**Chapter 27**

**Secure Systems**  
 **Development**

**My own experience is that developers with a clean, expressive set of**  
 **speciﬁc security requirements can build a very tight machine. They**  
 **don’t have to be security gurus, but they have to understand what**

**they’re trying to build and how it should work.**

– Rick Smith

**When it comes to being slaves to fashion, American managers make**

**adolescent girls look like rugged individualists.**

– Geo↵ Nunberg

**The fox knows many things; the hedgehog one big thing.**

– Archilochus

**27.1** **Introduction**

So far we’ve discussed a great variety of security applications, technologies and  
 concerns. If you’re a working engineer, manager or consultant, paid to build or  
 maintain a system with some security assurance requirements, you will by now  
 be looking for a systematic way to go about it. This brings us to such topics  
 as risk analysis, system engineering methodology, and, ﬁnally, the secret sauce:  
 how you manage a team to write secure code.

The secret is that there isn’t actually a secret, whether sauce or anything

else. Lots of people claim there is one and get religious fervour for the passion  
 of the moment, from the Orange Book in the 1980s to Agile Development now.  
 But the ﬁrst take o↵ered on this was the right one. In the 1960s Fred Brooks  
 led the team on the world’s ﬁrst really large software project, the operating  
 system for the IBM S/360 mainframe. In his classic book “The Mythical Man-  
 Month” he describes all the problems they struggled with, and his conclusion  
 is that “there is no silver bullet” [328]. There’s no magic formula that makes

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an intrinsically hard job easy. There’s also the famous line from Archilochus  
 at the head of this chapter: the fox knows many things, while the hedgehog  
 knows one big thing. Managing secure development is fox knowledge rather  
 than hedgehog knowledge. An experienced security engineering manager has  
 to know thousands of little things; that’s why this book is so fat! And the

security engineering manager’s job is getting harder all the time as software  
 gets everywhere and starts to interact with safety.

In 2017, I changed the way I teach undergraduates at Cambridge. Up till

then we’d taught security courses separately from software engineering, with the  
 latter focusing on safety. But most real-world systems require both, and they’re  
 entangled in complex ways. Both safety and security are emergent properties  
 that really have to be baked in from the beginning. Both involve systematic  
 thinking about what can go wrong, whether by accident or as a result of mal-  
 ice. Accidents can expose systems to attacks, and attacks can degrade systems  
 so they become dangerous. The course was developed further by my colleague  
 Alastair Beresford while I was on sabbatical in 2019, and the 2020 course on  
 Software and Security Engineering is now online as ten video lectures, thanks  
 to the pandemic [89]. That course is designed to give our ﬁrst-year undergrad-  
 uates a solid foundation for later work in security, cryptography and software  
 engineering. Like this book, it introduces the basics, from deﬁnitions through  
 the basics of protocols and crypto, then the importance of human and organiza-  
 tional issues as well as technical ones, illustrated with case histories. It discusses  
 how you set goals for safety and security, how you manage them as a system  
 evolves, and how you instil suitable ways of thinking and working into your  
 team. Success is about attitudes and work practices as well as skills.

The two questions you have to ask are, “Are we building the right system?”

and “Are we building it right?” In the rest of this chapter I’m going to start  
 with how we assess and manage risks – to both safety and security; and then  
 go on to discuss how we build systems, once we’ve got a speciﬁcation to work  
 to. I’ll then discuss some of the hazards that arise as a result of organisational  
 behaviour – a real but often ignored kind of insider threat.

**27.2** **Risk Management**

At the heart of both safety engineering and security engineering lie decisions  
 about priorities: how much to spend on protection against what. Risk man-  
 agement must be done within a broader framework of managing all the risks  
 to an enterprise or indeed to a nation. That is often done badly. The coron-  
 avirus crisis should have made it obvious to everyone that although pandemics  
 were at the top of the risk register of many countries, including the UK, most  
 governments spent much more of their resilience budget on terrorism, which  
 was several places down the list. Countries with recent experience of SARS or  
 MERS, such as Taiwan and South Korea, did better: they were ready to test  
 residents and trace contacts at scale, and responded quickly. Britain wasted two  
 months before realising the disease was serious, at a cost of tens of thousands  
 of lives.

So what actually is a *risk register*? A common methodology, as used by

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the governing body of my university, is to draw up a list of things that could  
 go wrong, giving them scores of 1 to 5 for seriousness and for probability of  
 occurrence, and multiplying these together to get a number between 1 and 25.  
 For example, a university might rate ‘loss of research contract income due to  
 economic downturn’ at 5/5 for seriousness if 20% of its income is from that  
 source, and rate ‘probability’ at 4/5 as downturns happen frequently but not  
 every year, giving a raw product of 20. You then write down the measures you  
 take to mitigate each of these risks, and have an argument in a risk committee  
 about how well each risk is mitigated. For example, you control the risk of  
 variable research contract income by making a rule that it can be used to hire  
 only contract sta↵, not tenured faculty; you might then agree that this rule cuts  
 that risk from 20 to 16. You then rank all the risks in order and assign one  
 senior o�cer to be the owner of each of them.

National risk assessments are somewhat similar: you rate each possible bad

event (pandemic, earthquake, forest ﬁre, terrorist attack, ...) by how many peo-  
 ple it might kill (millions? thousands? dozens?) and then rate it for probability  
 by how many you expect each century. The UK national risk register, for ex-  
 ample, put pandemic inﬂuenza at the top, with a 5 for severity (could kill up to  
 750,000) and a 4 for likelihood, saying in 2017: “one or more major hazards can  
 be expected to materialise in the UK in every ﬁve-year period. The most seri-  
 ous are pandemic inﬂuenza, national blackout and severe ﬂooding” [361]. You  
 then work out what’s reasonably practical by way of mitigation, be it quaran-  
 tine plans and PPE stockpiles for a pandemic, or building codes and zoning to  
 limit the damage from ﬂoods and earthquakes. You do the cost-beneﬁt analysis  
 and turn priorities into policy. You can get things wrong in various ways. The  
 UK largely ignored pandemics because the National Security Council had been  
 captured by the security and intelligence agencies; they prioritised terrorism,  
 and the health secretary was not a regular attendee [1848]. I already discussed  
 terrorism in section 26.3; here I’ll just add that another aspect of the failure  
 was policy overshoot. When 9/11 taught the world that terrorist attacks can  
 kill thousands rather than just dozens, and the agencies got a lot more of the  
 resilience budget, it made them greedy: they started talking up the risk of ter-  
 rorists getting hold of a nuke so they’d have an even scarier threat on the register  
 to justify their budgets.

In business too you can ﬁnd that both political behaviour and organisational

behaviour get in the way of rational risk management. But you often have real  
 data on the more common losses, so you can attempt a more quantitative ap-  
 proach. The standard method is to calculate the *annual loss expectancy* (ALE)  
 for each possible loss scenario, as the expected loss multiplied by the number of  
 incidents expected in an average year. A typical ALE analysis for a bank’s IT  
 systems might have several hundred entries, including items such as we see in  
 Figure 27.1.

Note that while accurate ﬁgures are likely to be available for common losses

(such as ‘teller takes cash’), the incidence of low-probability high-risk losses such  
 as a large money-transfer fraud is largely guesswork – though you can sometimes  
 get a rough sanity check by asking for insurance quotes.

ALEs have long been standardized by NIST as the technique to use in US

government procurements. The UK government uses a tool called CRAMM for

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| **Loss type** **Amount** **Incidence** **ALE** |
| SWIFT fraud $50,000,000 .005 $250,000  ATM fraud (large) $250,000 .2 $100,000  ATM fraud (small) $20,000 .5 $10,000  Teller takes cash $3,240 200 $648,000 |

Figure 27.1: – items of annualized loss expectancy (ALE)

systematic analysis of information security risks, and the modern audit culture  
 is spreading such tools everywhere. But the process of producing such a table  
 for low-probability threats tends to be just iterative guesswork. The consultants  
 list all the threats they can think of, attach notional probabilities, work out the  
 ALEs, add them up, and ﬁnd that the bank’s ALE exceeds its income. They  
 then tweak the total down to whatever will justify the largest security budget  
 that their client the CISO has said is politically possible. I’m sorry if this sounds  
 a bit cynical; but it’s what often seems to happen. The point is, ALEs may be  
 of some value, but you need to understand what parts are based on data, what  
 parts on guesswork and what parts on o�ce politics.

Product risks are di↵erent. Di↵erent industries do things di↵erently because

of the way they evolved and the history of regulation. The rules for each sector,  
 whether cars or aircraft or medical devices or railway signals, have evolved  
 in response to accidents and industry lobbying. Increasingly, the European

Union is becoming the world’s safety regulator as it’s the biggest market, as  
 Washington cares less about safety than Brussels does, and as it’s simpler for  
 OEMs to engineer to EU safety speciﬁcations than to have multiple products.  
 I’ll discuss safety and security certiﬁcation in more detail in the next chapter.  
 For present purposes, software for cars, planes and medical devices must be  
 developed according to approved procedures, subjected to analyses we’ll discuss  
 later, and tested in speciﬁc ways.

Insurance can be of some help in managing large but unlikely risks. But the

insurance business is not completely scientiﬁc either. Your insurance premiums  
 used to give some signal of the risk your business was running, especially if you  
 bought cover for losses of eight ﬁgures or above. But insurance is a cyclical  
 industry, and since about 2017 a host of new companies have started o↵ering  
 insurance against cybercrime, squeezing the proﬁts out of the market. As a  
 result, customers will no longer put up with intrusive questionnaires, let alone  
 site visits from assessors. So most insurers’ ability to assess risk is now limited;  
 I will discuss the mechanics of what they do further in section 28.2.9. They are  
 also wary of correlated risks that give rise to many claims at once, as that would  
 force them to hold greater reserves; as some cyber risks are correlated, policies  
 tend to either exclude them or be relatively expensive [275]. (The coronavirus  
 crisis is teaching ﬁrms about correlated risk as some insurers refuse to pay up  
 on business-interruption risk policies – even those that explicitly mention the  
 risk of sta↵ not being able to get to the o�ce because of epidemics; businesses  
 are asking insurers in turn what the point of insurance is.)

Actuarial risks aside, a very important reason for large companies to take

out insurance cover – and for much other corporate behaviour – is to protect

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executives, rather than shareholders. The risks that are being tackled may seem  
 on the surface to be operational but are actually legal, regulatory and PR risks.  
 Directors demand liability insurance, and under UK and US law, professional  
 negligence occurs when a professional fails to perform their responsibilities to the  
 level required of a reasonably competent person in their profession. So negligence  
 claims are assessed by the current standards of the industry or profession, giving  
 a strong incentive to follow the herd. This is one reason why management is  
 such a fashion-driven business (as per the quote at the head of this chapter).  
 This spills over into the discourse used to justify security budgets. During the  
 mid 1980’s, everyone talked about hackers (even if their numbers were tiny).  
 From the late 80’s, viruses took over the corporate imagination, and people got  
 rich selling antivirus software. In the mid-1990s, the ﬁrewall became the star  
 product. The late 1990s saw a frenzy over PKI. By 2017 it was blockchains.  
 Amidst all this hoopla, the security professional must keep a level head and  
 strive to understand what the real threats are.

We will return to organisational behaviour in a later section. First, let’s see

what we can learn from safety engineering.

**27.3** **Lessons from safety-critical systems**

*Critical computer systems* are those in which a certain class of failure is to  
 be avoided if at all possible. Depending on the class of failure, they may be  
 safety-critical, business-critical, security-critical, or critical to the environment.  
 Obvious examples of the safety-critical variety include ﬂight controls and auto-  
 matic braking systems. There’s a large literature on this subject, and a lot of  
 methodologies have been developed to help manage risk intelligently.

**27.3.1** **Safety engineering methodologies**

Safety engineering methodologies, like classical security engineering, tend to  
 work systematically from a safety analysis to a speciﬁcation through to a prod-  
 uct, and assume you’re building safety in from the start rather than trying to  
 retroﬁt it. The usual procedure is to identify hazards and assess risks; decide  
 on a strategy to cope with them (avoidance, constraint, redundancy ...); trace  
 the hazards to hardware and software components which are thereby identiﬁed  
 as critical; identify the operator procedures which are also critical and study  
 the various applied psychology and operations research issues; set out the safety  
 functional requirements which specify what the safety mechanisms must do, and  
 safety integrity requirements that specify the likelihood of a safety function be-  
 ing performed satisfactorily; and ﬁnally decide on a test plan. The outcome of  
 testing is not just a system you’re conﬁdent to run live, but an integrated part of  
 a *safety case* to justify running it. The basic framework is set out in standards  
 such as ISO 61508, a basic safety framework for relatively simple programmable  
 electronics such as the control systems for chemical plants. This has been ex-  
 tended with more specialised standards for particular industries, such as ISO  
 26262 for road vehicles.

This safety case will provide the evidence, if something does go wrong, that

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Figure 27.2: – hazard elimination in motor reversing circuit

you exercised due care. It will typically consist of the hazard analysis, the

safety functional and integrity requirements, and the results of tests (both at  
 component level and system level) which show that the required failure rates  
 have been achieved. The testing may have to be done by an accredited third  
 party; with motor vehicles ﬁrms get away with the safety case being done by  
 a di↵erent department in the same company, with independent management.  
 Vehicles are a more complex case because of their supply chains. At the top is  
 the brand, whose badge you see on the front of the car. Then there’s the *original*  
 *equipment manufacturer* (OEM) which in the case of cars is usually the same  
 company, but not always; in other industries the brand and the OEM are quite  
 separate. A modern car will have components from dozens of manufacturers,  
 of which the Tier 1 suppliers who deal directly with the brand do much of the  
 research and development work but get components from other ﬁrms in turn.  
 In the car industry, the brand puts the car through type approval and carries  
 the primary liability, but demands indemnities from component suppliers in case  
 things go wrong (the law in most countries does not allow you to disclaim liability  
 for death and injury). The brand relies on the supply chain for signiﬁcant parts  
 of the safety functionality and integrity and thus for the safety case. There are  
 also tensions: as we already noted, safety certiﬁcation can prevent the timely  
 application of security patches. Let’s now look at common safety engineering  
 methods and what they can teach us.

**27.3.2** **Hazard analysis**

In an ideal case, we might be able to design hazards out of a system completely.  
 As an example, consider the motor reversing circuits in Figure 27.2. In the

design on the left, a double-pole double-throw switch reverses the current passing  
 from the battery through the motor. However, this has a potential problem: if  
 only one of the two poles of the switch moves, the battery will be shorted and  
 a ﬁre may result. The solution is to exchange the battery and the motor, as in  
 the modiﬁed circuit on the right. Here, a switch failure will only short out the  
 motor, not the battery. Safety engineering is not just about correct operation,  
 but about correct failure too.

