3. Market design, economic efficiency, and game theory for spectrum auctions

Summary

- Markets come in many shapes and sizes, including those created by conscious design to promote economic efficiency like spectrum auctions.
- Spectrum auctions show that markets can be a malleable instrument of public policy, in cases where well-considered design choices can harness incentives of self-interest, such as companies seeking profits, for socially desirable outcomes.
- Features that can make a market successful include: a clearinghouse; effective competition; sound incentives; institutions with good reputations; transparency, simplicity, and flexibility for timely decisions by participants; and respecting social and cultural constraints of fairness and public acceptability.
- A valuable analytical approach when considering intervention in markets is to assess the existence and sources of market failure.
- The tools of game theory and auction theory contribute greatly to the practical design of spectrum auctions. There is a symbiotic relationship, because the theory also develops by learning from practical challenges and bidding experiences.

There are many different types of markets, operating in a wide variety of contexts. Spectrum auctions are one particular type of market. Their existence and operation are due to conscious 'market design'. The rules chosen for them and the market infrastructure designed are intended to achieve specified objectives. The first section of this chapter explains the perspective of market design and one of its key objectives, economic efficiency. This sets the specific market of a spectrum auction in a broader context (and indicates features that are examined in greater depth in Part II). The second section provides a non-technical introduction to auction theory which supports practical market design, building on the tools of game theory. The third section shows the important role that experts play in spectrum auction design in a mutually beneficial relationship between theory and practical implementation,

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each learning from the other. The final section provides some wider lessons for public policy that can be taken from the experience of spectrum auctions as a market mechanism to promote the public interest.

3.1 Market design and economic efficiency

The understanding of how and why markets can be successful, or go wrong, is greatly enriched by the field of study of market design. In essence, market design opens the 'black box' of how markets work. It grew out of game theory, a mathematical field in economics that illuminates strategic behaviour and can be described as the 'formal study of conflict and cooperation'.[1] Although the theory can be abstract and esoteric, the applied side of market design is intensely practical as it seeks to develop workable market solutions to real-world challenges. A high-level insight from market design is that 'a free market is a market with rules and institutions that let it operate freely'.[2] In this fundamental sense, the operation of markets is underpinned by regulation (broadly defined) – the role and nature of regulation are considered in Chapter 4.[3] Examples of designed markets other than spectrum auctions include wholesale electricity, tradeable pollution permits, online advertising, labour market clearing-houses for newly qualified doctors and hospitals, procedures to match students to schools or colleges, and centralised systems for the allocation of human organs from donors to patients.[4]

When markets are designed by public authorities, one objective is usually to achieve economically efficient outcomes, explained in the following subsection. Broader objectives can also be very important – these are covered in Chapter 4. The second subsection uses insights from market design to set out features that facilitate a healthy market which is successful in achieving economic efficiency (and other relevant objectives). However, markets can and do go wrong, so the third subsection characterises sources of market failure. To round out the section, the last subsection indicates the potential offered by the market design perspective.

Economic efficiency (social value)

The concept of economic efficiency has several dimensions:

- Allocative efficiency means that scarce resources (like parts of the radio spectrum) are allocated to those users who will best deploy them to maximise the total outputs valued by economic agents.[5]
- Productive efficiency involves minimising the costs and resource inputs used to supply or achieve a given output, such as spectral efficiency in providing mobile data services.
- Dynamic efficiency involves maximising valuable investment and innovation, such as revolutionary new mobile services which change the way we live and work, as has already occurred and may happen again with 5G and future technologies.[6]

Together these types of efficiency specify the maximum social value focused on by economists. It can be described as the overall size of the economic 'cake' – the extent to which agents' preferences can be satisfied, given resource and technological limitations. Two key underlying concepts in welfare economics are widely used. So-called Pareto efficiency is achieved if no-one can be made better off without someone else being worse off.[7] It is a foundational concept, but restrictive as a criterion for ranking different allocations of society's resources to decide which is more or less 'efficient', because many changes in allocation involve losers as well as gainers. The compensation principle significantly expands the applicability of welfare economics.[8] It holds that economic efficiency is increased if the agents (whether producers or consumers) that are made better off *could* compensate the losers by a sufficient amount so that all would be at least as well off as before. But it is not essential that such compensation actually occurs.

A distinction between the size of the cake (economic efficiency) and the 'slices' obtained by different agents (distributional issues) is analytically useful. But there are value judgements involved in suggesting that a larger cake is necessarily better than a smaller one. Some people might consider that a Pareto change, increasing economic efficiency, from a large increase in wealth to billionaires that magnified inequality would not truly be an overall welfare improvement, even if others' welfare stayed the same or increased in absolute terms. The compensation principle involves stronger value judgements, given that it relies just on the potential for compensation, whether or not it actually occurs. Therefore, it would, for example, 'approve a change that makes the wealthiest man in society richer by $1 billion, while making each of the million poorest people worse off by $999. This is a judgement that many people would reject as wrong or immoral'.[9] Such considerations of fairness can lead public policy choices to go beyond potential compensation and actually recompense those who are worse off. A spectrum example is incumbent users for television broadcasting, who were cleared from a band for re-award to mobile operators, receiving financial payments to cover their costs (Section 6.1).

