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The Role of Auctions in Allocating Public Resources

Staff Research Paper

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Preface

Auctions offer a means of allocating public resources. Effective use of auctions by governments depends on understanding auction design issues and their implications for pursuing policy goals.

Auction theory and practice is a burgeoning field of economic research; however, it is not easily accessible. Techniques for analysing strategic behaviour, such as bidding decisions, differ remarkably from those techniques used in traditional economic theory. Much of the literature is presented in a technical way. As a result, many insights remain obscure to outsiders.

This paper is intended as a primer of auction theory, thereby filling the knowledge gap between researchers in the field and officials who might consider using auctions to allocate public resources. It complements other studies of market creation that look at issues in establishing tradeable property rights. Those issues are explored in the Commission's recent publications, such as *Radiocommunications* and *Creating Markets for Ecosystem Services*. Well-defined property rights and well-designed market mechanisms (including auctions) are both essential for implementing a market based approach to resource allocation.

This paper was written by Chris Chan, Patrick Laplagne and David Appels. The views expressed therein are those of the authors and do not necessarily reflect those of the Commission.

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Key points

- Governments in Australia and elsewhere increasingly recognise the potential of auctions as a policy tool for allocating public resources.
- Well-designed auctions can promote efficient allocation of resources without requiring governments to have prior knowledge of resource values or costs. Compared with administrative allocations, auctions are more transparent and less dependent on officials' subjective judgment, and can yield greater revenues or cost savings for governments.
- Success of government auctions depends on having a thorough understanding of bidding behaviour and paying close attention to auction design. Simple auction forms can cope with a simple environment but may not apply generally.
- Auction theory provides a framework for developing practical design guidelines. Individuals competing for public resources often have the incentive and ability to misrepresent resource values or costs. Auction design is about devising bidding rules to address such incentive problems and their implications for revenue and allocative efficiency.
- Public funds for conservation activities can be allocated through an auction in which landholders compete on compensation, land areas conserved and site-specific conservation benefits. In this application, auction design involves the following issues:
  - how to realise synergies from conserving adjacent lands that belong to different landholders;
  - how to minimise disbursements; and
  - how to use information on conservation benefits in selecting bids.
- In auctioning rights to use radio-spectrum, bidders should be allowed to combine spectrum lots in the most efficient way. Synergies exist in the use of spectrum in Australia. This finding strengthens the case for package bidding in spectrum auctions.

Overview

Auctions have become an increasingly popular tool for allocating public resources. Spectrum licences, conservation funds, pollutant emission permits, power supply contracts and water rights have now been allocated at auction. Through the novel use of auctions, market forces reach into areas in which resource allocations used to be decided by administrative fiat.

Auctions as a market based policy instrument

The main advantage of an auction is its tendency to attain allocative efficiency without requiring governments to have accurate prior knowledge of resource values or costs. This outcome is achievable by promoting competition among bidders; those who place a relatively high value on the good on sale will generally be willing to bid highest for it. Auctions can therefore assign resources to those able to make the best use of them. Compared with administrative methods of allocating public resources, auctions are more transparent and less dependent on officials' subjective judgment. Last but not least, bidding competition can yield revenues or cost savings for governments.

Despite their potential merits, auctions can perform poorly if they are not carefully designed and conducted. Specific market conditions and design issues can distort auction outcomes and affect the revenue raising potential of an efficient allocation.

Improved auction design enhances government budgets and allocative efficiency. To understand auction design issues, a formal analysis is necessary because anecdotal evidence on auction performance is often spurious and intuition unreliable, especially for complex resource allocation problems.

Scope of the paper

This paper considers the effectiveness and limitations of auctions in allocating public resources. It draws on auction theory to examine the key elements of an auction — including the auction form, the auction environment and the bidding behaviour — and their implications for allocative efficiency and revenue. The analysis relates auction outcomes to bidders' behavioural characteristics and to the lack or imbalance of information available to governments and bidders. Whenever possible, the paper highlights the implications of auction theory for design practices in government auctions. It includes two case studies that illustrate specific design issues in auctions of conservation contracts and spectrum auctions.

Two types of readers may find the paper useful. For those making public resource decisions or giving policy advice, it is a primer on the practical potential of auctions. For those engaged in designing, conducting, evaluating or participating in government auctions, it provides a compendium of recent auction theory that should assist them in their task.

Auction design matters

Effective use of auctions as a policy tool rests on the notion that market mechanisms can be 'designed' to achieve particular outcomes. Game theory clarifies how markets coordinate transactions among a small number of buyers or sellers under incomplete information. As buyers and sellers adopt trading strategies based on self interest, markets determine prices and allocate resources to the most highly valued uses. In this framework, the functioning of markets is not based on the 'invisible hand' concept, which assumes the presence of many sellers and many buyers as well as free and equal access to information.

Auctioning public resources does not fit the ideal model of perfect competition for two reasons. First, the rationales for entrusting resources to the public sector — that is, the existence of a natural monopoly, common property and market externalities — can preclude the alignment of private and public interests. Second, many government auctions are 'thin' markets, in which bidders are too few to ensure competitive bidding.

These hurdles to 'perfect' competition do not preclude efficient allocation at auction; however, they do call for a deliberate choice of auction form to avoid adverse outcomes. For government auctions, an arbitrarily chosen auction form may not work well in terms of meeting policy goals. Success of auction markets depends on understanding bidding behaviour and paying close attention to design details.

Understanding the auction environment

Understanding the auction environment is a prerequisite for identifying and addressing relevant design issues. The auction environment reflects the resource allocation problem at hand, comprising the good(s) being auctioned as well as the potential bidders and their valuation bases, preferences, behavioural characteristics and access to information.

Different auction environments give rise to different design problems. Simple auction forms can cope with a simple environment, but may not be applicable more generally. Conversely, complex resource allocation problems require comprehensive solutions and therefore a strong command of design intricacies.

A simple auction environment

A simple auction environment refers to one involving the allocation of a single good to bidders with predetermined valuations. It establishes the benchmark case in which simple auction forms can deliver satisfactory outcomes.

For selling a single good, four basic auction forms are used: (i) the English auction (also known as the oral, outcry, or ascending-bid auction); (ii) the Dutch (or descending-bid) auction; (iii) the first-price sealed-bid auction; and (iv) the second-price sealed-bid (Vickrey) auction.

Revenue equivalence theorem

The 'revenue equivalence theorem' predicts, *for a simple environment*, that the four basic auction forms yield on average the same price. Put differently, there is no advantage of one basic auction form over another in terms of expected revenue.

The prediction of similar outcomes for different auction forms may seem counter-intuitive; for example, setting the price equal to the highest bid in a first-price auction would seemingly lead to a higher price than setting the price equal to the second highest bid in a second-price (Vickrey) auction. This intuitive logic overlooks the fact that different pricing rules will induce bidders to bid differently; for example, bidders tend to bid lower under the first-price rule than under the second-price rule, although the different pricing rules may lead to the same price on average.

Price determination and efficient allocation

The economic gain from auction trading is the excess of the bidders' highest valuation over the seller's cost of supplying the good. The auction price falls between the highest valuation and the supply cost, enabling the seller and the buyer to share the gain from trade. The price rises with an increased number of bidders; it approximates the winner's valuation if the number of bidders is sufficiently large.

Generally, an auction elicits bids that rank the bidders in order of their valuations, so the good goes to the highest-valuation bidder. Bid competition therefore promotes efficient allocation, even though the price may not necessarily equal the good's opportunity cost (measured by the winner's valuation), unless there are sufficiently many bidders. Bidders typically anticipate being able to win the good without paying their own valuation in full. Without bidder collusion and bid manipulation, consistent ranking of bids and valuations would lead to efficient allocation.

Complications in auction design

If bidders' behavioural characteristics differ from those assumed in the benchmark case, incentive problems need to be addressed by choosing suitable design features. Likewise, selling related goods gives rise to design complications.

The winner's curse

Bidders may perceive one another to have a common value for the traded good but be individually unsure about that value. They try to guess what competitors will bid and adjust their own bids accordingly. In this situation, naive bidders face what is known as the winner's curse: by coming up with a higher value estimate than those guessed by others, the winner is whoever most overestimates the true value. Winning therefore implies overbidding (that is, the winning bid exceeds the good's true value). Rational bidders, however, are mindful of overbidding and discount their value estimates to avoid the 'curse'. This cautious bidding behaviour reduces the revenue potential of an auction.

To counter the winner's curse problem, the seller should reveal any knowledge of the good's value and use an open, ascending-bid auction format. These measures help boost bidders' confidence in their own value estimates, thereby reducing their incentive to discount bids, resulting in higher prices at auction.

Bidders' risk attitudes

Losing an auction may expose bidders to a major business risk, especially in bidding for indispensable inputs or market access rights. Bidders' incentive to avoid this type of risk reduces the likelihood of efficient allocation in first-price and Dutch auctions, but not in English and Vickrey auctions.

Bidder collusion

There can be incentives for bidders to collude, especially in repeated auctions or auctions with multiple rounds of bidding. Auction design should limit the scope for bidders to coordinate bids and to enforce collusive arrangements. A sealed-bid format, a secret reserve price, or an adaptive allocation rule can help curtail collusive bidding.

Bidder participation

Not all potential bidders choose to enter an auction if they have to bear expenses for entry and bidding. By reducing these expenses, the seller can attract bidders and strengthen bidding competition.

A more serious problem affecting the number of bidders may occur if some bidders have a strategic motive for not taking part in an auction or for blocking the entry of others. Bidders seeking to deter entry may hope to gain indirectly from specific outcomes (as opposed to the direct gain from trade). For example, a firm can preserve its monopoly position in a lucrative market if it succeeds in blocking the sale of an input that is vital to potential entrants. To attract entrants, auction design should reduce the importance of such indirect benefits in bidders' valuations. Remedial measures include allowing flexible allocations, giving preferential treatment to low-valuation bidders, and reducing the profit potential from collusive entry strategies.

