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Paul David Klemperer (1956–)

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1 Introduction

Paul Klemperer was born in Southampton, England, in 1956. At the age of six, he moved to Birmingham with his parents who were both academic scientists: his mother Ruth at Aston University and father Hugh at the University of Birmingham.[1] He went to the local Bournville Primary School and later won a scholarship to King Edward's School. From an early age, Klemperer was fascinated by geometry. On his teenage bedroom wall hung a poster of Albrecht Dürer's engraving *Saint Jerome in His Study*. The engraving did not catch his attention because of his interest in Jerome's translation of the Hebrew Old Testament and Greek New Testament into the Latin around 400 CE. It was the geometry of perspective (of which Dürer was a pioneer): the way the parallel lines met at a point in the background. This interest in geometry was to be a lasting influence on how Klemperer thought about the issues and problems he studied later in life. He was admitted to study Mathematics at Cambridge University in 1975, and for his final year he switched to the Engineering Tripos, in order to be able to focus on more applicable

[1] His family did not follow the musical career of his distant relative, the conductor Otto Klemperer.

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mathematics, especially operations research (OR). Before going to Cambridge, he had vacations: For IBM in Birmingham, where he developed an early computer-aided design program. He also worked during his university vacations: For IBM again, for Monsanto in its world headquarters in St Louis, the United States, and for BP in London (all doing programming and OR).

At the end of the course in 1978, he was eager to get back into the real world, joining Arthur Andersen and Co.'s management consulting division in London (this was subsequently spun off as Accenture). His most significant project was a secondment of about a year to the Department of Health and Social Security. It had developed a complex linear-programming model to allocate resources both within the National Health Service (NHS) and among the NHS and local authorities (who delivered social care) and housing authorities (then a different level of local government). Unfortunately, the model was so complex that no one really understood it, so no one really trusted its answers. His most important contribution was to develop a much simpler model, which not only generated very similar answers but also brought out the intuition clearly, so users trusted the answers and could understand the effects of modifying the assumptions or changing the resources available. The work done in this period later led to Klemperer and McClenahan (1981). Klemperer's ability to make the complex simple to be comprehensible to policy makers was to stand him in good stead later in life when he advised the Bank of England during the financial crisis.

In 1980, Klemperer was awarded a Harkness Fellowship to pursue a two-year MBA at Stanford University. However, at an early stage, he decided he wanted to do a PhD, which he started in 1982 and completed in 1986. The faculty members advising his doctorate were Tim Bresnahan, John Roberts and Jeremy Bulow. Bulow not only advised on the thesis research but also started joint work with Klemperer that resulted in his first two economics papers (see Bulow et al. 1985a, b).

At the end of 1984, Klemperer moved back to England to take up a post as Lecturer in Operations Research and Mathematics at Oxford, based at St Catherine's as college Tutor in Economics. He was to remain in Oxford for the rest of his career to date. He became a Reader in 1990 and moved to Nuffield College in 1995 becoming the Edgeworth Professor of Economics following the retirement of the first Edgeworth Professor Sir James Mirrlees. He inherited not only the post but also the room and some of the furniture from Mirrlees. Klemperer remains in this post at the time of writing.

Klemperer's research can broadly be divided into two main parts. The first is oligopoly theory, interpreted in a wide sense, with 20 or so publications covering the decade at St Catherine's. His best-known research in oligopoly

theory is on switching costs. The second part is auction theory, which started with the renewal of his partnership with Jeremy Bulow (see Bulow and Klemperer 1996) and continues to the present.

Klemperer's work in auction theory led to his involvement in public policy. This included designing the auction for the sale of the British 3G Telecom Licences in 2000 and later the design of artificial markets for the Bank of England (and other central banks) to make loans to commercial banks for assets of differing quality (including toxic assets) in the aftermath of the financial crisis.

In this chapter, I will first deal with the two stages of Klemperer's research and then go on to look at his involvement advising public bodies about designing auctions.

2 Oligopoly

The research career of Paul Klemperer started with two articles with his Stanford supervisor Jeremy Bulow and Yale economist John Geanakoplos (see Bulow et al. 1985a, b). The most revolutionary paper was the first: "Multimarket Oligopoly: Strategic Substitutes and Complements". The idea of a strategic complement (substitute) is defined by the cross-partial derivative of the payoff function. In a symmetric payoff game, the payoff U of each player depends on their own action (x) and that of the other player (y): $U(x, y)$. The strategies of the two players are strategic complements (substitutes) depending on whether the cross-partial derivative is strictly positive (negative):

$$\frac{d^2U}{dxdy} > 0 \quad \text{Strategic complements}$$

$$\frac{d^2U}{dxdy} < 0 \quad \text{Strategic substitutes}$$

Why is the cross-partial derivative so important? Because the reaction function is defined by the (necessary) standard first-order condition that the derivative of the chosen action is zero. In the case of strategic complements, the reaction function will be upward sloping (as in the usual case of price competition with differentiated products): in the case of strategic substitutes the reaction function will be downward sloping (as is typically the case in homogeneous Cournot oligopoly). However, price competition can sometimes lead to strategic substitutes and quantity competition to strategic complements.

