Chapter 8

Economics

The great fortunes of the information age lie in the hands of companies that have established proprietary architectures that are used by a

large installed base of locked-in customers.

– CARL SHAPIRO AND HAL VARIAN

There are two things I am sure of after all these years: there is a growing societal need for high assurance software, and market forces are never going to provide it.

– EARL BOEBERT

The law locks up the man or woman Who steals the goose from o↵ the common But leaves the greater villain loose

Who steals the common from the goose.

– TRADITIONAL, 17th CENTURY

# Introduction

Round about 2000, we started to realise that many security failures weren’t due to technical errors so much as to wrong incentives: if the people who guard a system are not the people who su↵er when it fails, then you can expect trouble. In fact, security mechanisms are often designed deliberately to shift liability, which can lead to even worse trouble.

Economics has always been important to engineering, at the raw level of cost accounting; a good engineer was one who could build a bridge safely with a thousand tons of concrete when everyone else used two thousand tons. But the perverse incentives that arise in complex systems with multiple owners make eco- nomic questions both more important and more subtle for the security engineer. Truly global-scale systems like the Internet arise from the actions of millions of independent principals with divergent interests; we hope that reasonable global

263

outcomes will result from selﬁsh local actions. The outcome we get is typically a market equilibrium, and often a surprisingly stable one. Attempts to make large complex systems more secure, or safer, will usually fail if this isn’t understood. At the macro level, cybercrime patterns have been remarkably stable through the 2010s even though technology changed completely, with phones replacing laptops, with society moving to social networks and servers moving to the cloud. Network insecurity is somewhat like air pollution or congestion, in that people who connect insecure machines to the Internet do not bear the full consequences of their actions while people who try to do things right su↵er the side-e↵ects of others’ carelessness.

In general, people won’t change their behaviour unless they have an incentive to. If their actions take place in some kind of market, then the equilibrium will be where the forces pushing and pulling in di↵erent directions balance each other out. But markets can fail; the computer industry has been dogged by monopolies since its earliest days. The reasons for this are now understood, and their interaction with security is starting to be.

Security economics has developed rapidly as a discipline since the early 2000s. It provides valuable insights not just into ‘security’ topics such as privacy, bugs, spam, and phishing, but into more general areas of system dependability. For example, what’s the optimal balance of e↵ort by programmers and testers? (For the answer, see section 8.6.3 below.) It also enables us to analyse many impor- tant policy problems – such as the costs of cybercrime and the most e↵ective responses to it. And when protection mechanisms are used to limit what some- one can do with their possessions or their data, questions of competition policy and consumer rights follow – which we need economics to analyse. There are also questions of the balance between public and private action: how much of the protection e↵ort should be left to individuals, and how much should be borne by vendors, regulators or the police? Everybody tries to pass the buck.

In this chapter I ﬁrst describe how we analyse monopolies in the classical economic model, how information goods and services markets are di↵erent, and how network e↵ects and technical lock-in make monopoly more likely. I then look at asymmetric information, another source of market power. Next is game theory, which enables us to analyse whether people will cooperate or compete; and auction theory, which lets us understand the working of the ad markets

that drive much of the Internet – and how they fail. These basics then let us analyse key components of the information security ecosystem, such as the software patching cycle. We also get to understand why systems are less reliable than they should be: why there are too many vulnerabilities and why too few cyber-crooks get caught.

# Classical economics

Modern economics is an enormous ﬁeld covering many di↵erent aspects of human behaviour. The parts of it that have found application in security so far are largely drawn from microeconomics, game theory and behavioral economics. In this section, I’ll start with a helicopter tour of the most relevant ideas from microeconomics. My objective is not to provide a tutorial on economics, but to

get across the basic language and ideas, so we can move on to discuss security economics.

The modern subject started in the 18th century when growing trade changed the world, leading to the industrial revolution, and people wanted to under- stand what was going on. In 1776, Adam Smith’s classic *‘The Wealth of Na- tions’* [1788] provided a ﬁrst draft: he explained how rational self-interest in a free market leads to progress. Specialisation leads to productivity gains, as people try to produce something others value to survive in a competitive mar- ket. In his famous phrase, “It is not from the benevolence of the butcher, the brewer, or the baker, that we can expect our dinner, but from their regard to their own interest.” The same mechanisms scale up from a farmers’ market or small factory to international trade.

These ideas were reﬁned by nineteenth-century economists; David Ricardo clariﬁed and strengthened Smith’s arguments in favour of free trade, while Stan- ley Jevons, L´eon Walras and Carl Menger built detailed models of supply and demand. One of the insights from Jevons and Menger is that the price of a

good, at equilibrium in a competitive market, is the marginal cost of produc- tion. When coal cost nine shillings a ton in 1870, that didn’t mean that every mine dug coal at this price, merely that the marginal producers – those who were only just managing to stay in business – could sell at that price. If the price went down, these mines would close; if it went up, even more marginal mines would open. That’s how supply responded to changes in demand. (It also gives us an insight into why so many online services nowadays are free; as the marginal cost of duplicating information is about zero, lots of online busi- nesses can’t sell it and have to make their money in other ways, such as from advertising. But we’re getting ahead of ourselves.)

By the end of the century Alfred Marshall had combined models of supply and demand in markets for goods, labour and capital into an overarching ‘clas- sical’ model in which, at equilibrium, all the excess proﬁts would be competed away and the economy would be functioning eﬃciently. By 1948, Kenneth Ar- row and G´erard Debreu had put this on a rigorous mathematical foundation by proving that markets give eﬃcient outcomes, subject to certain conditions, including that the buyers and sellers have full property rights, that they have complete information, that they are rational and that the costs of doing trans-

actions can be neglected.

Much of the interest in economics comes from the circumstances in which one or more of these conditions aren’t met. For example, suppose that trans- actions have side-e↵ects that are not captured by the available property rights. Economists call these *externalities*, and they can be either positive or negative. An example of a positive externality is scientiﬁc research, from which every- one can beneﬁt once it’s published. As a result, the researcher doesn’t capture the full beneﬁt of their work, and we get less research than would be ideal (economists reckon we do only a quarter of the ideal amount of research). An example of a negative externality is environmental pollution; if I burn a coal ﬁre,

I get the positive e↵ect of heating my house but my neighbour gets the negative

e↵ect of smell and ash, while everyone shares the negative e↵ect of increased CO2 emissions.

Externalities, and other causes of market failure, are of real importance to the computer industry, and to security folks in particular, as they shape many of the problems we wrestle with, from industry monopolies to insecure software. Where one player has enough power to charge more than the market clearing price, or nobody has the power to ﬁx a common problem, then markets alone may not be able to sort things out. Strategy is about acquiring power, or preventing other people having power over you; so the most basic business strategy is to acquire market power in order to extract extra proﬁts, while distributing the costs of your activity on others to the greatest extent possible. Let’s explore that now in more detail.

## Monopoly

As an introduction, let’s consider a textbook case of monopoly. Suppose we have a market for apartments in a university town, and the students have di↵erent incomes. We might have one rich student able to pay $4000 a month, maybe 300 people willing to pay at least $2000 a month, and (to give us round numbers) at least 1000 prepared to pay at least $1000 a month. That gives us the *demand curve* shown in Figure 8.1 below.

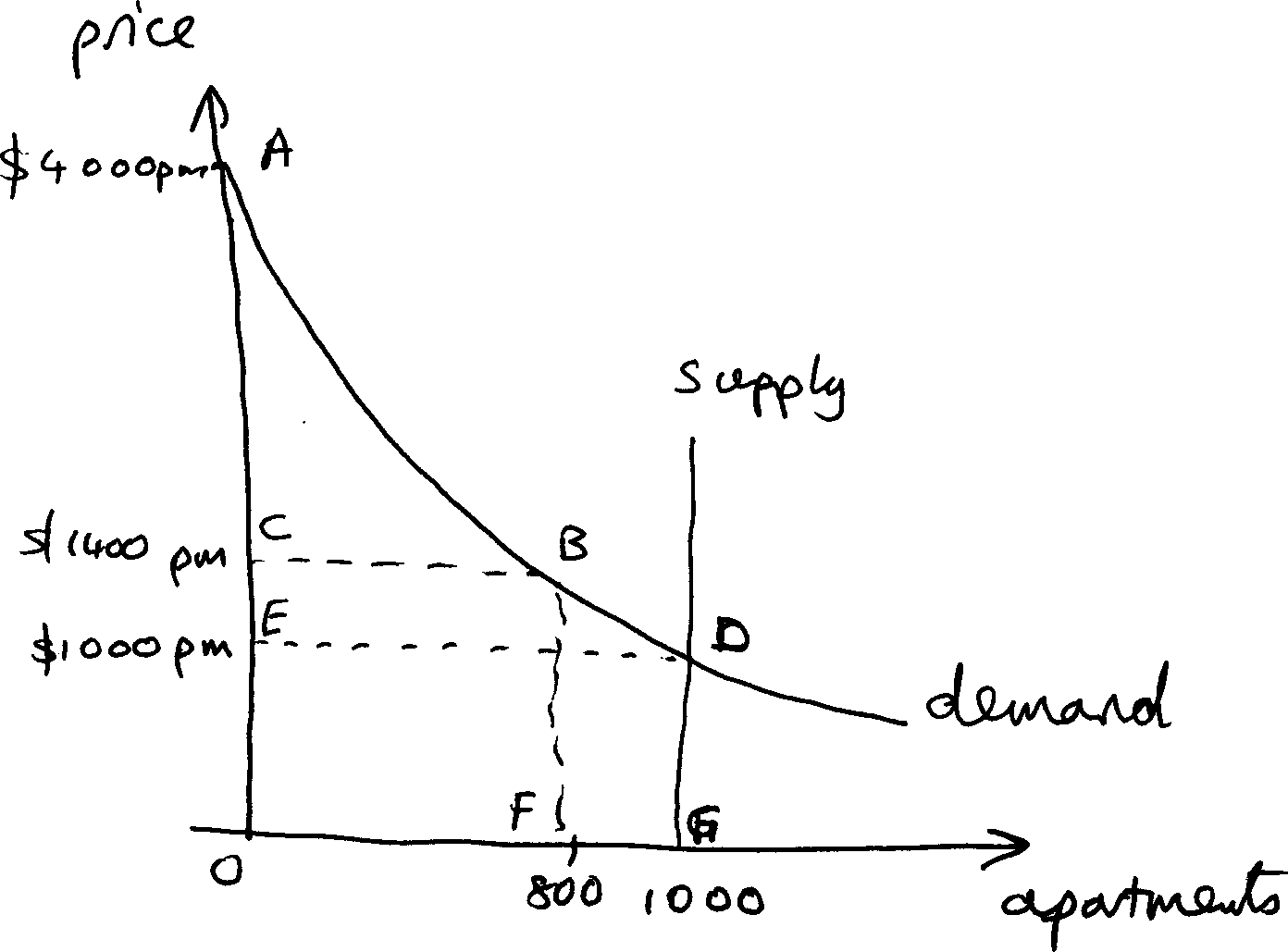


Figure 8.1: the market for apartments

So if there are 1000 apartments being let by many competing landlords, the market-clearing price will be at the intersection of the demand curve with the vertical supply curve, namely $1000. But suppose the market is rigged – say the landlords have set up a cartel, or the university makes its students rent through a tied agency. A monopolist landlord examines the demand curve, and notices that if he rents out only 800 apartments, he can get $1400 per month for each of them. Now 800 times $1400 is $1,120,000 per month, which is more than the million dollars a month he’ll make from the market price at $1000. (Economists

would say that his ‘revenue box’ is the box CBFO rather than EDGO in ﬁgure 8.1.) So he sets an artiﬁcially high price, and 200 apartments remain empty.