Hazard elimination is useful in security engineering too. We saw an example

in the early design of SWIFT in section 12.3.2: there, the keys used to authen-  
 ticate transactions between one bank and another were exchanged between the

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| Successful card forgery�  Shoulder� Cryptanalysis of DES�  surfing�  False�  terminal�  attack� Protocol failure�  attack� Protocol failure�  Bank insider� Maintenance�  contractor�  Abuse of� Trojan� Theft of� Bug in� Encryption� Falsify�  security� keys� ATM� replacement� auth�  module� response� |

Figure 27.3: – a threat tree

banks directly, so SWIFT did not have the means to forge a valid transaction  
 and its sta↵ and systems had to be trusted less. In general, minimizing the  
 trusted computing base is an exercise in hazard elimination. The same applies  
 in privacy engineering too. For example, if you’re designing a contact tracing  
 app to monitor who might have infected whom in an epidemic, one approach is  
 to have a central database of everyone’s mobile phone location history. However  
 that has obvious privacy hazards, which can be reduced by keeping a Bluetooth  
 contact history on everyone’s mobile phone instead, and uploading the contact  
 history of anyone who calls in sick. You then have a policy decision to take  
 between better privacy and better tracing.

**27.3.3** **Fault trees and threat trees**

Once you have eliminated as many hazards as possible, the next step is to iden-  
 tify failures that could cause accidents. A common top-down way of identifying  
 the things that can go wrong is *fault tree analysis* where a tree is constructed  
 whose root is the undesired behavior and whose successive nodes are its possible  
 causes. This top-down approach is natural where you have a complex system  
 with a small number of well-known bad outcomes that you have to avoid. It  
 carries over in a natural way to security engineering. Figure 27.3 shows an ex-  
 ample of a fault tree (or *threat tree*, as it’s often called in security engineering)  
 for fraud from automatic teller machines.

Threat trees are used in the US Department of Defense. You start out from

each undesirable outcome, and work backwards by writing down each possible  
 immediate cause. You then recurse by adding each precursor condition. By  
 working round the tree’s leaves you should be able to see each combination  
 of technical attack, operational blunder, physical penetration and so on which  
 could break your security policy. The other nice thing you get from this is a  
 visualisation of commonality between attack paths, which makes it easier to  
 reason about how to disrupt the most attacks with the least e↵ort. In some

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variants, attack branches have countermeasure sub-branches, which may have  
 counter-countermeasure attack branches, and so on, in di↵erent colours for em-  
 phasis. A threat tree can amount to an attack manual for the system, so it may  
 be highly classiﬁed, but it’s a DoD requirement – and if the system evaluators  
 or accreditors can ﬁnd signiﬁcant extra attacks, they may fail the product.

**27.3.4** **Failure modes and e↵ects analysis**

Returning to the safety-critical world, another way of doing hazard analysis  
 is *failure modes and e↵ects analysis* (FMEA), pioneered by NASA, which is  
 bottom-up rather than top-down1. This involves tracing the consequences of a  
 failure of each of the system’s components all the way up to the e↵ect on the  
 mission. This is the natural approach in systems with a small number of well-  
 understood critical components or subsystems, such as aircraft. For example, if  
 you’re going to ﬂy a plane over an ocean or mountains where you can’t glide to an  
 airport in the case of engine failure, then engine power is critical. You therefore  
 study the mean time to failure of your powerplant and its failure modes, from  
 a broken connecting rod to running out of fuel. You insist that single-engine  
 aircraft use reliable engines and you regulate the maintenance schedules; planes  
 have more than one fuel tank. When carrying a lot of passengers, you insist on  
 multi-engine aircraft and drill the crews to deal with engine failure.

An aerospace example of people missing a failure mode that turned out to

be critical is the 1986 loss of the space shuttle Challenger. The O-rings in

the booster rockets were known to be a risk by the NASA project manager, and  
 damage had been found on previous ﬂights; meanwhile the contractor knew that  
 low temperatures increased the risk; but the concerns did not come together  
 or get through to NASA’s top management. An O-ring, made brittle by the  
 cold, failed – causing the loss of the shuttle and seven crew. On the resulting  
 board of inquiry, the physicist Richard Feynman famously demonstrated this  
 on TV by putting a sample of O-ring in a clamp, freezing it in iced water and  
 then showing that when he released it, it remained dented and did not spring  
 back [1612]. This illustrates that failures are often not just technical but also  
 involve how people behave in organisations: when protection mechanisms cross  
 institutional boundaries, as for example with cars, you need to think of the law  
 and economics as well as just the engineering. Such problems will become much  
 more complex as we move towards autonomous vehicles, which will rely on all  
 sorts of third-party services and infrastructure.

**27.3.5** **Threat modelling**

Both fault trees and FMEA depend on the analyst understanding the system  
 really well; they are hard to automate, not fully repeatable and can be up-ended  
 by a subtle change to a subsystem. So a thorough analysis of failure modes will  
 often combine top-down and bottom-up approaches with some methods speciﬁc

1FMEA is bottom-up in the technical sense that the analysis works up from individual

components, but its actual management often has a top-down ﬂavour as you start work on  
 the safety case once you have an outline design and reﬁne it progressively as the design is  
 evolved into a product.

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to the application that people have learned over time. Many industries now have  
 to rethink their traditional safety analysis methods to incorporate security.

In car safety, complex supply chains mean we have to do multiple interlocking

analyses of vehicles and their subsystems. A traditional subsystem analysis

might work through the failure modes of headlamps, since losing them while  
 driving at night can lead to an accident. As well as mitigating the risk of a  
 lamp failure by having two or more lamps, you worry about switch failure, and  
 when the switch becomes electronic you build a fault tree of possible hardware  
 and software faults. When we extend this from safety to security, we think

about whether an attacker might take over the entertainment system in a car,  
 and use it to send a malicious ‘lamp o↵’ message on the CAN bus once the car  
 is moving quickly enough for this to be dangerous. This analysis may lead to a  
 design decision to have a ﬁrewall between the cabin CAN bus and the powertrain  
 CAN bus. (This is the worked example in the new draft ISO 21434 standard  
 for cybersecurity in road vehicles [962].)

More generally, the shift from safety to security means having to think sys-

tematically about insiders. Just as double-entry bookkeeping was designed to  
 be resilient against a single dishonest clerk and has been re-engineered against  
 the similar threat of a clerk with malware on their PC, so modern large-scale  
 systems are typically designed to limit the damage if a single component is com-  
 promised. So how can you incorporate malicious insiders into a threat model? If  
 you’re using FMEA, you can just add an opponent at various locations, as with  
 our malicious ‘lamp o↵’ message. As for more complex systems, the methodol-  
 ogy adopted by Microsoft following its big push in 2003 to make Windows and  
 O�ce more secure is described by Frank Swiderski and Window Snyder [1851].  
 Rather than being purely top-down or bottom-up, this is a meet-in-the-middle  
 approach. The basic idea is that you list not just the assets you’re trying to  
 protect (ability to do transactions, access to conﬁdential data, whatever) but  
 also the assets available to an attacker (perhaps the ability to subscribe to your  
 system, or to manipulate inputs to the smartcard you supply him, or to get a  
 job at your call center). You then trace the attack paths through the system,  
 from one module to another. You try to ﬁgure out what the trust levels might  
 be; where the barriers are; and what techniques, such as spooﬁng, tampering,  
 repudiation, information disclosure, service denial and elevation of privilege,  
 might be used to overcome particular barriers. The threat model can be used  
 for various purposes at di↵erent points in the security development lifecycle,  
 from architecture reviews through targeting code reviews and penetration tests.

There are various ways to manage the resulting mass of data. An elemen-

tary approach is to construct a matrix of hazards against safety mechanisms,  
 and if the safety policy is that each serious hazard must be constrained by at  
 least two independent mechanisms, then you can check for two entries in each  
 of the relevant columns. So you can demonstrate graphically that in the pres-  
 ence of the hazard in question, at least two failures will be required to cause an  
 accident. An alternative approach, *system theoretic process analysis* (STPA),  
 starts o↵ with the hazards and then designs controls in a top-down process,  
 leading to an architectural design for the system; this can be helpful in teasing  
 apart interacting control loops [1150]. Such methodologies go across to secu-  
 rity engineering [1556]. One way or another, in order to make the complexity

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manageable, you may have to organise a hierarchy of safety and security goals.  
 The security policies discussed in Part II of this book may give you the begin-  
 nings of an answer for the applications we discussed there, and some inspiration  
 for others. This hierarchy can then drive a risk matrix or risk treatment plan  
 depending on the terminology in use in your industry.

**27.3.6** **Quantifying risks**

The safety-critical systems community has a number of techniques for dealing  
 with failure and error rates. Component failure rates can be measured statisti-  
 cally; the number of bugs in software can be tracked by techniques I’ll discuss in  
 the next chapter; and there is a lot of experience with the probability of opera-  
 tor error at di↵erent types of activity. The bible for human-factors engineering  
 in safety-critical systems is James Reason’s book *‘Human Error’*; I discussed in  
 Chapter 3 the rising tide of research in security usability through the 2010s as  
 the lessons from the safety world have started to percolate into our ﬁeld.

The error rate in a task depends on its familiarity and complexity, the

amount of pressure and the number of cues to success. Where a task is simple,  
 performed often and there are strong cues to success, the error rate might be  
 1 in 100,000 operations. However, when a task is performed for the ﬁrst time  
 in a confusing environment where logical thought is required and the operator  
 is under pressure, then the odds can be against successful completion. Three  
 Mile Island and Chernobyl taught nuclear engineers that no matter how many  
 design walkthroughs you do, it’s when the red lights go on for real that the  
 worst mistakes get made. The same lesson has come out of one air accident  
 investigation after another. When dozens of alarms go o↵ at once, there’s a fair  
 chance that someone will push the wrong button. One guiding principle is to  
 default to a safe state: to damp down a nuclear reaction, to return an aircraft  
 to straight and level ﬂight, or to bring an autonomous vehicle to a stop at the  
 side of the road. No principle is foolproof, and a safe state may be hard to  
 measure. A vehicle can ﬁnd it hard to tell where the side of the road is if there’s  
 a grass verge; and in the Boeing 737Max crashes (which I describe in detail in  
 section 28.2.4) the ﬂight control computer tried to keep the plane level but was  
 confused by a faulty angle-of-attack sensor and dived the plane into the ground  
 instead.

Another principle of safety usability in an emergency is to keep the infor-

mation given to operators, and the controls available for them to use, both  
 simple and intuitive. In the old days, each feed went to a single gauge or dial  
 and there was only so much space for them. The temptation nowadays is to  
 give the operator everything, because you can. In the old days, designers knew  
 that an emergency would give the pilots tunnel vision so they put the six in-  
 struments they really needed right in the middle. Nowadays there can be ﬁfty  
 alarms rather than two and pilots struggle to work out which screen on which  
 menu of the electronic ﬂight information system to look at. It is much broader  
 than aviation. A naval example is the 2017 collision of the USS McCain in the  
 Straits of Singapore, where UI confusion was a major factor. Steering control  
 was shifted to the wrong helm station and an engine was not throttled back in  
 time, resulting in an uncommanded turn to port across a busy shipping lane,

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*27.3. LESSONS FROM SAFETY-CRITICAL SYSTEMS*

impact with a chemical tanker, and the death of ten sailors [1929].

So systems that are not fully autonomous must remain controllable, and for

that the likely human errors need to be understood. Quite a lot is known about  
 the cognitive biases and other psychological factors that make particular types of  
 error more common; we discussed them in Chapter 3, and a prudent engineer will  
 study how they work out in their ﬁeld. Errors are rare in frequently-performed  
 tasks at which the operator has developed some skill, and are more likely when  
 operators are stressed and surprised. This starts to get us out of the territory  
 of risk, where the odds are known, and into that of uncertainty, where they’re  
 not.

In security systems, too, the most egregious blunders can be expected in

important but rarely performed tasks. Security usability isn’t just about pre-  
 senting a nice intuitive interface to the end-user. It should present the risks in  
 a way that accords with common mental models of threat and protection, and  
 the likely user reactions to stress should lead to safe outcomes.

It is important to be realistic about the skill level of the people who will

perform each critical task and any known estimates of the likelihood of error.  
 An airplane designer can rely on a predictable skill level from anyone with a  
 commercial pilot’s license, and a shipbuilder knows the strengths and weaknesses  
 of an o�cer in the merchant marine. Cars can and do get operated by drivers  
 who are old and frail, young and inexperienced, distracted by passengers, or  
 under the inﬂuence of alcohol. At the professional end of things, usability testing  
 can be proﬁtably integrated with sta↵ training: when pilots go for their refresher  
 courses in the simulator, instructors throw all sorts of combinations of equipment  
 failure, bad weather, cabin crisis and air-tra�c-control confusion at them. They  
 observe what combinations of stress result in fatal accidents, and how these di↵er  
 across cockpit types. Such data are valuable feedback to cockpit designers. In  
 aviation, the incentives for safe operation are su�ciently strong and well aligned,  
 and the scale is large enough, to support a learning system. Even so, there are  
 expensive disasters, such as the Boeing 737Max ﬂight control software This not  
 only had at least one serious bug, but escaped a proper failure modes and e↵ects  
 analysis because the engineers responsible – under pressure from their managers  
 to complete the project on time – wrongly assumed that pilots would be able  
 to cope with any failure [89]. As a result, the software relied on a single angle-  
 of-attack sensor rather than using the two sensors with which the aircraft was  
 ﬁtted, and sensor failure led to fatal accidents2.

When testing the usability of redundant systems, you need to pay attention

to *fault masking*: if the output is determined by majority voting between three  
 processors, and one of them fails, then the system will continue to work ﬁne  
 – but its safety margin will have been eroded, perhaps in ways the operators  
 won’t understand properly. Several air crashes have resulted from ﬂying an

airliner with one of the cockpit systems out of action; although pilots may  
 be intellectually aware that one of the data feeds to the cockpit displays is  
 unreliable, they may rely on it under pressure by reﬂex rather than checking  
 with other instruments. So you have to think hard about how faults can remain

2Aviation safety standards such as DO178 and DO254 generally require diversity in mea-

surement type, physics, processing characteristics in addition to redundancy to mitigate  
 common-mode failures.

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*27.4. PRIORITISING PROTECTION GOALS*

visible and testable even when their immediate e↵ects are mitigated.