Selling multiple goods

The value of a good to a bidder may depend on the other goods that the bidder acquires. In selling multiple goods, the major design problem is how to discover the most highly valued resource combinations and allocations. The solution depends on whether the goods are substitutes or complements.

In the case of substitutes, the seller can adopt either a uniform or a discriminatory pricing rule. Under uniform pricing, all winners pay the same price for every item they acquire. Under discriminatory pricing, winners pay their own bids, in which case identical items can sell for different prices. Compared with uniform pricing, discriminatory pricing is less prone to distorting allocative efficiency.

Complementary goods, if acquired and used together, can generate a synergy value. In bidding for complements, bidders typically cannot decide how much a particular good is worth until they know which other goods they will acquire. The main design issue is to minimise bidders' guesswork in valuing complementary goods. Several sophisticated designs have been proposed for a simultaneous sale of multiple goods, giving bidders the flexibility to select their desired items on which to bid.

Auctions of conservation contracts

Conservation management is hampered by a lack of information about the costs and benefits of different conservation activities. To overcome the information gap, an auction can be conducted to select those landholders who will receive government funds for undertaking activities designed to meet conservation goals. In the United States, the Department of Agriculture has been running auctions under the Conservation Reserve Program since 1986. In Victoria, the Department of Natural Resources and Environment launched a pilot auction of conservation contracts, called the BushTender Trial, in 2001.

In this type of auction, bids specify not only contract prices but also land areas conserved and site-specific conservation benefits. Bidding on these multiple criteria leads to the following design issues that affect the potential for an auction to attain cost-effective conservation outcomes.

- Conservation activities can be more effective if nearby land areas are conserved at the same time. One design refinement is to allow adjacent landholders to submit a joint bid, so that lands with a complementary conservation value can be selected together.
- Landholders can bid for conserving land of different sizes; moreover, numerous landholders can win contracts in the same auction. These allocation patterns lead to incentive problems similar to those found in a multi-item auction, namely the impact of bidders' guesswork in determining bids on the auction outcome. The choice of payment rule can affect the total amount of contract payments subject to efficient allocation.
- A government agency may know better than landholders the ecological significance of their lands and the match between conservation goals and land characteristics. The agency's decision to conceal or disclose such information can affect bidding behaviour and auction outcomes and therefore has to be carefully considered.

Synergies in spectrum auctions

Synergies in radio-spectrum use arise for several reasons, including benefits for roaming communications, increases in spectrum productivity, and cost savings in operations and infrastructure investment. Bidders seek to obtain their preferred spectrum lots in aggregate (a lot is a single item of spectrum offered for sale).

Synergy values are peculiar to individual bidders. One of the key design issues, therefore, is to provide flexibility that enables individual bidders to combine lots in the most efficient way.

Many countries, including Australia, have adopted the simultaneous ascending auction design for selling spectrum. This design is akin to running several English auctions in parallel, in which bidders can choose to enter particular auctions and switch between auctions at any time. Compared with a sequence of auctions that sell numerous lots one after another, a simultaneous sale permits more flexible spectrum aggregation. However, this form of bidding cannot eliminate the risk that a bidder fails to win some of the complementary lots that yield the highest synergy values, leading to an inefficient assignment of spectrum.

This drawback of simultaneous ascending auctions has led to proposals for package bidding. In a package auction, a bidder can submit an 'all or nothing' bid for a preferred combination of lots. Laboratory experiments show, for selling items with significant synergies, that package auctions attain higher allocative efficiency than simultaneous ascending auctions. The empirical question about the existence and extent of spectrum synergies, therefore, has important implications for the choice between the alternative auction designs and for the efficient assignment of spectrum in Australia.

Evidence from some recent Australian spectrum auctions confirms the existence of synergies, mainly in geographically contiguous spectrum lots. Econometric estimation of spectrum values suggests a price premium of between 18 per cent and 25 per cent for a set of complementary lots. This size of spectrum synergies is significant for spectrum users as well as the community at large. As a result, the study findings strengthen the case for allowing package bidding in Australian spectrum auctions.

1 Introduction

In allocating public resources for competing uses, governments have traditionally relied on administrative decisions. This reliance is being replaced by an increasing use of market instruments, particularly auctions. Governments' use of auctions is not limited to selling assets: it includes assigning spectrum, funding conservation activities, allocating pollutant emission permits, operating electricity markets, trading water rights, and many other purposes. These auctions may instil market competition to guide the efficient allocation of public resources. They help governments overcome the information gap in determining resource values and production costs.

1.1 Auction design matters

Economists have long advocated exploiting market forces to manage public resources. Their pro-market arguments are mostly theoretical; that is, market competition that occurs within a sound legal framework is more likely to attain allocative efficiency compared with administrative fiat. Accordingly, in areas in which no market has previously existed, auctions are a way of mimicking market forces to solve resource allocation problems. However, it is evident that government auctions in which a faulty design is used can perform poorly. If auctions are to become an effective policy instrument, governments have to resolve the practical problem of how to properly design and implement them.

Herzel (1951) and Coase (1959), for example, proposed using auctions to allocate spectrum access rights but gave little thought to how such auctions could be conducted. Despite their long-standing advice, successful spectrum auctions took place only many years later, after the US spectrum regulator engaged a team of economists in the early 1990s to devise a suitable auction form. Since then, more new designs have been developed, enabling governments to use auctions as a policy tool in areas previously thought unsuitable, including the trading of gas storage capacity, electrical power and carbon dioxide emission rights.

Game theory plays a central role in auction design. John Nash, John Harsanyi and Reinhard Selten extended game theory as a means of understanding human strategic behaviour. (For this contribution, they won the 1994 Nobel Prize in economics.)

Game theory is concerned with strategic decision-making in situations similar to playing adversarial games such as chess, poker and ‘paper, rock, scissors’. It analyses the complex web of rivalry and cooperation among a small number of entities that have a mix of conflicting and common interests, such as individuals, governments and corporations.

In a contemporary context, game theory enables the way in which markets work to be clarified. Self interest motivates buyers and sellers alike to adopt compatible trading strategies. Markets coordinate buyers’ and sellers’ strategic decisions to determine prices and resource allocations. Most importantly, markets can coordinate economic activity without relying on the ‘invisible hand’ that, by assumption, operates only in ‘dense’ markets with many sellers and many buyers. This finding has initiated a sea change in the approach to analysing markets: many markets, including auctions, can be viewed as trading mechanisms and analysed from a design perspective — that is, how these markets can be ‘created’ in such a way that they achieve specific outcomes.

An outcome commonly sought in the public sector is allocative efficiency — that is, the allocation of resources to their most valuable uses. Like other market mechanisms, auctions will deliver this type of outcome under the assumption of perfect competition; strong market competition and consistency of private and public interests can lead to auction prices revealing the values of resources in their best uses. Under those conditions, virtually any auction form can achieve efficient allocation, so the task of auction design is greatly simplified; in a sense, perfect competition is sufficient, yet not necessary, for the possibility of efficient allocation at auction.

Government auctions do not generally fit the ideal model of market competition for two reasons. First, the rationales for entrusting particular resources to the public sector — that is, the existence of a natural monopoly, common property and market externalities — can preclude the alignment of private and public interests. Second, many government auctions are ‘thin’ markets, in which bidders are too few to ensure competitive bidding.

These hurdles to prefect competition do not preclude efficient resource allocation at auction; however, they do call for a deliberate choice of auction form to avoid efficiency distortions. For government auctions, no one auction form will work consistently well in terms of meeting policy goals. Success in exploiting market forces requires that governments understand bidding behaviour and pay close attention to auction design details.

1.2 Scope of the paper

This paper provides an economic framework with which to consider the effectiveness and limitations of auction markets in allocating public resources. It links auction outcomes to bidders' behavioural characteristics and to the lack or imbalance of information available to governments and bidders. The analysis covers the key elements of an auction, including the auction form, the auction environment, the bidding behaviour and the implications for allocative efficiency and revenue.

The application of auctions by governments requires a strong command of design intricacies. Good design has direct relevance for achieving policy goals. This paper devotes special attention to auction design details. It uses selected government auctions to illustrate the complexity and repercussions of auction design in a real-life setting.

This paper draws on auction theory, which differs from traditional economic theory in many respects. Conventional market analysis assumes the existence of well-defined supply and demand relationships and abstracts from the influence of trading rules on economic behaviour. In contrast, auction theory is based on the logic of strategic decisions under incomplete information. The literature on auction theory uses probability models to analyse bidding behaviour in the context of specific trading rules. The lack of a non-technical presentation of auction theory, however, can obstruct understanding auction design issues.

This paper presents a descriptive treatment of auction theory to help fill the knowledge gap between a general audience and researchers in the field. Two types of readers may find the paper useful. For those making public resource decisions or giving policy advice, it is a primer on the practical potential of auctions. For those engaged in designing, conducting or evaluating government auctions, it provides a compendium of recent auction theory that should assist them in their task.

1.3 How to read this paper

Auction design issues are complex — the paper reflects this. Readers may refer to different parts of the paper, depending on their needs for general knowledge and specific recommendations. Chapters 2 and 3, for example, are useful for understanding basic features of auction markets. Chapter 4 helps readers appreciate auction design problems in specific types of environment. The other chapters and the appendices raise important design issues confronting governments in making use of multi-item auctions. In these auctions, the value of the resources on offer depends on how these resources are used in combination and how resource users coordinate their production tasks. The problem of allocating complementary resources calls for the design of sophisticated auction forms to reveal the most highly valued resource combinations and allocations.