This is clearly ineﬃcient, and the Italian economist Vilfredo Pareto invented a neat way to formalise this. A *Pareto improvement* is any change that would make some people better o↵ without making anyone else worse o↵, and an allo- cation is *Pareto e*ﬃ*cient* if there isn’t any Pareto improvement available. Here, the allocation is not eﬃcient, as the monopolist could rent out one empty apart- ment to anyone at a lower price, making both him and them better o↵. Now Pareto eﬃciency is a rather weak criterion; both perfect communism (every- one gets the same income) and perfect dictatorship (the king gets the lot) are Pareto-eﬃcient. In neither case can you make anyone better o↵ without making someone else worse o↵! Yet the simple monopoly described here is not eﬃcient even in this very weak sense.

So what can the monopolist do? There is one possibility – if he can charge everyone a di↵erent price, then he can set each student’s rent at exactly what they are prepared to pay. We call such a landlord a *price-discriminating monop- olist*; he charges the rich student exactly $4000, and so on down to the 1000th student whom he charges exactly $1000. The same students get apartments as before, yet almost all of them are worse o↵. The rich student loses $3000, money that he was prepared to pay but previously didn’t have to; economists refer to this money he saved as *surplus*. The discriminating monopolist manages to extract all the consumer surplus.

Merchants have tried to price-discriminate since antiquity. The carpet seller in Istanbul who expects you to haggle down his price is playing this game, as is an airline selling ﬁrst, business and cattle class seats. The extent to which ﬁrms can charge people di↵erent prices depends on a number of factors, principally their *market power* and their *information asymmetry*. Market power is a measure of

how close a merchant is to being a monopolist; under monopoly the merchant is a *price setter*, while under perfect competition he is a *price taker* who has to accept whatever price the market establishes. Merchants naturally try to avoid this. Information asymmetry can help them in several ways. A carpet seller has much more information about local carpet prices than a tourist who’s passing through, and who won’t have the time to haggle in ten di↵erent shops. So the

merchant may prefer to haggle rather than display ﬁxed prices. An airline is

slightly di↵erent. Thanks to price-comparison sites, its passengers have good information on base prices, but if it does discount to ﬁll seats, it may be able to target its o↵ers using information from the advertising ecosystem. It can also create its own loyalty ecosystem by o↵ering occasional upgrades. Technology tends to make ﬁrms more like airlines and less like small carpet shops; the information asymmetry isn’t so much whether you know about average prices,

as what the system knows about you and how it locks you in.

Monopoly can be complex. The classic monopolist, like the landlord or cartel in our example, may simply push up prices for everyone, resulting in a clear loss of consumer surplus. Competition law in the USA looks for welfare loss of this kind, which often happens where a cartel operates price discrimination.

During the late 19th century, railroad operators charged di↵erent freight rates to di↵erent customers, depending on how proﬁtable they were, how perishable their goods were and other factors – basically, shaking them all down according

to their ability to pay. This led to massive resentment and to railway regulation. In the same way, telcos used to price-discriminate like crazy; SMSes used to cost a lot more than voice, and voice a lot more than data, especially over distance. This led to services like Skype and WhatsApp which use data services to provide cheaper calls and messaging, and also to net neutrality regulation in a number of countries. This is still a tussle space, with President Trump’s appointee at the FCC reversing many previous net neutrality rulings.

However, many ﬁrms with real market power like Google and Facebook give their products away free to most of their users, while others, like Amazon (and Walmart), cut prices for their customers. This challenges the traditional basis that economists and lawyers used to think about monopoly, in the USA at least. Yet there’s no doubt about monopoly power in tech. We may have gone from one dominant player in the 1970s (IBM) to two in the 1990s (Microsoft and Intel) and a handful now (Google, Facebook, Amazon, Microsoft, maybe Netﬂix) but each dominates its ﬁeld; although Arm managed to compete with Intel, there has been no new search startup since Bing in 2009 (whose market share is slipping), and no big social network since Instagram in 2011 (now owned by Facebook). So there’s been a negative e↵ect on innovation, and the question

what we do about it is becoming a hot political topic. The EU has ﬁned tech majors multiple times for competition o↵ences.

To understand what’s going on, we need to dive more deeply into how infor- mation monopolies work.

# Information economics

The information and communications industries are di↵erent from traditional manufacturing in a number of ways, and among the most striking is that these markets have been very concentrated for generations. Even before computers came along, newspapers tended to be monopolies, except in the biggest cities. Much the same happened with railways, and before that with canals. When electrical tabulating equipment came along in the late 19th century, it was dominated by NCR, until a spin-o↵ from NCR’s Manhattan sales oﬃce called IBM took over. IBM dominated the computer industry in the 1960s and 70s, then Microsoft came along and took pole position in the 90s. Since then, Google and Facebook have come to dominate advertising, Apple and Google sell phone operating systems, ARM and Intel do CPUs, while many other ﬁrms dominate their own particular speciality. Why should this be so?

## Why information markets are di↵erent

Recall that in a competitive equilibrium, the price of a good should be its marginal cost of production. But for information that’s almost zero! That’s why there is so much free stu↵ online; zero is its fair price. If two or more suppliers compete to o↵er an operating system, or a map, or an encyclopedia, that they can duplicate for no cost, then they will keep on cutting their prices

without limit. Take for example encyclopedias; the Britannica used to cost

$1,600 for 32 volumes; then Microsoft brought out Encarta for $49.95, forcing

Britannica to produce a cheap CD edition; and now we have Wikipedia for free [1718]. One ﬁrm after another has had to move to a business model in which the goods are given away free, and the money comes from advertising or in some parallel market. And it can be hard to compete with services that are free, or are so cheap it’s hard to recoup the capital investment you need to get started. So other industries with high ﬁxed costs and low marginal costs tend to be concentrated – such as newspapers, airlines and hotels.

Second, there are often *network externalities*, whereby the value of a network grows more than linearly in the number of users. Networks such as the telephone and email took some time to get going because at the start there were only a few other enthusiasts to talk to, but once they passed a certain threshold in each social group, everyone needed to join and the network rapidly became main- stream. The same thing happened again with social media from the mid-2000s; initially there were 40–50 startups doing social networks, but once Facebook started to pull ahead, suddenly all young people had to be there, as that was where all your friends were, and if you weren’t there then you missed out on

the party invitations. This *positive feedback* is one of the mechanisms by which network e↵ects can get established. It can also operate in a *two-sided market* which brings together two types of user. For example, when local newspapers got going in the nineteenth century, businesses wanted to advertise in the papers with lots of readers, and readers wanted papers with lots of small ads so they could ﬁnd stu↵. So once a paper got going, it often grew to be a local monopoly; it was hard for a competitor to break in. The same thing happened when the railways allowed the industrialisation of agriculture; powerful ﬁrms like Cargill and Armour owned the grain elevators and meat-packers, dealing with small farmers on one side and the retail industry on the other. We saw the same pat- tern in the 1960s when IBM mainframes dominated computing: ﬁrms used to develop software for IBM as they’d have access to more users, while many users bought IBM because there was more software for it. When PCs came along, Microsoft beat Apple for the same reason; and now that phones are replacing laptops, we see a similar pattern with Android and iPhone. Another winner was eBay in the late 1990s: most people wanting to auction stu↵ will want to

use the largest auction, as it will attract more bidders. Network e↵ects can

also be negative; once a website such as Myspace starts losing custom, negative feedback can turn the loss into a rout.

Third, there are various supply-side scale economies enjoyed by leading in- formation services ﬁrms, ranging from access to unmatchable quantities of user data to the ability to run large numbers of A/B tests to understand user pref- erences and optimise system performance. These enable early movers to create, and incumbents to defend, competitive advantage in service provision.

Fourth, there’s often lock-in stemming from *interoperability*, or a lack thereof. Once a software ﬁrm commits to using a platform such as Windows or Oracle for its product, it can be expensive to change. This has both technical and human components, and the latter are often dominant; it’s cheaper to replace tools than to retrain programmers. The same holds for customers, too: it can be hard to close a sale if they not only have to buy new software and convert ﬁles, but retrain their sta↵ too. These *switching costs* deter migration. Earlier platforms where interoperability mattered included the telephone system, the

telegraph, mains electricity and even the railways.

These four features separately – low marginal costs, network externalities, supply-side scale economies and technical lock-in – can lead to industries with dominant ﬁrms; in combination, they are even more likely to. If users want to be compatible with other users (and with vendors of complementary products such as software) then they will logically buy from the vendor they expect to win the biggest market share.

## The value of lock-in

There is an interesting result, due to Carl Shapiro and Hal Varian: that the value of a software company is the total lock-in (due to both technical and network e↵ects) of all its customers [1718]. To see how this might work, consider a ﬁrm with 100 sta↵ each using Oﬃce, for which it has paid $150 per copy. It could

save this $15,000 by moving to a free program such as LibreOﬃce, so if the

costs of installing this product, retraining its sta↵, converting ﬁles and so on

– in other words the total switching costs – were less than $15,000, it would switch. But if the costs of switching were more than $15,000, then Microsoft would put up its prices.

As an example of the link between lock-in, pricing and value, consider how prices changed over a decade. In the second edition of this book, this example had the cost of Oﬃce as $500; since then, cloud-based services that worked just like Oﬃce, such as Google Docs, cut the costs of switching – so Microsoft had to

slash its prices. As I started writing this edition in 2019, I saw standalone Oﬃce

for sale at prices ranging between $59.99 and £164. Microsoft’s response since

2013 has been trying to move its customers to an online subscription service (Oﬃce365) which costs universities a few tens of pounds per seat depending on what options they choose and how good they are at negotiating, while Google is also trying to move organisations away from their free services to paid G Suite versions that cost about the same. Charging $30 a year for an online service is better business than charging $60 for a program that the customer might use for ﬁve years or even seven. When I revised this chapter in 2020, I saw I can now get a ‘lifetime key’ for about double the cost of a standalone product last year. There’s a new form of lock-in, namely that the cloud provider now looks after all your data.

Lock-in explains why so much e↵ort gets expended in standards wars and antitrust suits. It also helps explain the move to the cloud (though cost cutting is a bigger driver). It’s also why so many security mechanisms aim at controlling compatibility. In such cases, the likely attackers are not malicious outsiders, but the owners of the equipment, or new ﬁrms trying to challenge the incumbent by making compatible products. This doesn’t just damage competition, but innovation too. Locking things down too hard can also be bad for business, as innovation is often incremental, and products succeed when new ﬁrms ﬁnd killer applications for them [903]. The PC, for example, was designed by IBM as a machine to run spreadsheets; if they had locked it down to this application alone, then a massive opportunity would have been lost. Indeed, the fact that the IBM PC was more open than the Apple Mac was a factor in its becoming the dominant desktop platform. (That Microsoft and Intel later stole IBM’s

lunch is a separate issue.)