Another lesson from safety-critical systems is that although a safety require-

ments speciﬁcation and test criteria will be needed as part of the safety case for  
 the lawyers and regulators, it is good practice to integrate both of them with  
 the mainstream product documentation. If the safety case is separate, then it’s  
 easy to sideline it after approval and fail to maintain it properly. (This was a  
 factor in the Boeing 737Max disaster as the usability assumptions underlying  
 the safety case for the ﬂight control software were not updated from the pre-  
 vious model of 737.) The move from project-based software management to  
 agile methodologies, and via DevOps to DevSecOps, is ﬁnally starting to embed  
 security management into the way products evolve. We will discuss this in the  
 next section.

Finally, safety is like security in that it really has to be built in as a system

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| is developed, rather than retroﬁtted. The main di↵erence between the two is  in the failure model. Safety deals with the e↵ects of random failure, while in  security we assume a hostile opponent who can cause some of the components  of our system to fail at the least convenient time and in the most damaging way  possible. People are naturally more risk-averse in the presence of an adversary;  I will discuss this in section 28.4. A safety engineer will certify a critical ﬂight-  control system with an MTBF of 109 hours; a security engineer has to worry  whether an adversary can force the preconditions for that one-in-a-billion failure  and crash the plane on demand. |

In e↵ect, our task is to program a computer that gives answers which are

subtly and maliciously wrong at the most inconvenient moment possible. I’ve  
 described this as ‘programming Satan’s computer’ to distinguish it from the  
 more common problem of programming Murphy’s [113]. This is one of the

reasons security engineering is hard: Satan’s computer is harder to test [1668].

**27.4** **Prioritising protection goals**

If you’ve a project to create an entirely new product, or to radically change an  
 existing one, it’s an idea to spend some time thinking through the protection  
 priorities from ﬁrst principles. A careful safety analysis or threat modelling

exercise can provide some numbers to inform this. When developing a safety  
 case or a security policy in detail, it’s essential to understand the context, and  
 much of this book has been about the threat models relevant to a wide range  
 of applications. You should try to reﬁne numerical estimates of risk from the  
 environment or context as well.

In the case of a business system, analysis will hinge on the tradeo↵ between

risk and reward. Security people often focus too much on the former. If your  
 ﬁrm has a turnover of $10m, gross proﬁts of $1m and theft losses of $150,000,  
 you might make a loss-reduction pitch about ‘how to increase proﬁts by 15%  
 by stopping theft’; but if you could double the turnover to $20m, then the  
 shareholders would prefer that even if it triples the losses to $450,000. Proﬁt  
 is now $1.55m, up 85%, rather than 15%. This is borne out by the experience  
 of online fraud engines. When discussing fraud management strategies with a

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*27.4. PRIORITISING PROTECTION GOALS*

number of retailers, I noticed that the ﬁrms who got the best results were those  
 where the fraud management team reported to sales rather than ﬁnance. A  
 typical bricks-and-clicks retailer in the UK might decline something like 4% of  
 o↵ered shopping baskets because the fraud engine alerts at the combination of  
 goods, delivery address and payment details. So if you can improve the fraud  
 engine and reject only 3%, that’s 1% more sales – a prospect to light up your  
 Chief Marketing O�cer’s eyes. But if the fraud team reports instead to the  
 Chief Financial O�cer, they’re likely to be seen as a cost rather than as an  
 opportunity.

Similarly, the site reliability engineers of online services have learned not

to make a system too reliable. If local Internet availability is only 99%, then  
 a service that’s up 99.9% of the time will be ﬁne; there’s no point spending  
 millions more to hit 99.99% if none of your users will notice the di↵erence.  
 You’re better o↵ deliberately setting an 0.1% *error budget* which you can use  
 productively, such as by causing occasional deliberate failures to exercise your  
 resilience mechanisms [236]. This brings me to one of the open debates in

security management: should one aim at having no CVEs open in any of the  
 software on which one relies? The tick-box approach is to say ‘Of course there  
 must be no open CVEs’, but that may impose a rather high compliance cost.  
 If you’re Google, and wrote all your own infrastructure, maybe you can aim at  
 that; many ﬁrms can’t and have to prioritise. I’ll discuss CVEs in more detail  
 in section 27.5.7.1 later.

So don’t trust people who can only talk about ‘tightening security’. Often

it’s too tight already, and what you really need to do is just focus it slightly  
 di↵erently. In the ﬁrst edition of this book, I presented a case study of self-service  
 checkout at supermarkets. Twenty years ago, a number of supermarkets started  
 to introduce self-checkout lanes. Some started to obsess about losses, and let  
 security get in the way of usability by aggressively challenging customers about  
 product weight. One of the stores that got an advantage started with a more  
 forgiving approach which they tuned up gradually in the light of experience.  
 Eventually the industry ﬁgured out how to operate self-checkout lanes, but  
 the quality of the implementation still varies signiﬁcantly. By early 2020, the  
 pioneers are small convenience stores like Lifvs in Sweden which have no sta↵;  
 you open the store’s door with an app, scan your purchases and pay online.  
 Amazon was also experimenting with fully self-service food stores. We saw the  
 next 20 years of innovation crammed into the few months of the 2020 coronavirus  
 lockdown; by June, other supermarkets have been urging us to download their  
 scanning app, scan our purchases as we pick them, charge them to a card, and  
 just go.

Many modern business models were once considered too risky, starting with

the self-service supermarket itself back in the days when grocers kept all the  
 goods behind the counter. Everyone thought Richard Sears would go bust when  
 he adopted the slogan ‘Satisfaction guaranteed or your money back’ in the 1880s,  
 yet he invented the modern mail-order business. In business, proﬁt is the reward  
 for risk. But entrepreneurs who succeed may have to improve security quickly.  
 One recent example is the videoconferencing platform Zoom – which grew from  
 20 million users to 200 million in March 2020, and changed in the process from  
 an enterprise platform into something more like a public utility – forcing them

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into a major security engineering e↵ort [1763].

Trade-o↵s in safety are harder. Logically, the value of a human life in a de-

veloped country might be a few million dollars, that being an average person’s  
 lifetime earnings. However our actual valuation of a human life as revealed by  
 safety behaviour varies from about $50,000 for improvements to road junctions,  
 up to over $500m for train protection systems – and that’s just in the context of  
 transport policy. The variance in health policy is even greater, with costs per life  
 saved ranging from a few hundred dollars for ﬂu jabs and some cancer screening  
 to billions for the least e↵ective interventions [1869]; in other safety contexts, do-  
 mestic smoke alarms cost a few hundred dollars per life saved while the number  
 for the “war on terror” is in the billions [1350]. The reasons for this irrational-  
 ity are fairly well understood – I discussed the psychology in section 3.2.5 and  
 the policy aspects in 26.3.3. Safety preferences can be changed very sharply by  
 the threat of hostile action; people may completely ignore a 1-in-10,000 risk of  
 being killed by poorly-designed medical devices until there’s a possibility that  
 the devices might be hacked, at which point even a 1-in-10,000,000 risk becomes  
 scary. I discuss this phenomenon in section 28.4.

**27.5** **Methodology**

Software projects usually take longer than planned, cost more than budgeted  
 and have more bugs than expected3. By the 1960s, this had become known as  
 the *software crisis*, although the word ‘crisis’ may be inappropriate for a state  
 of a↵airs that has now lasted, like computer insecurity, for two generations.  
 Anyway, the term *software engineering* was proposed by Brian Randall in 1968  
 and deﬁned to be:

Software engineering is the establishment and use of sound engineer-  
 ing principles in order to obtain economically software that is reliable  
 and works e�ciently on real machines.

The pioneers hoped that the problem could be solved in the same way we

build ships and aircraft, with a foundation in basic science and a framework of  
 design rules [1420]. Since then there’s been a lot of progress, but the results  
 have been unexpected. Back in the late 1960s, people hoped that we’d cut the  
 number of large software projects failing from the 30% or so that was observed  
 at the time. But we still see about 30% of large projects failing – the di↵erence is  
 that the failures are much bigger. Modern tools get us farther up the complexity  
 mountain before we fall o↵, but the rate of failure is set by company managers’  
 appetite for risk. We’ll discuss this further in the section on organisational

behaviour at the end of this chapter.

Software engineering is about managing complexity, of which there are two

kinds. There is the *incidental complexity* involved in programming using inap-  
 propriate tools, such as the assembly languages which were all that some early  
 machines supported; programming a modern application with a graphical user  
 interface in such a language would be impossibly tedious and error-prone. There

3This is sometimes known as “Cheops’ law” after the builder of the Great Pyramid.

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is also the *intrinsic complexity* of dealing with large and complicated problems.  
 A bank’s core systems, for example, may involve tens of millions of lines of code  
 that implement hundreds of di↵erent products sold through several di↵erent  
 delivery channels, and are just too much for any one person to understand.

Incidental complexity is largely dealt with using technical tools. The most

important are high-level languages that hide much of the drudgery of dealing  
 with machine-speciﬁc detail and enable the programmer to develop code at an  
 appropriate level of abstraction. They bring their own costs; many vulnerabili-  
 ties are the result of the properties of the C language, and if we were rerunning  
 history we’d surely use something like Rust instead. There are also formal meth-  
 ods such as static analysis tools, that enable particularly error-prone design and  
 programming tasks to be checked.

Intrinsic complexity requires something subtly di↵erent: methodologies that

help us divide up a problem into manageable subproblems and restrict the extent  
 to which these subproblems can interact. These in turn are supported by their  
 own sets of tools. There are basically two approaches – top-down and iterative.

**27.5.1** **Top-down design**

The classical model of system development is the *waterfall model* formalised  
 by Win Royce in the 1960s for the US Air Force [1628]. The idea is that you  
 start from a concise statement of the system’s requirements; elaborate this into  
 a speciﬁcation; implement and test the system’s components; then integrate  
 them together and test them as a system; then roll out the system for live  
 operation. From the 1970s until the mid-2000s, this was how all systems for the  
 US Department of Defense were supposed to be developed, and their lead was  
 followed by many governments worldwide, including not just in defence but in  
 administration and healthcare. When I worked in banking in the 1980s, it was  
 the approved process there too, promoted assiduously by IBM, by governments  
 and by the big accountancy ﬁrms.

The idea is that the requirements are written in the user language, the

speciﬁcation is written in technical language, the unit testing checks the units  
 against the speciﬁcation and the system testing checks whether the requirements  
 are met. At the ﬁrst two steps in this chain there is feedback on whether we’re  
 building the right system (*validation*) and at the next two on whether we’re  
 building it right (*veriﬁcation*). There may be more than four steps: a common  
 elaboration is to have a sequence of *reﬁnement* steps as the requirements are  
 developed into ever more detailed speciﬁcations. But that’s by the way.

The deﬁning feature of the waterfall model is that development ﬂows inex-

orably downwards from the ﬁrst statement of the requirements to the deploy-  
 ment of the system in the ﬁeld. Although there is feedback from each stage to  
 its predecessor, there is no system-level feedback from (say) system testing to  
 the requirements.

There is a version used in safety-critical systems development called the V

model, where the system ﬂows down to implementation, then climbs back up a  
 hill of veriﬁcation and validation on the other side, where it’s tested successively  
 against the implementation, the speciﬁcation and the requirements. This is a

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| Requirements� Refine�  Specification� Code�  Validate�  Implementation� Build�  Validate� & unit testing�  Integration &� Field�  Verify� system testing�  Integration &� Field�  Operations &�  Verify� maintenance� |

Figure 27.4: – the waterfall model

German government standard, and also used in the aerospace industry world-  
 wide; it’s found in the ISO 26262 standard for car software safety. But although  
 it’s written from left to right rather than top-down, it’s still a one-way process  
 where the requirements drive the system and the acceptance test ensures that  
 the requirements were met, rather than a mechanism for evolving the require-  
 ments in the light of experience. It’s more a di↵erent diagram than a di↵erent  
 animal.

The waterfall model had a precursor in a methodology developed by Gerhard

Pahl and Wolfgang Beitz in Germany just after World War 2 for the design and  
 construction of mechanical equipment such as machine tools [1490]; apparently  
 one of Pahl’s students later recounted that it was originally designed as a means  
 of getting the engineering student started, rather than as an accurate description  
 of what experienced designers actually do. Win Royce also saw his model as  
 a means of starting to get order out of chaos, rather than as the prescriptive  
 system it developed into.

The strengths of the waterfall model are that it compels early clariﬁcation

of system goals, architecture, and interfaces; it makes the project manager’s  
 task easier by providing deﬁnite milestones to aim at; it may increase cost  
 transparency by enabling separate charges to be made for each step, and for  
 any late speciﬁcation changes; and it’s compatible with a wide range of tools.  
 Where it can be made to work, it’s often the best approach. The critical question  
 is whether the requirements are known in detail in advance of any development  
 or prototyping work. Sometimes this is the case, such as when writing a compiler  
 or (in the security world) designing a cryptographic processor to implement a  
 known transaction set and pass a certain level of evaluation. Sometimes a top-  
 down approach is necessary for external reasons, as with an interplanetary space  
 probe where you’ll only get one shot at it.

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But very often the detailed requirements aren’t known in advance and an

iterative approach is necessary. The technology may be changing; the environ-  
 ment could be changing; or a critical part of the project may be the design of  
 a human-computer interface, which will probably involve testing several proto-  
 types. Very often the designer’s most important task is to help the customer  
 decide what they want, and although this can sometimes be done by discussion,  
 there will often be a need for some prototyping.

Sometimes a formal project is just too slow. Reginald Jones attributes much

of the UK’s relative success in electronic warfare in World War 2 to the fact that  
 British scientists hacked stu↵ together quickly, while the Germans used a rigid  
 top-down development methodology, getting beautifully engineered equipment  
 but always six months too late [990].

But the most common reason for using iterative development is that we’re

starting from an existing product that we want to improve. Even in the early  
 days of computing, most programmer e↵ort was always expended on maintain-  
 ing and enhancing existing programs rather than developing new ones; surveys  
 suggest that 70–80% of the total cost of ownership of a successful IT product is  
 incurred after it ﬁrst goes into service, even when a waterfall methodology was  
 used [2060]. Nowadays, as software becomes a matter of embedded code, apps  
 and cloud services which all become ever more complex, the reality in many  
 ﬁrms is that ‘the maintenance is the product’.

Even in the late 1990s, when the most complex human artefacts were soft-

ware packages such as Microsoft O�ce, the only way to write such a thing was  
 to start o↵ from the existing version and enhance it. That does not make the  
 waterfall model obsolete; on the contrary, it is often used to manage a project to  
 develop a major new feature, or to refactor existing code. However, the overall  
 management of a major product nowadays is likely to be based on iteration.