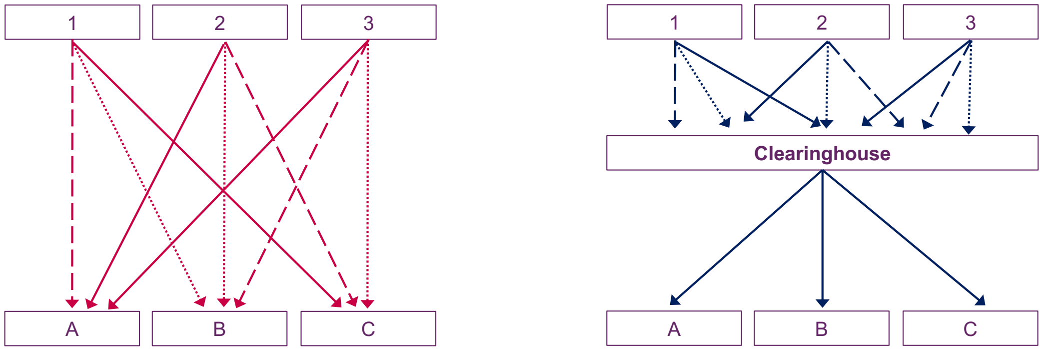
Features of successful markets

The tools of market design can be used to identify features of a well-functioning market, like a spectrum auction. There is no simple recipe to make sure a market succeeds, but market design experts have established how a range of features can generally contribute, drawing on theoretical insights and practical experience.[10] Markets involve rules and infrastructure. The rules govern how the market works, and the term 'infrastructure' is used broadly, meaning not just physical or virtual infrastructure like an exchange or software platform but also institutions that help to run the market. The features outlined in this subsection are explored in later chapters in Part II in their practical application in spectrum auctions.

A centralised *clearinghouse* can sometimes assist a market to work well, as in matching markets. Figure 3.1 provides a simple illustration of the difference with and without a clearinghouse, showing three participants or objects on each side of the market. The unbroken, dashed, and dotted arrows from the top signify an order or strength of preference of participants, labelled 1, 2, and 3 for the objects shown as A, B, and C. These could be students to be matched to schools, trainee doctors matched to hospitals, or mobile operators seeking to acquire different spectrum blocks.[11]

The coordination provided by a clearinghouse can bring benefits like simplifying choices or encouraging participation to improve the thickness (volume) of transactions with enough buyers and sellers. This can allow more *competition* and achieve an improved allocation. Participants transacting through a clearinghouse is not always the right answer, but it can offer additional possibilities. An example is comparing a series of bilateral negotiations for trades of spectrum licences (illustrated by the left-hand side of Figure 3.1) against a multilateral spectrum auction with the regulator as the clearinghouse (on the right-hand side). The auction can reduce transactions costs, assist coordination, and

Figure 3.1. Simplified illustration of a bilateral uncoordinated process compared to a multilateral coordinated process with a clearinghouse



Source: Auhor.

improve incentives. There was a period of time in the USA when spectrum licences were allocated by lottery relying on subsequent bilateral trading to get the licences into the hands of the highest-value operators. Spectrum auctions have brought allocation improvements, as well as other efficiencies such as reduced rent-seeking.[12] Command-and-control administrative allocation of licences involves the regulator as a clearinghouse, but without the vital dispersed knowledge of participants powerfully coordinated through a market mechanism.[13] For example, imagine the clearinghouse on the right-hand side of Figure 3.1 making the allocation decisions for items A, B, and C in the bottom half without reliable access to the information on preferences of operators 1, 2, and 3 in the top half.[14]

The rules and institutions of the market affect the *incentives* of participants for straightforward over strategic behaviour. The importance of incentives is brought out in the next section when describing game theory. In addition, bidder incentives in spectrum auctions are examined in in Part II, especially in Chapter 8 which builds on insights from auction theory.

Another feature is to reduce 'congestion' for a safe environment to engage in *timely* transactions. Timeliness has different aspects, including when a participant is asked to make decisions, their sequencing, and how much time it is given. Section 6.2 considers some aspects of timeliness (licence duration and when to hold an auction), and Section 11.2 analyses congestion in terms of the pace of the auction.

The behaviour and reputation of *institutions* influences whether participants see the regulator as reliable, neutral, and trustworthy to run the market fairly. Operational issues are also relevant, such as secure systems for bidding and protection of confidential data. Section 7.6 examines how attributes and actions of the regulator can affect the trust of market participants.

Transparency, flexibility, and simplicity assist market participants to make informed decisions. Chapter 8 uses these important considerations to structure the detailed analysis of trade-offs in spectrum auction design. For example, the final prices in the CCA, second prices based on the highest-losing bids, are less transparent and simple than in the SMRA, but they are more flexible (such as reflecting synergy values for complements).