The paper proceeds as follows:

- Chapter 2 defines auctions as a market process and compares auctions with other resource allocation methods used by governments.
- Chapter 3 introduces common auction forms and discusses using them to sell a single item in some stylised environment. This analysis establishes a benchmark case in which simple auction forms can be effective for attaining allocative efficiency and revealing resource values.
- Chapter 4 discusses auction environments that deviate from the benchmark case in respect of bidders' behavioural characteristics. This analysis illustrates the incentive problems that lead to price manipulation by bidders and allocative inefficiencies in auction markets. These environments call for careful design of auctions to avoid unintended or adverse outcomes.
- Chapter 5 analyses auctions that allocate public funds for land conservation purposes. Design complications arise in these auctions because bid selection involves comparing not only contract prices but also land areas conserved and land attributes.
- Chapter 6 investigates one aspect of spectrum auctions in Australia: whether synergy values exist between different parts of the radiofrequency spectrum. The answer to this question has important implications for the choice of an appropriate auction form for selling spectrum licences (discussed in appendix B).
- Appendix A examines how the identities of winners and the amounts of resources allocated to individual winners can affect the competitive structure of downstream markets.
- Appendix B compares different auction forms for selling spectrum licences, analysing design details with both theoretical and empirical evidence.

2 What is an auction?

An auction is a market process in which an explicit comparison of bids determines the identities of buyers and sellers and the terms of trade, including price (Milgrom 1996). Bids specify payment and, in some cases, quality or quantity of the traded goods or services. These dimensions of a bid need to be measurable, so that they can be explicitly evaluated together.

An auction typically involves a seller dealing with numerous potential buyers (a selling auction) or a buyer dealing with numerous potential sellers (a procurement auction). The choice of either setting does not affect the analysis of bidding behaviour and auction outcomes. For the most part, this paper adopts the former setting. In this context, the seller determines the auction rules and the amount of goods to sell. Potential buyers are the bidders, of whom the highest wins the auction. In a procurement auction (an example of which is discussed in chapter 5), suppliers bid to be awarded the contract to provide goods or services to the buyer; in this scenario, the lowest bidder is the winner.

2.1 Auctions as a market mechanism

Traditional market analysis focuses on the determinants of supply and demand, and their effects on prices and resource allocations. By assumption, buyers or sellers are price-takers — that is, they take prices as given and react to price changes by adjusting their demand or supply quantities. This way of analysis assumes that market participants have free access to complete information and that trading rules have no impact on market outcomes. These assumptions leave open the question of how markets attain equilibrium prices in reality.

In contrast, an auction operates with specific trading rules that shape the bidding process and thereby influence prices and allocations. Bid prices reflect buyers' willingness to pay for the good being sold, subject to competitors' reactions. Potential buyers compete with one another by bidding high enough to win an auction. Ask prices are based on the seller's cost of supplying the good. Bid prices and ask prices differ as a result of dispersed, incomplete information about seller costs and buyer preferences or valuations. Bidding competition discovers the common bid and ask prices that equate supply and demand.

Auction design is about devising trading rules to translate bids into prices and specify allocations. Auction design needs to account for bidding behaviour. Bidders adapt to auction forms by making strategic decisions regarding their bids, while attempting to anticipate their competitors' reactions. The use of different auction forms for a particular sale can lead to different trading outcomes.

The study of auctions informs market analysis in the following ways.

- The auction mechanism explains market clearance as price convergence in competitive bidding (Milgrom 2000; Wilson 1976). An open outcry auction, for example, involves successively raising bids until one bidder remains. This bidding process resembles the *tâtonnement* process that is postulated in economic theory to explain price determination in competitive markets. Given sufficient bidders, the winning bid reveals the market value of the good being auctioned (box 2.1).
- Price setting by sellers is a normal way of clearing markets, not necessarily a sign of insufficient competition (Spulber 1996). Sellers with a market advantage can select trading rules to influence prices and allocations.
- Market outcomes depend on the trading rules adopted, not just on the determinants of supply and demand. A simplistic analysis of supply and demand can be spurious. Where the effects of trading mechanism design and strategic pricing behaviour are ignored, auction outcomes deviate from predicted prices and allocations.

Box 2.1 **Market price determination**

The *tâtonnement* process assumes that each market has a fictitious 'market manager' who quotes a price for the good being traded. Traders express the amount of good that they wish to buy or sell at the price. The manager then increases or decreases the price depending on whether there is an excess demand or supply. Each time the manager quotes a new price, traders revise the amount of good that they wish to buy or sell. This process continues until a price is quoted such that total supply matches total demand; until then, no actual trading takes place. Under certain assumptions about the manager's and traders' behaviour, this process brings about a stable equilibrium of supply and demand and thereby determines the market clearing price.

An open outcry auction differs from the hypothetical process of price adjustment in several ways. First, every bid is a real commitment to trading. Second, the auction price adjusts in only one direction. Third, bidders themselves determine bids. These differences underpin some fundamental limitations of the auction mechanism in discovering prices that are consistent with efficient resource allocations.

Sources: Milgrom (2000); Takayama (1974).

2.2 Auctions as a policy tool

Governments use auctions as a market based policy tool to solve resource allocation problems and raise revenue without knowing the market values or user costs of the resources at issue. When no market for a resource yet exists, the auction price provides a guide to its value.

Advantages over other allocation methods

Empirical evidence suggests that well-designed auctions are generally superior to other allocation methods used by governments, including comparative bidding, lottery, 'first-come, first-served' and negotiation (Cramton 2001; McMillan 1995; Saleth, Braden and Eheart 1991; Schmidt and Schnitzer 1997).

Comparative bidding

Comparative bidding (also called comparative hearings) requires bidders to propose how they intend to use the resources on offer. This method is sometimes referred to as a 'beauty contest' because governments apply a set of criteria to select the most attractive proposals. The key difference between an auction and a comparative bidding process is in the degree of reliance on explicit price comparisons, rather than the scope for defining resource rights or specifying contract terms. An auction can require bidders to fulfil certain technical or service requirements, while comparative bidding can include price based criteria. Price competition, however, is pivotal in an auction but not in comparative bidding. For resource allocations that take account of multiple criteria, IC (1996) provides guidelines for developing and managing government contracts. Hybrid forms combining these two allocation methods can be used (Pratt and Valletti 2001).

Comparative bidding is affected by several problems. First, allocations can be delayed because the government seller needs time to evaluate proposals, run public hearings and settle appeals. Also, bidders need time to prepare detailed proposals. The reliance on administrative decisions means that allocations respond to changed market conditions with a time lag and imprecision. Second, bidders may engage in unproductive rent-seeking activities aimed at influencing administrative decisions. Third, the bid selection process lacks transparency because it is not always obvious why one proposal wins over another. Subjective judgment replaces objective evaluation when selection criteria are vague and when arbitrary weights are applied to different criteria.

Lotteries and the 'first-come, first-served' rule

Lotteries randomly allocate resources among those who apply. This method is quick but attracts frivolous applicants and speculators. Chance decides whether resources are assigned to competent users. Resales of lottery prizes by winners can transfer resources to productive users, yet at the costs of delayed allocations and revenue losses to the government seller. Unjust enrichment of lottery winners is also a concern for the public.

The 'first-come, first-served' rule is easy to execute, producing quick outcomes. This method, however, has the same disadvantages of random allocation that occur in a lottery.

Negotiation

To allocate resources by negotiation, the government seller shortlists a few potential buyers and bargains with them one by one over the terms of trade. As Bulow and Klemperer (1986) and Milgrom (1989) point out, this method results in revenue and efficiency losses. Allocation choices are restricted to a single buyer at any stage of the negotiation, preventing the seller from comparing simultaneous bids of competing buyers. The seller is in a weak bargaining position, being under pressure to sell the resources at any price while lacking information on buyers' valuations of these resources. Further, incomplete information on costs and valuations poses a barrier to the bargaining on complicated contract terms.

Comparative advantages of an auction

The primary advantage of an auction is its tendency to allocate resources to those who are most capable of using them. Generally, only bidders with high valuations for the resources on offer are willing to bid high and thus likely to acquire the resources. Bidders are best able to assess resource values on the basis of available private and public information, taking into account their own productive capabilities and business risks.

Compared with alternative allocation methods, an auction is less subjective because bidders rather than bureaucracies determine valuations and allocations; an auction is more transparent because resource allocation is based on an explicit rule for comparing bids. The auction mechanism need not compromise particular policy goals, because the government seller can specify auction terms and conditions to steer the allocation and use of resources. Auctions can incorporate complex allocation constraints and objectives, provided the government seller is able to express them in precise and explicit terms.

Necessary conditions for attaining allocative efficiency

Auctions attain allocative efficiency under the following conditions.

- Resources are allocated to bidders with the highest valuations.
- Bidders' valuations reflect the social values of resources — that is, their returns when used for production in competitive end markets.

Revealing value information

The first condition requires designing auctions to induce bidders to bid consistently close to their own valuations. With a limited number of bidders, not all auction forms can guarantee efficient outcomes. Well-designed auctions account for the strength of bidding competition, bidders' information advantages in assessing values, bidders' attitudes towards risk and bidders' tendency to collude. Incentive problems hinder a full revelation of value information, especially in 'thin' auction markets where serious bidders are too few to ensure competitive bidding. Governments often find themselves in this position, creating scope for bid manipulation. Unless governments adopt suitable trading rules to counter bidders' strategic moves, the potential efficiency gains from market based allocations cannot be fully realised.

Enhancing market competition

The second condition relates to the basis of bidders' valuations. Bidders' valuations need not always equate with social values. The private value and social value of a good diverge if a buyer's valuation does not include some of the costs or benefits to the broader community.

Market power that results from a lack of competition in end markets can distort the values of resources used as inputs. A natural monopolist, for example, can produce at a lower average cost than that of two or more firms supplying the market; in bidding for a vital input, an incumbent monopoly can therefore outbid entrants seeking to break the monopoly. Efficiency distortions arise in an auction if the winner's identity affects other bidders' valuations, potentially perpetuating a non-competitive market structure.

Like other market processes, auctions are not immune from market failures. The very reasons for entrusting particular resources to the public sector — that is, the existence of a natural monopoly, common property and market externalities — can preclude socially desirable auction outcomes (McMillan 2001). While the auction mechanism can reveal the value information needed to allocate public resources, it cannot replace government intervention in some cases. Governments are still required to, for example, enforce property rights and ensure that auction outcomes do not lessen competition in end markets. Conversely, auction design can influence market structure and promote competition in certain circumstances. There is scope, therefore, for properly designed auctions to replace restrictive regulatory regimes.