This very simple classification turned out to have a fundamental importance in terms of how oligopoly models behave—the paper applied the idea to a variety of settings. Its key insight led to the development of a whole literature on supermodular games, which generalised the notion of strategic complementarity for payoff functions that were not twice continuously differentiable.

The other paper "Holding Idle Capacity to Deter Entry" applied the classification of strategic complements and substitutes to Avinash Dixit's model of entry deterrence (see Dixit 1980). Dixit's model had assumed an incumbent firm would always reduce output if a new firm was to enter, but Bulow et al. (1985b) showed that this depended on the post-entry oligopoly game being one of strategic substitutes: if the goods were strategic complements, then the incumbent might install capacity, in order to expand output if entry occurs, but leave it idle if no entry occurs. The idea of strategic complementarity went on to have a life of its own and became a term used widely across economics, including macroeconomics.

Klemperer teamed up with his future wife Margaret Meyer[2] (see Klemperer and Meyer 1986) to write a paper on the foundations of price versus quantity competition. Suppose that firms can choose whether to set price (and supply the quantity demanded) or choose quantity (and let the price be determined by the market). Furthermore, suppose there is a demand system linking the prices and outputs demanded of the firms. In the absence of uncertainty, firms are indifferent between setting a price or quantity. They face a demand curve and simply choose the profit maximising point on that curve (where marginal revenue equals marginal cost). The action of firm A does influence the demand curve for firm B, and hence firm B's best response. However, the best response can be attained by choosing either price or quantity. There are thus four types of (pure strategy Nash) equilibria with no uncertainty: the two firms both choose price, both choose quantity or one choses price and the other quantity. Bertrand and Cournot are both equilibria, as is the mixed price and quantity setting case. With demand uncertainty, matters are rather different. Firms will in general have a strict preference for setting price or quantity. The preference will depend on a variety of factors: the shape of the demand curve, the marginal cost curve and the size of shocks. For example, a steep marginal cost curve makes quantity choice more attractive, and a flatter marginal cost curve favours price. If the model is symmetric, then the factors will influence both firms in the same way and tend to make the mixed equilibria less likely. The

[2] They were to marry in 1989 and have three children.

nature of technology, demand and uncertainty will lead to either price- or quantity-setting equilibrium being chosen.

In two further papers, Klemperer and Meyer looked at equilibria in reaction functions (Klemperer and Meyer 1988) and supply functions (Klemperer and Meyer 1989). The 1988 paper, "Consistent Conjectures Equilibria: A Reformulation Showing Non-Uniqueness", contributed to the literature on consistent conjectures which had been a topic rekindled by Timothy Bresnahan's 1981 paper. Bresnahan was an Assistant Professor at Stanford in the period of Klemperer's PhD. The conjectural variation (CV) acts to alter the first-order conditions for the optimal response and hence acts as a shift variable for the firm's reaction function. By varying its CV, in effect a firm can move its reaction function. Firm A treats the reaction function of its competitor B as given: there will be a (unique) point on the other firm's reaction function that yields the highest profit for firm A. This point will be where there is a tangency between the iso-profit curve of firm A and firm B's reaction function. It can then choose its reaction function (via its CV) so that its own reaction function passes through this optimal point. Firm B can reason in the same way. What Klemperer and Meyer showed was that: (a) the equilibrium in reaction functions involves (Bresnahan) consistent conjectures (the conjectural variation equals the slope of the other firm's reaction function); and (b) the equilibrium is highly non-unique in that almost any output pair corresponds to an equilibrium. The result rested on a geometrical intuition. If you pick any output pair, iso-profit curves of both firms pass through that point. The reaction functions that support this are the tangents to the iso-profit curves at that point. Neither firm can increase its profits by changing its reaction function given the other's choice.

In the 1989 paper, "Supply Function Equilibria in Oligopoly Under Uncertainty", Klemperer and Meyer revisited the issue of the strategic choice of whether to set a price or quantity. This time, however, they argued that since neither a fixed price nor a fixed quantity allows a firm to adapt optimally to demand shocks, it is natural for firms to use more general supply functions as strategic variables; they therefore looked at equilibrium in supply functions. Uncertainty then acted to restrict the choice of supply functions to choices that ensured ex-post optimality in the face of the supply functions of competitors and uncertain demands. Klemperer and Meyer's supply function analysis has frequently been used since, in both theoretical and applied work. In particular, it has been used to study electricity markets in which producers offer supply functions specifying the quantities of energy they are willing to supply at different prices. More generally, the equilibrium supply functions of firms which supply a market are precisely (a constant minus) the equilibrium

bidding schedules of bidders in a uniform-price multi-unit auction, so the 1989 paper also contributed to the development of multi-unit auction theory.

2.1 Switching Costs

The title of Klemperer's 1986 PhD at Stanford was "Markets with Consumer Switching Costs", which gave rise to a series of publications on switching costs in different contexts (these and other papers he reviewed in Klemperer 1995a). The idea that the presence of lump sum costs (pecuniary or psychic) paid by consumers when changing seller might make markets less competitive was not new. However, a rigorous dynamic modelling of the switching costs was new.