Success also depends on respecting constraints set by society – an example is that monetary transactions in some cases are considered ethically *repugnant*. Markets can only work if they operate consistently with public values (which can modify over time, but for present purposes they are taken as given). An elegant theory of efficient allocation of kidney organs based on monetary payments could be developed, but it would not work in practice and could not be implemented effectively if public values reject the fundamental financial mechanism being used in the allocation. This still leaves plenty of scope for market design solutions using non-monetary transactions to improve the efficiency of the allocation, such as rules and infrastructure of medical exchanges acting as a clearinghouse.

Beyond repugnance, there are broader matters of *fairness*, including distributional effects and political acceptability. In the world of radio spectrum, there are a few types of spectrum user for whom the use of markets and financial payments is more contentious, such as safety-of-life applications of the emergency services, or wireless microphones and cameras in theatres. But the focus of this book is on spectrum markets for cellular mobile services, for which markets and monetary transactions are generally deemed socially acceptable or even expected. Nevertheless, the fairness of spectrum auctions is still important, as considered in the reputational issues in Section 7.6, or in Section 3.2 for fair prices from the second-price rule of the CCA format.

Sources of market failure

Many of the considerations can be formulated as features of well-functioning markets or their absence, market failures – see Figure 3.2. The market failure framework provides a powerful analytical tool to diagnose whether and why markets are performing well. Identifying the source of a problem is at the heart of prescribing the effective 'medicine'. Different sources of market failure are relevant to analyse a range of issues. Spillovers of broader social benefits may be insufficiently reflected in market

Figure 3.2. Reasons why a market does or does not work well including sources of market failure

Features of well-functioning market	Source of market failure
Spillover effects on those not directly involved are taken into account	Externalities
Rights of ownership or access enable transactions to occur effectively	No or unclear property rights
Transactions costs are not too large relative to the gains from exchange	High transactions costs
Institutional arrangements promote trust between transacting parties	Absent or unreliable institutions and lack of trustworthiness
Incentives to use resources efficiently	Distorted or missing signals, such as prices (where they are not considered repugnant)
Information flows smoothly between market participants	Asymmetric information
Competition is fostered	Weak competition, such as companies with market power
Market participants take unbiased, well-informed decisions	Behavioural biases[15]

Source: Author, drawing in particular on McMillan (2002).

outcomes for mobile coverage (Section 5.3). Externalities of radio signals interfering with each other provides a rationale for spectrum licensing to define property rights, and transactions costs can be a barrier to efficiency-enhancing spectrum licence trades (Section 6.2). The reliability of the regulator as an institution can affect the performance of the market (Section 7.6). Price discovery and asymmetric information are fundamental challenges in auction design (Chapters 7 and 8). Competition measures are often imposed in the auction to avoid weak competition in downstream markets (Chapter 9). Behavioural biases of fear of losing or overconfidence may have contributed to overbidding in the UK's 3G auction in 2000 (Sections 2.3 and 11.1, and Annex A2).

The potential of market design

It is far from accurate to suggest that every problem has a market solution. As well as markets in some contexts being prone to systematic failure, there are also values at stake.[16] Some economists consider their analysis is 'value-free', but leaving aside the questionable accuracy of such a proposition within the field of economics, the use of markets is not perceived more generally to be value-neutral. Market design theorists and practitioners interested in developing solutions to real-world public policy problems are eclectic, not dogmatic. They grapple with challenges of broader social considerations beyond the narrower values reflected in economic efficiency, such as recognising that monetary transactions are publicly unacceptable in some cases. They have shown there are more problems that markets can assist in addressing than non-specialists might think. The contributions to matching problems like human organ donation are noteworthy examples. One of the high-level insights is that markets can come in all shapes and sizes, and they can often be harnessed to serve the public interest. The rest of this book is the story of what has been achieved in the context of spectrum auctions, especially using evidence from the UK, and their future potential.

3.2 Introduction to game theory and auction theory

Modern microeconomics has developed to place greater reliance on game theory in explaining the behaviour of rational actors and especially their strategies in complex situations. This section sets out a high-level, non-technical introduction to fundamental features of game theory as utilised in auction theory. Auction theory is a branch of market design, whose implications are drawn on when analysing design choices in later chapters, doing so starting from a practitioner perspective. The confluence of theory and practice was recognised in the 2020 Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel, awarded to Professors Paul Milgrom and Robert Wilson 'for improvements to auction theory and inventions of new auction formats'. The citation noted that their 'theoretical discoveries have improved auctions in practice' and referred prominently to spectrum auctions, highlighting it as a key area of practical application and stimulus for innovative developments [emphasis added]:

> This year's Laureates, Paul Milgrom and Robert Wilson, have studied how auctions work. They have also used their insights to design new auction formats for goods and services that are difficult to sell in a traditional way, such as *radio frequencies*. Their discoveries have benefitted sellers, buyers and taxpayers around the world.[17]

Figure 3.3. Illustrative payoff matrix in the prisoner's dilemma game

	Aardvark	
Beaver	Stay silent	Confess
Stay silent	−0.5 −0.5	0 −5
Confess	−5 0	−2 −2

Source: Author from Rapoport (1987).

