taiwan, arrived on the market in about 1995; thieves  
 would lurk in parking lots or outside a target’s house, record the signal used to  
 lock the car and then replay it once the owner had gone1.

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| 1With garage doors it’s even worse. A common chip is the Princeton PT2262, which uses 12 tri-state pins to encode 312 or 531,441 address codes. However implementers often don’t | | |
| read the data sheet carefully enough to understand tri-state inputs and treat them as binary instead, getting 212. Many of them only use eight inputs, as the other four are on the other side of the chip. And as the chip has no retry-lockout logic, an attacker can cycle through | | |
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The ﬁrst countermeasure was to use separate codes for lock and unlock.

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| But the thief can lurk outside your house and record the unlock code before  you drive away in the morning, and then come back at night and help himself.  Second, sixteen-bit passwords are too short. Occasionally people found they  could unlock the wrong car by mistake, or even set the alarm on a car whose  owner didn’t know he had one [308]. And by the mid-1990’s, devices appeared  that could try all possible codes one after the other. A code will be found on  average after about 215 tries, and at ten per second that takes under an hour.  A thief operating in a parking lot with a hundred vehicles within range would  be rewarded in less than a minute with a car helpfully ﬂashing its lights. |

The next countermeasure was to double the length of the password from 16

to 32 bits. The manufacturers proudly advertised ‘over 4 billion codes’. But  
 this only showed they hadn’t really understood the problem. There were still  
 only one or two codes for each car, and grabbers still worked ﬁne.

Using a serial number as a password has a further vulnerability: lots of

people have access to it. In the case of a car, this might mean all the dealer  
 sta↵, and perhaps the state motor vehicle registration agency. Some burglar  
 alarms have also used serial numbers as master passwords, and here it’s even  
 worse: when a bank buys a burglar alarm, the serial number may appear on the  
 order, the delivery note and the invoice. And banks don’t like sending someone  
 out to buy something for cash.

Simple passwords are sometimes the appropriate technology. For example,

a monthly season ticket for our local swimming pool simply has a barcode. I’m  
 sure I could make a passable forgery, but as the turnstile attendants get to know  
 the ‘regulars’, there’s no need for anything more expensive. For things that are  
 online, however, static passwords are hazardous; the Mirai botnet got going by  
 recruiting wiﬁ-connected CCTV cameras which had a password that couldn’t be  
 changed. And for things people want to steal, like cars, we also need something  
 better. This brings us to cryptographic authentication protocols.

**4.3** **Who goes there? – simple authentication**

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| A simple modern authentication device is the token that some multistorey park-  ing garages give subscribers to raise the barrier. The token has a single button;  when you press it, it ﬁrst transmits its serial number and then sends an au-  thentication block consisting of the same serial number, followed by a random  number, all encrypted using a key unique to the device, and sent to the garage  barrier (typically by radio at 434MHz, though infrared is also used). We will  postpone discussion of how to encrypt data to the next chapter, and simply |
| write *{X}K* for the message *X* encrypted under the key *K*.  Then the protocol between the access token and the parking garage can be |

written as:

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| *T �! G* : *T, {T, N}KT*  the combinations quickly and open your garage door after 27 attempts on average. Twelve | | |
| years after I noted these problems in the second edition of this book, the chip has not been  withdrawn. It’s now also sold for home security systems and for the remote control of toys. | | |
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This is standard protocol notation, so we’ll take it slowly.

The token *T* sends a message to the garage *G* consisting of its name *T*

followed by the encrypted value of *T* concatenated with *N*, where *N* stands for  
 ‘number used once’, or *nonce*. Everything within the braces is encrypted, and  
 the encryption binds *T* and *N* together as well as obscuring their values. The  
 purpose of the nonce is to assure the recipient that the message is *fresh*, that is,  
 it is not a replay of an old message. Veriﬁcation is simple: the garage reads *T*,  
 gets the corresponding key *KT*, deciphers the rest of the message, checks that  
 the nonce *N* has not been seen before, and ﬁnally that the plaintext contains  
 *T*.

One reason many people get confused is that to the left of the colon, *T*

identiﬁes one of the principals (the token that represents the subscriber) whereas  
 to the right it means the name (that is, the unique device number) of the token.  
 Another is that once we start discussing attacks on protocols, we may ﬁnd that a  
 message intended for one principal was intercepted and played back by another.  
 So you might think of the *T �! G* to the left of the colon as a hint as to what

A *nonce* can be anything that guarantees the freshness of a message. It can

be a random number, a counter, a random challenge received from a third party,  
 or even a timestamp. There are subtle di↵erences between them, such as in the  
 level of resistance they o↵er to various kinds of replay attack, and the ways  
 in which they increase system cost and complexity. In very low-cost systems,  
 random numbers and counters predominate as it’s cheaper to communicate in  
 one direction only, and cheap devices usually don’t have clocks.

Key management in such devices can be very simple. In a typical garage

token product, each token’s key is just its unique device number encrypted under  
 a global master key *KM* known to the garage:

*KT* = *{T}KM*

This is known as *key diversiﬁcation* or *key derivation*. It’s a common way

of implementing access tokens, and is widely used in smartcards too. The goal  
 is that someone who compromises a token by drilling into it and extracting  
 the key cannot masquerade as any other token; all he can do is make a copy  
 of one particular subscriber’s token. In order to do a complete break of the  
 system, and extract the master key that would enable him to pretend to be  
 any of the system’s users, an attacker has to compromise the central server at  
 the garage (which might protect this key in a tamper-resistant smartcard or  
 hardware security module).

But there is still room for error. A common failure mode is for the serial

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| numbers – whether unique device numbers or protocol counters – not to be  long enough, so that someone occasionally ﬁnds that their remote control works  for another car in the car park as well. This can be masked by cryptography.  Having 128-bit keys doesn’t help if the key is derived by encrypting a 16-bit  device number, or by taking a 16-bit key and repeating it eight times. In either  case, there are only 216 possible keys, and that’s unlikely to be enough even if | | |
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they appear to be random2.

Protocol vulnerabilities usually give rise to more, and simpler, attacks than

cryptographic weaknesses do. An example comes from the world of prepayment  
 utility meters. Over a million households in the UK, plus over 400 million in  
 developing countries, have an electricity or gas meter that accepts encrypted  
 tokens: the householder buys a magic number and types it into the meter,  
 which then dispenses the purchased quantity of energy. One early meter that  
 was widely used in South Africa checked only that the nonce was di↵erent from  
 last time. So the customer could charge their meter indeﬁnitely by buying two  
 low-value power tickets and then feeding them in one after the other; given two  
 valid codes *A* and *B*, the series *ABABAB...* was seen as valid [93].

So the question of whether to use a random number or a counter is not as

easy as it looks. If you use random numbers, the lock has to remember a lot  
 of past codes. There’s the *valet attack*, where someone with temporary access,  
 such as a valet parking attendant, records some access codes and replays them  
 later to steal your car. In addition, someone might rent a car, record enough  
 unlock codes, and then go back later to the rental lot to steal it. Providing  
 enough nonvolatile memory to remember thousands of old codes might add a  
 few cents to the cost of your lock.