Ex ante homogeneous products may, after the purchase of one of them, be ex post differentiated by switching costs including learning costs, transaction costs or artificial costs imposed by firms, such as repeat-purchase discounts. The non-cooperative equilibrium in an oligopoly with switching costs may be the same as the collusive outcome in an otherwise identical market without switching costs. However, the prospect of future collusive profits leads to vigorous competition for market share in the early stages of a market's development. The model thus explains the emphasis placed on market share as a goal of corporate strategy (Klemperer 1987a: 375).

In his paper "The Competitiveness of Markets with Switching Costs" (Klemperer 1987b), Klemperer modelled a two-period model with two firms. Switching costs can arise in the second period if consumers decide to switch from one seller to the other. Customers are modelled in a locational setting with the sellers at either end of the street. Customer demand in the first period is given by prices and linear transport costs. In the second period, there is an additional switching cost. The prices in the first period are influenced not only by maximising profit in that period but also by building up a customer base for the second period. It is in the second period that the firms can exploit the monopoly power created by the switching costs. The model allows for rational expectations on the part of consumers who can predict the second period pricing decisions by firms. Even though there are no switching costs in the first period, demand is less elastic in that period than if there were no switching costs in the second period. Consumers realise that the seller with the larger consumer base in period 1 will extort higher prices in period 2 and so are less attracted to the low-priced seller than they would be without switching costs. So, although prices will be lower in period 1 than in period 2, they may be higher in both periods because of the switching costs.

"Entry Deterrence in Markets with Customer Switching Costs" (Klemperer 1987c) also looked at a two-stage game, but where the only mover in the first period was an incumbent, who could influence the second stage entry game. The key here was the ability of the incumbent to build up a captive customer base (captive due to switching costs); modelling was of Cournot oligopoly with firms choosing quantities. Switching costs were captured by making second period purchases depend on the first period (positively). In the first period, the incumbent may over-invest in output to lock in customers and so deter any entry (or reduce the entrant's output) in the second period. However, for some parameter values, the incumbent prefers to deter entry by under-investing in output, thus committing to competing aggressively for new customers with any entrant in the second period (Klemperer named this phenomenon limit over-pricing).

"Welfare Effects of Entry into Markets with Switching Costs" (Klemperer 1988) showed that the presence of switching costs can lead to excessive entry that reduces social welfare. This is even possible if new entrants have lower costs than incumbents. The mechanism is that 'a large amount of social surplus is dissipated by the consumers' cost of switching to the new competitor' (ibid.: 164). This phenomenon can even occur if industry output increases, resulting in lower prices. However, Klemperer cautioned that in spite of his results: 'Probably most entry into markets with switching costs is socially desirable' (ibid.).

In "Price Wars Caused by Switching Costs", Klemperer (1989) extended the switching cost model to four periods. In the first two pre-entry periods, the monopolist sets up shop. In period three, a fringe of competitors enters (treating the incumbent's output as given) and there is the threat of additional fringe entry in period four. The path of prices over time is then traced. In the final period, with the switching costs, prices tend to rise to a higher level. Firms have just one period left to exploit all of their monopoly power. In period three, entry drives a price war. New entrants and the incumbent lower prices to build up or maintain their customer base to exploit in the final period. The effect of entry is to lower prices in period three relative to the pre-entry periods (and the incumbent may also lower prices in period two, immediately prior to the new entry). 'In our model of a market in which consumers have switching costs, the entry of new firms leads to a price war, and we have argued that this conclusion is robust' (ibid.: 415).

In a paper with his then-student, Alan Beggs (Beggs and Klemperer 1992), "Multi-Period Competition with Switching Costs", the switching costs approach was generalised to an infinite-period version of the duopoly model found in Klemperer (1987b). Firms have a discount rate and customers turn

over, with some dying to be replaced with new-born customers. The paper established the conditions for existence of a symmetric steady-state equilibrium and showed that equilibrium prices will be higher when there are switching costs than when they are absent. Indeed, the net present values of firms' profits are usually larger—even for a new entrant which has no customer base—when there are switching costs.

In a paper with Kenneth Froot titled "Exchange Rate Pass-Through When Market Share Matters" (Froot and Klemperer 1989) took the basic idea of switching costs that market share in one period can lock in demand to subsequent periods, and applied it to the classic issue of exchange rate pass-through. They found that:

> Foreign firms may either raise or lower their dollar export prices when the dollar appreciates temporarily (i.e., the pass-through may be perverse) and import prices may be more sensitive to expected future than to current exchange rates. We explore whether expected future exchange rates provide a clue to the puzzling recent behavior of US import prices (ibid.: 637).

Indeed, the paper had an empirical dimension that was not usual in the other papers on switching costs, in that it looked at data on import and export prices between the major economies in the 1980s.

In his 1992 paper "Equilibrium Product Lines: Competing Head-to-Head May Be Less Competitive", Klemperer took a model where consumers face shopping costs, which mean that consumers prefer to shop at fewer outlets. In this case, Klemperer showed that in equilibrium, firms may prefer to offer identical product ranges so that customers will only choose one shop to visit. This head-to-head competition can lead to higher prices. If they are only shopping at one outlet, it requires a bigger price incentive for a consumer to switch outlets or shop at both outlets. If firms offer distinct product ranges, consumers shop at both outlets and can respond to quite small price differentials. This line of thought went against some then-established economic models where firms maximise product differentiation in order to increase monopolistic markups. However, Klemperer argued that his model fitted with the marketing literature which identified umbrella branding (selling goods in related markets under the same brand name) and brand extension (selling new brands under an established brand name).