Game theory, in essence, is an analytical tool to study strategic interactions of conflict and cooperation between 'players' where there are interdependent outcomes. For illustration, the players could be called Aardvark and Beaver. Aardvark's best choice depends not only what it decides, but on Beaver's action as well, in situations where they may not have the same information and only imperfectly observe each other's actions.[18] Incentives and outcomes then depend on the environment, motivations, and expected payoffs.

A well-known example of a game is the prisoner's dilemma.[19] Two prisoners suspected of burglary are held captive separately with no means of communicating. Each has two options: to confess, blaming the other prisoner; or to stay silent. If Aardvark confesses but Beaver does not, it is set free but Beaver is convicted of burglary and faces a prison sentence of five years, and vice versa. If both confess, they share the blame for two years each in prison. If both stay silent, they are convicted of the lesser crime of possessing stolen goods with only six months in prison. The payoffs to both prisoners are represented in Figure 3.3 where the negative numbers indicate the number of years in prison, in red for Aardvark and in green for Beaver.

The best combined outcome for the prisoners is if both stay silent and face a short prison sentence. However, the game theory analysis shows instead that both have a dominant incentive to confess, so the confess/confess outcome with two years in prison forms the unique equilibrium. Aardvark reasons that it is better off confessing, whatever action Beaver chooses:

- If Beaver stays silent, Aardvark's possible outcomes are shown in red in the first row in Figure 3.3 and it prefers to confess (payoff of 0, set free, instead of -0.5, half a year in prison).
- If Beaver confesses, Aardvark is again better off by confessing, given the choice of outcomes in the second row (payoff of -2 instead of -5, two not five years in prison).

Beaver's reasoning is the same because the payoff matrix is symmetric. So the prisoners face a worse outcome by confessing (two years in prison) than if both stayed silent (six months). The prisoner's dilemma game therefore shows the importance of players' incentives. A version of the game with many players models the 'tragedy of the commons', overuse of resources like spectrum due to individual incentives leading to an undesirable collective outcome.[20] These insights are directly relevant to spectrum licensing (Section 6.2). Simple game and spectrum auction examples can also illustrate key game theory concepts.

There are two basic types of game, *cooperative* and *non-cooperative*, and the prisoner's dilemma is an example of the latter. Non-cooperative games examine decisions of individual players, whereas the unit of analysis in cooperative games is groups of players who can make binding agreements to form different coalitions. A cooperative game version of the prisoner's dilemma would be different. If the prisoners could make a binding agreement with each other, they could agree to stay silent and be better off. The agreement would have to be binding, however, as otherwise the incentives of the non-cooperative version would come to the fore and both would have an incentive to cheat on the deal. In non-cooperative games there are only 'agreements' between players if they are self-reinforcing, if each is better off agreeing than disagreeing so that no player has an incentive to deviate (which makes the confess/confess outcome the equilibrium of the non-cooperative prisoner's dilemma game).

Cooperative and non-cooperative game theory are broadly aligned with two branches of market design: *matching* theory and *auction* theory. Both involve marketplaces, for matching without monetary transactions, and in auctions with financial bids. Insights of matching theory are used in a range of allocation systems, such as assigning students to schools, newly qualified doctors to hospitals, or kidney donors to patients.[21] Implications of auction theory are crucial to designing the rules of spectrum auctions.

One element of a game is a specification of each player's available strategic choices and their associated payoffs, as shown in Figure 3.3 for the prisoner's dilemma. To be an accurate representation, the choices modelled in the game have to be complete or at least not omit significant available actions (which is not straightforward in more strategically complex environments). The payoffs perceived by the players depend on their motivations and what they value. For instance, social norms about informing on fellow prisoners could change the relative payoffs shown in Figure 3.3 to make confessing a far more costly choice. A company bidding in a spectrum auction usually cares about profit on the items won (their value to the firm less the prices paid). But Chapters 8 and 9 also consider other influences on the payoff from strategic bidding, such as forcing rivals to pay higher auction prices (so-called 'price driving') or denying spectrum to a rival to weaken downstream competition ('strategic investment').

Another element is the structure of the game, involving *simultaneous* or *sequential* decisions by players. There are simultaneous decisions in the prisoner's dilemma in the sense that Aardvark does not know Beaver's action when it has to make its decision, and vice versa. Similarly, a sealed-bid spectrum auction is a simultaneous game between bidders. An example of a sequential game is auction design. The regulator sets the auction rules in the first stage of the game, which are then known to the bidders when they choose their bids in the second stage. To set the rules in the first stage to achieve desirable outcomes, the regulator has to understand how bidders will respond in the second stage to different choices of rules. This set-up is used in auction theory models to yield insights that are explored in Chapters 7 and 8. Another example is that the outcome of the auction affects the strength of downstream retail competition between mobile operators. The competition assessment set out in Chapter 9 requires the regulator to understand how different auction outcomes would impact downstream competition and the associated incentives for strategic investment in the auction, in order to make the right prior decisions about competition measures to impose as auction rules.