If you opt for counters, the problem is synchronization. The key might be

used for more than one lock; it may also be activated repeatedly by accident  
 (I once took an experimental token home where it was gnawed by my dogs).  
 So you need a way to recover after the counter has been incremented hundreds  
 or possibly even thousands of times. One common product uses a sixteen bit  
 counter, and allows access when the deciphered counter value is the last valid  
 code incremented by no more than sixteen. To cope with cases where the token  
 has been used more than sixteen times elsewhere (or gnawed by a family pet),  
 the lock will open on a second press provided that the counter value has been  
 incremented between 17 and 32,767 times since a valid code was entered (the  
 counter rolls over so that 0 is the successor of 65,535). This is ﬁne in many  
 applications, but a thief who can get six well-chosen access codes – say for values  
 0, 1, 20,000, 20,001, 40,000 and 40,001 – can break the system completely. In  
 your application, would you be worried about that?

So designing even a simple token authentication mechanism is not as easy

as it looks, and if you assume that your product will only attract low-grade  
 adversaries, this assumption might fail over time. An example is *accessory*

*control*. Many printer companies embed authentication mechanisms in printers  
 to ensure that genuine toner cartridges are used. If a competitor’s product is  
 loaded instead, the printer may quietly downgrade from 1200 dpi to 300 dpi, or  
 simply refuse to work at all. All sorts of other industries are getting in on the act,  
 from scientiﬁc instruments to games consoles. The cryptographic mechanisms  
 used to support this started o↵ in the 1990s being fairly rudimentary, as vendors  
 thought that any competitor who circumvented them on an industrial scale could  
 be sued or even jailed under copyright law. But then a judge found, in the case  
 Lexmark v SCC, that while a vendor had the right to hire the best cryptographer  
 they could ﬁnd to lock their customers in, a competitor also had the right to

2We’ll go into this in more detail in section 5.3.1.2 where we discuss the birthday theorem

in probability theory.

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hire the best cryptanalyst they could ﬁnd to set them free to buy accessories  
 from elsewhere. This set o↵ a serious arms race, which we’ll meet from time to  
 time in later chapters. Here I’ll just remark that security isn’t always a good  
 thing. Security mechanisms are used to support many business models, where  
 they’re typically stopping the device’s owner doing things she wants to rather  
 than protecting her from the bad guys. The e↵ect may be contrary to public  
 policy; one example is cellphone locking, which results in hundreds of millions  
 of handsets ending up in landﬁlls each year, with toxic heavy metals as well as  
 the embedded carbon cost.

**4.3.1** **Challenge and response**

Since 1995, all cars sold in Europe were required to have a ‘cryptographically  
 enabled immobiliser’ and by 2010, most cars had remote-controlled door un-  
 locking too, though most also have a fallback metal key so you can still get into  
 your car even if the key fob battery is ﬂat. The engine immobiliser is harder  
 to bypass using physical means and uses a two-pass *challenge-response protocol*  
 to authorise engine start. As the car key is inserted into the steering lock, the  
 engine controller sends a challenge consisting of a random *n*-bit number to the  
 key using short-range radio. The car key computes a response by encrypting  
 the challenge; this is often done by a separate RFID chip that’s powered by the  
 incoming radio signal and so keeps on working even if the battery is ﬂat. The  
 frequency is low (125kHz) so the car can power the transponder directly, and  
 the exchange is also relatively immune to a noisy RF environment.

Writing *E* for the engine controller, *T* for the transponder in the car key,

*K* for the cryptographic key shared between the transponder and the engine  
 controller, and *N* for the random challenge, the protocol may look something  
 like:

*E �! T* : *N*  
 *T �! E* : *T, {T, N}K*

This is sound in theory, but implementations of security mechanisms often

fail the ﬁrst two or three times people try it.

Between 2005 and 2015, all the main remote key entry and immobiliser

systems were broken, whether by security researchers, car thieves or both. The  
 attacks involved a combination of protocol errors, peer key management, weak  
 ciphers, and short keys mandated by export control laws.

The ﬁrst to fall was TI’s DST transponder chip, which was used by at least

two large car makers and was also the basis of the SpeedPass toll payment  
 system. Stephen Bono and colleagues found in 2005 that it used a block ci-  
 pher with a 40-bit key, which could be calculated by brute force from just two  
 responses [297]. This was one side-e↵ect of US cryptography export controls,  
 which I discuss in 26.2.7.1. From 2010, Ford, Toyota and Hyundai adopted

a successor product, the DST80. The DST80 was broken in turn in 2020 by  
 Lennert Wouters and colleagues, who found that as well as side-channel attacks  
 on the chip, there are serious implementation problems with key management:  
 Hyundai keys have only 24 bits of entropy, while Toyota keys are derived from

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the device serial number that an attacker can read (Tesla was also vulnerable but  
 unlike the older ﬁrms it could ﬁx the problem with a software upgrade) [2048].  
 Next was Keeloq, which was used for garage door openers as well as by some  
 car makers; in 2007, Eli Biham and others found that given an hour’s access to  
 a token they could collect enough data to recover the key [243]. Worse, in some  
 types of car, there is also a protocol bug, in that the key diversiﬁcation used  
 exclusive-or: *KT* = *T � KM*. So you can rent a car of the type you want to

Also in 2007, someone published the Philips Hitag 2 cipher, which also had

a 48-bit secret key. But this cipher is also weak, and as it was attacked by  
 various cryptanalysts, the time needed to extract a key fell from days to hours  
 to minutes. By 2016, attacks took 8 authentication attempts and a minute of  
 computation on a laptop; they worked against cars from all the French and  
 Italian makers, along with Nissan, Mitsubishi and Chevrolet [748].

The last to fall was the Megamos Crypto transponder, used by Volkswagen

and others. Car locksmithing tools appeared on the market from 2008, which  
 included the Megamos cipher and were reverse engineered by researchers from  
 Birmingham and Nijmegen – Roel Verdult, Flavio Garcia and Barı¸s Ege – who  
 cracked it [1952]. Although it has a 96-bit secret key, the e↵ective key length  
 is only 49 bits, about the same as Hitag 2. Volkswagen got an injunction in  
 the High Court in London to stop them presenting their work at Usenix 2013,  
 claiming that their trade secrets had been violated. The researchers resisted,  
 arguing that the locksmithing tool supplier had extracted the secrets. After  
 two years of argument, the case settled without admission of liability on either  
 side. Closer study then threw up a number of further problems. There’s also a  
 protocol attack as an adversary can rewrite each 16-bit word of the 96-bit key,  
 one after another, and search for the key 16 bits at a time; this reduces the time  
 needed for an attack from days to minutes [1953].

Key management was pervasively bad. A number of Volkswagen implemen-

tations did not diversify keys across cars and transponders, but used a ﬁxed  
 global master key for millions of cars at a time. Up till 2009, this used a cipher  
 called AUT64 to generate device keys; thereafter they moved to a stronger ci-  
 pher called XTEA but kept on using global master keys, which were found in  
 23 models from the Volkswagen-Audi group up till 2016 [748]3.