**27.5.2** **Iterative design: from spiral to agile**

There are di↵erent ﬂavours of iterative development, ranging from a rapid pro-  
 totyping exercise to ﬁrm up the speciﬁcation of a new product, through to a  
 managed process for ﬁxing or enhancing an existing system.

In the ﬁrst case, one approach is the *spiral model* in which development

proceeds through a pre-agreed number of iterations in which a prototype is  
 built and tested, with managers being able to evaluate the risk at each stage  
 so they can decide whether to proceed with the next iteration or to cut their  
 losses. Devised by Barry Boehm, it’s called the spiral model because the process  
 is often depicted as in Figure 27.5. There are many applications where an initial  
 prototype is the key ﬁrst step; from a startup aiming to produce a demo to show  
 to investors, through a company building a mockup of a new product to show  
 a focus group, to DARPA seedling projects that aim to establish that some  
 proposed technology isn’t completely impossible. Prototype applications for

the security engineer range from security usability testbeds to proof-of-concept  
 attack code. The key is to solve the worst problem you’re facing, so as to reduce  
 the project risk as much as possible.

The second case we now describe as *agile development*, which may be summed

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| Risk�  analysis�  Commit� | Progress�  Prototype�  #2�  Prototype�  #1�  Test� |
| Development�  plan� | Settle final design�  Product� Code�  design�  Test system�  Ship� |

Figure 27.5: – the spiral model

up in the slogan: “Solve your worst problem. Repeat”.

An early advocate for an evolutionary approach was Harlan Mills, who

taught that you should build the smallest system that works, try it out on  
 real users, and then add functionality in small increments. This is how the

packaged software industry had learned to work by the 1990s: as PCs became  
 more capable, software products became so complex that they could not be  
 economically developed (or redeveloped) from scratch. Indeed, Microsoft tried  
 more than once to rewrite Word, but gave up each time. A landmark early  
 book on evolutionary development was ‘Debugging the Development Process’  
 by Steve Maguire of Microsoft in 1994 [1209]. In this view of the world, products  
 aren’t the result of a project but of a process that involves continually modi-  
 fying previous versions. Microsoft contrasted its approach with that of IBM,  
 then still the largest IT company; in the IBM ecosystem, the waterfall approach  
 was dominant. (IBMers for their part decried Microsoft as a bunch of undis-  
 ciplined hackers who produced buggy, unreliable code; but IBM’s near-death  
 experience after Microsoft stole their main business markets has been ascribed  
 to the rigidity of the IBM approach to development [390].) Professional practice  
 has evolved in the quarter century since then, and evolutionary development is  
 now known as ‘agile’, but it is recognisably the same beast.

A key insight about evolutionary development is that just as each genera-

tion of a biological species has to be viable for the species to continue, so each  
 generation of an evolving software product must be viable. The core technology  
 is *regression testing*. At regular intervals – typically once a day – all the teams  
 working on di↵erent features of a product check in their code, which gets com-  
 piled to a *build* that is then tested automatically against a large set of inputs.  
 The regression test checks whether things that used to work still work, and that  
 old bugs haven’t found their way back. It’s always possible that someone’s code  
 broke the build, so we consider the current ‘generation’ to be the last build that  
 worked. Things are slightly more complex when systems have to work together,  
 as when an app has to talk to a cloud service, or when several electronic com-  
 ponents in a vehicle have to work together, or where a single vehicle component  
 has to be customised to work in several di↵erent vehicles. You can end up with

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a hierarchy of builds and test regimes. But one way or another, we always have  
 viable code that we can ship out for beta testing, or whatever the next stage of  
 our process might be.

The technology of testing was probably the biggest practical improvement

in software engineering during the 1990s and early 2000s. Before automated  
 regression tests were widely used, IBM engineers used to reckon that 15% of  
 bug ﬁxes either introduced new bugs or reintroduced old ones [18]. The move to  
 evolutionary development was associated with a number of other changes. For  
 example, IBM had separated the roles of system analyst, programmer and tester;  
 the analyst spoke to the customer and produced a design, which the programmer  
 coded, and then the tester looked for bugs in the code. The incentives weren’t  
 quite right, as the programmer could throw lots of buggy code over the fence  
 and hope that someone else would ﬁx it. This was slow and led to bloated code.  
 Microsoft abolished the distinction between analysts, programmers and testers;  
 it had only developers, who spoke to the customer and were also responsible  
 for ﬁxing their own bugs. This held up the bad programmers who wrote lots  
 of bugs, so that more of the code was produced by the more skilful and careful  
 developers. According to Steve Maguire, this is what enabled Microsoft to win  
 the battle to rule the world of 32-bit operating systems; their better development  
 methodology let them take a $100bn business-software market from IBM [1209].

**27.5.3** **The secure development lifecycle**

By the early 2000s, Microsoft had overtaken IBM as the leading tech company,  
 but it was facing ever more criticism for security vulnerabilities in Windows and  
 O�ce that led to more and more malware. Servers were moving to Linux and  
 individual users were starting to buy Macs. Eventually in January 2002 Bill  
 Gates sent all sta↵ a ‘trustworthy computing’ memo ordering them to prioritise  
 security over features, and stopping all development while engineers got security  
 training. Their internal training materials became books and papers that helped  
 drive change in the broader ecosystem. I already discussed their threat modelling  
 in section 27.3.5; their ﬁrst take on secure development appeared in 2002 in  
 Michael Howard and David LeBlanc’s ‘Writing Secure Code’ [927], which sets  
 out the early Microsoft approach to managing the security lifecycle, and which I  
 discussed in the second edition of this book. More appeared over time and their  
 *security development lifecycle* (SDL) appeared in 2008, being adopted widely by  
 Windows developers.

The widely used 2010 ‘simpliﬁed implementation’ of SDL is essentially a

waterfall process [1308]. It ‘aims to reduce the number and severity of vulnera-  
 bilities in software’ and ‘introduces security and privacy throughout all phases  
 of the development process’. The ‘pre-SDL’ component is security training; it’s  
 assumed that all the developers get a basic course, the contents of which will de-  
 pend on whether they’re building operating systems, web services or whatever.  
 There are then ﬁve SDL components.

1. Requirements: this involves a risk assessment and the establishment of

quality gates or ‘bug bars’ which will prevent code getting to the next  
 stage if it contains certain types of ﬂaw. The requirements themselves

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are reviewed regularly; at Microsoft, the reviews are never more than six  
 months apart.

2. Design: this stage requires threat modelling and establishment of the at-

tack surface, to feed into the detailed design of the product.

3. Implementation: here, developers have to use approved tools, avoid or

deprecate unsafe functions, and perform static analysis on the code to  
 check this has been done.

4. Veriﬁcation: this step involves dynamic analysis, fuzz testing, and a review

of the attack surface.

5. Release: this is predicated on an incident response plan and a ﬁnal security

review.

As well as providing some basic security training to all developers, there

are some further organisational aspects. First, security needs a subject-matter  
 expert (SME) from outside the dev team, and a security or privacy champion  
 within the team itself to check that everything gets done.

Second, there is a maturity model. Starting in 1989, Watts Humphrey devel-

oped the *Capability Maturity Model* (CMM) at the Software Engineering Insti-  
 tute at Carnegie-Mellon University (CMU), based on the idea that competence  
 is a function of teams rather than just individual developers. There’s more to  
 a band than just throwing together half-a-dozen competent musicians, and the  
 same holds for software. Developers start o↵ with di↵erent coding styles, di↵er-  
 ent conventions for commenting and formatting code, di↵erent ways of manag-  
 ing APIs, and even di↵erent workﬂow rhythms. The CMU research showed that  
 newly-formed teams tended to underestimate the amount of work in a project,  
 and also had a high variance in the amount of time they took; the teams that  
 worked best together were much better able to predict how long they’d take, in  
 terms of the mean development time, but reduced the variance as well [1937].  
 This requires the self-discipline to sacriﬁce some e�ciency in resource alloca-  
 tion in order to provide continuity for individual engineers and to maintain the  
 team’s collective expertise. Microsoft adapted this and deﬁnes four levels of  
 security maturity for developer teams.

**27.5.4** **Gated development**

It’s telling that the biggest ﬁrm pushing evolutionary development reverted to  
 a waterfall approach for security. Many of the security engineering approaches  
 of the time were tied up with waterfall assumptions, and automated testing on  
 its own is less useful for the security engineer for a number of reasons. Secu-  
 rity properties are both emergent and diverse, we security engineers are fewer  
 in number, and there hasn’t been as much investment in tools. Speciﬁc attack  
 types often need speciﬁc remedies, and many security ﬂaws cross a system’s  
 levels of abstraction, such as when speciﬁcation errors interact with user inter-  
 face features – the sort of problem for which it’s di�cult to devise automated  
 tests. But although regression testing is not su�cient, it is necessary, as it ﬁnds  
 functionality that’s been a↵ected by a change. It’s particularly important when

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development sprints add lots of features that can interact with each other. For  
 this reason, security patches to Windows are an example of *gated development*:  
 at regular intervals, a pre-release version of the product is pushed through a  
 whole series of additional tests and reviews and prepared for release. This is  
 fairly common across systems with safety or security requirements. The prepa-  
 ration may involve testing with a wide variety of peripherals and applications  
 in the case of Windows, or recertiﬁcation in the case of software for a regulated  
 product.

An issue many neglect is that security requirements evolve, and also have to

be maintained and upgraded. They can be driven by changing environments,  
 evolving threats, new dependencies on platforms old and new, and a bundle  
 of other things. Some changes are implicit; for example, when you upgrade

your static analysis tools you may ﬁnd hundreds of ‘new’ bugs in your existing  
 codebase, which you have to triage. Once more Microsoft was a pioneer here.  
 When a vulnerability was found in Windows, it’s not enough to just patch it;  
 whoever wrote it might have written a dozen similar ones that are now scattered  
 throughout the codebase, and once you publish a patch, the bad guys study it  
 and understand it. So rather than just ﬁxing a single bug, you update your  
 toolchain so you ﬁnd and eliminate all similar bugs across your products. In  
 order to manage the costs, both for Microsoft and its customers, the company  
 started bundling patches together into a monthly update, the now famous ‘patch  
 Tuesday’, in 2003. From then until 2015, all customers – from enterprises to  
 the users of home PCs and tablets – had their software updated on the second  
 Tuesday every month. And such patching creates further dependencies. Modern  
 quality tools can help you check that no code has a CVE open, so all your  
 customers should have to patch too, if they live by such tools. But many don’t:  
 as many as 70% of apps on both phones and desktops have vulnerabilities in  
 the open-source libraries they use, and which could usually be ﬁxed by a simple  
 update [1695]. Since 2015, Windows home users receive continuous updates4.

Much the same considerations apply to safety-critical systems, which are

similar in many respects to secure systems. Safety, like security, is an emergent  
 property of whole systems, and it doesn’t compose. Safety used to depend, in  
 most applications, on extensive pre-market testing. But it’s hard for a connected  
 device to have safety without security, and now that devices such as cars are  
 connected to the Internet, they are acquiring patch cycles too. Yet ensuring  
 that the latest version of a safety-critical system satisﬁes the safety case may  
 require extensive and expensive testing. For example, a car may contain dozens  
 of *electronic control units* (ECUs) from di↵erent component suppliers, and in  
 addition to testing the individual ECUs you have to test how they work together.  
 Firms in the car industry are mutually suspicious and won’t share source code  
 with each other, even under NDA, so testing can be complex. The main test  
 rig may be a ‘lab car’ containing all the electronics from a particular model of  
 car, plus extra test systems that let you simulate various maneuvers and even  
 accidents. These cost real money, and you also need to keep real vehicles for

4This also breaks things: we were once about to demonstrate an experiment using a body

motion-capture suit to a TV crew when the Windows laptop we used to drive it updated itself,  
 and suddenly the capture software wouldn’t work any more. There followed frantic phone calls  
 to the software developer in the Netherlands and thankfully we got their update a few hours  
 later, just in time for the show.

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road testing. The cost of maintaining ﬂeets of lab cars and real test cars is one  
 of the reasons car companies dragged their heels when the EU decided to require  
 them to patch car software for ten years after the last vehicle left the showroom.

This is one respect in which Tesla has a signiﬁcant advantage; as a tech com-

pany with software at the core of its business, Tesla can test and ship changes in  
 weeks which take the legacy car ﬁrms years, as they leave most of the software  
 development to the component suppliers [404]. Traditionally, automotive soft-  
 ware contracts involved ten years’ support; now you need to support a product  
 for three years’ development, seven years in the showroom and a further ten  
 after that. I’ll discuss the sustainability aspects of this in the next chapter.  
 Meanwhile, Tesla is forcing the legacy industry to raise its game, with VW an-  
 nouncing they’ve spent $8bn to create a proper software division, just as their  
 Tesla competitor project runs late [1686].

**27.5.5** **Software as a Service**

Since the early 2010s, more and more software has been hosted on central servers,  
 accessed by thin clients and paid for on a subscription basis, rather than being  
 sold and distributed to users. The typical customer has many costs for running  
 software beyond the license fee, including not just the cost of servers and oper-  
 ators but of deploying it, upgrading it regularly and managing it. If the vendor  
 can take over these tasks from all their customers, many duplicated costs are  
 removed, and they can manage things better because of their specialised knowl-  
 edge. Software can be instrumented so that developers can monitor all aspects  
 of its performance on a dashboard.

The key technical innovations behind *Software as a Service* (SaaS) are *con-*

*tinuous integration* and *continuous deployment*. Rather than having thousands  
 of customers managing dozens of di↵erent versions of the software, the vendor  
 can migrate a few customers to a new version to test it, and then migrate the  
 rest. Upgrades become much more controllable, as they can be tested in a dry  
 run against a snapshot of the real customer data, called a *staging environment*.  
 Some companies now deploy several times a day, as their experience is that fre-  
 quent small changes can be safer and have less risk of breaking something than  
 a larger deployment, such as Microsoft’s Patch Tuesday.

Deployment itself is tentative. A SaaS company will typically run its software

on a number of service instances running on VMs behind a load balancer, which  
 provides a point of indirection for managing running services. The separate

instances also provide separate *failure domains* to improve robustness. To do  
 a *rolling deployment* we conﬁgure a load balancer to send say 1% of the tra�c  
 to an instance with the new version, often called the ‘canary’ after the caged  
 bird used by miners to detect carbon monoxide leaks. If the canary survives,  
 deployment can be rolled forward progressively to new service instances. If the  
 logging system detects any problems, developers are alerted. Some care needs to  
 be taken that things don’t go wrong if users ﬂap between old and new versions  
 of a design between transactions. If you make a change that breaks backwards  
 compatibility, you typically build an intermediate stage that will work with both  
 old and new systems (we were doing this in the world of bank mainframes back  
 in the 1980s anyway).