A further structural feature is whether the game is *one-shot* or *repeated*. The prisoner's dilemma is a one-shot game since it is played only once by Aardvark and Beaver.[22] A sealed-bid auction is a one-shot game, whereas SMRA and CCA as multiple-round auctions are more like repeated games, where bidders receive information on what happened at the end of each round and (within defined limits) can change their choices in the next round accordingly. The sequence of spectrum auctions over time in a country (e.g. 3G, 4G, and 5G) can also be seen as a repeated game, which involve the same or significant overlap in players. Or there can be a sequence of auctions across countries with overlap in bidders because many mobile operators are multinational. In this sense, any one spectrum auction can be viewed as a game within a bigger game, increasing the strategic complexity of the environment since players' actions could be designed to affect future or overseas auctions as well as the current one. Sections 2.3 and Annex A informally present the sequence of high-stakes UK auctions as games within a bigger game of learning over time by bidders and the regulator. Auction design is a process of constant change, involving evolutionary and more radical changes affected by prior experiences. A further example is the repeated game for universal mobile coverage (informally) examined in Section 5.3, with the same players (the government, the regulator, mobile operators, and the public) periodically interacting over time, resulting in sporadic action to enhance coverage. But there is always another stage of the game, with more to be done to extend coverage or bring it up to date to the latest technology.

The information conditions of the game are important, giving a precise formulation of who knows what and when. Private information is only known by each player for itself, such as each bidder's value of spectrum in the auction. Rivals often estimate each others' values to inform their bid strategies. Since mobile operators know each other well, in some cases their estimates can be fairly accurate, assisting strategic bidding such as price driving, by knowing how high to push up the price. But private information means that estimates can be wrong, such as a price-driving bidder misjudging and ending up paying for spectrum that it does not want. Common knowledge is information known to all players (and everyone knows that everyone knows it), such as published by the regulator as part of the 'information policy' before the auction, or revealed to all bidders during the auction. As explained in Part II, the regulator's choice of information policy affects both incentives for strategic bidding and the economic efficiency of the outcomes.

Outcomes of games are modelled using solution concepts. The 'Nash equilibrium' of self-reinforcing, mutually consistent strategies is commonly used to solve non-cooperative games (named after the mathematician John Nash, who was depicted in the popular film *A Beautiful Mind*). Each player does its best to achieve its objectives, taking as given the choice of other players. For example, the logic of the Nash equilibrium was used when describing the reasons for the confess/confess outcome of the prisoner's dilemma game. In cooperative games the solution concept is usually about stability. For example, the 'core' is the set of undominated outcomes 'for which no "blocking coalitions" can form and produce an outcome that its members prefer'.[23] The core is specifically used in the (complex) pricing rule of CCA spectrum auctions for its stability and associated fairness properties. It ensures that no losing bidder (as expressed through its bids) was willing to pay more than the auction price for spectrum won by others (see Annex B2 for further explanation).

Cooperative and non-cooperative games are now considered complementary because there is always a bigger game outside the market designer's control:

> For parts of the game that we're designing, we use 'noncooperative' strategic models to precisely specify actions available to players. For parts of the game that we don't have complete control over, we use 'cooperative' coalitional models to tell us something about the incentives that agents and coalitions of agents may have to circumvent the rules.[24]

For example, core pricing should mean that bidders do not have an incentive to do deals outside the auction to change the allocation of spectrum. Also, Section 5.3 tells the story of UK mobile operators disliking the regulator's proposed CCA design to incorporate coverage obligations into the 2021 auction (a non-cooperative game). Their response can be seen as forming a coalition (cooperative game) to negotiate a coverage deal with the government, which led to a binding agreement. The coverage obligations were therefore superseded and removed from the auction, which led to the auction format being changed to SMRA which the operators preferred. In addition, although spectrum auctions are usually analysed as non-cooperative games, they can be characterised as 'heterogeneous matching with prices and complementary goods', emphasising the relationship to cooperative games and matching theory.[25] The matching is between mobile operators and spectrum blocks. It is heterogeneous, because operators have differing demands and spectrum bands vary in their characteristics; and complementary goods are involved if there are synergies between items in the auction.