It’s easy to ﬁnd out if a car is vulnerable: just try to buy a spare key. If

the locksmith companies have ﬁgured out how to duplicate the key, your local  
 garage will sell you a spare for a few bucks. We have a spare key for my wife’s  
 2005 Lexus, bought by the previous owner. But when we lost one of the keys  
 for my 2012 Mercedes, we had to go to a main dealer, pay over £200, show  
 my passport and the car log book, have the mechanic photograph the vehicle  
 identiﬁcation number on the chassis, send it all o↵ to Mercedes and wait for

3There are some applications where universal master keys are inevitable, such as in com-

municating with a heart pacemaker – where a cardiologist may need to tweak the pacemaker  
 of any patient who walks in, regardless of where it was ﬁrst ﬁtted, and regardless of whether  
 the network’s up – so the vendor puts the same key in all its equipment. Another exam-

ple is the subscriber smartcard in a satellite-TV set-top box, which we’ll discuss later. But  
 they often result in a break-once-run-anywhere (BORA) attack. To install universal master  
 keys in valuable assets like cars in a way that facilitated theft and without even using proper  
 tamper-resistant chips to protect them was an egregious error.

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a week. We saw in Chapter 3 that the hard part of designing a password

system was recovering from compromise without the recovery mechanism itself  
 becoming either a vulnerability or a nuisance. Exactly the same applies here!

But the worst was still to come: passive keyless entry systems (PKES).

Challenge-response seemed so good that car vendors started using it with just  
 a push button on the dashboard to start the car, rather than with a metal key.  
 Then they increased the radio frequency to extend the range, so that it worked  
 not just for short-range authentication once the driver was sitting in the car,  
 but as a keyless entry mechanism. The marketing pitch was that so long as  
 you keep the key in your pocket or handbag you don’t have to worry about it;  
 the car will unlock when you walk up to it, lock as you walk away, and start  
 automatically when you touch the controls. What’s not to like?

Well, now you don’t have to press a button to unlock your car, it’s easy for

thieves to use devices that amplify or relay the signals. The thief sneaks up to  
 your front door with one relay while leaving the other next to your car. If you  
 left your keys on the table in the hall, the car door opens and away he goes.  
 Even if the car is immobilised he can still steal your stu↵. And after many years  
 of falling car thefts, the statistics surged in 2017 with 56% more vehicles stolen  
 in the UK, followed by a further 9% in 2018 [823]4.

The takeaway message is that the attempt since about 1990 to use cryp-

tography to make cars harder to steal had some initial success, as immobilisers  
 made cars harder to steal and insurance premiums fell. It has since backﬁred,  
 as the politicians and then the marketing people got in the way. The politicians  
 said it would be disastrous for law enforcement if people were allowed to use  
 cryptography they couldn’t crack, even for stopping car theft. Then the immo-  
 biliser vendors’ marketing people wanted proprietary algorithms to lock in the  
 car companies, whose own marketing people wanted passive keyless entry as it  
 seemed cool.

What can we do? Well, at least two car makers have put an accelerometer

in the key fob, so it won’t work unless the key is moving. One of our friends  
 left her key on the car seat while carrying her child indoors, and got locked out.  
 The local police advise us to use old-fashioned metal steering-wheel locks; our  
 residents’ association recommends keeping keys in a biscuit tin. As for me, we  
 bought such a car but found that the keyless entry was simply too ﬂaky; my  
 wife got stranded in a supermarket car park when it just wouldn’t work at all.  
 So we took that car back, and got a second-hand one with a proper push-button  
 remote lock. There are now chips using AES from NXP, Atmel and TI – of  
 which the Atmel is open source with an open protocol stack.

However crypto by itself can’t ﬁx relay attacks; the proper ﬁx is a new radio

protocol based on ultrawideband (UWB) with intrinsic ranging, which measures  
 the distance from the key fob to the car with a precision of 10cm up to a range of  
 150m. This is fairly complex to do properly, and the design of the new 802.15.4z  
 Enhanced Impulse Radio is described by Srdjan Capkun and colleagues [1764];

4To be fair this was not due solely to relay attacks, as about half of the high-value thefts

seem to involve connecting a car theft kit to the onboard diagnostic port under the glove box.  
 As it happens, the authentication protocols used on the CAN bus inside the vehicle are also  
 vulnerable in a number of ways [891]. Updating these protocols will take many years because  
 of the huge industry investment.

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the ﬁrst chip became available in 2019, and it will ship in cars from 2020. Such  
 chips have the potential to replace both the Bluetooth and NFC protocols, but  
 they might not all be compatible; there’s a low-rate pulse (LRP) mode that has  
 an open design, and a high-rate pulse (HRP) variant that’s partly proprietary.  
 Were I advising a car startup, LRP would be my starting point.

Locks are not the only application of challenge-response protocols. In HTTP

Digest Authentication, a web server challenges a client or proxy, with whom it  
 shares a password, by sending it a nonce. The response consists of the hash  
 of the nonce, the password, and the requested URI [715]. This provides a

mechanism that’s not vulnerable to password snooping. It’s used, for example,  
 to authenticate clients and servers in SIP, the protocol for Voice-Over-IP (VOIP)  
 telephony. It’s much better than sending a password in the clear, but like keyless  
 entry it su↵ers from middleperson attacks (the beneﬁciaries are the spooks).

**4.3.2** **Two-factor authentication**

The most visible use of challenge-response is probably in *two-factor authentica-*  
 *tion*. Many organizations issue their sta↵ with password generators to let them  
 log on to corporate computer systems, and many banks give similar devices to  
 customers. They may look like little calculators (and some even work as such)  
 but their main function is as follows. When you want to log in, you are presented  
 with a random nonce of maybe seven digits. You key this into your password  
 generator, together with a PIN of maybe four digits. The device encrypts these  
 eleven digits using a secret key shared with the corporate security server, and  
 displays the ﬁrst seven digits of the result. You enter these seven digits as your  
 password. This protocol is illustrated in Figure 4.1. If you had a password gen-  
 erator with the right secret key, and you entered the PIN right, and you typed  
 in the result correctly, then you get in.

Formally, with *S* for the server, *P* for the password generator, *PIN* for the

user’s Personal Identiﬁcation Number, *U* for the user and *N* for the nonce:

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| *S �! U* :  *U �! P* :  *P �! U* :  *U �! S* : | *N*  *N, PIN*  *{N, PIN}K*  *{N, PIN}K* |

These devices appeared from the early 1980s and caught on ﬁrst with phone

companies, then in the 1990s with banks for use by sta↵. There are simpliﬁed  
 versions that don’t have a keyboard, but just generate new access codes by  
 encrypting a counter or a clock. And they work; the US Defense Department  
 announced in 2007 that an authentication system based on the DoD Common  
 Access Card had cut network intrusions by 46% in the previous year [320].

This was just when crooks started phishing bank customers at scale, so many

banks adopted the technology. One of my banks gives me a small calculator that  
 generates a new code for each logon, and also allows me to authenticate new  
 payees by using the last four digits of their account number in place of the  
 challenge. My other bank uses the Chip Authentication Program (CAP), a

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| N?  N, PIN K |

Figure 4.1: – password generator use

calculator in which I can insert my bank card to do the crypto.

But this still isn’t foolproof. In the second edition of this book, I noted

‘someone who takes your bank card from you at knifepoint can now verify that  
 you’ve told them the right PIN’, and this now happens. I also noted that ‘once  
 lots of banks use one-time passwords, the phishermen will just rewrite their  
 scripts to do real-time man-in-the-middle attacks’ and this has also become  
 widespread. To see how such attacks work, let’s look at a military example.