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The ability to manage risks through phased release and rolling deployment

changes the economics of testing. The fact that you can ﬁx bugs extremely  
 quickly mean that you can achieve a target quality level with much less testing.  
 You can also see everything the users do, so for the ﬁrst time you can really  
 understand how usability fails from the point of view of security, safety – and  
 revenue. Of course it’s revenue that usually drives the exploitation of this.

Analytics collectors write all behavioural events to a log, which is fed into a data  
 pipeline for metrics, analytics and queries. This in turn supports experiment  
 frameworks that can do extensive A/B testing of possible features. Ad-driven  
 services can optimise by engagement metrics such as active users, time per  
 user session and use of speciﬁc features. Controlled experiments are used to  
 improve security too; for example, Google has tuned its browser warnings by  
 measuring how millions of users react to di↵erent warnings of expired certiﬁcates.  
 Such improvements are usually fairly small by themselves, so you really need  
 controlled experiments to measure them; but when you do lots of them, they add  
 up. The investment in building such frameworks into the phased deployment  
 mechanisms gives an increasing return to scale; the more users you have, the  
 faster you can achieve statistical signiﬁcance. So large ﬁrms can optimise their  
 products more quickly than their smaller competitors; SaaS, like a lot of other  
 digital technology, not only cuts costs in the short term, but increases lock-in in  
 the long term. Each time you access a service from a large SaaS ﬁrm, you may  
 be an unwitting participant in tens or even hundreds of experiments. There are  
 lots of ﬁddly details about running multiple concurrent experiments while also  
 deploying system enhancements.

Things can get more complex still when you have services put together from

multiple microservices. This brings us to the world of *infrastructure as code*, also  
 known as cloud native development or DevOps, where everything is developed  
 in containers, VMs etc, so all the infrastructure is based on code and can be  
 replicated quickly. You can also use containers to simplify things, packaging  
 as many security dependencies with the code as possible. New code can be

deployed to a test infrastructure rapidly and tested realistically. You could

if you wanted manage rolling deployment manually, but this is not scalable  
 and prone to error. The solution is to write *deployment code*, as part of the  
 application development process, that uses the cloud platform APIs to allow  
 applications to deploy themselves and the associated infrastructure, and to hook  
 into the monitoring mechanisms. In the last few years, some toolkits have

become available that allow engineers to do this in a more declarative fashion.

The best guide to this I know is Google’s 2013 book *‘Site Reliability Engi-*

*neering’*; SRE is their term for DevOps [236]. Google led the industry in the  
 art of building large dependable systems out of large ﬂeets of low-cost PCs,  
 building the necessary engineering for load balancing, replication, sharding and  
 redundancy. As they operated at a larger scale than anybody else through the  
 2000s and early 2010s, they had to automate more tasks and became good at  
 it. The goals of SRE are availability, latency, performance, e�ciency, change  
 management, monitoring, emergency response, and capacity planning. The core  
 strategy is to apply software engineering techniques to automate system admin-  
 istration tasks so as to balance rapid innovation with availability.

As we already noted, there’s no point striving for 99.9999% availability if

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ISPs only let users get to your servers 99% or 99.9% of the time. If you set  
 a realistic error budget, say 0.1% or 0.01% unavailability, you can use that  
 to achieve a number of things. First, most outages are due to live system

changes, so you monitor latency, tra�c, errors and saturation well and roll  
 back quickly whenever anything goes wrong. You use the rest of the error

budget to support your experimental framework, and doing controlled outages to  
 ﬂush dependencies. (This was pioneered by Netﬂix whose ‘chaos monkey’ would  
 occasionally take down routers, servers, load balancers and other components,  
 to check that the resilience mechanisms worked as intended; such ‘ﬁre drills’ are  
 now an industry standard and involve taking down whole data centres.)

In section 12.2.6.2, we mentioned *technical debt*. This concept, due to Ward

Cunningham, encapsulates the observation that development shortcuts are like  
 debt. Whenever we skimp on documentation, ﬁx a problem with a quick-and-  
 dirty kludge, don’t test a ﬁx thoroughly, fail to build in security controls, or  
 fail to work through the consequences of errors, we’re storing up problems that  
 may have to be repaid with interest in the future [41]. Technical debt may make  
 sense for a startup, or a system nearing the end of its life, but it’s more often a  
 product of poor management or poorly-aligned incentives. Over time, systems  
 can fall so deeply into debt that they become too hard to maintain or to use;  
 they have to be refactored or replaced. For a bank to have to replace its core  
 banking systems is hugely expensive and disruptive. So managing technical debt  
 is really important; this is one of the changes in system management thinking  
 since the second edition of this book. One important aspect of the philosophy  
 of DevOps is to run debt-free.

**27.5.6** **From DevOps to DevSecOps**

As I write, in 2020, the cutting edge is applying agile ideas and methodology  
 not just to development and operations, but to security too. In theory this can  
 mean a strategy of ‘everything as code’; in practice it means not just maintaining  
 an existing security rating (and safety case if relevant) but responding to new  
 threats, environmental changes, and surprising vulnerabilities. Bringing the

two together involves real work, and sometimes things need to be reinvented. I  
 mentioned for example in section 12.2.2 that DevOps undermines the separation  
 between development and production on which banks have relied for years;  
 where separation of duties is necessary, we have to reimagine it.

We see several di↵erent approaches in the companies with which we work. In

what follows I will give two examples, which we might roughly call the Microsoft  
 world and the Google world. There are of course many others.

**27.5.6.1** **The Azure ecosystem**

Most of the world’s largest commercial ﬁrms from banks and insurers through  
 retail to shipping and mining have built their enterprise systems on Windows  
 over the past 25 years and are now migrating them to Azure, often using systems  
 integration and facilities management ﬁrms to do the actual work. The typical  
 client has a mixture of on-premises and cloud systems with new developments  
 mostly migrating from the former to the latter. Here policy is largely set by

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the Big Four auditors who, in addition to their standard set of internal control  
 features, follow Microsoft in requiring a secure development lifecycle. The sev-  
 eral dozen tools used to do threat modelling, static analysis, dynamic analysis,  
 fuzz testing, app and network monitoring, security orchestration and incident  
 response impose a signiﬁcant overhead with dozens of people copying data from  
 one tool to another. The DevSecOps task here is to progressively integrate the  
 tools by automating these administrative tasks.

To support this ecosystem, Microsoft has extended its SDL with further

steps: deﬁning metrics and compliance reporting; threat modelling; cryptog-  
 raphy standards; managing the security risks of third-party components; pen-  
 etration testing; and a standardised incident response. The ﬁrm now claims  
 that 10% of its engineering investment is in cybersecurity. The capable system  
 integration and facilities management ﬁrms have worked out ways of building  
 these steps into their workﬂows; much of the actual work involves integrating  
 the third-party security products that they or their customers have bought.  
 Appropriate automation is vital for the security team to continue raising their  
 game, extending their scope and increasing e↵ectiveness; without it, they fall  
 further and further behind, and burn out [1846].

The organising principles for DevSecOps in such a company will be to ‘shift

left’ which can cover a number of things: the unifying theme is moving security,  
 like software and infrastructure, into the codebase. One strategy is to cause  
 things to ‘fail fast’ including engaging security experts early enough in the de-  
 velopment process to avoid delays later: doing pre-commit static analysis of each  
 developer’s code to minimise failed builds; buying or building specialist tools to  
 detect errors such as incorrect authentication, mistakes in using crypto func-  
 tions, and injection opportunities; both automated and manual security testing  
 of new versions; and automated testing of conﬁguration and deployment includ-  
 ing scanning of the staging network and checks on credentials, encryption keys  
 and so on. And while, back in 2010, Microsoft considered operational security  
 to be separate from software security, a modern Azure shop will close the loop  
 by following up deployment with continuous monitoring, manual penetration  
 tests and ﬁnally bug bounties for third parties who spot something wrong. We  
 will discuss these in more detail later.

**27.5.6.2** **The Google ecosystem**

A second view comes from engineers working on infrastructure, and the best  
 reference I know is a 2020 book by six Google engineers, *‘Building Secure and*  
 *Reliable Systems’* [23]. The DevSecOps strategy is somewhat similar at Amazon,  
 but optimised for their product o↵erings; it is described by their CTO Werner  
 Vogels at [1966]. However the Google experience is described in much more  
 detail. This section draws on their book, and on colleagues who have worked  
 recently at the major service ﬁrms.

When building infrastructure systems on which hundreds of millions of peo-

ple will rely, it is critical to automate support functions quickly, and to have  
 really robust processes for threat identiﬁcation, incident response, damage lim-  
 itation and service recovery. So while a facilities-management ﬁrm might work  
 at integrating support functions to save money and reduce errors, the emphasis

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at major service ﬁrms is reliability. I already mentioned the Google approach to  
 site reliability engineering: set a realistic target, of say 99.9% availability, and  
 then use the residual error budget of 0.1% downtime by apportioning it between  
 failure recovery, upgrades and experiments.

This in turn drives further principles such as design for recoverability, de-

sign for understandability, and a desire to stop humans touching production  
 systems wherever possible. It’s not enough to have automation for the incre-  
 mental deployment of new binaries; you also want to stop sysadmins having  
 to type complicated command lines into routers to conﬁgure networks; this is  
 where most of the network outages come from, as we noted in section 21.2.1.  
 You manage such risks by building suitable tool proxies. This can involve quite  
 a lot of work to align the update of binary and conﬁg ﬁles and work out how  
 to allocate support and recovery e↵ort between SRE and security engineering  
 teams. Further complexity arises with secure testing. How do you build test  
 infrastructures to exercise least privilege? How do you test systems that contain  
 large amounts of personal information? How do you test the break-glass mech-  
 anisms that give SRE teams emergency human access to live systems? Most of  
 these are questions we already had to deal with in the mainframe world of the  
 1980s, but they arose only occasionally and were dealt with by human ingenuity  
 and by trusting some key sta↵. Scaling everything up from thousands of users  
 to billions means that a lot more has to be automated.

There are still tensions. In site reliability engineering, alarms should be as

simple, predictable and reliable as possible; but in security, some randomisation  
 is often a good idea.

At the application level, systems are increasingly compartmentalised into mi-

croservice components with defensible security boundaries and tamper-resistant  
 security contexts, so that if Alice compromises a shopping system’s catalogue,  
 she still can’t spend money as Bob as the payment service is separate. Each com-  
 ponent will typically be implemented as a number of parallel copies or shards,  
 giving still smaller failure domains. Such domains enable you to limit the blast  
 radius of any compromise; ideally, you want to be able to deal with an intrusion  
 without taking your whole system o✏ine. Compartmentalised systems can be  
 engineered for resilience too but this is not straightforward. When a failure do-  
 main fails, when do you just spin up a new one, and when do you do something  
 di↵erent? What are the dependencies? Which components should fail open,  
 and which should fail secure? What sort of degraded performance is acceptable  
 under congestion, or under attack? What’s the role of load shedding and throt-  
 tling? And what sort of pain can you rationally inﬂict on users, and on business  
 models? Do you ditch some of the ads, require extra CAPTCHAs for logons, or  
 both? And how do you test and validate all these resilience mechanisms?

Large ﬁrms invest a lot of engineering time in building application frame-

works for such services. There are also standard frameworks for web pages,

which should not only prevent SQL injection and cross-site scripting attacks  
 in the ﬁrst place, but also provide support for dozens of di↵erent languages.  
 Having a single front end to terminate all http(s) and TLS tra�c means that if  
 you have to update your certiﬁcate management mechanisms or ciphersuites you  
 only need to do it once, not in all your di↵erent services. A single front end can  
 also provide a single location for load balancing and DDoS protection, as well

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as for many other functions such as supporting dozens of di↵erent languages.

Using type encapsulation to enforce properties of URLs, SQL and so on can

reduce the amount of code you need to verify. If you have secure-by-construction  
 APIs that are also understandable, that’s best. Google has a crypto API called  
 Tink that forces more correct use. It requires use of a key management service,  
 whether in the Google cloud, AWS or the Android keystore. This ﬁts into an  
 overall framework for managing crypto termination, code provenance, integrity  
 veriﬁcation and workload isolation, called BeyondProd [998].

**27.5.6.3** **Creating a learning system**

Whether you follow the Microsoft approach, the Google approach or your own,  
 to tune such a process you need metrics, and suitable candidates include the  
 numbers of security tickets opened to dev teams, the number of security-failed  
 builds, and the time it takes for a new application to achieve compliance under  
 the relevant regulation (whether SOX, GDPR or HIPAA). As Dev, Sec and Ops  
 converge, the metrics and management processes converge with the network de-  
 fence mechanisms discussed in section 21.4, from network monitoring to security  
 incident and event management. But all this needs to be managed intelligently.  
 A well-run ﬁrm can make the security process more visible to all the dev / ops  
 sta↵ via the sprints that you do to work up a privacy impact assessment, im-  
 prove access controls, extend logging or whatever. A badly-run ﬁrm will manage  
 to the metrics, which will create tensions: their security sta↵ can end up with  
 conﬂicting goals of keeping the bad guys out, and also of ‘feeding the beast’  
 by hitting all the metrics used to justify the team’s own existence [1846]. It’s  
 important to understand where conﬂicts naturally arise as a function of the  
 organisation’s management structure, and somehow keep them constructive.

One of the big drivers in either case, though, will be the vulnerability lifecy-

cle. The processes whereby bugs become exploits and then attacks, and these  
 attacks are noticed leading to vulnerability reports, interim defences using de-  
 vices such as ﬁrewalls, then deﬁnitive patches that are rolled out not just to  
 direct users but along complex supply chains, is ever more central to security  
 management.

**27.5.7** **The vulnerability cycle**

Back in the 1970s and 1980s, people sometimes described the evolutionary pro-  
 cedure of ﬁnding security bugs in systems and then ﬁxing them dismissively as  
 *penetrate-and-patch*. It was hoped that some combination of an architecture  
 that limited the attack surface and the application of formal methods would  
 enable us to escape. As we’ve seen, that didn’t really work, except in a few edge  
 cases such as cryptographic equipment. By the early 2000s, we had come to the  
 conclusion that we just had to manage the patch cycle better, and the modern  
 approach of security breach disclosure laws, CERTs and responsible disclosure  
 bedded down during this period.

The vulnerability cycle consists of the process whereby someone, the *re-*

*searcher*, discovers a vulnerability in a system that is maintained by a *vendor*.