Game theory is relevant not only to auction design choices, but also to the analysis of decision-making roles and processes. For example, Section 4.2 considers incentives to coordinate between professional skill groups within a regulator. Simple games can illuminate the basic incentive structure for players to cooperate with each other, such as the prisoner's dilemma being a case of individual incentives not to coordinate.[26] Another simple example with different incentive properties is the assurance game where cooperation is desirable but risky.[27]

3.3 Using expertise in spectrum auction design

The work of auction theory experts and practitioners is intertwined for designing spectrum auctions, because they present a challenge to distil complex analysis into practical rules attuned to specific circumstances. Designing spectrum auctions, drawing on or inspired by auction theory, involves public policy choices that combine practical appreciation of bidder behaviour, commercial realities, and technological opportunities with deep understanding of the implications of different auction formats and their associated rules. As may become obvious to readers of Part II, such as the in-depth discussion of auction design choices in Chapters 7 and 8, a significant degree of expertise is valuable for well-informed judgements. A notable example of an external expert is one of the recipients of the Nobel Memorial Prize in 2020, Paul Milgrom, who was instrumental in innovative designs for the Federal Communications Commission (FCC) in the USA in 1994 and in 2016–17 (the so-called incentive auction). He also advised Ofcom on the UK's 2018 and 2021 auctions. In addition, internal experts are important for practical decision-making, showing why effective choices depend on embedding technocratic expertise in processes that include wider public policy concerns. Chapter 5 explores different aspects of the role of experts in policymaking.

Governments have used auctions since Roman times, but the first spectrum auctions took place in New Zealand and Australia in 1989–90 and 1993.[28] They were somewhat troubled with bidder default problems in Australia and questions in New Zealand about allocation efficiency and low revenue (85 per cent less than forecast).[29] For example, there was adverse publicity when some of the licences sold at rock-bottom prices set on the basis of the highest losing bid (second price). In a few cases, prices were less than 0.1 per cent of the winning bid (for example, a price of NZ$6 compared to the winning bid of NZ$100,000, or NZ$5,000 price vs bid of NZ$7 million).[30] In contrast, the 1994 auction in the USA was widely regarded as a great success. Some commentators stressed the importance of experiments and simulations, but one of the key things different about the design of this auction was heavy involvement from academia of auction theorists: 'The story of how the spectrum auction was designed is a case study in the policy application of economic theory'.[31]

A two-way feedback loop between auction theory and practice has, therefore, been in play since the USA's 1994 auction. The auction format proposed by the theorists and adopted by the FCC did not come from the textbook, but was newly developed for the challenges of that auction.[32] Paul Milgrom, one of the developers of what came to be known as the SMRA, described how he was inspired by practical observation of silent charity auctions, where multiple items are offered simultaneously within a fixed time window, and bidders write their names and bids on a sheet of paper for each item and displace the current provisional winner by making a higher bid.[33] The influence was to learn from both successful attributes and weaknesses. Like silent charity auctions, the SMRA provides clarity on which bidders are winning at any point in the auction through a 'standing high bid' mechanism. The auction is simultaneous, with multiple items being awarded in the same process, allowing bidders to switch between them, and prices to rise if there is excess demand. A problem in silent auctions is that a bidder can swoop in at the last minute, leaving no time for other bidders to respond ('bid sniping'), which has also been observed in internet auctions such as eBay.[34] One mitigating feature introduced in the SMRA is that bidders always have an opportunity to bid back if their standing high bids are displaced (because the closing rule is that the auction ends only if there are no new bids in any category). Another mitigation is an 'activity rule' that prevents a bidder from increasing the amount of spectrum it bids for as prices rise (consistent with straightforward bidding) to prevent a firm from hiding its demand and engaging in a 'snake-in-the-grass' strategy like bid sniping.[35]

Therefore, since the early days, auction theory experts have played a significant role in practical design of spectrum auctions, bridging the 'ivory tower' and the messy real world. Auction theory cannot be applied mechanically because realistic conditions of spectrum auctions are usually more complicated than the theoretical models with their inevitably simplified or stylised assumptions for 'useful idealisations' as they seek to capture insights or particular aspects of reality.[36] Models can be informative for the practitioner, focusing on one type of effect by assuming others are not present using a 'well-chosen simplification', whereas the real world is sprawling and multifaceted, and regulators have limited ability to restrict the auction environment.[37] In this sense, 'each economic model is like a partial map that illuminates a fragment of the terrain'.[38]

The specification of motivations of participants in models may be wrong or incomplete (whether for bidders or regulators). For example, bidders may care not only about profit from the auction, as they could be playing a bigger game due to interactions with wider policy questions or relationships. Or they could view it as a repeated game with future auctions. The bid team could have their own objectives which are not fully aligned with the company's owners.[39] Or the firm could be subject to behavioural biases.[40] Another example of limitations of auction theory is that it is usually based on solving for an equilibrium of the relevant game, whereas 'in practice, participants do not always play according to equilibrium'.[41]

The theory can still greatly advance understanding by enabling experts, alongside practical experience, experimentation, and computation, to develop intuition that can illuminate design implications of specific effects which are part of, but not the complete, picture.[42] Experts can assist in understanding how different rules and parts of the auction interact with each other. Perhaps most importantly they can provide insights into which details or trade-offs matter the most, and which are of lesser importance. The regulator's auction design decisions can be made by combining these insights with practical know-how.[43] One of the Nobel Laureates in 2020, Robert Wilson, noted the particular importance of the practitioner point of view in market design:

> So concepts from game theory have been useful guides in efforts to improve the performance of trading platforms. But scholarly theorizing is minor compared to hands-on engineering using knowledge of an industry's technology and practices, and familiarity with participants' concerns is necessary if one is to help them obtain better outcomes overall.[44]

The interaction is two-way as practical experience and the complex reality highlight gaps in the theory, often leading to subsequent scholarly developments providing new, richer insights. The practical use of the SMRA in 1994 spurred the theorists to develop a better understanding of the attributes of this auction format.[45] Although this book refers for simplicity to 'the SMRA', it is in fact a family of evolving auction designs. Various modifications have been developed to mitigate previously unforeseen behaviour by bidders. An example is to limit 'jump bids', where bidders increase their bid amounts by more than a single bid increment, which can provide signals to other bidders. Another development is to incorporate new theoretical insights such as 'generic lots' to group similar but not identical frequencies for a faster, more efficient bidding process (Section 7.5). In response to limitations of the SMRA, theorists have also invented new auction designs. A difficulty for bidders in the SMRA format is 'aggregation risk' where different spectrum lots in the auction are complements so that a bidder can be left stranded, winning one lot but not the other needed to realise the synergies. Allowing package bids that win or lose in their entirety removes aggregation risk for bidders. Theorists (again including Paul Milgrom) developed the 'clock-proxy auction' with package bidding, which in modified form was then put into practice by regulators.[46] The UK regulator was an early adopter of the resulting format which came to be known as the CCA.[47] Another example of new formats is the descending clock auction developed (yet again by Paul Milgrom and colleagues) to address the hugely complex challenges of buying spectrum from TV broadcasters in the USA's 2016–17 incentive auction.[48] The symbiotic fields of academic study and practical implementation are therefore constantly evolving, seeking both evolutionary improvements and more innovative, revolutionary step-changes.[49]

3.4 Wider lessons for public policy

A number of broader lessons for public policy can be taken from the case of spectrum auctions as an important example of market design in practice, such as the UK experience outlined in Section 2.3. Spectrum auctions exemplify the value of well-judged use of *expertise* because of the vivid examples of successes and failures. The UK's largely successful auctions benefitted from the advice of external experts with deep understanding of auction theory and practice (Ken Binmore and Paul Klemperer in 2000, Peter Cramton in 2013, and Paul Milgrom in 2018 and 2021) in addition to well-informed economic consultants and internal experts.[50] Failures can sometimes be a product of circumstances. But earlier chapters highlighted undesirable examples in other countries that were avoidable due to high reserve prices that left spectrum unsold in Australia and India, faulty design choices that led to questionable spectrum allocation in New Zealand, or agonisingly slow auctions in Finland and Portugal. The consequences of insufficient use of expertise were losses suffered by the public in delayed or lower-quality services.

Another lesson is the importance of *learning* from ongoing processes by both public and private participants. We can see any auction as a game within the wider game of a series of auctions over time, involving the same or overlapping players. The UK experience shows how learnings from one auction were applied to later occurrences. This happened in a nuanced way for the regulator (such as changing from less flexibility for bidders in 2000 to more granularity in later auctions). Companies bidding in the auctions learned starker lessons from overbidding at the height of a telecommunications stock market boom in 2000. They avoided repeating the costly mistake (estimated at £10 billion by one of the bidders, Peter Bonfield, BT's chief executive at the time).

More fundamentally, the theory and practice of market design also show that we can see 'the market' as far from immutable, because markets can operate in so many different ways. We can instead recognise the potential of markets as a *malleable* policy instrument. They can be shaped and designed for public purposes in cases where it is feasible to harness self-interest, such as companies' profit incentives, to yield socially desirable outcomes. For example, careful design of spectrum auctions has promoted efficient allocation and strong retail competition, and incorporated obligations for enhanced mobile coverage to benefit the public as consumers and as citizens. As a by-product, taxpayers have also gained from the scale of auction receipts for the government. In addition, there have been gains to industry through access to valuable scarce resources, and to the economy through improved mobile infrastructure. However, a simplistic read-across of success in one policy area to other contexts should be avoided. The requirement instead is for experts as skilled practitioners to wield precision tools, scalpels not sledgehammers, identifying the right surgery after careful diagnosis of the source of past problems and the future potential.

Notes

1 Turocy and von Stengel (2001, p.4).

2 Roth (2012).

3 Koop and Lodge (2017).

4 See Chen et al (2021) for a survey of market design research in online auctions, spectrum auctions, financial markets, online feedback systems, and matching in education and labour markets.

5 Reiter (2008).

6 A universally agreed definition of dynamic efficiency is lacking. In one view, it is less distinctive – for example, process innovation for cost reduction can be related to productive efficiency, and product innovation to allocative efficiency. However, another view regards dynamic efficiency as a transformational contrast to 'static' allocative and productive efficiency. For a regulatory agenda about dynamic efficiency promoting investment in 5G through access to spectrum, see EU (2021).