The issue of product lines, variety and welfare was explored in a paper with another of his students at the time, Jorge Padilla (see Klemperer and Padilla 1997), titled "Do Firms' Product Lines Include Too Many Varieties?" A firm that offers an additional product can capture business from rival firms for

other products when consumers prefer to concentrate their purchases at a single supplier. This may lead firms to offer excessive product variety from the social standpoint. A firm may even completely foreclose competing firms from the market by introducing a new product. Restricting the ability of firms to offer new products could increase welfare. Klemperer and Padilla even applied the model to the then live policy debate about Sunday trading, arguing that 'if—as many shopkeepers argue—customer loyalty to shops is important, then [under certain conditions] shops will open for a socially excessive number of hours' (ibid.: 483).

Gilbert and Klemperer (2000) developed an equilibrium theory of rationing. In a simple model of pricing, a monopolist would never want to set a price in which all consumer demand was not met (a price with rationing). The argument is simple: the monopolist can make more money by raising the price and selling the same output. However, Gilbert and Klemperer considered a two-stage set-up where consumers have to make an upfront investment to enter the market. In this case, the monopolist might want to *precommit* to keep the price low in order to encourage more consumers to enter. Although ex post the rationing is inefficient, it can yield higher profits if the firm is able to commit to it. This paper was later developed in the context of auction theory in Bulow and Klemperer (2002).

Klemperer's interest in oligopoly theory was not just theoretical. He wanted to apply his theoretical ideas to policy and his opinion was sought after. He was an adviser to the US Federal Trade Commission 1999–2001 (adviser on merger and competition cases and policy) and also a member of the UK Competition Commission 2001–2005 (and later adviser 2006–2014). He also undertook an applied analysis of the major economic issues raised by the 1997 Tobacco Resolution and the ensuing proposed legislation that were intended to settle tobacco litigation in the United States (see Bulow and Klemperer 1998). In addition, Klemperer wrote about the appropriate breadth of patent or copyright protection (see Klemperer 1990), stimulated by a debate about whether Japan's very narrowly defined patents took unfair advantage of American technology, and he has contributed to subsequent public policy debate in this area (see Klemperer 2004a).[3]

[3] Klemperer also contributed to the UK government's 2006 *Gowers Review of Intellectual Property*.

3 Auctions in Theory

'Auction Theory is one of economics' success stories. It is of both practical and theoretical importance: practical because many of the world's most important markets are auction markets…; theoretical because lessons from auction theory have led to important insights elsewhere in economics' (Klemperer 2004b: 1).

A new line of study started with Klemperer in the mid-1990s, coinciding with a renewal of an old partnership with Jeremy Bulow. However, it is important to note that Klemperer had already used an auction framework both in his 1987 paper with Peter Cramton and Robert Gibbons (see Cramton et al. 1987) and in Klemperer and Meyer (1989), discussed above. Significantly, for future research, the Cramton et al. paper was inspired by the Federal Communications Commission's allocation of licences for cellular telephone franchises and also the Federal Aviation Administration's allocation of landing slots. Cramton et al. showed that achieving the optimal allocation involved payments depending on all bids and not just the winning bidder paying—this is very different to standard auction mechanisms such as first- or second-price auctions. However, they also showed that standard mechanisms can achieve the efficient outcome if the initial partner shares are close enough to equal.

The title of Bulow and Klemperer (1994), "Rational Frenzies and Crashes", does not mention auctions, but is about a Dutch auction where a seller has multiple units to sell and starts from a high price. Buyers have a valuation for buying one unit coming from a common distribution, which is known. The key point is that buyers can choose to bid or delay. If at least one buyer offers to buy at the current price, the other buyers are also asked if they wish to buy at the current price. This simple auction is solved using revenue equivalence. What Bulow and Klemperer showed is that once one person has bid and been allocated a unit, others may wish to also buy since removing the unit purchased will raise the price buyers can expect to pay. This case of multiple purchases at a single price is a frenzy. However, if unexpectedly few bidders then participate in the frenzy, the information that that reveals about demand means the price has to fall a long way to tempt another bidder to make an offer—a crash. Although derived for a specific model, Bulow and Klemperer believe the lessons will apply to a wide range of models.

In their 1996 paper "Auctions Versus Negotiations", Bulow and Klemperer pose the question: when selling a firm, should you employ 'an auction with no reserve price or an optimally-structured negotiation with one less bidder? We show under reasonable assumptions that the auction is always preferable'

(ibid.: 180). However, the paper is as important for the way it models the auction process in terms of a monopoly, and looks at *marginal revenues* instead of prices. The price is the value of the bidder; the quantity is defined by the cumulative density of the bidder's value. Marginal revenue (MR) is then the derivative of price times quantity, with the optimal price for the monopolist occurring when MR is zero (assuming the seller has no cost). The analogy works because,

> just as the expected revenue from a take-it-or-leave-it price can be calculated by multiplying that price by the probability of sale at that price, expected revenue can also be found by taking the area under the MR curve for all the values in excess of the take-it-or-leave-it price. The seller may be thought of as receiving, in expectation, the MR of the buyer when it is positive, and zero when the buyer's MR is negative (ibid.: 183–184).