So the law in many countries gives companies a right to reverse-engineer their competitors’ products for compatibility [1647]. Incumbents try to build ecosystems in which their o↵erings work better together than with their com- petitors’. They lock down their products using digital components such as cloud services and cryptography so that even if competitors have the legal right to try to reverse engineer these products, they are not always going to succeed in prac- tice. Incumbents also use their ecosystems to learn a lot about their customers, the better to lock them in; while a variety of digital mechanisms are to con- trol aftermarkets and enforce planned obsolescence. I will discuss these more complex ecosystem strategies in more detail below in section 8.6.4.

## Asymmetric information

Another way markets can fail, beyond monopoly and public goods, is when some principals know more than others, or know it slightly earlier, or can ﬁnd it out more cheaply. We discussed how an old-fashioned carpet trader has an information advantage over tourists buying in his store; but the formal study of *asymmetric information* was kicked o↵ by a famous paper in 1970 on the ‘market for lemons’ [34], for which George Akerlof won a Nobel prize. It presents the following simple yet profound insight: suppose that there are 100 used cars for sale in a town: 50 well-maintained cars worth $2000 each, and 50 ‘lemons’ worth $1000. The sellers know which is which, but the buyers don’t. What is the market price of a used car?

You might think $1500; but at that price, no good cars will be o↵ered for sale. So the market price will be close to $1000. This is why, if you buy a new car, maybe 20% falls o↵ the price the second you drive it out of the dealer’s lot. Asymmetric information is also why poor security products dominate some markets. When users can’t tell good from bad, they might as well buy the cheapest. When the market for antivirus software took o↵ in the 1990s, people would buy the $10 product rather than the $20 one. (Nowadays there’s much less reason to buy AV, as the malware writers test their code against all available products before releasing it – you should focus on patching systems instead. That people still buy lots of AV is another example of asymmetric information.)

A further distinction can be drawn between hidden information and hidden action. For example, Volvo has a reputation for building safe cars that help their occupants survive accidents, yet Volvo drivers have more accidents. Is this because people who know they’re bad drivers buy Volvos so they’re less likely to get killed, or because people in Volvos believe they’re safer and drive faster?

The ﬁrst is the hidden-information case, also known as *adverse selection*, and the second is the hidden-action case, also known as *moral hazard*. Both e↵ects are important in security, and both may combine in speciﬁc cases. (In the case of drivers, people adjust their driving behaviour to keep their risk exposure at the level with which they’re comfortable. This also explains why mandatory seat- belt laws tend not to save lives overall, merely to move fatalities from vehicle

occupants to pedestrians and cyclists [19].)

Asymmetric information explains many market failures in the real world,

from low prices in used-car markets to the high price of cyber-risks insurance (ﬁrms who know they cut corners may buy more of it, making it expensive for the careful). In the world of information security, it’s made worse by the fact that most stakeholders are not motivated to tell the truth; police and intelligence agencies, as well as security vendors, try to talk up the threats while software vendors, e-commerce sites and banks downplay them [111].

## Public goods

An interesting case of positive externalities is when everyone gets the same quantity of some good, whether they want it or not. Classic examples are air quality, national defense and scientiﬁc research. Economists call these *public goods*, and the formal deﬁnition is that such goods are non-rivalrous (my using them doesn’t mean there’s less for you) and non-excludable (there’s no practical

way to stop people consuming them). Uncoordinated markets are generally unable to provide public goods in socially optimal quantities.

Public goods may be supplied by governments directly, as with national defense, or by using indirect mechanisms such as laws on patents and copyrights to encourage people to produce inventions, books and music by giving them a temporary monopoly. Very often, public goods are provided by some mix of public and private action; scientiﬁc research is done in universities that get some public subsidy, earn some income from student fees, and get some research contracts from industry (which may get patents on the useful inventions).

Many aspects of security are public goods. I do not have an anti-aircraft gun on the roof of my house; air-defense threats come from a small number of actors, and are most eﬃciently dealt with by government action. So what about Internet security? Certainly there are strong externalities; people who connect insecure machines to the Internet end up dumping costs on others, as they enable bad actors to build botnets. Self-protection has some aspects of a public good, while insurance is more of a private good. So what should we do about it?

The answer may depend on whether the bad actors we’re concerned with are concentrated or dispersed. In our quick survey of cybercrime in section 2.3 we noted that many threats have consolidated as malware writers, spammers and others have become commercial. By 2007, the number of serious spammers had dropped to a handful, and by 2019, the same had become true of denial-of- service (DoS) attacks: there seems to be one dominant DoS-for-hire provider. This suggests a more centralised defence strategy, namely, ﬁnding the bad guys and throwing them in jail.

Some have imagined a gentler government response, with rewards paid to researchers who discover vulnerabilities, paid for by ﬁnes imposed on the ﬁrms whose software contained them. To some extent this happens already via bug bounty programs and vulnerability markets, without government intervention. But a cynic will point out that in real life what happens is that vulnerabilities are sold to cyber-arms manufacturers who sell them to governments who then stockpile them – and industry pays for the collateral damage, as with NotPetya. So is air pollution the right analogy – or air defense? This brings us to game

theory.

# Game theory

Game theory has some of the most fundamental insights of modern economics. It’s about when we cooperate, and when we ﬁght.

There are really just two ways to get something you want if you can’t ﬁnd or make it yourself. You either make something useful and trade it; or you take what you need, by force, by the ballot box or whatever. Choices between cooperation and conﬂict are made every day at all sorts of levels, by both humans and animals.

The main tool we can use to study and analyse them is *game theory* – the study of problems of cooperation and conﬂict among independent decision mak- ers. Game theory provides a common language used by economists, biologists and political scientists as well as computer scientists, and is a useful tool for building collaboration across disciplines. We’re interested in games of strategy, and we try to get to the core of a decision by abstracting away much of the de- tail. For example, consider the school playground game of ‘matching pennies’: Alice and Bob toss coins and reveal them simultaneously, upon which Alice gets Bob’s penny if they’re di↵erent and Bob gets Alice’s penny if they’re the same. I’ll write this as in Figure 7.2:

Bob

|  |  |  |
| --- | --- | --- |
|  | H | T |
| H | -1,1 | 1,-1 |
| T | 1,-1 | -1,1 |

Alice

Figure 7.2 – matching pennies

Each entry in the table shows ﬁrst Alice’s outcome and then Bob’s. Thus if the coins fall (H,H) Alice loses a penny and Bob gains a penny. This is an example of a *zero-sum game*: Alice’s gain is Bob’s loss.

Often we can solve a game quickly by writing out a *payo*↵ *matrix* like this.

Here’s an example (Figure 7.3):

Bob

|  |  |  |
| --- | --- | --- |
|  | Left | Right |
| Top | 1,2 | 0,1 |
| Bottom | 2,1 | 1,0 |

Alice

Figure 7.3 – dominant strategy equilibrium

In game theory, a *strategy* is just an algorithm that takes a game state and

outputs a move1. In this game, no matter what Bob plays, Alice is better o↵ playing ‘Bottom’; and no matter what Alice plays, Bob is better o↵ playing ‘Left’. Each player has a *dominant strategy* – an optimal choice regardless of what the other does. So Alice’s strategy should be a constant ‘Bottom’ and

Bob’s a constant ‘Left’. We call this a *dominant strategy equilibrium*.

Another example is shown in Figure 7.4:

Bob

|  |  |  |
| --- | --- | --- |
|  | Left | Right |
| Top | 2,1 | 0,0 |
| Bottom | 0,0 | 1,2 |

Alice

Figure 7.4 – Nash equilibrium

Here each player’s optimal strategy depends on what they think the other player will do. We say that two strategies are in Nash equilibrium when Alice’s choice is optimal given Bob’s, and vice versa. Here there are two symmetric Nash equilibria, at top left and bottom right. You can think of them as being like local optima while a dominant strategy equilibrium is a global optimum.

## The prisoners’ dilemma

We’re now ready to look at a famous problem that applies to many situations from international trade negotiations through cooperation between hunting an- imals to whether the autonomous systems that make up the Internet cooperate e↵ectively to protect its infrastructure. It was ﬁrst studied by scientists at the Rand corporation in 1950 in the context of US and USSR defense spending; Rand was paid to think about possible strategies in nuclear war. But they presented it using the following simple example.

Two prisoners are arrested on suspicion of planning a bank robbery. The po- lice interview them separately and tell each of them: “If neither of you confesses you’ll each get a year for carrying a concealed ﬁrearm without a permit. If only one of you confesses, he’ll go free and the other will get 6 years for conspiracy to rob. If both of you confess, you will each get three years.”

What should the prisoners do? Here’s their payo↵ matrix:

Benjy

|  |  |  |
| --- | --- | --- |
|  | Confess | Deny |
| Confess | -3,-3 | 0,-6 |
| Deny | -6,0 | -1,-1 |

Alﬁe

Figure 7.5 – the prisoners’ dilemma

When Alﬁe looks at this table, he will reason as follows: “If Benjy’s going to confess then I should too as then I get 3 years rather than 6; and if he’s going to

1In business and politics, a strategy a means of acquiring power, such as monopoly power or military advantage, by a sequence of moves; the game-theoretic meaning is a somewhat simpliﬁed version, to make problems more tractable.

deny then I should still confess as I’ll walk rather than doing a year”. Benjy will reason similarly. The two of them confess, and get three years each. This is not just a Nash equilibrium; it’s a dominant strategy equilibrium. Each prisoner should confess regardless of what the other does.

But hang on, you say, if they had agreed to keep quiet then they’ll get a year each, which is a better outcome for them! In fact the strategy (deny,deny) is Pareto eﬃcient, while the dominant strategy equilibrium is not. (That’s one reason it’s useful to have concepts like ‘Pareto eﬃcient’ and ‘dominant strategy equilibrium’ rather than just arguing over ‘best’.)

So what’s the solution? Well, so long as the game is going to be played once only, and this is the only game in town, there isn’t a solution. Both prisoners will confess and get three years.

You may think this is fair enough, as it serves them right. However, the Prisoners’ Dilemma can be used to model all sorts of interactions where we decide whether or not to cooperate: international trade, nuclear arms control, ﬁsheries protection, the reduction of CO2 emissions, and the civility of political discourse. Even matters of self-control such as obesity and addiction can be seen as failures of cooperation with our future selves. In these applications, we really want cooperation so we can get good outcomes, but the way a single-shot game is structured can make them really hard to achieve. We can only change this if somehow we can change the game itself.

There are many possibilities: there can be laws of various kinds from in- ternational treaties on trade to the gangster’s *omert`a*. In practice, a prisoner’s dilemma game is changed by altering the rules or the context so as to turn it into another game where the equilibrium is more eﬃcient.