That said, this paper does not elaborate on the implications of auction design for market structure (apart from a brief discussion in appendix A). These issues are important from a policy perspective but can be analysed only in terms of specific industries and regulatory arrangements. Unlike the effects on bidding behaviour, design considerations are an issue for market structure in only some auctions.

Instead, the paper focuses on the role of auction design in revealing value information, taking the structure of end markets as given. It discusses design issues aimed at addressing the problems of conduct under incomplete information. In this context, allocative efficiency is defined as the allocation of resources to bidders with the highest valuations.

3 Basic auction forms

This chapter explains the basic concepts in auction theory and provides a simplified analysis of auction markets. Section 3.1 introduces auction theory. Section 3.2 defines a stylised auction environment. Section 3.3 describes the basic auction forms. Section 3.4 compares these auction forms in terms of their performance in the stylised environment. Section 3.5 explains how an auction can establish price and attain efficient allocation on the basis of bids. Section 3.6 discusses the role of a reserve price. Section 3.7 draws lessons from the foregoing analysis.

3.1 Bidding as a strategic decision

Auction theory analyses the conduct and outcomes of competitive bidding — that is:

- how bidders choose their bids, not knowing with certainty how competitors value the good for sale; and
- how the seller can exploit competition among bidders, not knowing precisely how much each bidder is willing to pay for the good.

The seller and bidders may each have some market power in an auction. The seller controls the availability of a good and decides auction rules; bidders have private information on their own valuations of the good. The uneven distribution of value information among the seller and bidders is called information asymmetry.

Bidders make strategic decisions with consequences that depend on not only the decision-makers' own actions but also the actions of others and chance (Milgrom 1989). Bidding strategies specify bids as a function of bidders' own valuations and available information about their competitors. Typically, bidders choose the strategies that maximise their potential profits from an auction under the assumption that competitors also adopt the most profitable strategies. This behaviour leads to the use of two different types of bidding strategy.

- Bidders are said to adopt a *dominant strategy* if this strategy is the best for themselves no matter what others do. For example, a bid that depends only on a bidder's own valuation represents a dominant strategy of this bidder.

- Bidders are said to adopt a *Nash strategy* if they anticipate competitors' bidding strategies and accordingly select their own bids. This type of bid depends on a bidder's own valuation as well as a bidder's expectations on others' strategy choices. Under the assumption of rational expectations, each bidder's strategy is consistent with others' strategies — that is, bidders make no systematic, regular errors in predicting others' strategy choices. The use of these consistent bidding strategies by all bidders constitutes a Nash equilibrium, which represents a set of mutual best responses for individual bidders. At this equilibrium, all bidders correctly anticipate the others' strategy choices, so none could gain from revising their own bids (see Nasar 1998, p. 97–8).

3.2 Auction environments

An auction environment describes a specific group of potential buyers or bidders and their preferences, valuation bases, behavioural characteristics and access to information. It also specifies the good(s) being auctioned, stating the number of good of each type and whether there are any restrictions on how the good(s) can be allocated. Different auction environments give rise to different design problems. Understanding the auction environment is a prerequisite for designing an effective auction form that achieves particular goals such as attaining allocative efficiency and raising sufficient revenue. The following conditions jointly define an important class of auction environments that are commonly used to benchmark design performance.

- The auction sells a single item.
- Each bidder has a valuation of the traded good that is unknown to the seller and other bidders and that is not influenced by others' views. This is the assumption of independent private valuation.
- The seller does not know each bidder's exact valuation of the traded good and perceives that valuation to be drawn randomly from some probability distribution. Likewise, bidders have prior knowledge about the probability distribution of competitors' valuations, not about competitors' exact valuations.
- The probability distribution of valuations is identical for all bidders, reflecting the assumption of symmetric bidders. This assumption allows for bidders having different or similar valuations; however, the comparison of actual valuations remains a matter of conjecture until an auction is completed.
- All potential buyers bid with intent to win and know the number of bidders, therefore ruling out bidder collusion and bidders having the ability to influence market demand in an auction.

Together, these assumptions are used to define a specific class of auction environment, which is referred to as the 'stylised auction environment' in this paper. They simplify an analysis of bidding behaviour and auction outcomes. From the seller's perspective, bidders are homogeneous in the sense that they have the same profile of possible valuations; their exact valuations may differ. This environment trait implies that bidders would all use the same bidding strategy in an auction. From the bidders' perspective, bid decisions are confined to the payoff from winning a single good. They each hold a fixed, private view about how much the good is worth to them and so can readily decide how high they can bid. To win an auction by making the lowest possible payment, bidders use available information on others' bids or valuations to decide how low a winning bid can be. In this environment, bidders have a limited scope for bid manipulation.

The assumption of independent private valuation does not mean bidders' own valuations of the traded good are necessarily accurate. Bidders' valuations may involve some estimation of uncertain market factors, such as those affecting the net worth of an asset. Learning competitors' valuations, however, cannot improve a bidder's own value estimate. In other words, bidders are the best judges of their own value estimates of the good.

The profile of bidders' valuations has two key aspects that affect auction outcomes. The first is bidders' private valuations. The second is bidders' perceived probability of winning the good on offer at different prices. Typically, bidders anticipate being able to win the good without paying their valuation in full. This belief underpins a gap between the price paid and the winner's valuation of the good. For the seller, a trade is profitable only if the good is priced above its supply cost, which sets a lower bound of the price. Consequently, the price falls between the winner's valuation and the seller's cost.

The stylised auction environment may adequately represent auctions of consumer goods for buyers' own use and not for resale. It may also apply to procurement auctions in which bidders use different production technologies and only they know their own contract costs. Nevertheless, many government auctions do not fit well into this simple environment and involve complicated design issues (discussed in chapters 4 to 6).

3.3 Auction forms

New auction forms keep emerging. No matter how complex auctions become, however, there are essentially four basic forms: English, Dutch, first-price sealed-bid and Vickrey.

- *English auctions* have the ascending outcry format. The price is successively raised until one bidder remains. The good is sold to the last remaining bidder at a price just above that which sees the second last bidder retire.
- *Dutch auctions* are the reverse of English auctions, with bids announced in a descending order. A bidder wins by being the first to accept an announced bid and pays that price. This design is so named because it has traditionally been used in the Netherlands' flower markets.
- *First-price sealed-bid auctions* require bidders to submit single confidential bids to the seller. The bidder with the highest bid wins and pays that bid.
- *Vickrey auctions* (named after economist William Vickrey) have a second-price sealed-bid format. The bidder making the highest bid wins and pays the next highest bid.

3.4 Revenue equivalence theorem

The four basic auction forms generate *on average* the same revenue (price) in the stylised environment — this celebrated result is known as the revenue equivalence theorem. It may seem counter-intuitive at first glance; for example, setting the price equal to the highest bid in a first-price sealed-bid auction might be expected to generate greater revenue for the seller than setting the price equal to the second highest bid in a Vickrey auction. This conjecture overlooks the fact that bidders each make different bids under different auction forms; in particular, bidders bid higher in a Vickrey (second-price) auction than in a first-price auction.[1]

Bidding strategies under different auction forms

To explain the result of equivalent outcomes, consider how bidders decide their bids under the different auction forms.

English auctions

In an English auction, bidders bid so long as the current bid price remains below their own valuations. As the price rises, bidders successively withdraw from bidding

[1] The revenue equivalence theorem is sensitive to its underlying assumptions. A proper test of it requires empirically validating the relevant assumptions and comparing auction revenues in an environment that satisfies those assumptions. Many revenue comparison results, however, are obtained without strictly meeting those assumptions and therefore provide no clear evidence for rejecting or confirming the theorem (Laffont 1997).

in order of their relative valuations. The second last bidder drops out of the bidding as soon as the price rises above this bidder's valuation. The highest-valuation bidder remains in contention, so wins and pays a price not exceeding the second last bidder's valuation by a minimum bid increment.

Vickrey auctions

In a Vickrey (second-price) auction, the price is set equal to a loser's bid and so beyond the winner's control. Bidders' most profitable strategy is to bid their own valuations. This bidding behaviour is called demand revelation because bids reveal bidders' valuations (Vickrey 1961).

Compared with the dominant strategy of bidding an own valuation, any other strategy would reduce a bidder's potential gain from an auction. By bidding below valuation, for example, a bidder increases the risk of losing because a unilateral decision to lower the bid may result in this bidder's bid being topped by someone else's. Were a bidder able to win with a bid lower than an own valuation, this bidder would not benefit from bidding below valuation. This is because, given the competitors' bids, a decrease in the winning bid cannot reduce the winner's payment.

Conversely, a bidder might hope to win by bidding above an own valuation in order to overtake a competitor. This strategy may succeed but is unprofitable because this bidder may need to pay more than an own valuation for the good acquired.

Consequently, the highest-valuation bidder would win by making the highest bid and pay a price equal to the second highest bid (valuation). A Vickrey auction thereby duplicates the outcome of an English auction.

First-price and Dutch auctions

In a first-price sealed-bid auction or Dutch auction, a bid determines both a bidder's chance of winning and the required payment if this bidder wins. Bidders bid just high enough to win. Unlike in an English or Vickrey auction, however, their bids will not follow a dominant strategy. Instead, the auction outcome can be analysed as a Nash equilibrium. This analysis assumes that bidders bid in a way that is consistent with their expectations. Each bidder determines a bid as if an own valuation is the highest among all of the bidders' valuations. With this expectation, a bidder is rational to bid exactly an own estimate of the next highest valuation of some competitor; bidding either above or below that value estimate violates the Nash equilibrium.