This approach was originally developed by Bulow and Roberts (1989) for bidders with independent private values, but the Bulow and Klemperer paper shows how to extend the approach to all auctions in which bidders' signals are independent, whether values are private or common or something in between, and then—a key insight—to all ascending auctions, whether or not bidders have independent signals. So, the expected revenue from any ascending auction is given by the marginal revenue of the bidder with the highest signal.

The Bulow and Klemperer paper also shows the usefulness of this approach. Using marginal revenue analysis, it is simple to show what was not otherwise obvious: that so long as all bidders are serious (in the sense that their valuations exceed the seller's actual value), then adding an extra (serious) bidder to an ascending auction with no reserve price will, under mild conditions, always increase expected revenue more than adding the use of a reserve price.[4]

Klemperer went on to promote his view that 'connections between auction theory and standard economic theory run deeper than many people realise' (Klemperer 2000: 2) and applied the auction-theoretic perspective to a wide variety of applications, in his aptly titled Econometric Society World Congress lecture, "Why Every Economist Should Learn Some Auction Theory". Put simply, Klemperer believes that many markets can be understood as equivalent to particular type of auction markets. Alternatively, auctions are a

[4] Bulow and Klemperer also use a similar marginal revenue approach to examine the effect of price controls on rent-seeking and consumer welfare (see Bulow and Klemperer 2012). They further highlighted the importance of attracting new entrants in their paper "Why Do Sellers (Usually) Prefer Auctions?" (Bulow and Klemperer 2009).

way of setting up a market. A well-designed auction can yield a desirable outcome where for some reason no market exists.

In Klemperer (1998), "Auctions with Almost Common Values: The 'Wallet Game' and Its Applications", he considered the following classroom experiment: two students are picked, each checks how much is in his or her wallet; the combined contents of the wallets are then auctioned to the two students using an English auction. The problem for each student is that they only know the value of their own wallet, not the value of the other student's wallet. There are many equilibria to this, but only one symmetric equilibrium (both bidders offer up to twice what was in their own wallet). Klemperer went on to consider situations where bidders have almost common values: that is one bidder has a slightly higher value. He found that small differences in valuations would lead to far from symmetric outcomes. In terms of the Wallet Game, suppose player 1 has a small advantage (he gets a bonus of £1 if he wins). Even this tiny advantage can mean that player 1 always wins the Wallet Game, which is very unlike the symmetric equilibrium. In practice, many economic situations might involve situations where there is a small advantage. In a takeover, one firm might have a toe hold, leading it to bid more aggressively and lead to other bidders being discouraged due to an increased winner's curse (see Bulow et al. 1999). Alternatively, in a takeover contest, one of the firms might have more synergies to exploit than others. Klemperer argued that this applied to the 1995 takeover of Wellcome by Glaxo: Glaxo had more to gain than other potential bidders such as Zeneca and Roche. Glaxo made a first bid and the others dropped out. Possible ways around these problems included sealed-bid auctions or multi-stage auctions such as his Anglo-Dutch auction proposal (see Klemperer 1995b).

In "The Generalized War of Attrition", Bulow and Klemperer (1999) used the Revenue Equivalence Theorem from auction theory to solve the case where N+K firms were competing for N prizes. Such wars of attrition occur when a number of firms are competing for a fixed number of slots (for example, firms competing to supply wireless telephony in major US cities) or where there is a battle to control a new technology and set the standards. Previous analysis had focused on the two-firm case. Bulow and Klemperer instead looked at the more general natural oligopoly case: 'The natural oligopoly case yields a striking result: there is "instant sorting", so K-1 firms will exit immediately, leaving only N+1, or one too many firms to battle for the N prizes' (ibid.: 177). This instant sorting result is a general feature of these games.

Bulow and Klemperer (2002), "Prices and the Winner's Curse", developed themes from Klemperer (1998). In particular, they showed how in ascending-price auctions increasing supply might in fact lead to higher prices because it

encourages weaker bidders to participate, since the greater supply alleviates the winner's curse they face. More active bidders can result in a higher price. Furthermore, when there are even small deviations from common value, the auction can behave very differently from the common value auction. This insight was to have important implications when it came to designing auctions in practice because in real life, pure common values are almost never found. It is a case of economic theorists spending time looking at the case that is easy to solve. If auction theorists want to produce relevant models, they need to stop looking at the simple models and look at something more realistic. Even small deviations from the simple case can lead to very different outcomes.

4 Auctions in Practice

In an interview, Klemperer explains his fascination with auctions: 'I thought that if we couldn't understand auctions, then we probably couldn't understand how the whole economy works. But by learning about auctions, we could learn about more complex environments, and auction models could be the building blocks for modelling more complex economic systems' (Klemperer in Petropoulos 2015). Klemperer (2002a, 2003) discussed the pitfalls of moving from theory to practice. In his opinion, 'most of the extensive auction literature…is of second order importance for *practical* auction design. The literature largely focuses on a fixed number of bidders who bid non-cooperatively' (Klemperer 2002a: 170; italics in original). In contrast, 'what matters in auction design are the same issues that any industry regulator would recognise as key concerns: discouraging collusive, entry-deterring and predatory behaviour. In short, good auction design is mostly good elementary economics' (ibid.: 169–170). There was thus a link between the development of real-life auctions and the extensive research Klemperer had made in industrial organisation (IO) issues reviewed in Section 2 and his work with real-world regulation and competition policy in the United States and the United Kingdom.