7 Lockwood (2008).

8 Chipman (2008).

9 Feldman (2008, p.7).

10 Roth (2007), and Kominers, Teytelboym, and Crawford (2017).

11 A simplification in Figure 3.1 is the expression of preferences by agents shown on one side at the top (1, 2, and 3), but not the other side (A, B, and C). Preferences of both are relevant in a range of situations, such as doctors and hospitals, or marriage partners.

12 FCC (1997, section III).

[13] Hayek (1945).

[14] Another example is the USA's incentive auction in 2016–17, when the regulator, the Federal Communications Commission, was the clearinghouse linking broadcasters selling their spectrum rights to mobile operators buying them: 'For the incentive auction, however, finding a good plan (including how many channels to clear, which stations to retune, and how to retune them in a way that satisfies millions of interference constraints) and the clearing prices while still enforcing all of the interference constraints is a computationally hard problem, which requires a coordinated solution involving very many parties. Thus, a central authority like the FCC has an indispensable coordinating role.' – Leyton-Brown, Milgrom and Segal (2017, p.7205).

[15] For a critique of treating consumers' decisions as biases or mistakes instead of context-dependent choices, see Sugden (2022, section 7).

[16] Values and norms can also be changed by use of markets – see Michael Sandel's 2009 Reith lecture 'Markets and Morals' https://www.bbc.co.uk/programmes/b00kt7sh.

[17] Nobel Prize (2020c).

[18] Roth and Wilson (2019, p.123).

[19] Rapoport (1987).

[20] Ostrom (2008).

[21] See Alvin Roth's 2017 Morishima Lecture at LSE, 'Marketplaces and Market Design' https://www.youtube.com/watch?v=D5qCvMqqwC8.

[22] The prisoner's dilemma can also be modelled in theory as a repeated game in which the prisoners both choosing to stay silent can emerge as an equilibrium. There have been many experiments showing this outcome, especially with more plays of the game – see Rapoport (1987).

[23] Roth and Wilson (2019, p.124).

[24] Roth and Wilson (2019, p.127).

[25] Milgrom and Vogt (2021, p.29).

[26] Scharpf (1997, chapter 4).

[27] The assurance game (which is sometimes also called the 'stag hunt') has multiple Nash equilibria that could form its outcome, e.g. see Wikipedia 'Stag hunt', https://perma.cc/CN2H-BR2Y. One equilibrium reflecting desirable cooperation is 'payoff dominant', meaning that both players earn their highest payoff by cooperating. But this is risky for the players because, if Aardvark chooses to cooperate but Beaver does not, Aardvark is left with its lowest payoff. Therefore, a different equilibrium without cooperation is 'risk dominant', since it avoids this risk.

[28] Smith (1987).

[29] Milgrom (2004, pp.11–12), and McMillan (1994, pp.148–50).

[30] Mueller (1993, table 5, p.169).

[31] McMillan (1994, p.146). For a trenchant, contrary view, see Nik-Khah (2008).

[32] The proposal was made by Paul Milgrom and Robert Wilson (who a little under 30 years later became the joint winners of the Nobel Memorial Prize in Economic Sciences in 2020), working for Pacific Bell. There was a similar proposal from Preston McAfee, working for Airtouch Communications. Auction theorists were also employed by other potential bidders, and John McMillan worked for the FCC.

[33] Milgrom (2021, p.1392).

[34] Roth and Ockenfels (2002).

[35] Milgrom (2000, p.249).

[36] Milgrom (2004, p.22).

[37] Milgrom (2021, p.1384).

[38] Rodrik (2015, p.12).

[39] Differences in objectives between the bid team and the firm's owners provide a possible rationale for the use of budget constraints – Bichler and Goeree (2017, section 4.4).

[40] Armstrong and Huck (2010).

[41] Milgrom (2011, p.312). Departures from equilibrium bidding are commonly observed in experimental analysis, such as Marszalec (2018).

[42] Roth (2002), and McAfee and McMillan (1996).

[43] See the account of 'economic engineers' by Alexandrova and Northcott (2009, p.333).

[44] Roth and Wilson (2019, p.139).

[45] More generally, the 1994 auction (and developments in US Treasury auctions) 'underscored some extremely serious limitations in auction theory', such as that 'relatively little was established concerning multi-item auctions' – Ausubel (2008, p.2).

[46] Ausubel, Cramton, and Milgrom (2006).

[47] Cramton (2013, section 4).

[48] Milgrom and Segal (2020) call this format the 'deferred-acceptance clock auction'. Milgrom and Vogt (2021, section 5 in) explain how it addressed the incentive auction's challenges of computational complexity, bidder trust, winner privacy, budget conditions, avoiding incentives for collusion ('group strategy-proof'), price competitiveness, and minimising procurement cost.

[49] Nobel Prize (2020b).

[50] The UK avoided clear-cut failures, but potential exceptions to the success story are potential adverse effects on investment of very high revenue in the 2000 auction, and question marks about the efficiency of the spectrum allocation in the 2013 auction. The evidence in relation to both is mixed (as set out in Section 7.2 and Annex A).

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Note: 🔓 means an open access publication.

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