- A bidder might hope to win 'at all cost', so bidding above an own estimated second highest valuation of some competitor. This strategy may succeed but the winning bid would represent an overpayment for the good acquired. In this scenario, the winning bidder correctly anticipates the relative valuations among bidders but fails to make the most profitable bid; a decrease in the winning bid should have led to a better payoff for the winner.
- A bidder might hope to win at a low cost, so bidding below an own estimated second highest valuation of some competitor. This strategy provides scope for that competitor to bid higher than this bidder's bid and win the auction at a profitable price. In this scenario, the losing bidder correctly anticipates the relative valuations among bidders but fails to make the most profitable bid; an increase in the bid should have led to a better payoff for this bidder.

Both scenarios contradict the Nash equilibrium because the bidders at issue can improve their bids while correctly anticipating competitors' relative valuations. Consequently, in a first-price auction or Dutch auction, each bidder's preferred strategy is to estimate the next highest valuation among competitors (as if this bidder's own valuation is the highest) and bid that value estimate. To implement this strategy, bidders need to guess others' valuations. Assuming that bidders make no systematic error in this guesswork, the winner is the one with the highest valuation. Furthermore, the winning bid is expected to match the second highest valuation among bidders.

Comparing average revenues

The revenue equivalence theorem predicts that the basic auction forms yield the same price *on average*, not that *every* auction using one of these auction forms achieves the same price. That is, if the basic auction forms are repeatedly used to sell a good to a given number of randomly selected bidders, they produce the same average revenue; the outcomes of individual auctions, however, may differ.

A practical difference exists between, on the one hand, the English and Vickrey forms, and on the other hand, the Dutch and first-price sealed-bid forms. An English auction or a Vickrey auction yields revenues that are less dispersed around the average than those from a Dutch auction or a first-price auction. English and Vickrey auctions present bidders with a simple strategic problem: bidders merely need to determine their own valuations for making bid decisions. By contrast, Dutch and first-price auctions require bidders to guess their competitors' valuations, leading to unstable auction outcomes. Bidders strategically bid lower than their own valuations (called bid shading). For each bidder, the amount of bid shading depends on a trial-and-error process, taking into account the number of competing bidders and their possible valuations.

Insights of the revenue equivalence theorem

Anecdotal evidence about the performance of different auction forms yields no useful guideline for auction design. There is a claim, for example, that the outcry of bids in an English auction generates more excitement and price competition than the submission of sealed bids. An opposite view holds that an English auction, unlike a sealed-bid auction, cannot raise the price beyond what is absolutely necessary for someone to win. Comparing sealed-bid auction formats, some prefer the first-price rule to the second-price rule on the ground that the latter may 'leave money on the table', referring to the excess of the winner's valuation (revealed by the highest bid) over the payment required (equal to the second highest bid).

The revenue equivalence theorem shows how only formal analysis helps clarify the effects of some design features. In the stylised auction environment, more than one auction form can achieve the same expected revenue; therefore, the seller would be free to consider objectives other than revenue in choosing between the basic designs (Milgrom 1996). Auction design should be aimed at yielding stable outcomes over time and across auction environments. A major design issue is to minimise bidders' guesswork, thereby reducing the scope of 'gaming' for bidders.

For selling a single item, the Vickrey design provides an effective way of inducing bidders to reveal their private valuations. Bidders are willing to do so because of the seller's commitment to the second-price rule; the seller ought not to exploit the value information obtained from bidders by charging a price that is higher than the second highest bid. Vickrey auctions are uncommon, however, as a result of bidders' concern about giving away private value information to the seller or competitors (Rothkopf, Teisberg and Kahn 1990). Compared with the Vickrey design, the other designs are more sensitive to the auction environment; they may perform well only in specific circumstances.

If the assumptions behind the revenue equivalence theorem do not hold, particular auction forms may emerge as superior. Assessing an auction environment against the benchmark assumptions helps identify design features that make one auction form more effective than another.

3.5 Outcome properties

In the stylised environment, there is no distinct advantage of one basic auction form over another in revenue terms. Prices are primarily driven by bidders' valuations, mainly reflecting the absence of collusive and manipulative bidding behaviour. The link between prices and valuations contributes to the efficient allocation of the traded good.

The gain from trade

The gain from auction trading is measured by the excess of the bidders' highest valuation over the seller's cost. The price determines how this excess is to be divided between the seller and the buyer. Nobody knows at the outset how much the traded good is worth and how the gain from trade is to be divided. Any outcome between all of the gain going to the seller and all of the gain going to some buyer is possible. Nevertheless, the seller and the buyer tend to share the gain from trade.

The gain from trade comprises different types of economic rent. ('Rent' is a return to the owner of some unique commodity or market advantage that others cannot emulate.) The seller acts as a monopolist in selling a unique good with no standard market value. The seller decides and enforces trading rules, controlling the supply of the traded good. In this role, the seller can earn a monopoly rent.

A lack of full knowledge about bidders' valuations, however, limits the seller's ability to extract all of the rent from auction trading. Without knowing bidders' valuations, the seller cannot set the highest possible price at which the good will sell. Instead, the seller relies on competition among bidders to drive the price as close as possible to the maximum. The final price is usually below the winner's valuation. The successful bidder can earn an information rent due to the advantage of possessing private value information.

The effect of bidding competition on price

The auction price is affected by the strength of bidding competition, which depends on the number of bidders and the profile of bidders' valuations. These factors affect a bidder's perception of the risk of being outbid by others.

- The less dispersed the possible valuations of all bidders, the closer will be the price to the bidders' highest valuation. Put differently, with a stronger market consensus on the traded good's value, the seller's monopoly rent increases and the buyer's information rent decreases.

- As the number of bidders increases, bidders generally need to bid closer to their own valuations to win an auction. Consider the situation in which a particular bidder has the highest valuation; a new competitor may have a valuation higher than those of the other existing bidders. The entry of this new competitor does not affect the outcome that the highest-valuation bidder wins; however, it may increase the second highest valuation among bidders and therefore the required payment for the winner. Consequently, the price is expected to rise with an increased number of bidders. An auction is perfectly competitive if the number of bidders is so large that adding one extra bona fide bidder causes only an arbitrarily small change in the price (McAfee and McMillan 1987a). Under this condition, the price equals the winner's valuation.

Bid data from most auctions cannot directly indicate to what extent prices differ from winners' valuations. This is the case because bidders tend to bid less than their valuations, except in Vickrey auctions (and even then, sealed-bid data may be accessible to only the seller). It is usually infeasible, therefore, to estimate the exact gains from trade for the buyer and the seller. It is possible, however, to determine the expected gains from trade on the basis of an assumed probability distribution of valuations. Table 3.1 presents estimates of the seller's share of gains from trade for different numbers of bidders and different numbers of goods being sold. These estimates are based on the assumptions of symmetric bidders, zero marginal cost, and straightforward bidding. It is also assumed that bidders each bid for one item at most and their private valuations are equally likely over a specific value range (that is, assuming a uniform probability distribution of valuations).

Table 3.1 **Seller's expected percentage share of gains from trade**

Number of bidders	*Auction of one item*	*Auction of four items*
1	0.0	0.0
2	50.0	0.0
3	66.7	0.0
4	75.0	0.0
5	80.0	28.6
6	83.3	44.4
7	85.7	54.5
8	87.5	61.5

a Assuming uniform distribution of valuations, zero marginal cost and that each bidder bids for one item at most.

Sources: Ayres and Cramton (1996); Bulow and Roberts (1989).

With an assumed distribution of valuations, the seller's share of expected gains from trade depends on the number of bidders in excess of the number of items being sold. If two bidders bid for one item, for example, the seller can expect to receive half of the potential gain from trade. That is, if the highest valuation is $100 and the seller's cost is zero, then the expected price is $50. An auction of four items needs to attract at least five bidders for the seller to capture any gain from trade. Additional bidders add to the seller's expected revenue, albeit at a diminishing rate. With sufficiently many bidders, the price rises to reveal the bidders' highest valuation, enabling the seller to extract all of the gain from trade as monopoly rent.

Apart from the number of bidders, the strength of bidding competition varies with the variance of an assumed distribution of valuations. The smaller the variance of valuations, the larger the seller's share of gains from trade. Over a given price range, a normal probability distribution of valuations, for example, implies greater bidding competition than a uniform probability distribution of valuations does. (This is the case because a random variable has stronger central tendency under a normal probability distribution than under a uniform probability distribution.) Greater bidding competition counteracts the seller's informational disadvantage, leading to a higher price. Collusion and strategic price manipulation by bidders, on the other hand, reduce the seller's revenue below the estimated levels.

Attaining allocative efficiency

An auction outcome is efficient when the good is sold to the bidder who values it most highly. For efficient allocation, the ranking of bids needs to be consistent with the ranking of bidders' valuations. This consistency is obvious in a Vickrey auction in which bids reveal valuations. Likewise, the drop-off prices in an English auction indicate bidders' valuations, except for the winner. In a first-price sealed-bid auction or Dutch auction, in which bidders are expected to shade their bids by the same proportion, bids tend to correlate with valuations. In the stylised environment, an auction can generate the necessary value information for an efficient allocation, although the price only approximates the winner's valuation.

3.6 Auction design for increasing revenue

The analysis in the previous section does not determine to what extent the seller can increase revenue by choosing a design other than those compared. The seller may want to select the selling mechanism that yields the most revenue. To this end, the seller needs to evaluate the highest possible expected revenue in a particular auction environment and design an auction that leads to that outcome.

Setting a reserve price

Adopting any of the basic auction forms in the stylised environment, the seller can maximise expected revenue by setting a credible reserve price — that is, the lowest price that would ever be accepted for the good. The reserve price adds to the risk that bidders might lose an auction by bidding too low. In a sense, the reserve price represents the seller's own bid for the good being sold. It increases bidding competition, enabling the seller to capture some of the information rent that would otherwise accrue to the winning bidder.