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The researcher may be a *customer*, an academic, a contractor for a national  
 intelligence agency or even a criminal. They may sell it in a market. The

idea of vulnerability markets was ﬁrst suggested by Jean Camp and Catherine  
 Wolfram in 2000 [371]; ﬁrms were set up to buy vulnerabilities, and over time  
 several markets emerged. Most of the big software and service ﬁrms now of-  
 fer bug bounties, which can range from thousands to hundreds of thousands of  
 dollars; at the other extreme are operators who buy up exploits for sale to *ex-*  
 *ploiters* such as cyber-arms manufacturers (who sell to military and intelligence  
 agencies) and forensic ﬁrms (who sell to law enforcement). Such operators now  
 o↵er millions of dollars for persistent remote exploits of Android and iOS.

The researcher may also disclose the bug to the vendor directly – nowadays

many vendors have a *bug bounty program* that pays rewards for disclosed vul-  
 nerabilities that attempt to match market prices, at least in order of magnitude.  
 As market prices for zero-day exploits against popular platforms have headed  
 into six and even seven ﬁgures, so have bug bounties. Apple, for example, o↵ers  
 $1M for anyone who can hack the iOS kernel without requiring any clicks by  
 the user. In 2019, it emerged that at least six hackers have now earned over  
 $1M through the bug bounty platform HackerOne alone [2030]. A downside  
 of large bug bounties is that while bugs used to occur naturally, we now see  
 them being introduced deliberately, for example by contributors to open-source  
 projects whose code ends up in signiﬁcant platforms. Such *supply-chain attacks*  
 used to be the preserve of nation states; now they’re opening up [890].

If an exploit is used in the wild before the vendor issues a patch, it is called

a *zero day*, and is typically used for targeted attacks. If it’s used enough, then  
 eventually someone will notice; the attack gets reported, and then vendor issues  
 a patch, which may then be reverse engineered so that many other actors now  
 have exploit code. Customers who fail to patch their systems are now vulnerable  
 to multiple exploits that can be deployed at scale by crime gangs.

Getting the patching cycle right is a problem in the economics of infor-

mation security as much as anything else, because the interests of the various  
 stakeholders can diverge quite radically.

1. The vendor would prefer that bugs weren’t found at all, to spare the

expense of patching. They’ll patch if they have to but want to minimise  
 the cost, which may include a lot of testing if their code appears in lots  
 of product versions. Indeed, if their code is used in customer devices that  
 now need patching (like cars) they may have to pay an indemnity to cover  
 their customer’s costs; so in such industries there’s an even more acute  
 incentive for foot-dragging and denial.

2. The average customer might prefer that bugs weren’t found, to avoid the

hassle of patching. Lazy customers may fail to patch, and get infected as a  
 result. (If all the infected machines do is send a bit of spam, their owners  
 may not notice or care.)

3. The typical security researcher wants some reward for their discoveries,

whether fame, cash or getting a ﬁx for a system they rely on.

4. The intelligence agencies want to learn of vulnerabilities quickly, so they

can be used in zero-day exploits before a patch is shipped.

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5. The security software ﬁrms beneﬁt from unpatched vulnerabilities as their

ﬁrewalls and AV software can look for their indicators of compromise to  
 block attacks that exploit them.

6. Large companies don’t like patches, and neither do government depart-

ments, as the process of testing a new patch against the enterprise’s crit-  
 ical systems and rolling it out is expensive. The better ones have built  
 automation to deal with regular events like Microsoft’s Patch Tuesday, but  
 updating or risk-assessing the zillions of IoT devices in their o�ces and  
 factories will be a headache for years to come. Most ﬁrms just don’t have  
 a good enough asset inventory system to cope.

During the 1990s, the debate was driven by people who were frustrated at

software vendors for leaving products unpatched for months or even years. The  
 bugtraq mailing list was set up to provide a way for people to disclose bugs  
 anonymously; but this meant that a product might be completely vulnerable  
 for a month or two until a patch was written, tested and shipped, and until  
 customer ﬁrms had tested it and installed it. This led to a debate on ‘respon-  
 sible disclosure’ with various proposals about how long a breathing space the  
 researcher should give the vendor [1572].

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| The consensus that emerged was that researchers should disclose vulnerabil-  ities to a computer emergency response team (CERT)5 and the global network |
| of CERTs would inform the vendor, with a delay for a patch to be issued before  the vulnerability was published. The threat of eventual disclosure got vendors  o↵ their butts; the delay gave them enough time to test a ﬁx properly before  releasing it; researchers got credit to put on their CVs; customers got bug ﬁxes  at the same time as bug reports; and the big companies organised regular up-  dates for which their corporate customers can plan. Oh, and the agencies had  a hot line into their local CERT, so they learned of naturally occurring exploits  This was part of the deal described inin advance and could exploit them. |

section 26.2.7.3 that ended Crypto War 1 back in 2000.

**27.5.7.1** **The CVE system**

An industrial aspect is the *Common Vulnerabilities and Exposures* (CVE) sys-  
 tem, launched in 1999, which assigns numbers to reported vulnerabilities in  
 publicly released software packages. This is maintained by Mitre, but it dele-  
 gates the assignment of CVEs to large vendors. CVE IDs are commonly included  
 in security advisories, enabling you to search for details of the reporting date,  
 a↵ected products, available remedies and other relevant information. There is  
 a Common Vulnerability Scoring System (CVSS) which provides a numerical  
 representation of the severity of a vulnerability. The method for calculating  
 this has become steadily more complex over time and now depends on whether  
 the attack requires local access, its complexity, the e↵ort required, its e↵ects,  
 the availability of exploit code and of patches, the number of targets and the  
 potential for damage.

5The EU is renaming these CSIRTs – computer security incident response teams.

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NIST’s *National Vulnerability Database* (NVD), described as a “comprehen-

sive cybersecurity vulnerability database that integrates all publicly available  
 U.S. Government vulnerability resources and provides references to industry re-  
 sources” is based on the CVE List. These resources are critical for automating  
 the tracking of vulnerabilities and updates. There are now so many thousands  
 of vulnerabilities reported, and so many hundreds of patches shipped, that au-  
 tomation is essential.

As the system was bedding down, it became a subject of study by secu-

rity economists. Traditionalists argued that since bugs are many and uncorre-  
 lated, and since most exploits use vulnerabilities reverse-engineered from exist-  
 ing patches, there should be minimal disclosure. Pragmatists argued that, from  
 both theoretical and empirical perspectives, the threat of disclosure was needed  
 to get vendors to patch. I discussed this argument in section 8.6.2. Since then  
 we have seen the introduction of automatic upgrades for mass-market users,  
 the establishment of ﬁrms that make markets in vulnerabilities, and empirical  
 research on the extent to which bugs are correlated. Modulo some tuning, the  
 current computer industry way of doing things has been stable for over a decade.

**27.5.7.2** **Coordinated disclosure**

Yet some industries are lagging well behind. In section 4.3.1 I described how  
 Volkswagen sued academics at Birmingham and Nijmegen universities after they  
 discovered, and responsibly disclosed, vulnerabilities in Volkswagen’s remote key  
 entry system that were already being exploited in car-theft tools that were avail-  
 able online. This was a mistake, as it drew attention to the vulnerability, and  
 Volkswagen duly lost in court. Companies like Microsoft and Google have had  
 twenty years to learn that running bug bounty programs and monthly patching  
 works better than threatening to sue people, but a lot of ﬁrms in legacy indus-  
 tries still haven’t worked this out even though their products contain more and  
 more software.

One of the problems in the Volkswagen case was that the researchers initially

disclosed the vulnerability to the supplier of its key entry system, which in turn  
 told Volkswagen only at the last minute. As a result of supply chain problems  
 like this, responsible disclosure has given way to *coordinated disclosure*. Few  
 ﬁrms build all their own tools any more, and even a child’s toy may have multiple  
 software dependencies. If it does speech and gesture recognition, it probably  
 contains an Arm chip running some ﬂavour of Linux or FreeBSD, communicates  
 with a cloud service running another ﬂavour of Linux, and can be controlled by  
 an app that may run on Android or iOS. The safety of the toy will depend on  
 secure communications; for example, it was discovered in February 2019 that  
 the communications between Enox’s ‘Safe-KID-One’ toy watch and its back-  
 end server were unencrypted, so that hackers could in theory track and call  
 kids. The response was an immediate EU-wide safety recall [654]. Getting this  
 sort of thing wrong can be sudden death for your product, and your company.

Now what happens when someone discovers an exploitable bug in a platform

used in dozens of embedded products? This can be traumatic, as with the

Shellshock bug in Linux and the Heartbleed bug in OpenSSL (which also a↵ected  
 Linux). If Linux gets an emergency patch, coordinating the disclosure is a

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nightmare: the Linux maintainers may be able to work in private with the  
 main Linux distributions, and with derivatives like Android whose developers  
 keep in close contact with them. But there are the thousands of products

that incorporate Linux, from alarm clocks to TVs and from kids’ toys to land  
 mines. You may suddenly ﬁnd that the CCTV cameras in your building security  
 system have all become hackable, and the vendor can’t ﬁx them quickly or at  
 all. Coordinating disclosure on platforms is one of the seriously hard problems.  
 There is no silver bullet but there are still many things you can do, ranging from  
 documenting your upstream and downstream dependencies, through aggressive  
 testing of software you depend on so you get to exercise and understand the bug  
 reporting mechanisms, to becoming part of its developer community.

Dealing with such shocks is just one aspect of a process that in the late 2010s

became a speciality of its own, namely security incident and event management.

**27.5.7.3** **Security incident and event management**

You need an incident response plan for what you’ll do when you learn of a  
 vulnerability or an attack. In the old days, vendors could take months to respond  
 with a new version of the product, and would often do nothing at all but issue a  
 warning (or even a denial). Nowadays, breach-notiﬁcation laws in both the USA  
 and Europe oblige ﬁrms to disclose attacks where individuals’ privacy could have  
 been compromised, and people expect that problems will be ﬁxed quickly. Your  
 plan needs four components: monitoring, repair, distribution and reassurance.

First, make sure you learn of vulnerabilities as soon as you can – and prefer-

ably no later than the bad guys (or the press) do. This means building a threat  
 intelligence team. In some applications you can just acquire threat intelligence  
 data from specialist ﬁrms, while if you’re an IoT vendor it may be prudent to  
 operate your own honeypots so you get immediate warning of people attacking  
 your products. Listening to customers is important: you need an e�cient way  
 for them to report bugs. It may be an idea to provide some incentive, such as  
 points towards their next upgrade, lottery tickets or even cash. You absolutely  
 need to engage with the larger technical ecosystem of bug bounties, vulnerability  
 markets, CERTs and CVEs described in section 27.5.7.

Second, you need to be able to repair the problem. Twenty years ago,

that meant having one member of each product team ‘on call’ with a pager  
 in case something needed ﬁxing at three in the morning. Nowadays it means  
 preparing an orchestrated response to anything from a vulnerability report to  
 a major breach. This will extend from the intrusion-detection and network

monitoring functions we discussed in section 21.4.2.3 and the threat intelligence  
 team through to identifying the dev teams responsible and notifying both your  
 suppliers upstream and your customers downstream. Responder teams may also  
 need alternative means of communication. Did you ever stop to think whether  
 you need satellite phones?

Third, you need to be able to deploy the patch rapidly: if all the software

runs on your own servers, then it may be easy, but if it involves patching code in  
 millions of consumer devices then advance planning is needed. It may seem easy  
 to get your customers to visit your website once a day and check for upgrades,

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but if their own systems depend on your devices and they need to test any  
 dependencies, there’s a tension [195]: pioneers who apply patches quickly can  
 discover problems that break their systems, while people who take time to test  
 will be more vulnerable to attack. The longer the supply chains get, the harder  
 the conﬂicts of interest are to manage. Operations matter hugely: an emergency  
 patch process that isn’t tested may do more harm than good, and experience  
 teaches that in an emergency you just run your normal patch process as fast as  
 possible [23].

Finally, you need to educate your CEO and main board directors in advance

about the need to deal quickly and honestly with a security breach in order to  
 keep conﬁdence and limit damage, by giving them compelling examples of ﬁrms  
 that did well and others that did badly. You need to have a mechanism to get  
 through to your CEO and brief them immediately so they can show the thing’s  
 under control and reassure your key customers. So you need to know the mobile  
 and home phone numbers of everyone who might be needed urgently. And you  
 need a plan to deal with the press. The last thing you need is for dozens of  
 journalists to phone up and be stonewalled by your PR person or even your  
 switchboard operator as you struggle madly to ﬁx the bug. Have a set of press  
 releases ready for incidents of varying severity, so that your CEO only has to  
 pick the right one and ﬁll in the details. This can then ship as soon as the ﬁrst  
 (or perhaps the second) journalist calls.

Remind your CEO that both the USA and Europe have security-breach

disclosure laws, so if your systems are hacked and millions of customer card  
 numbers compromised, you have to notify all current and former customers,  
 which costs real money. You can expect to be sued. If you have 10 million  
 customers’ personal data compromised, that might mean 10 million letters at  
 $5 each and 3 million reissued credit cards at $10 each, even if you don’t get  
 claims from banks for actual fraud losses on those accounts. (That may well  
 happen; you might expect that of 3 million accounts, a few tens of thousands  
 would su↵er some fraud in each year anyway, and the banks will sue you for all  
 of it.) The ﬁnancial loss from a signiﬁcant breach can easily hit nine ﬁgures. If  
 it happens to you more than once, you can expect to lose customers: customer  
 churn might only be 2% after one notiﬁed breach, but 30% after two and even  
 more after three [2037]. Since some CEOs have been ﬁred after large breaches,  
 information security has become a CEO issue.

**27.5.8** **Organizational mismanagement of risk**

Organizational issues are not just a contributory factor in system failure, as  
 with the loss of organizational memory and the lack of mechanisms for moni-  
 toring changing environments. They can often be a primary cause. There’s a  
 large literature on how people behave in organisations, which I touched on in  
 section 8.6.7, and I’ve given a number of further examples in various chapters.  
 However, the importance of organisational factors increases as projects get big-  
 ger. Bezos’ law says you can’t run a dev project with more people than can  
 be fed from two pizzas. A team of eight people is just about manageable, but  
 you can’t go six times as fast by having six such teams in parallel. If a project  
 involves multiple teams the members can’t talk to each other at random, or you

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get chaos; and they can’t route all their communications through the lowest  
 common manager as there isn’t the bandwidth. As you scale up, the coordina-  
 tion will start to involve a proliferation of middle managers, sta↵ departments  
 and committees. The communications complexity of a clean military chain of  
 command, for *N* people with no lateral interaction, is log *N*; where everybody  
 has to consult everybody else, it’s *N* 2; and where any subset can form a com-  
 mittee to think about the problem, it can head towards 2*N*. Business school  
 people have written extensively about this, and their methodology is generally  
 based on case studies.