**4.3.3** **The MIG-in-the-middle attack**

The ﬁrst use of challenge-response authentication protocols was probably in the  
 military, with ‘identify-friend-or-foe’ (IFF) systems. The ever-increasing speeds  
 of warplanes in the 1930s and 1940s, together with the invention of the jet engine,  
 radar and rocketry, made it ever more di�cult for air defence forces to tell their  
 own craft apart from the enemy’s. This led to a risk of pilots shooting down  
 their colleagues by mistake and drove the development of automatic systems to  
 prevent this. These were ﬁrst ﬁelded in World War II, and enabled an airplane  
 illuminated by radar to broadcast an identifying number to signal friendly intent.  
 In 1952, this system was adopted to identify civil aircraft to air tra�c controllers  
 and, worried about the loss of security once it became widely used, the US Air  
 Force started a research program to incorporate cryptographic protection in  
 the system. Nowadays, the typical air defense system sends random challenges  
 with its radar signals, and friendly aircraft can identify themselves with correct  
 responses.

It’s tricky to design a good IFF system. One of the problems is illustrated

by the following story, which I heard from an o�cer in the South African Air  
 Force (SAAF). After it was published in the ﬁrst edition of this book, the story

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was disputed – as I’ll discuss below. Be that as it may, similar games have been  
 played with other electronic warfare systems since World War 2. The ‘MIG-in-  
 the-middle’ story has since become part of the folklore, and it nicely illustrates  
 how attacks can be carried out in real time on challenge-response protocols.

In the late 1980’s, South African troops were ﬁghting a war in northern

Namibia and southern Angola. Their goals were to keep Namibia under white  
 rule, and impose a client government (UNITA) on Angola. Because the South  
 African Defence Force consisted largely of conscripts from a small white pop-  
 ulation, it was important to limit casualties, so most South African soldiers  
 remained in Namibia on policing duties while the ﬁghting to the north was done  
 by UNITA troops. The role of the SAAF was twofold: to provide tactical sup-  
 port to UNITA by bombing targets in Angola, and to ensure that the Angolans  
 and their Cuban allies did not return the compliment in Namibia.

|  |  |
| --- | --- |
|  | SAAF  N?  N K  ANGOLA  N K  N? |
|  |
| MIG  N?  N K  SAAF  NAMIBIA |

Figure 4.2: – the MIG-in-the middle attack

Suddenly, the Cubans broke through the South African air defenses and

carried out a bombing raid on a South African camp in northern Namibia,  
 killing a number of white conscripts. This proof that their air supremacy had  
 been lost helped the Pretoria government decide to hand over Namibia to the

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insurgents – itself a huge step on the road to majority rule in South Africa  
 several years later. The raid may also have been the last successful military  
 operation ever carried out by Soviet bloc forces.

Some years afterwards, a SAAF o�cer told me how the Cubans had pulled

it o↵. Several MIGs had loitered in southern Angola, just north of the South  
 African air defense belt, until a ﬂight of SAAF Impala bombers raided a tar-  
 get in Angola. Then the MIGs turned sharply and ﬂew openly through the  
 SAAF’s air defenses, which sent IFF challenges. The MIGs relayed them to the  
 Angolan air defense batteries, which transmitted them at a SAAF bomber; the  
 responses were relayed back to the MIGs, who retransmitted them and were  
 allowed through – as in Figure 4.2. According to my informant, this shocked  
 the general sta↵ in Pretoria. Being not only outfought by black opponents, but  
 actually outsmarted, was not consistent with the world view they had held up  
 till then.

After this tale was published in the ﬁrst edition of my book, I was contacted

by a former o�cer in SA Communications Security Agency who disputed the  
 story’s details. He said that their IFF equipment did not use cryptography yet at  
 the time of the Angolan war, and was always switched o↵ over enemy territory.  
 Thus, he said, any electronic trickery must have been of a more primitive kind.  
 However, others tell me that ‘Mig-in-the-middle’ tricks were signiﬁcant in Korea,  
 Vietnam and various Middle Eastern conﬂicts.

In any case, the tale gives us another illustration of the man-in-the-middle

attack. The relay attack against cars is another example. It also works against  
 password calculators: the phishing site invites the mark to log on and simul-  
 taneously opens a logon session with his bank. The bank sends a challenge;  
 the phisherman relays this to the mark, who uses his device to respond to it;  
 the phisherman relays the response to the bank, and the bank now accepts the  
 phisherman as the mark.

Stopping a middleperson attack is harder than it looks, and may involve mul-

tiple layers of defence. Banks typically look for a known machine, a password,  
 a second factor such as an authentication code from a CAP reader, and a risk  
 assessment of the transaction. For high-risk transactions, such as adding a new  
 payee to an account, both my banks demand that I compute an authentication  
 code on the payee account number. But they only authenticate the last four  
 digits, because of usability. If it takes two minutes and the entry of dozens of  
 digits to make a payment, then a lot of customers will get digits wrong, give up,  
 and then either call the call center or get annoyed and bank elsewhere. Also, the  
 bad guys may be able to exploit any fallback mechanisms, perhaps by spooﬁng  
 customers into calling phone numbers that run a middleperson attack between  
 the customer and the call center. I’ll discuss all this further in the chapter on  
 Banking and Bookkeeping.

We will come across such attacks again and again in applications ranging

from Internet security protocols to Bluetooth. They even apply in gaming. As  
 the mathematician John Conway once remarked, it’s easy to get at least a draw  
 against a grandmaster at postal chess: just play two grandmasters at once, one  
 as white and the other as black, and relay the moves between them!

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**4.3.4** **Reﬂection Attacks**

Further interesting problems arise when two principals have to identify each  
 other. Suppose that a challenge-response IFF system designed to prevent anti-  
 aircraft gunners attacking friendly aircraft had to be deployed in a ﬁghter-  
 bomber too. Now suppose that the air force simply installed one of their air  
 gunners’ challenge units in each aircraft and connected it to the ﬁre-control  
 radar.

But now when a ﬁghter challenges an enemy bomber, the bomber might just

reﬂect the challenge back to the ﬁghter’s wingman, get a correct response, and  
 then send that back as its own response:

|  |  |  |
| --- | --- | --- |
| *F �! B*  *B �! F 0*  *F 0 �! B*  *B �! F* | : | *N* |
| : | *N* |
| : | *{N}K*  *{N}K* |
| : |

There are a number of ways of stopping this, such as including the names

of the two parties in the exchange. In the above example, we might require a  
 friendly bomber to reply to the challenge:

*F �! B* : *N*

with a response such as:

*B �! F* : *{B, N}K*

|  |
| --- |
| Thus a reﬂected response *{F 0, N}* from the wingman *F 0* could be detected5.  This serves to illustrate the subtlety of the trust assumptions that underlie |

authentication. If you send out a challenge *N* and receive, within 20 millisec-  
 onds, a response *{N}K*, then – since light can travel a bit under 3,730 miles in  
 that’s all you know. If you can be sure that the response was not computed  
 using your own equipment, you now know that there is someone *else* with the  
 key *K* within two thousand miles. If you make the further assumption that all  
 copies of the key *K* are securely held in equipment which may be trusted to  
 operate properly, and you see *{B, N}K*, you might be justiﬁed in deducing that  
 assumptions and their consequences is at the heart of security protocol design.