To see how the reserve price can increase the selling price, suppose at least one bidder has a valuation above the reserve price. In an English auction, imposing a reserve price affects the auction outcome only if the second last bidder drops out before reaching the reserve price. In this circumstance, the winning bid is equal to the reserve price instead of the lower price at which the second last bidder withdraws from bidding. In a Vickrey auction, the winner pays whichever is the greater of the reserve price and the second highest bid. In a first-price sealed-bid auction or Dutch auction, the presence of a reserve price induces bidders to reduce bid shading, bidding higher than they otherwise would.

If the bidders' highest valuation is above the seller's cost and below the reserve price, then no sale occurs, even though some bidder would have been willing to pay more than what the good is worth to the seller. Setting a reserve price, therefore, can lead to an inefficient outcome — that is, no trade may take place even though some buyer could have used the good to generate value in excess of the good's opportunity cost.

To maximise expected revenue, the seller needs to set a reserve price at the appropriate level. This price level balances the positive effect of increasing bidding competition and the negative effect of losing revenue in the event of no sale. An appropriate reserve price is based on the distribution of bidders' valuations. If the seller perceives the valuations of individual bidders to be drawn from different probability distributions, revenue-maximisation would require setting different reserve prices for different groups of bidders. Under the assumption of symmetric bidders, however, the seller can set the same reserve price for all bidders; moreover, that reserve price is independent of the number of bidders. Assuming a uniform distribution of valuations, for example, the required reserve price is the average of the bidders' highest possible valuation and the seller's cost. Generally, the appropriate reserve price exceeds the seller's cost of the traded good.

Various practical methods for determining reserve prices have been proposed for different types of auction. McAfee (1998) reports a method to set reserve prices in auctions of business assets. That method involves computing the distribution of asset values on the basis of bidding firms' accounting procedures and data for asset valuation. McAfee, Quan and Vincent (2000) use historical price data to determine the appropriate reserve price for a real estate auction. Paarsch (1997) develops an econometric model to determine reserve prices in timber auctions.

Should reserve prices be used?

Potential buyers hope to make a profit from winning at auction. Along with any auction entry fees and bidding costs, a reserve price limits the winner's potential gain. This effect discourages bidder participation and reduces bidding competition (Levin and Smith 1994).

The disadvantages of a reserve price, particularly the potential conflict between revenue and efficiency in the event of no sale, raise the question of whether auctions should have reserve prices. The following reasons justify an above-cost reserve price, especially for auctions of valuable goods.

- If potential buyers have a firm basis of valuation, setting a reserve price is unlikely to affect their decision to take part in bidding (Menezes and Monteiro 2000).
- If the number of potential buyers is limited and the gain from trade is large relative to entry and bidding costs, the impact of a reserve price on bidder participation is insignificant. Under these conditions, all potential buyers have a strong incentive to compete in bidding. A spectrum auction, for example, can attract only a few eligible firms seeking entry into a lucrative communications market.
- A reserve price can play a dual role: it increases the seller's expected revenue and corrects inefficiencies that arise from misallocation (as opposed to non-allocation) of the good being auctioned. This source of inefficiency does not exist in the stylised environment because, whenever a trade occurs, an auction always allocates the good to the buyer with the highest valuation. In other environments, however, strategic price manipulation or collusion by bidders can distort allocation away from efficiency. An auction may yield low revenue and allocate goods to bidders with relatively low valuations, even when there is ample competition and the traded goods are highly valuable. In this circumstance, a reserve price can help avoid unintended or adverse outcomes and increase the seller's expected revenue (box 3.1; also see chapter 4).
- Allowing for re-auctions, a high reserve price set in an early auction allows the seller greater flexibility to sell a good that must be resold if the reserve price is not met. This selling strategy, however, does not generally increase the seller's expected revenue (box 3.2).

Box 3.1 **Setting a reserve price to increase revenue and attain an efficient allocation**

In this example, the seller adopts the modified Vickrey design to sell three identical items. The design allows bidders to place bids for individual items or packages of items (see appendix B for design details). Bidders A, B and C each seek to buy one item for a maximum price of $15. Bidder D has no use for a single item but is willing to pay up to $200 for the package of three items. Other bidders have such low valuations that their bids do not affect the auction outcome.

Without a reserve price, the auction outcome is for D to win the items and pay a price of $45 according to the modified ‘second-price’ rule. The allocation is efficient because the winner has the highest combined valuation for these items. No auction form can yield a higher expected revenue than $45 from an efficient allocation.

The main design problem in this auction is one of potential collusion. The relatively low price opens an opportunity for losing bidders to collude profitably. For example, if bidders A, B and C were to agree to each bid $100 for a different item, they could each win an item at virtually zero price. In this circumstance, the pricing rule requires a winner to pay the next highest single bid for a specific item, which is zero because A, B and C collude to bid for separate items and D has zero marginal value for one or two items. The collusive outcome is inefficient because it keeps D from putting the items to their best use.

A moderate reserve price can discourage bidder collusion, reducing the risk of resource misallocation. A reserve price of over $15, for example, eliminates any profit opportunity for the colluding bidders (A, B and C) and increases the seller’s revenue from selling all three items to the package bidder (D).

Box 3.2 Setting a reserve price with the possibility of re-auction

Facing the prospect that any unsold good will be re-auctioned, bidders can hold off bidding and hope to acquire the good at a re-auction with a reduced reserve price. Bid decisions depend on: (i) the perceived strength of bidding competition; and (ii) the length of time for which the seller can withhold an unsold good. The first factor affects a bidder's risk of losing the good to competitors. The second factor affects the present value of benefits forgone from not acquiring and using the good earlier.

In setting a reserve price, the seller considers the net effect of bidding competition and trading delays on expected revenue. Bidding competition determines how likely it is that a re-auction will be necessary and, if the good fails to sell at a given reserve price, the amount by which the reserve price needs to be lowered in a re-auction. Trading delays reduce the present value of auction revenue.

By running a sequence of auctions with decreasing reserve prices to sell a good, the seller can expect a lower revenue than that generated from a one-off auction with a credible reserve price. This result assumes that the market factors that affect bidders' valuations remain unchanged between re-auctions. The shorter the time between these re-auctions, the lower is the seller's expected revenue. If a re-auction is held immediately after the good is passed in, the expected revenue (for these re-auctions as a whole) declines to the same level as that of a single auction with no reserve price.

Consequently, if the seller cannot commit to a credible reserve price policy, re-auctions do not add to the seller's expected revenue because bidders have an incentive to shade bids in early auctions and the price tends to fall over time.

Source: McAfee and Vincent (1997).

3.7 Lessons from a formal analysis of auctions

Formal analysis is essential for understanding the effects of design on bidding behaviour and auction outcomes. Such analysis identifies the key features of an auction environment and considers how bidders may adapt to different auction rules in that environment. Bidders have an incentive to exploit auction rules to increase their potential gains from auction trading. Not knowing their competitors' valuations, they choose their own bids as a strategic decision. Bid decisions may involve guesswork that leads to unstable auction outcomes. In some auctions, bids reveal valuations; in others, bidders shade their bids below valuations. Auction design is a way of harnessing and guiding bidding behaviour; the intricacies of auction design matter for the delivery of desirable outcomes.

Raising revenue and attaining allocative efficiency are distinct goals of auction design. An auction attains allocative efficiency by eliciting bids that rank the bidders in order of their valuations. These bids determine a price that is less than the winner's valuation of the traded good. Allocative efficiency does not require the price to fully reflect the good's opportunity cost (measured by the winner's valuation). In some cases, the seller can increase revenue by choosing a design that may interfere with allocative efficiency. Well-designed auctions, however, induce bidders to bid close to their valuations, increasing the likelihood of efficient or near-efficient outcomes.

There are two ways of evaluating auction forms. The first is to compare a set of auction forms for their effects on revenue and efficiency. This approach cannot determine the scope for design improvement with an auction form outside the set compared. The second is to treat auction design as an optimisation problem; in this way, specific goals dictate the choice of auction form. The formal analysis of the basic auction forms illustrates both approaches. According to the revenue equivalence theorem, these auction forms have similar efficiency and revenue properties in the stylised environment. By including an appropriate reserve price, they maximise the seller's expected revenue. In other auction environments, the auction form(s) of choice can be much more complicated.

The stylised auction environment is simple and illustrates some of the economic concepts and analysis techniques used for auction design. However, many resource allocation problems and practical design issues are beyond the scope of this simplistic framework. The elementary results derived for the basic auction forms in this context may not extend to other, more complex auction environments. To address specific design issues, a thorough understanding of the pertinent auction environment is crucial.

4 Auction design issues

This chapter examines the following aspects of an auction environment and their implications for auction design:

- bidders' interdependent valuations (section 4.1);
- bidders' attitudes towards risk (section 4.2);
- bidder collusion (section 4.3);
- bidder participation (section 4.4); and
- synergy values of multiple items (section 4.5).

4.1 Bidders' interdependent valuations

The way in which bidders assess the value of the good being sold influences their bidding behaviour and has implications for the seller's choice of auction form.

Different models of valuation

Two different models are used to explain how bidders determine a good's value. The first model assumes independent private valuations — that is, bidders each have a predetermined valuation that others do not know and cannot influence (as in chapter 3).

The second valuation model incorporates the common-value assumption — that is, bidders perceive one another to have a common value for the traded good but are individually unsure about that value. In estimating the unknown value, bidders have access to different sources of information and so make value estimates subject to different estimation errors. The value of an oil field, for example, depends mainly on the oil quantity and the extraction cost. These value components may be similar to all bidders competing for that oil field. When bidders decide their own bids, however, they may each make a different assessment of the oil quantity and the extraction cost, arriving at different value estimates.

A good can have separate value components that are concordant with different valuation models. In the oil field example, bidders' valuations can be partly independent if bidders use different production technologies and only they know their own extraction cost; bidders' valuations are partly common given that bidders face the same output price for any oil extracted. Resale opportunities can create common values. Haile (2001) presents econometric evidence of common values in US Forest Service timber auctions; these common values arise from subcontracting activities and timber sales.