Many large development projects have crashed and burned. The problems

appear to be much the same whether the disaster is a matter of safety, of security  
 or of the software simply never working at all; so security people can learn a lot  
 from studying project failures documented in the general engineering literature.

A classic study of large software project disasters was written by Bill Curtis,

Herb Krasner, and Neil Iscoe [504]. They found that failure to understand the re-  
 quirements was mostly to blame: a thin spread of application domain knowledge  
 typically led to ﬂuctuating and conﬂicting requirements which in turn caused a  
 breakdown in communication. The example I give in my undergraduate lectures  
 is the meltdown of a new dispatch system for the London Ambulance Service  
 where a combination of an overly ambitious project, an inadequate speciﬁcation  
 and no real testing led to the city being without ambulance cover for a day.  
 There are all too many such examples; I use the London Ambulance Service  
 case because the subsequent inquiry documented the causes rather well [1805].  
 I also happened to be in London that day, so I remember it. If you haven’t ever  
 read the inquiry report, I recommend you do so. (In fact I strongly recommend  
 that you read lots of case studies of project failure.)

The millennium bug gives another useful data point. If one accepts that

many large commercial and government systems needed extensive repair work to  
 change two-digit dates into four-digit ones in preparation for the year 2000, and  
 the conventional experience that a signiﬁcant proportion of large development  
 projects are late or never delivered at all, many people naturally assumed that  
 a signiﬁcant number of systems would fail at the end of 1999, and predicted  
 widespread chaos. But this didn’t happen. Certainly, the risks to the systems  
 used by small and medium-sized ﬁrms were overstated; we did a thorough check  
 of all our systems at the university, and found nothing much that couldn’t be  
 ﬁxed fairly easily [69]. Nevertheless, the systems of some large ﬁrms whose

operations are critical to the economy, such as banks and utilities, did need  
 substantial repairs. Yet there were no reports of high-consequence failures. This  
 appears to support Curtis, Krasner, and Iscoe’s thesis. The requirement for Y2K  
 bug ﬁxes was known completely: “I want this system to keep on working, just  
 as it is now, through into 2000 and beyond”.

This is one of the reasons I chose the quote from Rick Smith to head this

chapter: “My own experience is that developers with a clean, expressive set of  
 speciﬁc security requirements can build a very tight machine. They don’t have  
 to be security gurus, but they have to understand what they’re trying to build  
 and how it should work.”

Organisations have di�culty dealing with uncertainty, as it gets in the way of

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setting objectives and planning to meet them. So capable teams tackle the hard  
 problem ﬁrst, to reduce uncertainty; that was DARPA’s mission, and the core  
 of the spiral model. There’s a signiﬁcant business-school literature on how to  
 manage uncertainty in projects [1179]. But it’s easy to get this wrong, even in a  
 fairly well-deﬁned project. Faced with a hard problem, it is common for people  
 to furiously attack a related but easier one; we’ve seen a number of examples,  
 such as in section 26.2.8.

Risk management can be even worse in security where the problem is open-

ended. We really have no idea where the next shitstorm will come from. In the  
 late 1990s, we thought we’d got secure smartcards; then along came di↵erential  
 power analysis. In the mid-2010s we thought we had secure enough CPUs for  
 competitor ﬁrms to run their workloads on the same machines in Amazon data  
 centres; then along came Spectre. We also used to think that Apple products  
 couldn’t get malware and that face recognition would never be good enough to  
 be a real privacy threat. Even though Moore’s law is slowing down, there will  
 be more surprises.

Middle managers prefer approaches that they can implement by box-ticking

their way down a checklist, but to deal with uncertainties and open-ended risks,  
 you need a process of open learning, with people paying attention to the alerts,  
 or the frauds, or the safety incidents, or the customer complaints – whatever  
 you can learn from. But checklists demand less management attention and

e↵ort, and the quality bureaucracy loves them. I noted in section 9.6.6 that  
 certiﬁed processes had a strong tendency to displace critical thought; instead of  
 constantly reviewing a system’s protection requirements, designers just reach for  
 their checklists. The result is often perverse. By not tackling the hard problem  
 ﬁrst, you hide the uncertainty and it’s worse later6. Also, people rapidly learn  
 how to game checklists. There is the eternal tension between us security experts  
 telling ﬁrms to pay smart people to anticipate what might go wrong, and boards  
 telling managers to deliver product faster using fewer and cheaper engineers.

When the threat model is politically sensitive, things get more complicated.

The classic question is whether attacks come from insiders or outsiders. Insiders  
 are often the biggest security risk, whether because some of them are malicious  
 or because most of them are careless. But you can’t just train all your sta↵ to be  
 unhelpful to each other and to customers, unless perhaps you are a government  
 department or other monopoly. You have to ﬁnd the sweet spot for control,  
 and that often means working out how to embed it in the culture. For example,  
 bank managers know that dual-control safe locks reduce the risk of their families  
 being taken hostage, and requiring two signatures on large transactions means  
 extra shoulders to take the burden when something goes wrong.

Getting the risk ecosystem right in an organisation can take both subtlety

and persistence. The cultural embedding of controls and other protective mea-  
 sures is hard work; if you come into contact with multiple ﬁrms then it’s interest-  
 ing to observe how they manage their rules around everything from code audits  
 (which the tech majors insist on) to tailgating (which semiconductor ﬁrms are  
 at pains to prevent) and whether people are expected to keep one hand on a

6I will discuss ISO 27001 in the next chapter. The executive summary for now is that

almost every ﬁrm hit by a big data breach had ISO 27001 certiﬁcation, but it failed because  
 their auditors said something was OK that wasn’t.

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banister as they walk up and down the stairs (a favourite of energy companies).  
 Where do these risk cultures come from, how are they promoted, and why do  
 they cluster by sector? Their transactional internal control structures may be  
 heavily inﬂuenced by their auditors, as we discussed in section 12.2.6.3, but the  
 broader security culture varies a lot – and matters.

A further factor is that good CISOs are almost as rare as hens’ teeth. There

are some stars at the top tech and ﬁntech ﬁrms, but being a CISO can be a  
 thankless job. Good engineers often don’t want it, or don’t have the people skills  
 to cope, while ambitious managers tend to avoid the job. In many organisations,  
 promotions are a matter of seniority and contacts; so if you want to be the CEO  
 you’ll have to spend 20 years climbing up the hierarchy without o↵ending too  
 many people on the way. Being CISO will mean saying no to people all the time,  
 and a generalist with no tech background can’t hack it anyway. The job also  
 brings a lot of stress, and the risk of burnout; a CISO’s average tenure is about  
 two years [430]. In any case, embedding an appropriate culture around risk and  
 security is for the CEO and the board. If they don’t think it’s important, the  
 CISO has no chance. But breaches have now led to enough CEOs being ﬁred,  
 or losing millions on their stock, that other members of that tribe are starting  
 to pay attention.

One way the risk ecosystem can be skewed is that if a company manages

to arrange things so that some of the the risks of the systems it operates get  
 dumped on third parties. This creates a moral hazard by removing the incentives  
 to take care. We discussed this in section 12.5.2 in the context of banks trying  
 to shift fraud liability in payment systems to cardholders, merchants or both.  
 Sta↵ can get lazy or even crooked if they know that customer complaints will be  
 brushed o↵. Another example is Henry Ford, who took the view that if you were  
 injured by one of his cars, you should sue the driver, not him; it took decades  
 for courts and lawmakers to nail down product liability.

Companies may also swing from being risk takers to being too risk averse,

and back again. The personality of key executives does matter. My own uni-  
 versity has been gung-ho when we hired an engineer to be Vice-Chancellor,  
 timorous when we hired a lawyer, and in the middle when we hired a medic.

Another source of problems is when system design decisions are taken by

people who are unlikely to be held accountable for them. This can happen for  
 many reasons. IT sta↵ turnover could be high, with much reliance placed on  
 contract sta↵; fear of redundancy can turn loyal sta↵ into surreptitious job-  
 seekers. This can be a particular problem in big public-sector IT projects: none  
 of the ministers or civil servants involved expect to be around when the thing  
 is delivered seven years from now. So when working on a big system project,  
 don’t forget to look round and ask yourself who’ll take the blame later when  
 things go wrong.

Yet another is that when hiring security or safety consultants to help with

product design, ﬁrms have an incentive to go for a ﬁrm that is ‘good enough’ but  
 will not be too demanding; a gentle review from a Big Four ﬁrm will be much  
 more useful than a detailed review from an expert who might recommend much  
 more expensive design changes. Indeed, if a ﬁrm was determined to get a com-  
 pletely secure product, then they should hire multiple experts. We described

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in section 14.2.3 how this helped with the design of prepayment electricity me-  
 ters, and a later experiment with students conﬁrmed that the more people you  
 got to think about a proposed system design, the more potential hazards and  
 vulnerabilities they could spot [68]. Of course, this rarely happens.

**27.6** **Managing the Team**

To develop secure and reliable code, you need to build a team with the right  
 culture, the right mix of skills, and the right incentives.

Many modern systems are already so complex that few developers can cope

with all aspects of them. So how do you build strong development teams with  
 complementary skills? This has been a subject of vigorous debate for over ﬁfty  
 years now, with di↵erent writers reﬂecting their personal style or company cul-  
 ture. It has long been entangled with cultural issues such as diversity, although  
 these have only got serious attention since the mid-2010s.

**27.6.1** **Elite engineers**

Going back to the 1960s, Fred Brooks’s famous book, ‘The Mythical Man-  
 Month’, describes the lessons learned from developing the world’s ﬁrst large  
 software product, the operating system for the IBM S/360 mainframe [328].  
 He describes the ‘chief programmer team’, a concept evolved by his colleague  
 Harlan Mills, in which a chief programmer – a development lead, in today’s  
 language – is supported by a toolsmith, a tester and a language lawyer. The  
 thinking was that some programmers are much more productive than others, so  
 rather than promoting them to management and ‘losing’ them you create posts  
 for them with the salary and esteem of senior managers. The same approach  
 was found in other tech companies in the 1960s through the 1980s, and even in  
 bank IT departments where I worked in the late 1980s.

The view taken by more modern companies such as Microsoft, Google and

Facebook is that you only want to hire the ultra-productive engineers in the  
 ﬁrst place – especially if you get a million CVs a year but plan to hire only  
 20,000 new engineers. One approach is to hire people as contractors for a few  
 months to see how they do; but that’s harder with fresh graduates, as even  
 bright students from elite schools can take a few months to become productive  
 in a commercial team. Productivity is also a matter of culture; engineers who  
 thrive at one company may do much less well at another. A related issue is that  
 if you have each candidate interviewed by a number of your engineers, that’s not  
 just a drain on engineer time, but can also perpetuate a culture that’s not very  
 welcoming to women engineers. Elite universities are in a similar situation to  
 the tech majors, with dozens of applicants for each place; over the years we’ve  
 learned to have mechanisms to monitor diversity in hiring and admissions.

The two approaches are not in conﬂict. Modern tech ﬁrms employ multiple

tech superstars from internationally known designers to Turing-award winning  
 computer scientists. The view at one such ﬁrm is that you cannot expect to write  
 good software if you don’t have a career structure for programmers. People who

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want to spend their lives writing software, and are good at it, have to get respect,  
 however your organisation signals that – whether it’s salary, bonuses, stock or  
 fripperies like access to the executive dining room. Universities get this; we  
 professors run the place. Tech companies get it too, and one or two banks have  
 started to. But governments are generally appalling. In the UK civil service, the  
 motto is that “scientists should be on tap but not on top.” And more than one  
 car company I know of has real problems hiring and retaining decent software  
 engineers. In one of them, software engineers are expected to become managers  
 after ﬁve years or remain on a junior pay grade, while in another all engineers  
 are expected to wear business suits to work (and still paid lousy money). I’ll  
 return to this in section 27.6.6.

**27.6.2** **Diversity**

At the beginning of computing, there were plenty of women programmers – they  
 were the majority until the late 1960s, and included pioneers such as Grace  
 Hopper and Dame Stephanie Shirley (who ran her company for years as ‘Steve  
 Shirley’). When I started in the early 1970s there was still a much better

gender balance than today. There were minorities too; the orbital calculations  
 for the Mercury, Gemini and Apollo missions were led by an African-American  
 woman, Katharine Johnson. But things have become male-dominated in the  
 USA and the UK. Since I became an academic in the 1990s, about a sixth of  
 local computer science students have been women, despite signiﬁcant e↵orts to  
 recruit more women students. However, in the formerly communist countries  
 of Eastern Europe, the ratio is about a third. (We’ve improved our gender

balance by admitting lots of students from southern and eastern Europe.) In  
 India there’s close to gender balance. So this is a cultural issue, and there’s a  
 lot of debate on how it came about. Is it a lack of role models, or is it the fault  
 of careers advisers in schools, or are many IT shops just an unpleasant working  
 environment for women? That has certainly been an issue: the Gamergate

scandal, which I discussed in section 2.5.1, exposed deep misogyny in some  
 gaming communities, while the #MeToo movement has highlighted many cases  
 of sexism in Silicon Valley.

Even within computer science we see a lot of subcultural variation. The last

time I went to a hardware conference – an Arm developer event – I saw about  
 500 men but only three women (all of them Indian). In the security ﬁeld, we  
 were overwhelmingly male in the 1990s when the emphasis was cryptology and  
 operating system internals, but are much more balanced now we have embraced  
 the importance of design, usability and psychology. Role models and history do  
 matter. Research groups with a woman faculty member get more applications  
 from able women7.

More diverse teams are more e↵ective, and the real change doesn’t come

with the ﬁrst woman you hire, but when you have enough to change the team  
 culture. That might mean three or more. It also means getting more enlightened  
 managers. Clearly it’s a bad idea to hire misogynistic bullies, though it can be  
 hard to spot them in advance. More subtly, if you want to attract more women

7We have gender balance in our natural language processing group, started in the 1960s

by the late Karen Sp¨arck Jones.

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and retain them, it can be an idea to manage the people rather than the work.  
 You have to protect your sta↵ and give them space to do what they’re good  
 at. Bullies are often creeps too; as well as bossing the people under them they  
 suck up to the people above them. Very often such people don’t understand  
 what’s going on technically so they have no idea who’s productive and have to  
 judge people by timekeeping or by how much they ingratiate themselves. If this  
 management style spreads through an organisation, my advice would be to go  
 somewhere else.

**27.6.3** **Nurturing skills and attitudes**

Modern development has a tension between the desire to keep teams together,  
 so that they get more e�cient and predictable, and moving people around to  
 develop their skills, stop them going stale, and ensure that there’s more than  
 one person able to maintain everything that matters.