By now you might think that we understand all the protocol design aspects

of IFF. But we’ve omitted one of the most important problems – and one which  
 the designers of early IFF systems didn’t anticipate. As radar is passive the  
 returns are weak, while IFF is active and so the signal from an IFF transmitter  
 will usually be audible at a much greater range than the same aircraft’s radar  
 return. The Allies learned this the hard way; in January 1944, decrypts of

5And don’t forget: you also have to check that the intruder didn’t just reﬂect your own

challenge back at you. You must be able to remember or recognise your own messages!

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*4.4. MANIPULATING THE MESSAGE*

Enigma messages revealed that the Germans were plotting British and American  
 bombers at twice the normal radar range by interrogating their IFF. So more  
 modern systems authenticate the challenge as well as the response. The NATO  
 mode XII, for example, has a 32 bit encrypted challenge, and a di↵erent valid  
 challenge is generated for every interrogation signal, of which there are typically  
 250 per second. Theoretically there is no need to switch o↵ over enemy territory,  
 but in practice an enemy who can record valid challenges can replay them as  
 part of an attack. Relays are made di�cult in mode XII using directionality  
 and time-of-ﬂight.

Other IFF design problems include the di�culties posed by neutrals, error

rates in dense operational environments, how to deal with equipment failure,  
 how to manage keys, and how to cope with multinational coalitions. I’ll return to  
 IFF in Chapter 23. For now, the spurious-challenge problem serves to reinforce  
 an important point: that the correctness of a security protocol depends on the  
 assumptions made about the requirements. A protocol that can protect against  
 one kind of attack (being shot down by your own side) but which increases the  
 exposure to an even more likely attack (being shot down by the other side)  
 might not help. In fact, the spurious-challenge problem became so serious in  
 World War II that some experts advocated abandoning IFF altogether, rather  
 than taking the risk that one bomber pilot in a formation of hundreds would  
 ignore orders and leave his IFF switched on while over enemy territory.

**4.4** **Manipulating the Message**

We’ve now seen a number of middleperson attacks that reﬂect or spoof the in-  
 formation used to authenticate a participant. However, there are more complex  
 attacks where the attacker doesn’t just impersonate someone, but manipulates  
 the message content.

One example we saw already is the prepayment meter that remembers only

the last ticket it saw, so it can be recharged without limit by copying in the  
 codes from two tickets *A* and *B* one after another: *ABABAB...*. Another is  
 when dishonest cabbies insert pulse generators in the cable that connects their  
 taximeter to a sensor in their taxi’s gearbox. The sensor sends pulses as the prop  
 shaft turns, which lets the meter work out how far the taxi has gone. A pirate  
 device can insert extra pulses, making the taxi appear to have gone further. A  
 truck driver who wants to drive faster or further than regulations allow can use  
 a similar device to discard some pulses, so he seems to have been driving more  
 slowly or not at all. We’ll discuss such attacks in the chapter on ‘Monitoring  
 Systems’, in section 14.3.

As well as monitoring systems, control systems often need to be hardened

against message-manipulation attacks. The Intelsat satellites used for interna-  
 tional telephone and data tra�c have mechanisms to prevent a command being  
 accepted twice – otherwise an attacker could replay control tra�c and repeat-  
 edly order the same maneuver to be carried out until the satellite ran out of  
 fuel [1526]. We will see lots of examples of protocol attacks involving message  
 manipulation in later chapters on speciﬁc applications.

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*4.5. CHANGING THE ENVIRONMENT*

**4.5** **Changing the Environment**

A common cause of protocol failure is that the environment changes, so that  
 the design assumptions no longer hold and the security protocols cannot cope  
 with the new threats.

A nice example comes from the world of cash machine fraud. In 1993, Hol-

land su↵ered an epidemic of ‘phantom withdrawals’; there was much controversy  
 in the press, with the banks claiming that their systems were secure while many  
 people wrote in to the papers claiming to have been cheated. Eventually the  
 banks noticed that many of the victims had used their bank cards at a certain  
 ﬁlling station near Utrecht. This was staked out and one of the sta↵ was ar-  
 rested. It turned out that he had tapped the line from the card reader to the  
 PC that controlled it; his tap recorded the magnetic stripe details from their  
 cards while he used his eyeballs to capture their PINs [54]. Exactly the same  
 fraud happened in the UK after the move to ‘chip and PIN’ smartcards in the  
 mid-2000s; a gang wiretapped perhaps 200 ﬁlling stations, collected card data  
 from the wire, observed the PINs using CCTV cameras, then made up thou-  
 sands of magnetic-strip clone cards that were used in countries whose ATMs still  
 used magnetic strip technology. At our local ﬁlling station, over 200 customers  
 suddenly found that their cards had been used in ATMs in Thailand.

Why had the system been designed so badly, and why did the design error

persist for over a decade through a major technology change? Well, when the  
 standards for managing magnetic stripe cards and PINs were developed in the  
 early 1980’s by organizations such as IBM and VISA, the engineers had made  
 two assumptions. The ﬁrst was that the contents of the magnetic strip – the card  
 number, version number and expiration date – were not secret, while the PIN  
 was [1301]. (The analogy used was that the magnetic strip was your name and  
 the PIN your password.) The second assumption was that bank card equipment  
 would only be operated in trustworthy environments, such as in a physically  
 robust automatic teller machine, or by a bank clerk at a teller station. So it was  
 ‘clearly’ only necessary to encrypt the PIN, on its way from the PIN pad to the  
 server; the magnetic strip data could be sent in clear from the card reader.

Both of these assumptions had changed by 1993. An epidemic of card forgery,

mostly in the Far East in the late 1980’s, drove banks to introduce authenti-  
 cation codes on the magnetic strips. Also, the commercial success of the bank  
 card industry led banks in many countries to extend the use of debit cards  
 from ATMs to terminals in all manner of shops. The combination of these two  
 environmental changes destroyed the assumptions behind the original system  
 architecture. Instead of putting a card whose magnetic strip contained no secu-  
 rity data into a trusted machine, people were putting a card with clear security  
 data into an untrusted machine. These changes had come about so gradually,  
 and over such a long period, that the industry didn’t see the problem coming.

**4.6** **Chosen Protocol Attacks**

Governments keen to push ID cards have tried to get them used for many other  
 transactions; some want a single card to be used for ID, banking and even

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*4.6. CHOSEN PROTOCOL ATTACKS*

transport ticketing. Singapore went so far as to experiment with a bank card  
 that doubled as military ID. This introduced some interesting new risks: if a  
 Navy captain tries to withdraw some cash from an ATM after a good dinner and  
 forgets his PIN, will he be unable to take his ship to sea until Monday morning  
 when they open the bank and give him his card back?

Some ﬁrms are pushing multifunction authentication devices that could be

used in a wide range of transactions to save you having to carry around dozens  
 of di↵erent cards and keys. A more realistic view of the future may be that  
 people’s phones will be used for most private-sector authentication functions.