## Repeated and evolutionary games

Suppose the game is played repeatedly – say Alﬁe and Benjy are career criminals who expect to be dealing with each other again and again. Then of course there can be an incentive for them to cooperate. There are at least two ways of modelling this.

In the 1970s, Bob Axelrod started thinking about how people might play many rounds of prisoners’ dilemma. He set up a series of competitions to which people could submit programs, and these programs played each other repeatedly in tournaments. He found that one of the best strategies overall was *tit-for-tat*, which is simply that you cooperate in round one, and at each subsequent round you do to your opponent what he or she did in the previous round [147]. It began to be realised that strategy evolution could explain a lot. For example, in the presence of noise, players tend to get locked into (defect, defect) whenever one player’s cooperative behaviour is misread by the other as defection. So in this case it helps to ‘forgive’ the other player from time to time.

A parallel approach was opened up by John Maynard Smith and George Price [1251]. They considered what would happen if you had a mixed population of aggressive and docile individuals, ‘hawks’ and ‘doves’, with the behaviour that doves cooperate; hawks take food from doves; and hawks ﬁght, with a risk of

death. Suppose the value of the food at each interaction is *v* and the risk of death in a hawk ﬁght is *c* per encounter. Then the payo↵ matrix looks like Figure 7.6:

|  |  |  |
| --- | --- | --- |
|  | Hawk | Dove |
| Hawk | v−c , v−c  2 2 | *v*,0 |
| Dove | 0, *v* | v , v  2 2 |

Figure 7.6 – the hawk-dove game

Here, if *v > c*, the whole population will become hawk, as that’s the domi- nant strategy, but if *c > v* (ﬁghting is too expensive) then there is an equilibrium where the probability *p* that a bird is a hawk sets the hawk payo↵ and the dove payo↵ equal, that is

*v* − *c*

*p*

2

+ (1 − *p*)*v* = (1 − *p*) *v*

2

which is solved by *p* = *v/c*. In other words, you can have aggressive and docile individuals coexisting in a population, and the proportion of aggressive individuals will be a function of the costs of aggression; the more dangerous a ﬁght is, the fewer combative individuals there will be. Of course, the costs can change over time, and diversity can a good thing in evolutionary terms as a society with some hard men may be at an advantage when war breaks out. But it takes generations for a society to move to equilibrium. Perhaps our current high incidence of aggression reﬂects conditions in pre-state societies. Indeed, anthropologists believe that tribal warfare used to be endemic in such societies; the archaeological record shows that until states came along, about a quarter to a third of men and boys died of homicide [1132]. We just haven’t lived long enough in civilised societies for evolution to catch up.

Such insights, along with Bob Axelrod’s simulation methodology, got many people from moral philosophers to students of animal behaviour interested in evolutionary game theory. They o↵er further insights into how cooperation evolved. It turns out that many primates have an inbuilt sense of fairness and punish individuals who are seen to be cheating – the instinct for vengeance is one mechanism to enforce sociality. Fairness can operate in a number of di↵erent ways at di↵erent levels. For example, doves can get a better result against hawks if they can recognise each other and interact preferentially, giving a model for how some social movements and maybe even some religions establish themselves [1784]. Online reputation systems, as pioneered by eBay and now used by ﬁrms like Uber and AirBnB, perform a similar function: they help doves avoid hawks by making interactions into iterated games.

Of course, the basic idea behind tit-for-tat goes back a long way. The Old Testament has ‘An eye for an eye’ and the New Testament ‘Do unto others as you’d have them do unto you’ – the latter formulation being the more fault- tolerant – and versions of it can be found in Aristotle, in Confucius and else- where. More recently, Thomas Hobbes used similar arguments in the seven- teenth century to argue that a state did not need the Divine Right of Kings to

exist, paving the way for revolutions, republics and constitutions in the eigh- teenth.

Since 9/11, people have used hawk-dove games to model the ability of funda- mentalists to take over discourse in religions at a time of stress. Colleagues and I have used evolutionary games to model how insurgents organise themselves into cells [1373]. Evolutionary games also explain why cartel-like behaviour can appear in industries even where there are no secret deals.

For example, Internet service in the UK involves a regulated monopoly that provides the local loop, and competing retail companies that sell Internet service to households. If the local loop costs the ISPs £6 a month, how come the ISPs all charge about £35? Well, if one were to undercut the others, they’d all retaliate by cutting their own prices, punishing the defector. It’s exactly the same behavior you see if there are three airlines operating a proﬁtable route, and one lowers its prices to compete for volume; the others will often respond by

cutting prices even more sharply to punish it and make the route unproﬁtable. And just as airlines o↵er all sorts of deals, air miles and so on to confuse the customer, so also the telecomms providers o↵er their own confusion pricing. Similar structures lead to similar behaviour. Tacit collusion can happen in both industries without the company executives actually sitting down and agreeing to ﬁx prices (which would be illegal). As pricing becomes more algorithmic, both lawyers and economists may need to understand more computer science; and computer scientists need to understand economic analysis tools such as game

theory and auction theory.

# Auction Theory

Auction theory is vital for understanding how Internet services work, and what can go wrong. Much online activity is funded by the ad auctions run by ﬁrms like Google and Facebook, and many e-commerce sites run as auctions.

Auctions have been around for millennia, and are the standard way of selling livestock, ﬁne art, mineral rights, bonds and much else; many other transactions from corporate takeovers to house sales are also really auctions. They are the fundamental way of discovering prices for unique goods. There are many issues of game play, asymmetric information, cheating – and some solid theory to guide us.

Consider the following ﬁve traditional types of auction.

1. In the English, or ascending-bid, auction, the auctioneer starts at a reserve price and then raises the price until only one bidder is left. This is used to sell art and antiques.
2. In the Dutch, or descending-bid, auction, the auctioneer starts out at a high price and cuts it gradually until someone bids. This is used to sell ﬂowers.
3. In the ﬁrst-price sealed-bid auction, each bidder is allowed to make one bid. After bidding closes, all the bids are opened and the highest bid wins.

This has been used to auction TV rights; it’s also used for government contracts, where it’s the lowest bid that wins.

1. In the second-price sealed-bid auction, or Vickrey auction, we also get sealed bids and the highest bid wins, but that bidder pays the price in the second-highest bid. This is familiar from eBay, and is also how online ad auctions work; it evolved to sell rare postage stamps, though the earliest known use was by the poet Goethe to sell a manuscript to a publisher in the 18th century.
2. In the all-pay auction, every bidder pays at every round, until all but one drop out. This is a model of war, litigation, or a winner-take-all market race between several tech startups. It’s also used for charity fundraising.

The ﬁrst key concept is *strategic equivalence*. The Dutch auction and the ﬁrst-price sealed-bid auction give the same result, in that the highest bidder gets the goods at his *reservation price* – the maximum he’s prepared to bid. Similarly, the English auction and the Vickrey auction give the same result (modulo the

bid increment). However the two pairs are not strategically equivalent. In a Dutch auction, you should bid low if you believe your valuation is a lot higher than anybody else’s, while in a second-price auction it’s best to bid truthfully.

The second key concept is *revenue equivalence*. This is a weaker concept; it’s not about who will win, but how much money the auction is expected to raise. The interesting result here is the *revenue equivalence theorem*, which says that you get the same revenue from any well-behaved auction under ideal conditions. These conditions include risk-neutral bidders, no collusion, Pareto eﬃciency (the highest bidder gets the goods) and independent valuations (no externalities between bidders). In such circumstances, the bidders adjust their strategies and the English, Dutch and all-pay auctions all yield the same. So when you design an auction, you have to focus on the ways in which the conditions aren’t ideal. For details and examples, see Paul Klemperer’s book [1057].

And there are many things that can go wrong. There may be bidding rings, where all the buyers collude to lowball the auction; here, a ﬁrst-price auction is best as it takes only one defector to break ranks, rather than two. Second, there’s entry detection: in one UK auction of TV rights, bidders had to submit extensive programming schedules, which involved talking to production companies, so everyone in the industry knew who was bidding and the franchises with only one bidder went for peanuts. Third, there’s entry deterrence: bidders in corporate takeovers often declare that they will top any other bid. Fourth, there’s risk

aversion: if you prefer a certain proﬁt of $1 to a 50% chance of $2, you’ll bid higher at a ﬁrst-price auction. Fifth, there are signaling games; in US spectrum auctions, some bidders broke anonymity by putting zip codes in the least signiﬁcant digits of their bids, to signal what combinations of areas they were prepared to ﬁght for, and to deter competitors from starting a bidding war there. And then there are budget constraints: if bidders are cash-limited, all-pay auctions are more proﬁtable.

Advertisement auctions are big business, with Google, Facebook and Ama- zon making about $50bn, $30bn and $10bn respectively in 2019, while the rest of the industry gets about $40bn. The ad auction mechanism pioneered by

Google is a second-price auction tweaked to optimise revenue. Bidders o↵er to pay prices *b*i, the platform estimates their ad quality as *e*i, based on the ad’s relevance and clickthrough rate. It then calculates ‘ad rank’ as *a*i = *b*i*e*i. The idea is that if my ad is ﬁve times as likely to be clicked on as yours, then my bid of 10c is just as good as your bid of 50c. This is therefore a second-price auction, but based on ranking *a*i rather than *b*i. Thus if I have ﬁve times your ad quality, I bid 10c and you bid 40c, then I get the ad and pay 8c. It can be shown that under reasonable assumptions, this maximises platform revenue.

There’s one catch, though. Once media become social, then ad quality can easily segue into virality. If your ads are good clickbait and people click on them, you pay less. One outcome was that in the 2016 US Presidential Election, Hilary Clinton paid a lot more per ad than Donald Trump did [1234]. Both auction theory and empirical data show how the drive to optimise platform revenue may lead to ever more extreme content: in addition to virality e↵ects at the auction step, Facebook’s delivery algorithms put ads in front of the people most likely to click on them, strengthening the e↵ect of ﬁlter bubbles, and that this is not all due to user actions [40]. Some people feel this ‘delivery optimisation’ should be prohibited by electoral law; certainly it’s one more example of mechanisms with structural tension between eﬃciency and fairness. In fact, in the UK, election ads aren’t permitted on TV, along with some other categories such as tobacco. Maybe the cleanest solution in such jurisdictions is to ban them online too, just like tobacco. And ad pricing is not the only way social media promote extreme content; as former Googler Tristan Harris has explained, the platforms’ recommender algorithms are also optimised to maximise the time people spend on site, which means not just scrolling feeds and followers, but a bias towards anxiety and outrage. What’s more, ad delivery can be skewed by factors such as gender and race by market e↵ects, as advertisers compete for more ‘valuable’

demographics, and by content e↵ects because of the appeal of ad headlines or images; this can be deliberate or accidental, and can a↵ect a broad range of ads including employment and housing [39]. This all raises thorny political issues at the boundary between economics and psychology, but economic tools such as

auction theory can often be used to unpick them.