The effects of valuation uncertainties on auction outcomes

Uncertainties are common in bidders' valuations. For auction design purposes, it is important to distinguish the uncertainties that affect bidders' independent valuations from the uncertainties that affect a value common to all bidders. While the onus of estimating values ultimately rests with individual bidders, auction design can help reduce specific types of valuation uncertainty.

Bidders with independent valuations cannot resolve their valuation uncertainties by learning about how competitors determine a good's value (although their bids may change as a result of learning others' bids). Bidders should assess the risk associated with the contingencies that affect their own valuations, then factor this risk into their own valuations and bid on the basis of the risk-adjusted valuations. In the oil field example, a bidder facing a high level of cost uncertainty needs to subtract a large risk discount from any profit estimate. This strategy enables the winner to obtain a positive *expected* gain from auction trading that is commensurate with the level of risk.

The basic auction forms can attain allocative efficiency in an environment in which bidders are uncertain about their private, independent valuations. For this efficiency to occur, bidders must have similar attitudes towards risk; otherwise, bidders' efforts to avert risk may cause a lack of consistency between their bids and valuations. An aggressive bidder, for example, could win an auction by setting the risk premium proportionately lower than that set by a risk-averse bidder, even if both bidders face the same cost and revenue conditions. To avoid this type of efficiency distortion, the seller should include a royalty component in the payment rule to reduce the effect of risk on bidders' valuations (box 4.1).

If all bidders have the same (unknown) value of a good, then the issue of efficiency is trivial because allocating the good to any bidder is equally efficient.[1] Such pure

[1] This efficiency property depends on the assumption of symmetric bidders. Klemperer (1998) and Bulow and Klemperer (2002) argue that even a slight information advantage for one bidder over others could lead to potential efficiency distortions in an auction.

common-value auctions are rare. The common approach to valuation combines private and common values, in which case no auction can attain full efficiency. Typically, bidders want to learn what their competitors think the good is worth. Their bids therefore depend on how they expect others to bid; accordingly, dominant strategies cannot be used to produce an efficient allocation.

Box 4.1 **Royalty payments**

The payment for an auctioned good can include: (i) a price for the good; and (ii) a share of earnings to be generated from the good (that is, a royalty component). The seller can call for bids on the price or the royalty rate, or both. An increase in the royalty rate relative to the upfront payment reduces the risk discount that a bidder ought to subtract from an own valuation, thereby diminishing the effect of earnings risk on the auction outcome. A high royalty rate, however, dampens the buyer's incentive to generate high returns from the good after auction. It potentially decreases the buyer's production efficiency as well as the seller's total revenue. Another disadvantage of royalty payments is that the seller needs to monitor the buyer's earnings after auction.

Sources: Maskin (1992); McAfee and McMillan (1987).

Winner's curse arising from common-value uncertainties

In bidding for a good with a common value, bidders face the risk of paying more than the good is worth. This hazard is called the 'winner's curse'. When the true value is unknown, bidders may overestimate it or err in the opposite direction. Valuation errors need not reflect any systematic fault with bidders' valuation procedure. Nevertheless, all bidders face a bidding problem: by coming up with a

Box 4.2 **Experimental evidence on the winner's curse**

The winner's curse is inconsistent with the assumption of rational behaviour because rational bidders would adjust their bids downwards to avoid overbidding. Experiments confirm, however, that the curse exists in common-value auctions.

Researchers have set up auctions in a laboratory to study how bidders bid with uncertainties in a common value. According to their study results, experienced bidders bid cautiously but still fell prey to the winner's curse. These bidders' gains from trade were, on average, less than those predicted under the proposition that all bidders adopt rational strategies to avoid overbidding. On the other hand, less experienced bidders generally suffered losses due to overbidding.

Sources: Dyer, Kagel and Levin (1989); Kagel and Richard (2001); Land and Plott (1991).

Box 4.3 Discounting valuations for the winner's curse

To avoid the winner's curse, rational bidders discount their valuations and bid on the basis of the discounted valuations. The idea behind this discounting exercise is that the highest discounted bid will equal, rather than exceed, the true value of the traded good. The following table presents estimates of the discount factor for different numbers of bidders and different measures of dispersion in bidders' possible valuations (as indicated by the standard deviation of an assumed probability distribution).

Estimates of the discount factor[a]

Standard deviation	*Four bidders*	*Eight bidders*	*15 bidders*
0.25	0.29	0.33	0.37
0.50	0.46	0.53	0.59
1.00	0.65	0.75	0.82

a Based on a log-normal probability distribution.

With four bidders and a standard deviation of 0.25, for example, bidders should bid 29 per cent below their own valuations to avoid the winner's curse. With a greater number of bidders or a larger measure of standard deviation, a larger discount factor is required to counter an increased risk that a bidder's competitors know more about the common value than this bidder does. This observation implies that each bidder bids more cautiously when there are more competitors in an auction and, therefore, that the price may decline with an increased number of bidders.

Calculation of the discount factor is complicated for a multi-item auction and an auction involving bidders with partly independent valuations. In the case of a multi-item auction, the strength of the winner's curse depends on the number of items being sold and the number of items that a bidder is allowed to obtain. In the case that bidders' valuations are partly independent, the highest bid reveals little about the common value of a good. In both cases, a smaller discount factor than suggested above is applicable. Simulation results based on a spectrum auction show that the required discount factor is a function of the number of bidders (n), the amount of common-value uncertainty (σ_c) and the amount of private-value uncertainty (σ_p):

$$\text{Discount factor} = 0.002n + 0.78\sigma_c - 0.13\sigma_p - 0.05\,.$$

If there are four bidders and both the common-value and private-value uncertainties have a standard deviation of 0.25, then this equation predicts a discount factor of 0.12, compared with the corresponding estimate of 0.29 derived under the assumption of pure common-value uncertainty in a single-item auction.

Sources: Cramton (1995); Wilson (1992).

higher value estimate than those guessed by others, the winner is whoever most overestimates the true value. Winning therefore implies overbidding.

The winner's curse is commonly observed (box 4.2); however, it should not be confused with the effect of hindsight. After an auction, bidders can come to the conclusion that they have bid too high relative to the posterior market conditions. Even if market conditions remain the same before and after an auction, it is possible for bidders to realise that their value estimates for the traded good have been overly optimistic. This phenomenon is not a symptom of the winner's curse. The winner's curse arises because of the negative information that winning conveys — one wins because nobody else is willing to pay as much — irrespective of whether bidders have forecast market conditions accurately or not.

Typically, sophisticated bidders understand the winner's curse and discount their value estimates. These bidders can safely bid up to such adjusted valuations without fear of losing money through winning the auction (box 4.3). By learning that competitors have comparable value estimates, bidders face a higher chance of well estimating a common value and so would adjust their own value estimates with a smaller discount rate. Conversely, if bidders have no clue to how much other bidders think the traded good is worth, then they would treat their own value estimates with great caution, applying a larger discount rate. In a sealed-bid auction, for example, where bidders cannot observe their competitors' bids, they are subject to potentially large valuation errors and so tend to bid substantially less than their estimated values in order to avoid the winner's curse.

Auction features to address the winner's curse

If bidders are uncertain about the common value of a good, then the seller can benefit from any exchange of value information among bidders. Such information increases bidders' confidence in their own value estimates, adding to their discounted valuations and therefore the seller's expected revenue.

Bidders base their valuations on information gathered before and during an auction. One source of value information is the seller's disclosure about the good. Another source is other bidders' bids. Interaction among bidders during an auction enables them to collate fragmented information on the traded good's value. The closer the price is to the value information held by individual bidders, the weaker is the winner's curse. Milgrom and Weber (1982) propose the following auction features to help reduce the winner's curse.

- The seller should reveal any knowledge about the good's value potential, whether favourable or not. To increase expected revenue, honesty is the seller's best disclosure policy for any chosen auction form. Bidders interpret any censored information from the seller as a source of uncertainty or a negative signal for valuation. In a spectrum auction, for example, bidders' valuations are sensitive to prospective market structure and profitability, which hinge on future regulatory developments and spectrum availability.

- The seller should adopt an open ascending-bid format, so that the price reflects the value estimates of most bidders. In an English auction, for example, bidders can observe their competitors' bids and satisfy themselves that their own value estimates are not excessive as long as others stay in the bidding. By contrast, in a Vickrey auction, the price reflects only the value estimates of the highest and second-highest bidders; in a first-price sealed-bid auction, the price reflects only the winner's value estimate.

Dasgupta and Maskin (2000) suggest a way of modifying the Vickrey design in order to attain nearly efficient allocations among bidders with common values. Their design involves the use of contingent (conditional) bids — that is, bids dependent on other bidders' revealed valuations. In a bidding contest between bidders A and B, for example, bidder A registers a bid as *x* if bidder B bids *y*, or *v* if bidder B bids *w*. Likewise, bidder B registers a schedule of contingent bids. The auction includes complex rules to calculate the consistent bids for both bidders and thereby select the winner and determine the required payment. This design has yet to be empirically tested.

4.2 Bidders' risk attitudes

Bidders face the risk of winning an auction as well as the risk of losing an auction. These two types of risk interfere with efficient allocation in different ways.

The risk of winning an auction

The risk of winning an auction derives from purchasing a productive good that generates uncertain earnings. Cautious bidders discount their own bids to lower the chance of overbidding. The discount increases with bidders' incapacity to bear risk. Bidders choosing a large risk discount are, however, disadvantaged in bidding competition. To maintain allocative efficiency, an auction can incorporate measures to correct for differing bidder attitudes towards risk. As discussed earlier, these measures include: (i) the use of royalty payments to lower the risk from private-value uncertainties; and (ii) the use of ascending bids to lower the risk from common-value uncertainties. In some cases, however, auction rules turn an auction into a competition based on bidders' capacity to bear risk (box 4.4).