Klemperer has been involved in advising governments on many issues, but by far the highest profile policy engagements were applying auction theory to real auctions. Specifically, he has been closely involved in two very high-profile auctions.

4.1 The Biggest Auction Ever

The first auction was "The Biggest Auction Ever: The Sale of the British 3G Telecom Licences" (Binmore and Klemperer 2002). The biggest ever auction was held in the United Kingdom over the months of March and April 2000 and involved the sale of the third generation (3G) mobile spectrum licences. Klemperer was part of a team with other members, including Ken Binmore, Tilman Börgers, Jeremy Bulow, Philippe Jehiel and Joe Swierzbinski (this was the result of a successful bid for the assignment by the ESRC Centre for Learning and Social Evolution based at UCL; Klemperer's role was as the auction specialist). The team had started to advise the British government on the design of the auction three years earlier in 1997. The starting point was the view that 'a well-designed auction is the method most likely to allocate resources to those who can use them most valuably' (ibid.: C75). The only practical alternative was a beauty contest: government officials or experts choosing the most attractive bid, a process notoriously open to issues of political and legal influences. Auctions could also raise a lot of money for the public purse.

The aims of the UK auction were to assign the spectrum efficiently, to promote competition and to realise the full economic value. The auction was designed to meet these objectives taking into account the specific features of the British telecoms market. Early on in the process, the team recognised that it was very important to encourage entry and not to restrict competition to the existing 2G suppliers. Whilst the possibility of a royalties-based payment scheme was considered, this was ruled out as inferior to the one-off sunk cost payment which would involve less distortion in the operations of 3G after the auction.

The government initially proposed that the auction should be for a fixed number of four licences with no bidder getting more than one licence. Since the then current number of 2G incumbents was also four, there was a real concern that no potential entrant would be willing to bid against the (likely much-stronger) incumbents in an ascending auction—precisely the concern that Klemperer had raised in his 1998 Wallet Game paper discussed above—and that a pure sealed-bid auction would risk substantial inefficiency. So, the team went for a version of Klemperer's (1995b, 1998) Anglo-Dutch auction: the four licences would be auctioned with an English ascending price auction until there were five bidders left. Then the five bidders would make a sealed bid for the licences and the four highest would get the licences and pay the fourth highest bid. In the end, however, the government decided to issue five

licences. As such, since one licence was the most any one firm could be allocated, at least one new entrant would be guaranteed to win, and a simultaneous ascending auction was used.

The auction was a great success from the perspective of the government raising revenue. There were 13 bidders at the start of the process. In the end, the new entrant (Hutchison Whampoa, under the brand 3 Mobile) won the largest licence A, the four incumbents the other licences with total revenue of $34bn, which was used by Chancellor Gordon Brown to pay down the public debt. Binmore and Klemperer found that 'Auction design is a matter of "horses for courses", not one size fits all; each economic environment requires an auction design that is tailored to its special circumstances' (Binmore and Klemperer 2002: C94).

There were, however, many critics in the popular press who argued that the weakness of the auction was the (standard economists') belief that, since the auction payments were sunk costs, the prices consumers would pay in the United Kingdom would be unaffected. Soon after the auction, *The Guardian* newspaper ran an article titled "Consumers Pay the Price in 3G Auction", claiming, 'Those countries which opted for the beauty contest route—namely France, Portugal, Spain, Norway and Finland—face no such embarrassing post mortems and are likely to enjoy far more sophisticated 3G services as a result' (Osborn 2000: 33).[5] These fears do not seem to have been borne out in practice.[6] There was also a telecoms crash in 2001 in which the market value of shares in telecommunications companies across the developed world fell significantly and many jobs were lost in the UK and elsewhere. But Klemperer argued that the auction itself was not at fault: he pointed out that some of the firms that fared worst in the telecoms crash were ones who had bid unsuccessfully in the United Kingdom (citing NTL); that the fees paid in all the European 3G auctions amounted to only one-fortieth of the losses in the crash they allegedly caused; that the US telecoms sector lost more than four times as much money in the crash as its European counterpart (although there were no 3G auctions in the United States); and that the mobile industry lost a greater percentage of value in the crash than fixed-line operators (which suffered no auctions) (see Klemperer 2002b: 21).

Klemperer (2002a, c, 2003) explained why he thought the British auction was much more successful in meeting its objectives than most of the other 3G auctions held in Europe (there were almost simultaneous auctions held in

[5] For Klemperer's view on the state of auction theory at the turn of the century, see Klemperer (1999).

[6] For example, Park et al. (2011: 118) argue that the 'results show no evidence to support claims of negative effects of spectrum auctions [on consumers] in the mobile communications market'.