# The economics of security and dependability

Economists used to see a simple interaction between economics and security: richer nations could a↵ord bigger armies. But after 1945, nuclear weapons were thought to decouple national survival from economic power, and the ﬁelds of economics and strategic studies drifted apart [1238]. It has been left to the information security world to re-establish the connection.

Round about 2000, a number of us noticed persistent security failures that appeared at ﬁrst sight to be irrational, but which we started to understand once we looked more carefully at the incentives facing the various actors. I observed odd patterns of investment by banks in information security measures [54, 55]. Hal Varian looked into why people were not spending as much money on anti- virus software as the vendors hoped [1943]. When the two of us got to discussing these cases in 2001, we suddenly realised that there was an interesting and im-

portant research topic here, so we contacted other people with similar interests and organised a workshop for the following year. I was writing the ﬁrst edition of this book at the time, and found that describing many of the problems as incentive problems made the explanations much more compelling; so I distilled what I learned from the book’s ﬁnal edit into a paper ‘Why Information Security is Hard – An Economic Perspective”. This paper, plus the ﬁrst edition of this book, got people talking [72]. By the time they came out, the 9/11 attacks had taken place and people were searching for new perspectives on security.

We rapidly found many other examples of security failure associated with institutional incentives, such as hospital systems bought by medical directors and administrators that support their interests but don’t protect patient privacy. (Later, we found that patient safety failures often had similar roots.) Jean Camp had been writing about markets for vulnerabilities, and two startups had set up early vulnerability markets. Networking researchers were starting to use auction theory to design strategy-proof routing protocols. The Department of Defense had been mulling over its failure to get vendors to sell them secure systems, as you can see in the second quote at the head of this chapter. Microsoft was thinking about the economics of standards. All these ideas came together at the Workshop on the Economics of Information Security at Berkeley in June 2002,

which launched security economics as a new ﬁeld of study. The picture that started to emerge was of system security failing because the people guarding a system were not the people who su↵ered the costs of failure. Sometimes, security mechanisms are used to dump risks on others, and if you are one of those others you’d be better o↵ with an insecure system. Put di↵erently, security is often a power relationship; the principals who control what it means in a given system often use it to advance their own interests.

This was the initial insight, and the story of the birth of security economics is told in [78]. But once we started studying the subject seriously, we found that there’s a lot more to it than that.

## Why is Windows so insecure?

The hot topic in 2002, when security economics got going, was this. Why is Windows so insecure, despite Microsoft’s dominant market position? It’s possible to write much better software, and there are ﬁelds such as defense and healthcare where a serious e↵ort is made to produce dependable systems. Why

do we not see a comparable e↵ort made with commodity platforms, especially

since Microsoft has no real competitors?

By then, we understood the basics of information economics: the combina- tion of high ﬁxed and low marginal costs, network e↵ects and technical lock-in makes platform markets particularly likely to be dominated by single vendors, who stand to gain vast fortunes if they can win the race to dominate the mar- ket. In such a race, the Microsoft philosophy of the 1990s – ‘ship it Tuesday and get it right by version 3’ – is perfectly rational behaviour. In such a race, the platform vendor must appeal not just to users but also to complementers

– to the software companies who decide whether to write applications for its platform or for someone else’s. Security gets in the way of applications, and it tends to be a lemons market anyway. So the rational vendor engaged in a

race for platform dominance will enable all applications to run as root on his platform2, until his position is secure. Then he may add more security – but will be tempted to engineer it in such a way as to maximise customer lock-in, or to appeal to complementers in new markets such as digital media.

The same pattern was also seen in other platform products, from the old IBM mainframe operating systems through telephone exchange switches to the early Symbian operating system for mobile phones. Products are insecure at ﬁrst, and although they improve over time, many of the new security features are for the vendor’s beneﬁt as much as the user’s. And this is exactly what we saw with Microsoft’s product lines. DOS had no protection at all and kick-started the malware market; Windows 3 and Windows 95 were dreadful; Windows 98 was only slightly better; and security problems eventually so annoyed Microsoft’s customers that ﬁnally in 2003 Bill Gates decided to halt development until all its engineers had been on a secure coding course. This was followed by investment in better testing, static analysis tools, and regular patching. The number and lifetime of exploitable vulnerabilities continued to fall through later releases of Windows. But the attackers got better too, and the protection in Windows isn’t all for the user’s beneﬁt. As Peter Gutmann points out, much more e↵ort went into protecting premium video content than into protecting users’ credit card numbers [842].

From the viewpoint of the consumer, markets with lock-in are often ‘bargains then rip-o↵s’. You buy a nice new printer for $39.95, then ﬁnd to your disgust after just a few months that you need two new printer cartridges for $19.95 each. You wonder whether you’d not be better o↵ just buying a new printer. From the viewpoint of the application developer, markets with standards races based on lock-in look a bit like this. At ﬁrst it’s really easy to write code for them; later on, once you’re committed, there are many more hoops to jump through. From the viewpoint of the poor consumer, they could be described as ‘poor security, then security for someone else’.

The same pattern can be seen with externalities from security management costs to infrastructure decisions that the industry takes collectively. When rac- ing to establish a dominant position, vendors are tempted to engineer products so that most of the cost of managing security is dumped on the user. A clas- sic example is SSL/TLS encryption. This was adopted in the mid-1990s as Microsoft and Netscape battled for dominance of the browser market. As we

discussed in Chapter 5, SSL leaves it up to the user to assess the certiﬁcate o↵ered by a web site and decide whether to trust it; and this led to all kinds of phishing and other attacks. Yet dumping the compliance costs on the user made perfect sense at the time; competing protocols such as SET would have saddled banks with the cost of issuing certiﬁcates to every customer who wanted to buy stu↵ online, and that would just have cost too much [524]. The world ended up with an insecure system of credit card payments on the Internet, and with most of the stakeholders trying to dump liability on others in ways that block progress towards a better system.

There are also network e↵ects for bads, and well as for goods. Most malware writers targeted Windows rather than Mac or Linux through the 2000s and

2To make coding easier, and enable app developers to steal the user’s other data for sale in secondary markets.

2010s as there are simply more Windows machines to infect – leading to an odd equilibrium in which people who were prepared to pay more for their laptop could have a more secure one, albeit one that didn’t run as much software. This model replicated itself when smartphones took over the world in the 2010s; since Android took over from Windows as the world’s most popular operating system, we’re starting to see a lot of bad apps for Android, while people who pay more for an iPhone get better security but less choice. (There, the more stringent policies of Apple’s app store are more important now than market share.)

## Managing the patching cycle

The second big debate in security economics was about how to manage the patching cycle. If you discover a vulnerability, should you just publish it, which may force the vendor to patch it but may leave people exposed for months until they do so? Or should you report it privately to the vendor – and risk getting a lawyer’s letter threatening an expensive lawsuit if you tell anyone else, after which the vendor just doesn’t bother to patch it?

This debate goes back a long way; as we noted in the preface, the Victo- rians agonised over whether it was socially responsible to publish books about lockpicking, and eventually concluded that it was [1895]. People have worried more recently about whether the online availability of the US Army Improvised Munitions Handbook [1924] helps terrorists; in some countries it’s a crime to possess a copy.

Security economics provides both a theoretical and a quantitative framework for discussing some issues of this kind. We started in 2002 with simple models in which bugs were independent, identically distributed and discovered at random; these have nice statistical properties, as attackers and defenders are on an equal footing, and the dependability of a system is a function only of the initial code quality and the total amount of time spent testing it [74]. But is the real world actually like that? Or is it skewed by correlated bugs, or by the vendor’s inside knowledge? This led to a big policy debate. Eric Rescorla argued that software

is close enough to the ideal that removing one bug makes little di↵erence to the likelihood of an attacker ﬁnding another one later, so frequent disclosure and patching were an unnecessary expense unless the same vulnerabilities were likely to be rediscovered [1596]. Ashish Arora and others responded with data showing that public disclosure made vendors ﬁx bugs more quickly; attacks increased to begin with, but reported vulnerabilities declined over time [133]. In 2006, Andy

Ozment and Stuart Schechter found that the rate at which unique vulnerabilities were disclosed for the core OpenBSD operating system decreased over a six-year period [1488]. In short, in the right circumstances, software can be more like wine than like milk – it improves with age. (Sustainability is a holy grail, and I discuss it in more detail in Part 3.)

Several further institutional factors helped settle the debate in favour of *re- sponsible disclosure*, also known as *coordinated disclosure*, whereby people report bugs to vendors or to third parties that keep them conﬁdential for a period until patches are available, then let the reporters get credit for their discoveries. One was the political settlement at the end of Crypto War I whereby bugs would be reported to CERT which would share them with the NSA during the bug-

ﬁxing process, as I will discuss later in section 26.2.7.3. This got governments on board. The second was the emergence of commercial vulnerability markets such as those set up by iDefense and TippingPoint, where security researchers could sell bugs; these ﬁrms would then disclose each bug responsibly to the vendor, and also work out indicators of compromise that could be sold to ﬁrms operating ﬁrewall or intrusion-detection services. Third, smart software ﬁrms started their own bug-bounty programs, so that security researchers could sell their bugs directly, cutting out middlemen such as CERT and iDefense.

This marketplace sharpened considerably after Stuxnet drove governments to stockpile vulnerabilities. We’ve seen the emergence of ﬁrms like Zerodium that buy bugs and sell them to state actors, and to cyberweapons suppliers that also sell to states; zero-day exploits for platforms such as the iPhone can now sell for a million dollars or more. This had knock-on e↵ects on the supply chain. For example, in 2012 we came across the ﬁrst case of a volunteer deliberately contributing vulnerable code to an open-source project3, no doubt in the hope of a six-ﬁgure payo↵ if it had found its way into widely-used platforms. Already in 2010, Sam Ransbotham had shown that although open-source and proprietary software are equally secure in an ideal model, bugs get turned into exploits faster in the open source world, so attackers target it more [1579]. In 2014, Abdullah

Algarni and Yashwant Malaiya surveyed vulnerability markets and interviewed some of the more proliﬁc researchers; a combination of curiosity and economic incentives draw in many able young men, many from less developed countries, some disclose responsibly, some use vulnerability markets to get both money and recognition, while others sell for more money to the black hats; some will o↵er bugs to the vendor, but if not treated properly will o↵er them to the bad guys instead. Vendors have responded with comparable o↵ers: at Black Hat 2019, Apple announced a bug bounty schedule that goes up to $1m for exploits

that allow zero-click remote command execution on iOS. Oh, and many of the bug hunters retire after a few years [38]. Like it or not, volunteers running open-source projects now ﬁnd themselves some capable motivated opponents if their projects get anywhere, and even if they can’t match Apple’s pocket, it’s a good idea to keep as many of the researchers onside as possible.