But this too may not be as simple as it looks. The idea behind the ‘Chosen

Protocol Attack’ is that given a target protocol, you design a new protocol that  
 will attack it if the users can be inveigled into reusing the same token or crypto  
 key. So how might the Maﬁa design a protocol to attack the authentication of  
 bank transactions?

Here’s one approach. It used to be common for people visiting a porn website

to be asked for ‘proof of age,’ which usually involves giving a credit card number,  
 whether to the site itself or to an age checking service. If smartphones are used  
 to authenticate everything, it would be natural for the porn site to ask the  
 customer to authenticate a random challenge as proof of age. A porn site might  
 then mount a ‘Maﬁa-in-the-middle’ attack as shown in Figure 4.3. They wait  
 until an unsuspecting customer visits their site, then order something resellable  
 (such as gold coins) from a dealer, playing the role of the coin dealer’s customer.  
 When the coin dealer sends them the transaction data for authentication, they  
 relay it through their porn site to the waiting customer. The poor man OKs it,  
 the Maﬁa gets the gold coins, and when thousands of people suddenly complain  
 about the huge charges to their cards at the end of the month, the porn site has  
 vanished – along with the gold [1032].

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | Buy 10 gold  Sign ‘X | |
| Customer | sigK X | Mafia porn� | sigK X |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |
|  | | | | | |
| BANK | | | | | |

site

Figure 4.3: – the Maﬁa-in-the-middle attack

In the 1990s a vulnerability of this kind found its way into international

standards: the standards for digital signature and authentication could be run  
 back-to-back in this way. It has since been shown that many protocols, though  
 secure in themselves, can be broken if their users can be inveigled into reusing  
 the same keys in other applications [1032]. This is why, if we’re going to use  
 our phones to authenticate everything, it will be really important to keep the  
 banking apps and the porn apps separate. That will be the subject of our next  
 chapter, on Access Control.

In general, using crypto keys (or other authentication mechanisms) in more

than one application is dangerous, while letting other people bootstrap their

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*4.7. MANAGING ENCRYPTION KEYS*

own application security o↵ yours can be downright foolish. The classic case is  
 where a bank relies for two-factor authentication on sending SMSes to customers  
 as authentication codes. As I discussed in section 3.4.1, the bad guys have

learned to attack that system by SIM-swap fraud – pretending to the phone  
 company that they’re the target, claiming to have lost their phone, and getting  
 a replacement SIM card.

**4.7** **Managing encryption keys**

The examples of security protocols that we’ve discussed so far are mostly about  
 authenticating a principal’s name, or application data such as the impulses  
 driving a taximeter. There is one further class of authentication protocols that  
 is very important – the protocols used to manage cryptographic keys.

**4.7.1** **The resurrecting duckling**

In the Internet of Things, keys can sometimes be managed directly and physi-  
 cally, by local setup and a policy of *trust-on-ﬁrst-use* or TOFU.

Vehicles provided an early example. I mentioned above that crooked taxi

drivers used to put interruptors in the cable from their car’s gearbox sensor  
 to the taximeter, to add additional mileage. The same problem happened in  
 reverse with tachographs, the devices used by trucks to monitor drivers’ hours  
 and speed. When tachographs went digital in the late 1990s, we decided to  
 encrypt the pulse train from the sensor. But how could keys be managed? The  
 solution was that whenever a new tachograph is powered up after a factory  
 reset, it trusts the ﬁrst crypto key it receives over the sensor cable. I’ll discuss  
 this further in section 14.3.

A second example is Homeplug AV, the standard used to encrypt data com-

munications over domestic power lines, and widely used in LAN extenders. In  
 the default, ‘just-works’ mode, a new Homeplug device trusts the ﬁrst key it  
 sees; and if your new wiﬁ extender mates with the neighbour’s wiﬁ instead,  
 you just press the reset button and try again. There is also a ‘secure mode’  
 where you open a browser to the network management node and manually en-  
 ter a crypto key printed on the device packaging, but when we designed the  
 Homeplug protocol we realised that most people have no reason to bother with  
 that.

The TOFU approach is also known as the ‘resurrecting duckling’ after an

analysis that Frank Stajano and I did in the context of the tachograph work.  
 The idea is that when a baby duckling hatches, it imprints on the ﬁrst thing it  
 sees that moves and quacks, even if this is the farmer – who can end up being  
 followed everywhere by a duck that thinks he’s mummy. If such false imprinting  
 happens with an electronic device, you need a way to kill it and resurrect it into  
 a newborn state – which the reset button does [1819].

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**4.7.2** **Remote key management**

The more common, and interesting, case is the management of keys in remote  
 devices. The basic technology was developed from the late 1970s to manage  
 keys in distributed computer systems, with cash machines being an early ap-  
 plication. In this section we’ll discuss shared-key protocols such as Kerberos,  
 leaving public-key protocols such as TLS and SSH until after we’ve discussed  
 public-key cryptology in Chapter 5.

The basic idea behind key-distribution protocols is that where two principals

want to communicate, they may use a trusted third party to introduce them.  
 It’s customary to give them human names in order to avoid getting lost in too  
 much algebra. So we will call the two communicating principals ‘Alice’ and

‘Bob’, and the trusted third party ‘Sam’. Alice, Bob and Sam are likely to be  
 programs running on di↵erent devices. (For example, in a protocol to let a car  
 dealer mate a replacement key with a car, Alice might be the car, Bob the key  
 and Sam the car maker.)

A simple authentication protocol could run as follows.

1. Alice ﬁrst calls Sam and asks for a key for communicating with Bob.

2. Sam responds by sending Alice a pair of certiﬁcates. Each contains a copy

of a key, the ﬁrst encrypted so only Alice can read it, and the second  
 encrypted so only Bob can read it.

3. Alice then calls Bob and presents the second certiﬁcate as her introduction.

Each of them decrypts the appropriate certiﬁcate under the key they share  
 with Sam and thereby gets access to the new key. Alice can now use the  
 key to send encrypted messages to Bob, and to receive messages from him  
 in return.

We’ve seen that replay attacks are a known problem, so in order that both

Bob and Alice can check that the certiﬁcates are fresh, Sam may include a  
 timestamp in each of them. If certiﬁcates never expire, there might be serious  
 problems dealing with users whose privileges have been revoked.

Using our protocol notation, we could describe this as

|  |  |
| --- | --- |
| *A ! S* :  *S ! A* :  *A ! B* : | *A, B*  *{A, B, KAB, T}KAS, {A, B, KAB, T}KBS*  *{A, B, KAB, T}KBS, {M}KAB* |

Expanding the notation, Alice calls Sam and says she’d like to talk to Bob.

Sam makes up a message consisting of Alice’s name, Bob’s name, a session key  
 for them to use, and a timestamp. He encrypts all this under the key he shares  
 with Alice, and he encrypts another copy of it under the key he shares with  
 Bob. He gives both ciphertexts to Alice. Alice retrieves the session key from  
 the ciphertext that was encrypted to her, and passes on to Bob the ciphertext  
 encrypted for him. She now sends him whatever message she wanted to send,  
 encrypted using this session key.