Austria, Germany, Holland, Italy and Switzerland): '[M]any auctions—including some designed with help of leading academic economists—have worked badly' (Klemperer 2002a: 169). His judgement about the other European spectrum licence auctions was that, 'These other auctions were fiascos primarily because they were poorly designed' (ibid.). Auctions are often wide open to collusion. For example, in a German ascending auction in 1999 two bids were made by two large German telecoms companies which meant they had half each. The companies then stopped bidding, which in Klemperer's analysis was collusive 'live and let live' (ibid.: 171) behaviour. The other key issue in practice is to allow entry to occur in the auction process rather than restricting auctions to incumbents. 'In an ascending auction, there is a strong presumption that the firm that values winning the most will be the eventual winner, because even if it is outbid at an early stage, it can eventually top any opposition' (ibid.: 172). So, Klemperer believes that in many contexts an ascending auction favours stronger firms and incumbents against weaker firms and potential entrants. A good auction design needs to address these issues.

4.2 The Financial Crisis and the Product-Mix Auction

In the financial crisis, a new problem faced central banks. Central banks have a role as lender of last resort and from time to time need to provide liquidity to commercial banks and so on. As Bagehot had described it, the central bank made loans to solvent banks in return for collateral assets. In the past, since solvency implied that the value of assets was at least as great as liabilities, this was a straightforward procedure. However, the 2007 banking crisis[7] was different to what had happened in the previous half century: it was a systemic crisis that affected many banks and was in part triggered by the general uncertainty of some asset values and in particular some assets were held to be toxic (possibly worth very little). Banks had stopped lending to each other because of the uncertainty about the value of each other's balance sheets and required the Bank of England to step in and provide liquidity. The new problem faced by the Bank was how to allocate and price the liquidity provided given that some of the collateral on offer would be less than perfect. As Klemperer described it, after the 2007 Northern Rock bank run: 'The Bank of England wanted urgently to supply liquidity to banks and was therefore willing to accept a wider-than-usual range of collateral, but it wanted a correspondingly

[7] The crisis is often thought of as beginning with the collapse of Lehman Brothers in September 2008, but the September 2007 Northern Rock bank run—Britain's first bank run since the 1800s—was one of the early signs of trouble.

higher interest rate against any weaker collateral it took' (Klemperer 2010a: 526).

Paul Klemperer had a solution to the problem. It originated from his belief that auctions could act like markets, and that if you knew what the efficient or desired market outcome looked like, then an auction could be devised to yield the desired market outcome. In this case, the market Klemperer had in mind was one of competitive markets simultaneously clearing for different qualities of asset. He dubbed the auction the *Product-Mix auction*, the theory of which was written up in a 2008 Nuffield College Working Paper (see Klemperer 2008) and was eventually published in a slightly revised form as "The Product-Mix Auction: A New Auction Design for Differentiated Goods" (Klemperer 2010a). Banks needed an auction design that was quick to execute and not like the long drawn out 3G licence auction of 2000.

Let us assume that the collateral has two standards according to credit rating criteria: strong and weak. Bidders make sets of bids, with each bid specifying a quantity of money to be borrowed from the central bank and two prices, one price (the interest rate the bidder will pay) for each type of collateral the bidder might use. (If the bidder has only one type of collateral available it bids zero on the other type.) These bids make a demand curve for the liquidity supplied by the central bank. There are several banks bidding for liquidity from the central bank, which provides an element of competition. If there were only one bank, it could offer the lowest possible interest rate on just the weakest (worst) collateral. With more than one bank, this unattractive bid will be outbid, even if the other banks are bidding for the other collateral, because the auction decides the prices and quantities, given the bids, in both the strong and weak collateral markets at the same time.

The exact way the central bank decides to do this will depend on its objectives. It may have a fixed supply, or be willing to vary the quantity supplied with the interest rate. Either way, the auction can determine prices for each collateral, and how the supply is allocated across the two markets. The central bank can express its preferences in terms of its supply function: if it is unwilling to accept much weak collateral it can require a premium over the strong collateral that is increasing in the amount of weak collateral accepted.

In the auction, there is only one price for each type of collateral (uniform pricing), as in a competitive market. The central bank chooses a minimum cut off price for each collateral and accepts at most one offer from each bid, with all offers at or above the cut-off paying the cut-off price. Again, this mimics the competitive market where all demand for any good is met at the same price and all those with positive demands above this price get what they ask for (as in a standard competitive market, this is the source of consumer, i.e.

bidder, surplus). If the prices offered for the two collaterals in a bid are both above the cut-off price, the collateral that maximises the bidder's surplus is chosen. Each bidder can make multiple bids.

The product-mix auction proved to be a hit with the Bank or England: Governor Mervyn King said that the auction was 'a marvellous application of theoretical economics to a practical problem of vital importance to financial markets' (King quoted in R.D. 2012). In order to understand the importance of Klemperer's product mix auction one has to consider what the central bank would have done without it. The US Treasury had previously simply fixed either the price (interest rate) or quantity of different types of asset. In this case, it is easy to make a poor choice of price or quantity, since the auctioneer cannot condition on the information that is generated by the bids in Klemperer's design. Klemperer argues that it is best to have a single auction for all products (types of collateral) as it enables the central bank to use all the information to decide how much of each product to allocate. It also means bidders automatically use the collateral that is best for them given the auction prices, whereas they would have to guess which auction was best for them to bid in if the products were sold in separate auctions. The product-mix auction also reduces the market power of bidders as there is competition between buyers across the different products.