The lifecycle of a vulnerability now involves not just its discovery, but per- haps some covert use by an intelligence agency or other black-hat actor; then its rediscovery, perhaps by other black hats but eventually by a white hat; the shipment of a patch; and then further exploitation against users who didn’t ap- ply the patch. There are tensions between vendors and their customers over the frequency and timing of patch release, as well as with complementers and sec- ondary users over trust. A vulnerability in Linux doesn’t just a↵ect the server in your lab and your kid’s Raspberry Pi. Linux is embedded everywhere: in your air-conditioner, your smart TV and even your car. This is why responsible disclosure is being rebranded as coordinated disclosure. There may be simply too many ﬁrms using a platform for the core developers to trust them all about a forthcoming patch release. There are also thousands of vulnerabilities, of which dozens appear each year in the exploit kits used by criminals (and some no doubt used only once against high-value targets, so they never become known to defense systems). We have to study multiple overlapping ecosystems – of the

3Webkit, which is used in mobile phone browsers

vulnerabilities indexed by their CVE numbers; of the Indicators of Compromise (IoCs) that get fed to intrusion detection systems; of disclosure to vendors di- rectly, via markets, via CERTs and via ISACs; of the various botnets, crime gangs and state actors; and of the various recorded crime patterns. We have partial correlations between these ecosystems, but the data are generally noisy. I’ll come back to all this in Part III.

## Structural models of attack and defence

The late Jack Hirshleifer, the founder of conﬂict theory, told the story of Anar- chia, an island whose ﬂood defences were constructed by individual families each of whom maintained a section of the ﬂood wall. The island’s ﬂood defence thus depended on the weakest link, that is, the laziest family. He compared this with a city whose defences against missile attack depend on the single best defen-

sive shot [906]. Another example of best-shot is medieval warfare, where there could be a single combat between the two armies’ champions. This can lead to di↵erent political systems. Medieval Venice, the best example of weakest-link defence because of the risk of ﬂooding, had strong central government, with the

merchant families electing a Doge with near-dictatorial powers over ﬂood de-

fence. In much of the rest of late medieval Europe, kings or chieftains led their own armies to kill enemies and seize land; the strongest king built the biggest empire, and this led to a feudal system that optimised the number of men at arms.

Hal Varian extended this model to the dependability of information systems

– where performance can depend on the weakest link, the best e↵ort, or the sum-of-e↵orts [1945]. This last case, the sum-of-e↵orts, is the modern model for warfare: we pay our taxes and the government hires soldiers. It’s more eﬃcient than best-shot (where most people will free-ride behind the heroes), which in turn is more eﬃcient than weakest-link (where everyone will be vulnerable via the laziest). Information security is an interesting mix of all three modes. Pro- gram correctness can depend on the weakest link (the most careless programmer introducing a vulnerability) while software vulnerability testing may depend on the sum of everyone’s e↵orts. Security may also depend on the best e↵ort – the actions taken by an individual champion such as a security architect. As more agents are added, systems become more reliable in the sum-of-e↵orts case but less reliable in the weakest-link case. So as software companies get bigger, they

end up hiring more testers and fewer (but more competent) programmers; Mi- crosoft found by the early 2000s that they had more test engineers than software engineers.

Other models of attack and defence include epidemic models of malware spread, which were important back when computer viruses spread from machine to machine via ﬂoppy disks, but are of less interest now that we see relatively few wormable exploits; and models of security games that hinge on timing, notably the game of FlipIt by Ron Rivest and colleagues [559]; indeed, there’s a whole conference (Gamesec) devoted to game theory and information security. There are also models of social networks. For example, most social networks owe their connectivity to a relatively small number of nodes that have a relatively high number of links to other nodes [1994]. Knocking out these nodes can

rapidly disconnect things; William the Conqueror consolidated England after 1066 by killing the Anglo-Saxon nobility and replacing them with Normans, while Stalin killed the richer peasants. US and British forces similarly targeted highly-connected people in counterinsurgency operations during the Iraq war (and the resulting social breakdown in Sunni areas helped the emergence of ISIS). Such models also suggest that for insurgents to form into cells is the natural and most e↵ective response to repeated decapitation attacks [1373].

George Danezis and I also showed that where solidarity is needed for defence, smaller and more homogeneous groups will be more e↵ective [511]. Rainer Bo¨hme and Tyler Moore studied what happens where it isn’t – if people use defense mechanisms that bring only private beneﬁt, then the weakest-link model becomes one of low-hanging fruit. Examples include spammers who simply guess enough weak passwords to replenish their stock of compromised email accounts, and card-not-present fraud against e-commerce websites [276].

In short, the technology of conﬂict in any age can have deep and subtle e↵ects on politics, as it conditions the kind of institutions that can survive and thrive. These institutions in turn shape the security landscape. Tyler Moore, Allan Friedman and Ariel Procaccia studied whether a national agency such as the NSA with both defensive and o↵ensive missions would disclose vulnerabilities so

they could be ﬁxed, or stockpile them; they concluded that if it could ignore the

social costs that fall on others, it would stockpile [1338]. However the biggest institutions in the security ecosystem are probably not government agencies but the dominant ﬁrms.

## The economics of lock-in, tying and DRM

Technical lock-in is one of the factors that lead to dominant-ﬁrm markets, and software ﬁrms have spent billions over more than thirty years on mechanisms that make it hard for their customers to leave but easy for their competitors to defect. The 1980s saw ﬁle format wars where companies tried to stop anyone else accessing the word-processing ﬁles or spreadsheets their software generated. By the 1990s, the ﬁght had shifted to network compatibility as Microsoft tried to exclude other operating systems from LANs, until SAMBA created inter- operability with Apple; in the wake of a 1993 anti-trust suit, Microsoft held back from using the Windows contract to block it. Adversarial interoperability emerged as a kind of judo to ﬁght network e↵ects [570]. Similar mechanisms are used to control markets in neighbouring or complementary goods and services, examples being tying ink cartridges to printers, and digital rights management (DRM) systems that lock music and videos to a speciﬁc machine or family of machines, by preventing users from simply copying them as ﬁles. In an early security-economics paper, Hal Varian pointed out in 2002 that their unfettered use could damage competition [1944].

In 2003, Microsoft, Intel and others launched a ‘Trusted Computing’ ini- tiative that extended rights management to other types of ﬁle, and Windows Server 2003 o↵ered ‘Information Rights Management’ (IRM) whereby I could email you a Word document that you could only read on screen, not print, and only till the end of the month. There was obvious potential for competitive

abuse; by transferring control of user data from the owner of the machine on

which it is stored to the creator of the ﬁle in which it is stored, the potential for lock-in is hugely increased [73]. Think of the example in section 8.3.2 above, in which a ﬁrm has 100 sta↵, each with a PC on which they install Oﬃce for $150. The $15,000 they pay Microsoft is roughly equal to the total costs of switching to (say) LibreOﬃce, including training, converting ﬁles and so on. However, if control of the ﬁles moves to its thousands of customers, and the ﬁrm now has to contact each customer and request a digital certiﬁcate in order to migrate the ﬁle, then clearly the switching costs have increased – so you could expect the cost of Oﬃce to increase too. Now IRM failed to take o↵ at the time:

corporate America quickly understood that it was a lock-in play, European gov- ernments objected to the fact that the Trusted Computing initiative excluded small ﬁrms, and Microsoft couldn’t get the mechanisms to work properly with Vista. However, now that email has moved to the cloud, both Microsoft and Google are o↵ering restricted email services of just the type that was proposed, and objected to, back in 2003.

Another aspect concerns DRM and music. In the late 1990s and early 2000s, Hollywood and the music industry lobbied hard for mandatory DRM in con- sumer electronics equipment, and we still pay the costs of that in various ways; for example, when you switch your presentation from a VGA adapter to HDMI and you lose the audio. Hollywood’s claim that unlicensed peer-to-peer ﬁle- sharing would destroy the creative industries was always shaky; a 2004 study showed that downloads didn’t harm music industry revenues overall [1457] while a later one suggested that downloaders actually bought more CDs [50]. How- ever the real issue was explained in 2005 by Google’s chief economist [1946]: that a stronger link between the tech industry and music would help tech ﬁrms more than the music industry, because tech was more concentrated (with only three serious music platforms then – Microsoft, Sony and Apple). The content industry sco↵ed, but by the end of that year music publishers were protesting that Apple was getting too large a share of the cash from online music sales. Power in the supply chain moved from the music majors to the platforms, so the platforms (now Apple, Google, Amazon and Spotify) got most of the money and the residual power in the music industry shifted from the majors to the in- dependents – just as airline deregulation favoured aircraft makers and low-cost airlines. This is a striking demonstration of the predictive power of economic analysis. By ﬁghting a non-existent threat, the record industry helped the com- puter industry eat its lunch. I discuss this in more detail in section 24.5.

DRM had become much less of an issue by 2020; the move from removable media to streaming services means that few people copy music or movies any more; the question is whether you pay a subscription to avoid the ads. Similarly, the move to cloud-based services means that few people steal software. As a result, crimes involving copyright infringement have dropped sharply [91].

However, the move to the cloud is making lock-in a more complex matter, operating at the level of ecosystems as well as of individual products. We dis- cussed above how competition from Google Docs cut the price of Oﬃce, and so Microsoft responded with a move to Oﬃce365; and how the total cost of owner- ship of either that service or G-suite is greater than a standalone productivity

product. So where is the lock-in? Well, if you opt for the Google ecosystem, you’ll probably be using not just Gmail and Google Docs but a Google calendar,

maps and much else. Although you can always download all your data, rein- stalling it on a di↵erent platform (such as Microsoft’s or Apple’s) will be a lot of bother, so you’ll probably just grit your teeth and pay for more storage when the free quota runs out. Similarly, if you start using tools like Slack or Splunk in an IT company, you’ll end up customising them in all sorts of ways that make it diﬃcult to migrate. Again, this is nothing new; my own university’s dreadful accounting system has been a heavily customised version of Oracle Financials for about 20 years. Now everyone’s playing the lock-in game by inducing customers to buy or build complementary assets, or even to outsource whole functions. Salesforce has taken over many companies’ sales admin, Palantir has locked in many US police forces, and the big academic publishers are usurping the func- tions of university libraries. Where there’s no viable competition – as in the second of these cases – there’s a real policy issue. The depth of Microsoft lockin on public-sector IT is illustrated by the brave attempts made by the city of Mu- nich to break away and use Linux in public administration: this was eventually reverted after 15 years, several visits of Bill Gates, and a new mayor [759].

The control of whole ecosystems by cartels is nothing new; Joshua Specht tells the history of how the big food companies like Cargill and Armour grabbed control of the two-sided markets opened up by the railroads, consolidated their power by buying infrastructure such as grain elevators, dumped climate risk on small farmers, ran union organisers out of town and even got the politicians to pass ‘ag-gag’ laws that deﬁne animal-rights activism as terrorism [1808]. There

are interesting echoes of this in the way the big IT service ﬁrms have built out

their market power, controlling everything from the ad ecosystem through op- erating systems to datacentres. In fact, the whole global economy has become more monopolistic over the past couple of decades, and IT appears to account for much of the growth in industry concentration[234]. It isn’t the only factor

– other industries (such as defence contracting) have their own dynamic, while the regulators of natural monopolies such as utilities tend to be captured over time by lobbying. There is a growing literature on *moats* – structural barri- ers to competition, of which network e↵ects and technical lock-in are merely two examples; others range from patents and regulatory capture to customer insight derived from control of data [1431]. The dynamics of the information industries compound many of these existing problems and can make e↵ective competition even harder. Competition law scholars, led by Lina Khan of Har- vard, have been arguing for several years that American law needs to take a broader view of competition abuse than just consumer surplus (as is already the case in Europe) [1044], while Chicago-school economists such as Carl Shapiro denounce antitrust populism and argue that remedies should be targeted at spe- ciﬁc harms, as antitrust law is ill-suited to tackle the political power that large corporations wield [1716]. Carl does however concede that US antitrust law has been excessively narrowed by the Supreme Court in the last 40 years; that the consumer-welfare test is inadequate; that dominant ﬁrms’ exclusionary conduct and labour-market practices both need to be tackled, and that the USA needs to control horizontal mergers better [1717].