You will also need a diversity of skills. If you’re writing an app, for example,

you may want a couple of people to write the Android code, a couple for the  
 Apple code and a couple for the server. Depending on the task, there may be  
 a user advocate who leads usability testing; advocates for safety or security; an  
 architect whose job is to keep the overall design clean and e�cient; a language  
 lawyer who worries about APIs, a test engineer who runs the regression testing  
 machinery and a toolsmith who maintains the static and dynamic analysis tools.  
 If you’re doing continuous integration you’ll have an engineer specialising in  
 A/B testing while if you have a gated approach the test emphasis might be  
 on compatibility with third-party products or with security certiﬁcation. You’ll  
 need to give some thought to how many of these skills you try to get in each dev,  
 and how many are subject matter experts who work across teams or come in as  
 consultants. And as you can’t run a project with more people than you can feed  
 from two pizzas, you want some of your people to have two or more of these  
 skills. Good tech ﬁrms rotate engineers slowly through the company to acquire  
 a range of skills that maximises their value to the ﬁrm (even though it also  
 maximises their value to others, and makes it easier for them to leave) [1209].

But skills are not enough: you need to get people to work together. Here, too,

working practices have evolved over the years. By about 2010, agile developers  
 had adopted the ‘scrum’ where the whole dev team has a stand-up meeting  
 for ﬁve minutes each day, at which the only people allowed to speak are the  
 developers. They describe what they’ve done, what they’re about to do and  
 what the problems are. Some ﬁrms have moved teams to collaboration tools  
 such as Jira. In our team we combined daily lunches together with a formal  
 progress meeting once a week. (Since the coronavirus lockdown the formal

meeting has become more important and we’ve worked to complement it with  
 other online activities.)

It’s bad practice if people who ﬁnd bugs (even bugs that they coded them-

selves) just ﬁx them quietly; as bugs are correlated, there are likely to be more.  
 Bug tracking matters, and a ticketing system that enables good statistics to be  
 kept is an important tool in improving quality. As an example of good prac-  
 tice, in air tra�c control it’s expected that controllers making an error should  
 not only ﬁx it but declare it at once by open outcry: “I have Speedbird 123 at

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ﬂight level eight zero in the terminal control area by mistake, am instructing to  
 descend to six zero.” That way any other controller with potentially conﬂicting  
 tra�c can notice, shout out, and coordinate. Software is less dramatic, but is no  
 di↵erent: you need to get your devs comfortable with sharing their experiences,  
 including their errors.

Another factor in team building is the adoption of a standard style. One

signal of a poorly-managed team is that the codebase is in a chaotic mixture  
 of styles, with everybody doing their own thing. When a programmer checks  
 out some code to work on it, they may spend half an hour formatting it and  
 tweaking it into their own style. Apart from the wasted time, reformatted code  
 can trip up your analysis tools. You also want comments in the code, as people  
 typically spend more time reading code than writing it. You want to know

what a programmer who wrote a vulnerability thought they were doing: was it  
 a design error, or a coding blunder? But teams can easily ﬁght about the ‘right’  
 quantity and style of comments. So when you start a project, sit everyone down  
 and let them spend an afternoon hammering out what your house style will  
 be. Provided it’s enough for reading the code later and understanding bugs,  
 it doesn’t matter hugely what the style is: but it does matter that there is a  
 consistent style that people accept and that is ﬁt for purpose. Creating this style  
 is a better team-building activity than spending the afternoon paintballing, or  
 whatever the latest corporate team-building fad happens to be.

**27.6.4** **Emergent properties**

One debate is whether you make everyone responsible for securing their own  
 code, or have a security guru on whom everyone relies. The same question ap-  
 plies to safety in ﬁelds such as avionics. The answer, as the leading ﬁrms have  
 discovered, is ‘both’. We already noted that Microsoft found it more e↵ective  
 to have developers responsible for evolving their own designs and ﬁxing their  
 own bugs, rather than splitting these functions between analysts, programmers  
 and testers, as IBM did in the last century. Both Microsoft and Google now  
 put rookie engineers through a security ‘boot camp’, so that everyone knows the  
 basics, and also have subject matter experts at a number of levels. These range  
 from working security consultants with a masters degree or the equivalent inter-  
 nal qualiﬁcation, to people with PhDs in the intricate details of cryptography  
 or virtualisation.

The trick lies in managing the amount of specialisation in the team, and the

way in which the specialists (such as the security architect and the testing guru)  
 interact with the other developers.

**27.6.5** **Evolving your workﬂow**

You also need to think hard about the tools you’ll use. Professional development  
 teams avoid a large number of the problems described in this book by using  
 appropriate tools. You avoid bu↵er overﬂows by using a modern language such  
 as Rust, or if you must use C or C++ then have strict coding conventions  
 and enforce them using static-analysis tools such as SonarQube and Coverity.

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You avoid crypto problems, such as timing attacks and weak random number  
 generators, by using well-maintained libraries. But you need to understand

the limitations of your tools. In the case of Coverity, for example, its authors  
 explain that while it’s great if you use it from the start of a project, adopting it  
 in midstream imposes real costs, as you suddenly have 20,000 more bug reports  
 to triage, and your ship date slips by a few months [235]. Improvements in static  
 analysis tools, say in response to a new kind of attack, can also throw up a lot  
 of alarms in an existing codebase. In the case of crypto libraries, we discussed  
 in Chapter 6 how they tend to o↵er weak modes of operation such as ECB as  
 defaults, so you need to ensure your team uses GCM instead. (Crypto is one of  
 the areas where you need to talk to a subject matter expert.)

You’ll be constantly adding new tools, whether to avoid cross-site scripting

vulnerabilities and SQL injection as you update your website, or to make sure  
 you don’t leave your client data world-readable in an S3 bucket. If you don’t  
 follow the security news you may not be aware of the latest exploits and attacks,  
 so you may not realise when you have to either grow your own expertise or buy  
 it in. However you can’t just buy everything in; the security industry has

lots of unscrupulous operators who exploit ignorant customers. You need to  
 understand what you need to buy, and why, and then you will need to integrate  
 it with your existing tools, or your security ops people will spend ever more of  
 their time copying IP addresses from one tool to another. Doing some of your  
 own automation helps empower your sta↵ as well as saving time.

Your tools and libraries have to support your architecture. One critical thing

here is that you need to be able to evolve APIs safely. A system’s architecture  
 is deﬁned more than anything else by its interfaces, and it decays by a thousand  
 small cuts: by a programmer needing a ﬁle handling routine that uses two  
 more parameters than the existing one, and who therefore writes a new routine  
 – which may be dangerous in itself, or may just add to complexity and thus  
 contribute indirectly to an eventual failure. In an ideal world, you’d rely on your  
 programming language to prevent API problems using type safety mechanisms.

But the cross-system fan-out of dependencies is a real hazard to safe APIs.

We saw in section 20.5 how the APIs of cryptographic hardware security mod-  
 ules were extended to support hundreds of banks’ legacy ATM systems until we  
 suddenly realised that the resulting feature interactions made them completely  
 insecure. There are similar tensions in many other application areas, from mo-  
 bile phone baseband software used in over a hundred di↵erent models of phone,  
 to vehicle components used in over a hundred di↵erent cars. There must be  
 better ways of managing this; I expect that applications with high fan-out will  
 move in the direction of a microservices architecture with a common core and  
 pluggable proxies for di↵erent calling applications.

**27.6.6** **And ﬁnally...**

You also need to understand how to manage people, and the HR department  
 can’t do this for you8. Tech management cannot be done by generalists as

8The main job of HR is damage limitation – stopping leavers from suing you.

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they’re unlikely to win the trust of their sta↵9. It also cannot be done well by  
 engineers who are too introverted to engage and motivate others. Far too many  
 managers went for the job not because they thought they might be good at it,  
 but because it was the only way to get a decent salary. Successful managers in  
 tech have to love and understand tech; they also have to love and understand  
 people.

For your star engineers, you need to create other leadership roles. They

may be innovators who will be most productive in an R&D lab. They may be  
 the custodians of your institutional memory: old-timers who know the thirty  
 years of history behind your product and can stop people repeating the mistakes  
 of the past. They may provide moral leadership to your engineering sta↵ and  
 reassurance to your customers. They can help attract bright young recruits who  
 want to work with them. But the key, I feel, is this: that you have one or more  
 engineering professions in your ﬁrm. What’s their shape? Who leads them?  
 How do they compare to those in your competitors? How do you grow and  
 develop them? If you realise that all of a sudden you have to unify the safety  
 engineering and security engineering professions in your company, who is going  
 to do that, and how?

**27.7** **Summary**

Managing a project to build, or enhance, a system that has to meet critical  
 requirements for security, safety or both, is a hard problem. As more and

more devices acquire CPUs and communications, we need to build things that  
 do real work while keeping out any vulnerabilities that would make them a  
 target for attack. In other words, you want software security – together with  
 other functionality, and other emergent properties such as safety and real-time  
 performance.

If you’re building something entirely new, or a major functional enhancement

of an existing system, then understanding the requirements is often the hardest  
 part of the process. More gentle system evolution can involve subtler changes  
 to requirements. Larger changes can be forced externally; systems that succeed  
 and get popular, can expect to get attacked.

Writing secure code is hard because of this dynamic context: the ﬁrst prob-

lem is to ﬁgure out what you’re trying to do. However, even given a tight

speciﬁcation, or constant feedback from people hacking your product, you’re  
 not home and dry. There are a number of challenges in hiring the right people,  
 giving them the right tools, helping them develop the right ways of working,  
 backing them up with expertise in the right way, and above all creating an  
 environment in which they work to improve their security capability.

9As a math geek I always tended to see the MBA types and other corporate politicians

much as the Earl of Rochester saw King Charles II: “Here lies our sovereign lord the king,  
 Whose word no man relies on; He never says a foolish thing, Nor ever does a wise one.”

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**Research Problems**

The issues discussed in this chapter are among the hardest and the most impor-  
 tant of any in our ﬁeld. However, they receive little attention because they lie  
 at the boundaries with software engineering, applied psychology, economics and  
 management. Each of these interfaces could be a productive area of research.  
 Security economics and security psychology have made great strides in the last  
 few years, and we now know we need to do a lot more work on making security  
 tools easier for developers to use. One logical next step is integrating what we  
 know with safety economics and safe usability.

Yet many failures are due to organisational behaviour. Every experienced

developer or security consultant has their share of horror stories about ﬁrms with  
 perverse incentives, toxic cultures, high sta↵ turnover, incompetent management  
 and all the rest of the things we see in the Dilbert cartoons. It could be useful if  
 someone were to collect a library of case histories of security failures caused by  
 unsatisfactory incentives in organisations, such as [876, **?**]. What might follow  
 given a decent empirical foundation?

The late Jack Hirshleifer took the view that we should try to design organi-

zations in which managers were forced to learn from their mistakes: how could  
 we do that? How might you set up institutional structures to monitor changes  
 in the threat environment and feed them through into not just systems devel-  
 opment but into supporting activities such as internal control? Maybe we need  
 something like Management as Code? How can you design an organization that  
 is ‘safety-incentive-compatible’ in the sense that sta↵ behave with an appropri-  
 ate level of care? And what might the cultural anthropology of organisations  
 have to say? We saw in the last chapter how the response of governments to the  
 apparently novel threats posed by Al-Qaida was maladaptive in many ways: far  
 too much of our social resilience budget was spent on anti-terror theatre, at the  
 expense of preparedness for other societal risks such as pandemics. Similarly,  
 far too much of the typical ﬁrm’s resilience budget has been captured by compli-  
 ance, safety theatre and security theatre. As a result, too much of the security  
 development e↵ort is aimed at compliance rather than managing security and  
 safety risks properly. How can we design feedback mechanisms that will enable  
 us to put the right amount of e↵ort in the right place? Or do we need broader  
 structural change, such as the breakup of the Big Four accountancy ﬁrms?

**Further Reading**

Managing the development of information systems has a large, di↵use and mul-  
 tidisciplinary literature. There are classics everyone should read, such as Fred  
 Brooks’s ‘Mythical Man Month’ [328] and Nancy Leveson’s ‘Safeware’ [1149].  
 The economics of the software life cycle are discussed by Brooks and by Barry  
 Boehm [272]. The modern books everyone should read, as of 2020, are proba-  
 bly the Google books on SRE [236] and on‘Building Secure and Reliable Sys-  
 tems’ [23]. The Microsoft approach to the security development lifecycle has  
 many online resources; their doctrine on threat modelling is discussed by Frank  
 Swiderski and Window Snyder [1851]; and their security VP Mike Nash de-

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scribes the background to the big security push and the adoption of the security  
 development lifecycle at [1385]. The most general set of standards on safety  
 functional and integrity requirements, and the associated engineering processes,  
 is IEC 61508; there are further sets of industry-speciﬁc standards. For example,  
 there’s IEC 61511 for process plant control systems, IEC 62061 for safety of  
 machinery, and the EN 5012x series for railways. In aviation it’s RTCA DO-254  
 for electronic hardware and RTCA DO-178C for software, while in the motor  
 industry it’s ISO 26262 for safety and ISO 21434 for security – though at the  
 time of writing this is still just a draft. Standards for the Internet of Things are  
 also a work in progress, and the current draft is ETSI EN 303 645 V2.1.

We can learn a lot from other engineering disciplines. Henry Petroski dis-

cusses the history of bridge building, why bridges fall down, and how civil en-  
 gineers learned to learn from the collapses: what tends to happen is that an  
 established design paradigm is stretched and stretched until it suddenly fails  
 for some unforeseen reason [1518]. IT project failures are another necessary  
 subject of study; there’s a casebook on how to manage uncertainty in projects  
 by Christoph Loch, Arnoud DeMeyer and Michael Pich [1179]. For security  
 failures, it’s important to follow the leading security blogs such as Schneier on  
 Security, Krebs on Security and SANS, as well as the trade press.

Organizational aspects are discussed at length in the business school liter-

ature, but this can be bewildering to the outsider. Many business academics  
 praise business, which is ﬁne for selling airport books, but what we need is a more  
 critical understanding of how organisations fail. If you’re only going to read one  
 book, make it Lewis Pinault’s ‘Consulting Demons’ – the confessions of a former  
 insider about how the big consulting ﬁrms rip o↵ their customers [1527]. Or-  
 ganisational theorists such as Charles Handy talk of ﬁrms having cultures based  
 on power, roles, tasks or people, or some combination. It’s not just who has  
 access to whom, but who’s prepared to listen to whom and who will just ignore  
 orders from whom. Perhaps such insights might help us design more e↵ective  
 tools and workﬂows that support how people actually work best.

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