The Bank of England went on to develop the product-mix approach: in 2014, it no longer predetermined the total quantity and introduced more than two types of asset. Iceland also planned, and programmed, a version of the auction in 2015, although the plan to use it was dropped in the 2016 political crisis (see Klemperer 2018). Part of the reason for the success of the product-mix auction was that it can be explained in terms of a simple supply and demand figure (for the two asset-type case at least), which was easily understood by policy makers in the central banks. This was made possible by Klemperer having developed the idea that auctions are a form of market which itself is often easier to understand than what can often be complicated auction theory. This talent for making complex ideas and models simple harks back to his experience in designing allocation mechanisms for the NHS in the late 1970s. Complex models are unlikely to be accepted by policy makers unless they can be explained simply. This is a talent few academic economists possess.

In addition, Klemperer developed simple software which could be used to implement his ideas: *Product-Mix Auction Software*, which is free to use.[8] It includes options for maximising efficiency (the aggregate of the auctioneer's and bidders' profits) or maximising the auctioneer's profits. Also, the software

[8] The software can be downloaded at: http://pma.nuff.ox.ac.uk/.

includes the possibility of discriminatory (pay-as-bid) pricing replacing uniform pricing. In the *Version for Budget-Constrained Bidders*, Klemperer shares the design he developed for the Icelandic government. This version can be applied to situations where a country's creditors exchange their claims (nominal amounts of debt) for a choice among new debt instruments, or an acquired firm's shareholders exchange their holdings (numbers of shares) for a choice of cash or new shares. The software is developed with another of his students, Elizabeth Baldwin.[9]

Klemperer has also worked on auctions in other aspects of public policy. In 2002, he advised the UK government on the world's first auction for greenhouse gas emissions reductions, working with Nobel prize-winner Eric Maskin. He also participated in the meeting that drafted the Potsdam Memorandum to the 2007 UN Climate Change Conference in Bali (see Klemperer 2007, 2010b). Klemperer has also been on the Environmental Economics Academic Panel to the UK's Department of the Environment (Defra).

5 Conclusion

Paul Klemperer continues to innovate with ideas relating to new hybrid capital for banks in order to increase financial stability (see Bulow and Klemperer 2015); a new approach to modelling preferences and equilibrium based on geometry (see Baldwin and Klemperer 2019); the effect of price controls on rent-seeking and consumer welfare (see Bulow and Klemperer 2012); and continues to seek improvements in auctions (see Erdil and Klemperer 2010). However, it is possible to look back over his career from the perspective of 2019. One often finds when one looks at successful people and their lives that things just seem to effortlessly come together, with different parts reinforcing each other. This may be something of an ex-post rationalisation of what are unconnected random events. However, the temptation is very strong when one considers how the elements of Klemperer's research and auction design fit together almost perfectly.

His early experience in the world of consultancy and working for firms like IBM, Monsanto and Arthur Andersen gave him experience of real-world problems and the need to explain and apply complex ideas in a simple way. Whilst he started as a mathematician at Cambridge, he switched to

[9] In addition to being the main (usually, only) supervisor of around 15 doctoral students who have gone on to Professorships, Klemperer supervised the Master's theses that were the first research of many other students who went on to distinguished careers, such as Jon Levin, Eric Budish, and Shengwu Li (Professors at Stanford, Chicago, and Harvard, respectively, at the time of writing).

engineering because he wanted to apply mathematical ideas. However, driven by intellectual curiosity, he ended up at Stanford from 1980 to 1984, moving from MBA to PhD. Stanford was buzzing with ideas at that time and inspired much of Klemperer's research for the following decade and beyond; from strategic complements and substitutes to work on consistent conjectures and switching costs, Klemperer developed new ideas and approaches to problems both with co-authors and as sole author. If one met Paul during this period, as I did, one would have described him as an IO economist with a theoretical bent. He developed the understanding of market power over time, oligopolistic interaction and entry. His papers almost always have simple mathematical examples, diagrams which explain in a clear way what are often very abstract models and reasoning.

The next stage of his career was dominated by auction theory. There were of course many very smart theorists researching in this field. Klemperer soon developed his own way of understanding auctions as markets. In his view, most auction theorists looked at the details of special cases that assumed away the issues found in real-life auctions. Whilst there are techniques and insights that are central to auction theory, such as revenue equivalence, you need to go further to understand real auctions, considering the factors found in real markets such as collusion, entry and asymmetric equilibria. This is what Klemperer proceeded to do. He was involved in two large and important auctions: as a team member in the 2000 3G spectrum auction in the United Kingdom and later as the sole designer of the product-mix auction for the Bank of England in the wake of the financial crisis. This built upon his previous work in industrial economics and oligopoly theory. The importance of being able to explain solutions in a simple way was an essential part of his success in persuading central bankers and policy makers to adopt his advice. Part of his ability to do this was his geometric intuition which enabled him to depict simple cases in diagrams.

Indeed, Klemperer has become something of an apostle of auction theory. In his opinion, all economists should know some auction theory. Since one can think of an auction as a market, understanding auctions can help us understand markets and vice versa. Auctions can be set up to obtain efficient or desirable outcomes where markets fail or are absent. However, the design of auctions needs a sound grasp of how markets work. Klemperer has proven himself not only an apostle of the theory but also a wizard of auction design.

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