European competition law has for many years forbidden ﬁrms from using a dominant position in one market to establish one in another, and we’ve seen a whole series of judgements against the big tech ﬁrms. As for the likely future direction, a 2019 report for the European Commission’s Directorate-General

of Competition by Jacques Cr´emer, Yves-Alexandre de Montjoye and Heike Schweizter highlights not just the tech majors’ network externalities and extreme returns to scale, but also the fact that they control more and more of the data thanks to the move to online services and cloud computing [497]. As a result they have economies of scope: succeeding in one business makes it easier to succeed in another. It concludes that the EU’s competition-law framework is basically sound but needs some tuning: regulators need to protect both competition for the market and competition in the market, such as on dominant platforms, which have a responsibility not to distort competition there. In this environment,

regulators must pay attention to multihoming, switching, interoperability, data portability and the e↵ect on aftermarkets.

Tying spare parts is also regulated in Europe, with speciﬁc laws in some sectors requiring vendors to let other ﬁrms make compatible spare parts, and in others requiring that they make spares available for a certain period of time. Some some very speciﬁc policy issues can arise if you use security mechanisms to tie products to each other. This links in with laws on planned obsolesence,

which is reinforced for goods with digital components when the vendors limit the time period for which software updates are made available. The rules have recently been upgraded in the European Union by a new Sales of Goods Directive (2019/771) that from January 2022 requires ﬁrms selling goods with digital components – whether embedded software, cloud services or associated phone apps – to maintain this software for at least two years after the good are sold, and for longer if this is the reasonable expectation of the customer (for cars and white goods it’s likely to mean ten years). Such regulations will become more of an issue now we have software in durable goods such as cars and medical devices; I’ll discuss sustainability in the last chapter of this book.

## Perversely motivated guards

“There’s nane sae blind as them that will na see”, goes an old Scots proverb, and security engineering throws up lots of examples.

* + - * There’s very little police action against cybercrime, as they found it sim- pler to deter people from reporting it. As we noted in section 2.3, this enabled them to claim that crime was falling for many years even though it was just moving online like everything else.
      * Governments have imposed a duty on banks to spot money laundering, especially since 9/11. However no banker really wants to know that one of his customers is a Maﬁoso. So banks lobby for risk reduction to be formalised as due diligence; they press for detailed regulations that specify the forms of ID they need for new account opening, and the processing to be done to identify suspicious transactions.
      * When it comes to fraud, spotting a rare bank fraud pattern means a payment service provider should now carry the loss rather than just telling the customer she must be mistaken or lying. So they’re tempted to wait and learn about new fraud types from industry or from academics, rather than doing serious research of their own.
      * Click fraud is similar. Spotting a pattern of ‘inorganic clicks’ from a botnet means you can’t charge the advertisers for those clicks any more. You have to do some work to mitigate the worst of it, but if you have a dominant market position then the harder you work at ﬁghting click fraud, the less revenue you earn.
      * Finding bugs in your own code is another example. Of course you have to tweak the obvious bugs that stop it working, but what about the more subtle bugs that can be exploited by attackers? The more time you spend

looking for them, the more time you have to spend ﬁxing them. You can always go and buy static analysis tools, but then you’ll ﬁnd thousands more bugs and your ship date will slip by months. So ﬁrms tend to do that only if their customers demand it, and it’s only cheap if you do it from the start of a project (but in that case you could just as well write the code in Rust rather than in C).

There are more subtle examples, such as when it’s not politically acceptable to tell the truth about threats. In the old days, it was hard to talk to a board of directors about the insider threat, as directors mostly preferred to believe the best about their company; so a typical security manager would make chilling presentations about ‘evil hackers’ in order to get the budget to build internal controls. Nowadays, the security-policy space in many companies has been captured by the big four accountancy ﬁrms, whose consensus on internal controls is tied to their thought leadership on governance, which a cynic might say is optimised for the welfare not of their ostensible client, the shareholders, but for their real client, the CEO. Executive frauds are rarely spotted unless they bring the company down; the e↵ort goes instead into the annoying and irrelevant, such as changing passwords every month and insisting on original paper receipts. I discuss all this in detail in section 12.2.2.

Or consider the 2009 parliamentary expenses scandal in the UK described in section 2.3.6. Perhaps the oﬃcers of the Houses of Parliament didn’t defend the expenses system more vigorously because they have to think of MPs and peers as ‘honourable members’ in the context of a government that was pushing harsh surveillance legislation with a slogan of ‘If you’ve nothing to hide you have nothing to fear’. The author of that slogan, then Home Secretary Jacqui Smith, may have had nothing to hide, but her husband did: he was watching porn and charging it to her parliamentary expenses. Jacqui lost her job, and her seat in

Parliament too. Had oﬃcers known that the information on the expenses server could cost a cabinet minister her job, they probably ought to have classiﬁed it Top Secret and kept it in a vault. But how could the extra costs have been justiﬁed to the Treasury? On that cheerful note, let’s go on to privacy.

## Economics of privacy

The privacy paradox is that people say that they value privacy, yet act otherwise. If you stop people in the street and ask them their views, about a third say they are privacy fundamentalists and will never hand over their personal information to marketers or anyone else; about a third say they don’t care; and about a third are in the middle, saying they’d take a pragmatic view of the risks and beneﬁts

of any disclosure. However, their shopping behavior – both online and o✏ine – is quite di↵erent; the great majority of people pay little heed to privacy, and will give away the most sensitive information for little beneﬁt. Privacy-enhancing technologies have been o↵ered for sale by various ﬁrms, yet most have failed in the marketplace. Why should this be?

Privacy is one aspect of information security that interested economists be- fore 2000. In 1978, Richard Posner deﬁned privacy in terms of secrecy [1536], and the following year extended it to seclusion [1537]. In 1980, Jack Hirshleifer published a seminal paper in which he argued that rather than being about withdrawing from society, privacy was a means of organising society, arising from evolved territorial behavior; internalised respect for property supports au- tonomy. In 1996, Hal Varian analysed privacy in terms of information mar- kets [1940]. Consumers want to not be annoyed by irrelevant marketing calls while marketers do not want to waste e↵ort; yet both are frustrated, because of search costs, externalities and other factors. Varian suggested giving consumers rights in information about themselves, and letting contracts sort it out.

However, as we’ve seen, the information industries are prone to market failures leading to monopoly, and the proliferation of dominant, information- intensive business models demands a di↵erent approach. Andrew Odlyzko ar- gued in 2003 that these monopolies simultaneously increase both the incentives and the opportunities for price discrimination [1462]. Companies mine online interactions for data revealing individuals’ willingness to pay, and while the dif- ferential pricing we see in many markets from airline yield-management systems to telecommunications prices may be economically eﬃcient, it is increasingly resented. Peter Swire argued that we should measure the externalities of pri- vacy intrusion [1852]. If a telesales operator calls 100 prospects, sells three of them insurance, and annoys 80, then the conventional economic analysis con- siders only the beneﬁt to the three and to the insurer. But persistent annoyance causes millions of people to go ex-directory, screen calls through an answering machine, or just not have a landline at all. The long-run societal costs of robo- calls can be considerable. Empirical studies of people’s privacy valuations have supported this.

The privacy paradox has generated a signiﬁcant literature, and is com- pounded by at least three factors. First, there are many di↵erent types of pri- vacy harm, from discrimination in employment, credit and insurance, through

the kind of cybercrime that presents as payment fraud, to personal crimes such as stalking and non-consensual intimate imagery.

Second, the behavioral factors we discussed in section 3.2.5 play a large role. Leslie John and colleagues demonstrated the power of context with a neat experiment. She devised a ‘privacy meter’ in the form of a list of embarrassing questions; the score was how many questions a subject would answer before they balked. She tried this on three groups of students: a control group in a neutral university setting, a privacy treatment group who were given strong assurances that their data would be encrypted, their IP addresses not stored, and so on; and a gamer treatment group that was taken to an external website (howbadareyou.com with a logo of a smiling devil). You might think that the privacy treatment group would disclose more, but in fact they disclosed less – as privacy had been made salient to them. As for the gamer group, they happily

disclosed twice as much as the control group [987].

Third, the industry understands this, and goes out of its way to make privacy risks less salient. Privacy policies are usually not on the front page, but are easily ﬁndable by concerned users; policies typically start with anodyne text and leave the unpleasant stu↵ to the end, so they don’t alarm the casual viewer, but the

vigilant minority can quickly ﬁnd a reason not to use the site, so they also don’t

stop the other users clicking on the ads. The cookie warnings mandated in Europe are mostly anodyne, though some ﬁrms give users ﬁne-grained control; as noted in section 3.2.5, the illusion of control is enough to reassure many.

So what’s the overall e↵ect? In the 2000s and early 2010s there was evidence that the public were gradually learning what we engineers already understood about the risks; we could see this for example in the steadily rising proportion of Facebook users who opt to use privacy controls to narrow that system’s very open defaults.

In 2015, almost two years after the Snowden revelations, two surveys con- ducted by Pew Research disclosed a growing sense of learned helplessness among the US public. 93% of adults said that being in control of who can get infor- mation about them is important, and 90% that controlling what information is collected about them is important; 88% said it’s important that no-one watch or listen to them without their permission. Yet just 6% of adults said they were ‘very conﬁdent’ that government agencies could keep their records private and

secure, while another 25% said they were ‘somewhat conﬁdent.’ The ﬁgures

for phone companies and credit card companies were similar while those for advertisers, social media and search engines were signiﬁcantly worse. Yet few respondents had done anything signiﬁcant, beyond occasionally clearing their browser history or refusing particularly inappropriate demands for personal in- formation [1204].

These tensions have been growing since the 1960s, and have led to complex privacy regulation that di↵ers signiﬁcantly between the US and Europe. I’ll discuss this in much more detail in section 26.6.

## Organisations and human behaviour

Organisations often act in apparently irrational ways. We frequently see ﬁrms and even governments becoming so complacent that they’re unable to react to a threat until it’s a crisis, when they panic. The erosion of health service resilience and pandemic preparedness in Europe and North America in the century since the 1918–19 Spanish ﬂu is merely the most salient of many examples. As another example, it seems that there’s always one phone company, and one bank, that the bad guys are picking on. A low rate of fraud makes people complacent, until the bad guys notice. The rising tide of abuse is ignored, or blamed on customers, for as long as possible. Then it gets in the news and executives panic. Loads of money get spent for a year or two, stu↵ gets ﬁxed, and the bad guys move on to the next victim.