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*4.7. MANAGING ENCRYPTION KEYS*

**4.7.3** **The Needham-Schroeder protocol**

Many things can go wrong, and here is a famous historical example. Many

existing key distribution protocols are derived from the Needham-Schroeder  
 protocol, which appeared in 1978 [1426]. It is somewhat similar to the above,  
 but uses nonces rather than timestamps. It runs as follows:

|  |  |  |
| --- | --- | --- |
| Message 1 | *A ! S* :  *S ! A* :  *A ! B* :  *B ! A* :  *A ! B* : | *A, B, NA* |
| Message 2 | *{NA, B, KAB, {KAB, A}KBS}KAS*  *{KAB, A}KBS*  *{NB}KAB*  *{NB �* 1*}KAB* |
| Message 3 |
| Message 4 |
| Message 5 |

Here Alice takes the initiative, and tells Sam: ‘I’m Alice, I want to talk

to Bob, and my random nonce is *NA*.’ Sam provides her with a session key,  
 encrypted using the key she shares with him. This ciphertext also contains

her nonce so she can conﬁrm it’s not a replay. He also gives her a certiﬁcate to  
 convey this key to Bob. She passes it to Bob, who then does a challenge-response  
 to check that she is present and alert.

There is a subtle problem with this protocol – Bob has to assume that the

key *KAB* he receives from Sam (via Alice) is fresh. This is not necessarily so:  
 Alice could have waited a year between steps 2 and 3. In many applications this  
 may not be important; it might even help Alice to cache keys against possible  
 server failures. But if an opponent – say Charlie – ever got hold of Alice’s key,  
 he could use it to set up session keys with many other principals. And if Alice  
 ever got ﬁred, then Sam had better have a list of everyone in the ﬁrm to whom  
 he issued a key for communicating with her, to tell them not to believe it any  
 more. In other words, revocation is a problem: Sam may have to keep complete  
 logs of everything he’s ever done, and these logs would grow in size forever unless  
 the principals’ names expired at some ﬁxed time in the future.

Almost 40 years later, this example is still controversial. The simplistic view

is that Needham and Schroeder just got it wrong; the view argued by Susan  
 Pancho and Dieter Gollmann (for which I have some sympathy) is that this  
 is a protocol failure brought on by shifting assumptions [780, 1491]. 1978 was  
 a kinder, gentler world; computer security then concerned itself with keeping  
 ‘bad guys’ out, while nowadays we expect the ‘enemy’ to be among the users  
 of our system. The Needham-Schroeder paper assumed that all principals be-  
 have themselves, and that all attacks came from outsiders [1426]. Under those  
 assumptions, the protocol remains sound.

**4.7.4** **Kerberos**

The most important practical derivative of the Needham-Schroeder protocol is  
 Kerberos, a distributed access control system that originated at MIT and is now  
 one of the standard network authentication tools [1826]. It has become part of  
 the basic mechanics of authentication for both Windows and Linux, particularly  
 when machines share resources over a local area network. Instead of a single  
 trusted third party, Kerberos has two kinds: authentication servers to which

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users log on, and ticket granting servers which give them tickets allowing access  
 to various resources such as ﬁles. This enables scalable access management. In  
 a university, for example, one might manage students through their colleges or  
 halls of residence but manage ﬁle servers by departments; in a company, the  
 personnel people might register users to the payroll system while departmental  
 administrators manage resources such as servers and printers.

First, Alice logs on to the authentication server using a password. The client

software in her PC fetches a ticket from this server that is encrypted under her  
 password and that contains a session key *KAS*. Assuming she gets the password  
 right, she now controls *KAS* and to get access to a resource *B* controlled by the  
 ticket granting server *S*, the following protocol takes place. Its outcome is a  
 key *KAB* with timestamp *TS* and lifetime *L*, which will be used to authenticate  
 Alice’s subsequent tra�c with that resource:

|  |  |
| --- | --- |
| *A ! S* :  *S ! A* :  *A ! B* :  *B ! A* : | *A, B*  *{TS, L, KAB, B, {TS, L, KAB, A}KBS}KAS*  *{TS, L, KAB, A}KBS, {A, TA}KAB*  *{TA* + 1*}KAB* |

Translating this into English: Alice asks the ticket granting server for access

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| to *B*. If this is permissible, the ticket *{TS, L, KAB, A}KBS* is created containing  a suitable key *KAB* and given to Alice to use. She also gets a copy of the key in a  form readable by her, namely encrypted under *KAS*. She now veriﬁes the ticket  by sending a timestamp *TA* to the resource, which conﬁrms it’s alive by sending  back the timestamp incremented by one (this shows it was able to decrypt the  ticket correctly and extract the key *KAB*). |

The revocation issue with the Needham-Schroeder protocol has been ﬁxed

by introducing timestamps rather than random nonces. But, as in most of life,  
 we get little in security for free. There is now a new vulnerability, namely that  
 the clocks on our various clients and servers might get out of sync; they might  
 even be desynchronized deliberately as part of a more complex attack.

What’s more, Kerberos is a *trusted third-party* (TTP) protocol in that *S* is

trusted: if the police turn up with a warrant, they can get Sam to turn over  
 the keys and read the tra�c. Protocols with this feature were favoured during  
 the ‘crypto wars’ of the 1990s, as I will discuss in section 26.2.7. Protocols that  
 involve no or less trust in a third party generally use public-key cryptography,  
 which I describe in the next chapter.

A rather similar protocol to Kerberos is OAuth, a mechanism to allow secure

delegation. For example, if you log into Doodle using Google and allow Doo-  
 dle to update your Google calendar, Doodle’s website redirects you to Google,  
 which gets you to log in (or relies on a master cookie from a previous login)  
 and asks you for consent for Doodle to write to your calendar. Doodle then  
 gives you an access token for the calendar service [863]. I mentioned in sec-  
 tion 3.4.9.3 that this poses a cross-site phishing risk. OAuth was not designed  
 for user authentication, and access tokens are not strongly bound to clients. It’s  
 a complex framework within which delegation mechanisms can be built, with  
 both short-term and long-term access tokens; the details are tied up with how  
 cookies and web redirects operate and optimised to enable servers to be state-

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*4.8. DESIGN ASSURANCE*

less, so they scale well for modern web services. In the example above, you want  
 to be able to revoke Doodle’s access at Google, so behind the scenes Doodle only  
 gets short-lived access tokens. Because of this complexity, the OpenID Connect  
 protocol is a ‘proﬁle’ of OAuth which ties down the details for the case where  
 the only service required is authentication. OpenID Connect is what you use  
 when you log into your newspaper using your Google or Facebook account.

**4.7.5** **Practical key management**

So we can use a protocol like Kerberos to set up and manage working keys  
 between users given that each user shares one or more long-term keys with  
 a server that acts as a key distribution centre. But there may be encrypted  
 passwords for tens of thousands of sta↵ and keys for large numbers of devices  
 too. That’s a lot of key material. How is it to be managed?

Key management is a complex and di�cult business and is often got wrong

because it’s left as an afterthought. You need to sit down and think about how  
 many keys are needed, how they’re to be generated, how long they need to re-  
 main in service and how they’ll eventually be destroyed. There is a much longer  
 list of concerns – many of them articulated in the Federal Information Process-  
 ing Standard for key management [1408]. And things go wrong as applications  
 evolve; it’s important to provide headroom to support next year’s functionality.  
 It’s also important to support recovery from security failure. Yet there are no  
 standard ways of doing either.