So the security engineer needs to anticipate the ways in which human frailties express themselves through organizational behaviour.

There’s a substantial literature on institutional economics going back to Thorstein Veblen. One distinguished practitioner, Herb Simon, was also a com- puting pioneer and founded computer science at CMU. In a classic book on administrative behaviour, he explained that the decisions taken by managers are not just about eﬃciency but also organisational loyalty and authority, and the interaction between the organisation’s goals and the incentives facing in- dividual employees; there are messy hierarchies of purpose, while values and facts are mixed up [1754]. A more modern analysis of these problems typically sees them as principal-agency issues in the framework of microeconomics; this is a typical approach of professors of accountancy. We will discuss the failures of the actual practice of accountancy later, in section 12.2. Another approach is public-choice economics, which applies microeconomic methods to study the

behaviour of politicians, civil servants and people in public-sector organsations generally. I summarise public choice in section 26.3.3; the principles are illus- trated well in the TV sitcom “Yes Minister’ which explores the behaviour of British civil servants. Cynics note that bureaucracies seem to evolve in such a way as to minimise the likelihood of blame.

My own observation, having worked in banks, tech companies big and small and in the university sector too, is that competition is more important than whether an enterprise is publicly or privately owned. University professors com- pete hard with each other; our customer isn’t our Vice-Chancellor but the Nobel Prize committee or equivalent. But as university administrators work in a hier- archy with the VC at the top, they face the same incentives as civil servants and display many of the same strengths and weaknesses. Meanwhile, some private ﬁrms have such market power that internally they behave just like government (though with much better pay at the top).

## Economics of cybercrime

If you’re going to protect systems from attack, it’s a good idea to know who the attackers are, how many they are, where they come from, how they learn their jobs and how they’re motivated. This brings us to the economics of cybercrime. In section 2.3 we gave an overview of the cybercrime ecosystem, and there are many tools we can use to study it in more detail. At the Cambridge Cybercrime Centre we collect and curate the data needed to do this, and make it available to over a hundred researchers worldwide. As in other economic disciplines, there’s an iterative process of working out what the interesting questions are and collecting the data to answer them. The people with the questions are not just economists but engineers, psychologists, lawyers, law enforcement and, increasingly, criminologists.

One approach to crime is that of Chicago-school economists such as Gary Becker, who in 1968 analysed crime in terms of rewards and punishments [200]. This approach gives many valuable insights but isn’t the whole story. Why is crime clustered in bad neighbourhoods? Why do some kids from these neigh- bourhoods become proliﬁc and persistent o↵enders? Traditional criminologists

study questions like these, and ﬁnd explanations of value in crime prevention: the worst o↵enders often su↵er multiple deprivation, with poor parenting, with substance and alcohol abuse, and get drawn into cycles of o↵ending. The earlier

they start in their teens, the longer they’ll persist before they give up. Critical criminologists point out that laws are made by the powerful, who maintain their power by oppressing the poor, and that bad neighbourhoods are more likely to be over-policed and stigmatised than the nice suburbs where the rich white people live.

Drilling down further, we can look at the bad neighbourhoods, the psychol- ogy of o↵enders, and the pathways they take into crime. Since the 1960s there has been a substantial amount of research into using environmental design to suppress crime, initially in low-cost housing and then everywhere. For exam- ple, courtyards are better than parks, as residents are more likely to identify and challenge intruders; many of these ideas for *situational crime prevention* go across from criminology into systems design. In section 13.2.2 we’ll discuss this in more detail.

Second, psychologically normal people don’t like harming others; people who do so tend to have low empathy, perhaps because of childhood abuse, or (more often) to have minimisation strategies to justify their actions. Bank robbers see bankers as the real exploiters; soldiers dehumanise the enemy as ‘gooks’ or ‘terrs’; and most common murderers see their crimes as a matter of honour. “She cheated on me” and “He disrespected me” are typical triggers; we discussed the mechanisms in section 3.2.4. These mechanisms go across to the world of online and electronic fraud. Hackers on the wrong side of the law tend to

feel their actions are justiﬁed anyway: hacktivists are political activists after

all, while cyber-crooks use a variety of minimisation strategies to avoid feeling guilty. Some Russian cybercrooks take the view that the USA screwed Russian over after 1989, so they’re just getting their own back (and they’re supported in this by their own government’s attitudes and policies). As for bankers who dump fraud risks on customers, they talk internally about ‘the avalanche of fraudulent risks of fraud’ they’d face if they owned up to security holes.

Third, it’s important to understand the pathways to crime, the organisation of criminal gangs, and the di↵usion of skills. Steve Levitt studied the organi- sation and ﬁnances of Chicago crime gangs, ﬁnding that the street-level dealers were earning less than minimum wage [1151]. They were prepared to stand in the rain and be shot at for a chance to make it to the next level up, where the

neighbourhood boss drove around in a BMW with three girls. Arresting the boss won’t make any di↵erence as there are dozens of youngsters who’ll ﬁght to replace him. To get a result, the police should target the choke point, such as the importer’s system administrator. These ideas also go across. Many cyber- criminals start o↵ as gamers, then cheat on games, then deal in game cheats, then learn how to code game cheats, and within a few years the more talented have become malware devs. So one policy intervention is to try to stop kids crossing the line between legal and illegal game cheating. As I mentioned in section 3.2.4, the UK National Crime Agency bought Google ads which warned people in Britain searching for DDoS-for-hire services that the use of such ser- vices was illegal. Ben Collier and colleagues used our Cybercrime Centre data to show that this halted the growth of DDoS attacks in the UK, compared with the USA where they continued to grow [454].

We discussed the overall costs of cybercrime in section 2.3, noting that the ecosystem has been remarkably stable over the past decade, despite the fact that

the technology has changed; we now go online from phones more than laptops, use social networks, and keep everything in the cloud. Most acquisitive crime is now online; in 2019 we expect that about a million UK households su↵ered a burglary or car theft, while over two million su↵ered a fraud or scam, almost

always online. (In 2020 the di↵erence will be even more pronounced; burglary

has fallen still further with people staying at home through the lockdown.) Yet policy responses lag almost everywhere. Studies of speciﬁc crimes are reported at various places in this book.

The e↵ects of cybercrime are also studied via the e↵ects of breach disclosures. Alessandro Acquisti and colleagues have studied the e↵ects on the stock price of companies of reporting a security or privacy breach [15]; a single breach tends to cause a small dip that dissipates after a week or so, but a double breach can impair investor conﬁdence over the longer term. Breach disclosure laws have made breaches into insurable events; if TJX loses 47m records and has to pay

$5 to mail each customer, that’s a claim; we’ll discuss cyber-insurance later in section 28.2.9.

Overall, though, measurement is tricky. Most of the relevant publications come from organisations with an incentive to talk up the losses, from police agencies to anti-virus vendors; our preferred methodology is to count the losses by modus operandi and by sector, as presented in section 2.3.

# Summary

Many systems fail because the incentives are wrong, rather than because of some technical design mistake. As a result, the security engineer needs to understand basic economics as well as the basics of crypto, protocols, access controls and psychology. Security economics has grown rapidly to explain many of the things that we used to consider just ‘bad weather’. It constantly throws up fascinating new insights into all sorts of questions from how to optimise the patching cycle through whether people really care about privacy.

# Research problems

So far, three areas of economics have been explored for their relevance to se- curity, namely microeconomics, game theory and behavioural economics. But economics is a vast subject. What other ideas might it give us?

In the history paper I wrote on the origins of security economics, I suggested a new research student might follow the following heuristics to select a research topic. First, think of security and *X* for other subﬁelds *X* of economics. Second, think about the security economics of *Y* for di↵erent applications *Y* ; there have already been some papers on topics like payments, pornography, gaming, and

censorship, but these aren’t the only things computers are used for. Third, where you ﬁnd gold, keep digging (e.g. behavioral privacy) [78]. Since then I would add the following.

Fourth, there is a lot of scope for data-driven research now that we’re starting

to make large datasets available to academics (via the Cambridge Cybercrime Centre) and many students are keen to develop skills in data science. A related problem is how to gather more data that might be useful in exploring other ﬁelds, from the productivity of individual security sta↵ to how security works within institutions, particularly large complex institutions such as governments and

healthcare systems. Is there any good way of measuring the quality of a security culture? Fifth, now we’re starting to put software and online connectivity in durable safety-critical things like cars and medical devices, we need to know a lot more about the interaction between security and safety, and about how we can keep such systems patched and running for decades. This opens up all sorts of new topics in dependability and sustainability.

The current research in security economics is published mostly at the Work- shop on the Economics of Information Security (WEIS), which has been held annually since 2002 [76]. There are liveblogs of all but one of the workshops, consisting of a summary of each paper and a link to it, which you can get on my blog or linked directly from my Economics and Security Resource Page at [http://www.cl.cam.ac.uk/~rja14/econsec.html.](http://www.cl.cam.ac.uk/~rja14/econsec.html)

# Further reading

The classic introduction to information economics is Shapiro and Varian’s *‘In- formation Rules’* which remains remarkably fresh for a book written twenty years ago [1718]. This is still on our student reading list. The most up-to-date summary is probably Jacques Cr´emer, Yves-Alexandre de Montjoye and Heike Schweizter’s 2019 report for the European Commission’s Directorate-General of Competition, which analyses what goes wrong with markets in which informa- tion plays a signiﬁcant role [497]; I would read also Carl Shapiro’s 2019 review of the state of competition policy in the USA[1717].

Tim Wu’s “The Master Switch” discusses monopoly in telecomms and the information industries generally from the viewpoint of ten years ago [2049]. If you plan to do research in the subject and your degree wasn’t in economics, you might work through a standard textbook such as Varian [1941] or the Core Economics website. Adam Smith’s classic *‘An inquiry into the nature and causes of the wealth of nations’* is still worth a look, while Dick Thaler’s *‘Misbehaving’* tells the story of behavioural economics.

The early story of security economics is told in [78]; there’s an early (2007) survey of the ﬁeld that I wrote with Tyler Moore at [110], and a more com- prehensive 2011 survey, also with Tyler, at [111]. For privacy economics, see Alessandro Acquisti’s online bibliography, and the survey paper he wrote with George Loewenstein and Laura Brandimarte [16]; there’s also a survey of the literature on the privacy paradox by Spiros Kokolakis [1076]. Then, to dive into the research literature, I’d suggest the WEIS conference papers and liveblogs.

A number of economists study related areas. I mentioned Jack Hirshleifer’s conﬂict theory [907]; another important strand is the economics of crime, which was kick-started by Gary Becker [200], and has been popularised by Steve Levitt and Stephen Dubner’s “Freakonomics” [1151]. Diego Gambetta is probably the

leading scholar of organised crime; his *‘Codes of the Underworld: How Criminals Communicate’* is a classic [742]. Finally, there is a growing research community and literature on cyber-criminology, for which the website of our Cambridge Cybercrime Centre might be a reasonable starting point.