Public-key cryptography, which I’ll discuss in Chapter 5, can simplify the

key-management task slightly. In banking the usual answer is to use dedicated  
 cryptographic processors called hardware security modules, which I’ll describe  
 in detail later. Both of these introduce further complexities though, and even  
 more subtle ways of getting things wrong.

**4.8** **Design assurance**

Subtle di�culties of the kind we have seen above, and the many ways in which  
 protection properties depend on subtle assumptions that may be misunderstood,  
 have led researchers to apply formal methods to protocols. The goal of this  
 exercise was originally to decide whether a protocol was right or wrong: it  
 should either be proved correct, or an attack should be exhibited. We often ﬁnd  
 that the process helps clarify the assumptions that underlie a given protocol.

There are several di↵erent approaches to verifying the correctness of proto-

cols. One of the best known is the *logic of belief*, or *BAN logic*, named after its  
 inventors Burrows, Abadi and Needham [357]. It reasons about what a principal  
 might reasonably believe having seen certain messages, timestamps and so on.  
 Other researchers have applied mainstream formal methods such as CSP and  
 veriﬁcation tools such as Isabelle.

Some history exists of ﬂaws being found in protocols that had been proved

correct using formal methods; I described an example in Chapter 3 of the second  
 edition, of how the BAN logic was used to verify a bank card used for stored-

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value payments. That’s still used in Germany as the ‘Geldkarte’ but elsewhere  
 its use has died out (it was Net1 in South Africa, Proton in Belgium, Moneo  
 in France and a VISA product called COPAC). I’ve therefore decided to drop  
 the gory details from this edition; the second edition is free online, so you can  
 download and read the details.

Formal methods can be an excellent way of ﬁnding bugs in security protocol

designs as they force the designer to make everything explicit and thus confront  
 di�cult design choices that might otherwise be fudged. But they have their  
 limitations, too.

We often ﬁnd bugs in veriﬁed protocols; they’re just not in the part that we

veriﬁed. For example, Larry Paulson veriﬁed the SSL/TLS protocol using his  
 Isabelle theorem prover in 1998, and about one security bug has been found every  
 year since then. These have not been ﬂaws in the basic design but exploited  
 additional features that had been added later, and implementation issues such  
 as timing attacks, which we’ll discuss later. In this case there was no failure of  
 the formal method; that simply told the attackers where they needn’t bother  
 looking.

For these reasons, people have explored alternative ways of assuring the de-

sign of authentication protocols, including the idea of *protocol robustness*. Just  
 as structured programming techniques aim to ensure that software is designed  
 methodically and nothing of importance is left out, so robust protocol design is  
 largely about explicitness. Robustness principles include that the interpretation  
 of a protocol should depend only on its content, not its context; so everything of  
 importance (such as principals’ names) should be stated explicitly in the mes-  
 sages. It should not be possible to interpret data in more than one way; so the  
 message formats need to make clear what’s a name, what’s an address, what’s  
 a timestamp, and so on; string formats have to be unambiguous and it should  
 be impossible to use the protocol itself to mount attacks on the software that  
 handles it, such as by bu↵er overﬂows. There are other issues concerning the  
 freshness provided by counters, timestamps and random challenges, and on the  
 way encryption is used. If the protocol uses public key cryptography or digi-  
 tal signature mechanisms, there are more subtle attacks and further robustness  
 issues, which we’ll start to tackle in the next chapter. To whet your appetite,  
 randomness in protocol often helps robustness at other layers, since it makes  
 it harder to do a whole range of attacks – from those based on mathematical  
 cryptanalysis through those that exploit side-channels such as power consump-  
 tion and timing to physical attacks that involve microprobes or lasers.

**4.9** **Summary**

Passwords are just one example of a more general concept, the security protocol.  
 Protocols specify the steps that principals use to establish trust relationships in  
 a system, such as authenticating a claim to identity, demonstrating ownership of  
 a credential, or establishing a claim on a resource. Cryptographic authentication  
 protocols are used for a wide range of purposes, from basic entity authentication  
 to providing infrastructure for distributed systems that allows trust to be taken  
 from where it exists to where it is needed. Security protocols are ﬁelded in all

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sorts of systems from remote car door locks through military IFF systems to  
 authentication in distributed computer systems.

Protocols are surprisingly di�cult to get right. They can su↵er from a num-

ber of problems, including middleperson attacks, modiﬁcation attacks, reﬂection  
 attacks, and replay attacks. These threats can interact with implementation  
 vulnerabilities and poor cryptography. Using mathematical techniques to verify  
 the correctness of protocols can help, but it won’t catch all the bugs. Some of  
 the most pernicious failures are caused by creeping changes in the environment  
 for which a protocol was designed, so that the protection it gives is no longer  
 relevant. The upshot is that attacks are still found frequently on protocols

that we’ve been using for years, and sometimes even on protocols for which we  
 thought we had a security proof. Failures have real consequences, including the  
 rise in car crime worldwide since car makers started adopting passive keyless  
 entry systems without stopping to think about relay attacks. Please don’t de-  
 sign your own protocols; get a specialist to help, and ensure that your design is  
 published for thorough peer review by the research community. Even specialists  
 get the ﬁrst versions of a protocol wrong (I have, more than once). It’s a lot  
 cheaper to ﬁx the bugs before the protocol is actually deployed, both in terms  
 of cash and in terms of reputation.

**Research Problems**

At several times during the past 30 years, some people have thought that pro-  
 tocols had been ‘done’ and that we should turn to new research topics. They  
 have been repeatedly proved wrong by the emergence of new applications with  
 a new crop of errors and attacks to be explored. Formal methods blossomed  
 in the early 1990s, then key management protocols; during the mid-1990’s the  
 ﬂood of proposals for electronic commerce mechanisms kept us busy. Since

2000, one strand of protocol research has acquired an economic ﬂavour as se-  
 curity mechanisms are used more and more to support business models; the  
 designer’s ‘enemy’ is often a commercial competitor, or even the customer. An-  
 other has applied protocol analysis tools to look at the security of application  
 programming interfaces (APIs), a topic to which I’ll return later.

Much protocol research is problem-driven, but there are still deep questions.

How much can we get out of formal methods, for example? And how do we  
 manage the tension between the principle that robust protocols are generally  
 those in which everything is completely speciﬁed and checked and the system  
 engineering principle that a good speciﬁcation should not overconstrain the im-  
 plementer?

**Further Reading**

Research papers on security protocols are scattered fairly widely throughout the  
 literature. For the historical background you might read the original Needham-  
 Schroeder paper [1426], the Burrows-Abadi-Needham authentication logic [357],  
 papers on protocol robustness [2, 112] and a survey paper by Anderson and

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Needham [113]. Beyond that, there are many papers scattered around a wide  
 range of conferences; you might also start by studying the protocols used in a  
 speciﬁc application area, such as payments, which we cover in more detail in  
 Part 2. As for remote key entry and other security issues around cars, a good  
 starting point is a tech report by Charlie Miller and Chris Valasek on how to  
 hack a Jeep Cherokee [1316].

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