Box 4.4 Instalment payments creating default option values

To encourage the entry of small firms into the US communications market, the C-block spectrum auction in 1995–96 provided bidders with attractive payment terms designed to ease the difficulty of raising venture capital. Winners could pay 5 per cent of the licence prices within five business days of auction completion and 5 per cent at the time of licence delivery, then quarterly instalments over a period of 10 years, with the first six years requiring only interest payments charged at relatively low rates. These concessions amounted to an estimated saving of over 30 per cent of the licence cost for a winning firm.

The backloaded instalment plan created option values in the licences. Given the uncertainty about spectrum values, licensees would stand to gain from any post-auction spectrum revaluation. They could avoid financial losses due to any spectrum devaluation by choosing to default on their licences sometime between auction completion and full payment. The option to default makes a licence worth more than the net present value of its expected earnings, thus inflating the auction price. Bidders with risky business plans or limited assets find increased option values in a licence, because they have little to lose from defaulting. The payment rule biases allocations against prudent firms, contributing to the problem of nonpayments and defaults on assigned licences.

Sources: Cramton (1997); Scanlan (2001).

The risk of losing an auction

Firms can lose market share or be forced out of the market if they do not win an auction of some indispensable inputs or market access rights. The acquisition of spectrum licences, for example, influences a firm's prospects for growth or even survival in the telecommunications market. In Europe, would-be providers of third-generation mobile-phone services had little choice but to take part in auctions of specially earmarked spectrum. According to Coutts (2001), stock markets rewarded winners of those spectrum licences, while companies that did not secure licences were exposed to the risk of share sell-off or takeover. In Australia, where firms can substitute other spectrum bands for those being auctioned, the risk of losing a spectrum auction differs between incumbents and entrants. Start-up firms seeking market entry are more pressed than existing operators for spectrum, because the latter can choose to exploit their existing holdings to offer new services.

The risk of losing an auction lies in the uncertainty about who may win. This risk is not caused by valuation uncertainties facing the winner and is therefore unlike the winner's curse. Bidders cannot alleviate the risk of losing in the same way that they alleviate the risk of winning — that is, by discounting their valuations. Instead, they should bid close to (but not above) their own valuations, thereby raising the chance of winning an auction (but not that of losing money).

In English and Vickrey auctions, bidders' attitudes towards risk do not affect bidding behaviour because bidders bid their own valuations anyway. In first-price and Dutch auctions, however, bidders' efforts to avert this type of risk affect bidders' strategy choices because bidders typically shade bids below their own valuations (section 3.4). Risk-averse bidders are willing to insure against losing at the cost of an increased payment, and so shade their own bids by less than other bidders do. In other words, a bidder's extent of bid shading decreases with this bidder's incapacity to bear the risk of losing an auction.

Paradoxically, risk-averse behaviour drives a bidder to bid aggressively and close to valuation. This behaviour increases the chance of winning but decreases the gain from winning an auction because the price will likely rise. It need not diminish a bidder's expected gain from trade, because an increased chance of winning compensates for a reduced gain from trade if this bidder wins. As Matthews (1987) points out, risk-averse bidders benefit from reduced uncertainty about auction outcomes and prefer a first-price auction to an English auction and a Vickrey auction.

The effects of risk-averse behaviour on auction outcomes

The effects of risk-averse behaviour on auction outcomes depend on the relative significance of different sources of risk (Maskin and Riley 1984; Milgrom and Weber 1982). If losing is the major risk facing bidders, then the outcome of an English auction or a Vickrey auction is unaffected by bidders' attitudes towards risk, in terms of both efficiency and revenue. In contrast, in a first-price auction or a Dutch auction, risk-averse bidders are more likely to win, not for having a higher valuation, but for shading their bids by less than other bidders. This effect increases the seller's expected revenue but leads to inefficient outcomes, especially when bidders are few (then, the scope for bid shading and therefore efficiency distortion is large). Box 4.5 discusses auction features that maximise the revenue potential from risk-averse bidders.

If an auction entails both the risk of winning and the risk of losing, then bidders' risk-averse behaviour has an ambiguous impact on auction outcomes. The basic auction forms cannot be definitely ranked in terms of their revenue potential. Moreover, there is a potential conflict between allocative efficiency and revenue. Therefore, the auction form needs to be chosen on a case-by-case basis.

Box 4.5 **Maximising expected revenue from risk-averse bidders**

To maximise expected revenue from risk-averse bidders, the seller imposes fees on low bidders and pays subsidies to high bidders who lose. This payment rule 'insures' bidders against losing an auction, shifting part of the risk from risk-averse bidders to the seller. The seller can expect an increased price to more than compensate for payments made to losing bidders.

This design feature is often modified in practice. In a sealed-bid auction, for example, the seller can impose bidding fees (instead of both subsidies and fees) that vary inversely with bids. Alternatively, high but losing bids can be rewarded outside the auction through an award of job contracts that are not offered for public bidding.

Source: McAfee and McMillan (1987a).

4.3 Bidder collusion

Bidders collude in an auction if they coordinate their bids, allowing a designated bidder to win the traded good at a price that is substantially below what other colluding bidders are willing to pay. This definition of bidder collusion need not imply any illegal arrangement. In legal terms, collusion typically refers to 'any practice that a group of bidders uses to limit competition between themselves' (Mailath and Zemsky 1991, p. 468). Such a legal definition of collusion is too broad to be useful for analysing bidding behaviour, because individual bidders can adopt legitimate strategies to avoid bidding up prices. In a multi-item auction, for example, bidders can reduce demand to keep prices low (section 4.4). Demand reduction does not equate with bidder collusion, unless bidders subsequently split the traded items.

Different ways of colluding in an auction

Bidders may collude in an explicit or implicit way. Explicit collusion entails a prior agreement on how to bid and divide the 'spoils' (that is, profits from an auction). Implicit collusion relies on a tacit, mutual understanding to keep bids low. Bidders who collude in an implicit way need not directly communicate with each other. Implicit collusion is therefore more difficult to detect and prove than explicit collusion.

As Hendricks and Porter (1989) observe, bidder collusion is a widespread and diverse phenomenon. It is more likely to arise in repeated auctions or auctions with multiple rounds of bidding than in one-off, single-bid auctions. Recurrent interaction between bidders adds to the attractiveness and feasibility of collusive strategies. In bidding for government construction contracts, for example, bidders could engage in a bid rotation scheme to win contracts in turn. Large firms could join with small firms to form syndicates for particular auctions while they remain rivals in other markets. Members of a trade association could arrange for someone to win an auction at a low price, then hold an exclusive knockout auction among themselves. An econometric study by Baldwin, Marshall and Richard (1997) confirms the existence of bid rigging in a series of US Forest Service timber auctions. Evidence of tacit collusion is found in the US spectrum auctions, in which bidders used coded bids to warn competitors off bidding on some targeted licences (Cramton and Schwartz 2000).

Bidders have to resolve a few tactical problems in order to collude effectively. One is to decide how to divide the spoils so that bidders can each gain from collusion. Another is to enforce collusive agreements, which might be done through the threat of retaliation against those bidders who violate the ring rules. Bidding rings differ in their way of maintaining a viable and stable collusive arrangement.

- A *strong ring* is one in which a designated winner agrees to compensate other bidders with side payments.
- A *weak ring* is one in which bidders cannot make side payments, for two possible reasons. First, bidders are legally prohibited from making side payments to each other. Second, ring members decide against side payments to discourage free riding. Free riders, in this case, are low-valuation bidders who seek to share the ring's profit although they would have little chance of winning on their own.

These different types of bidding ring lead to the use of, respectively, explicit and implicit coordinated bidding strategies. In both cases, collusion reduces bidding competition and drives down prices. The impact on allocative efficiency, however, depends on the form of collusion: generally, a weak ring weakens the condition for efficiency while a strong ring does not (as explained below).

Bidder collusion in first-price sealed-bid auctions

McAfee and McMillan (1992) investigate the possibility for all bidders to collude in a first-price sealed-bid auction. For a weak ring, bidders might all bid the reserve price, even if they value the traded good at more than that price. Bidders with a valuation at or above the reserve price submit a minimum bid. Every ring member therefore has an equal chance of winning the good, subject to the seller's discretion in using some rule to break a tie bid. In effect, the ring counts on the seller to randomly determine the allocation. The allocation can be inefficient because the winner is chosen randomly rather than by using bids to rank valuations.

Ring members might hope to appoint someone with a relatively high valuation to be the winner. The ring, however, cannot reap any extra gain from this strategy compared with the outcome of random allocation. Given that side payments and communication are not possible, the only way for a member to express a high valuation to the rest of the ring is to bid higher than the reserve price. This high bid results in an extra payment to the seller, causing the ring as a whole to be worse off than with a random allocation. As a result, unless particular members want to break the ring agreement, they would prefer the outcome of random allocation.

For a strong ring, bidders arbitrarily pick a ring member to bid. The acquired good is re-auctioned among ring members so that they can share the gain from collusion, which is the difference between the price reached in the ring's own auction and the price reached in the original auction. This form of side payment enables a strong ring to achieve an efficient allocation, because the ring member with the highest valuation will eventually obtain the good.

Bidder collusion in Vickrey and English auctions

A Vickrey auction and an English auction are both susceptible to bidder collusion (Graham and Marshall 1987; Robinson 1985; von Ungern-Sternberg 1988). The second-price and ascending-bid features of these designs enable bidding rings to enforce collusive agreements because defectors would face the risk of overbidding (in a Vickrey auction) or the threat of immediate retaliation (in an English auction).

In a Vickrey auction, bidders could form a ring by agreeing to adopt different bidding strategies between a designated winner and other ring members who are designated losers. Their agreement exploits the second-price rule, which requires the winner to pay the next highest bid submitted by another bidder. The designated winner, who need not be the one with the highest valuation, would bid higher than an own valuation as well as the other members' valuations. The designated losers would bid close to the reserve price. Together, the different bidding strategies create a false sense of bidding competition and enable the winner to win the auction at a price close to the reserve.

The winner's high bid, while normally not affecting the price, pre-empts any of the other members violating the ring rules. A member other than the designated winner might hope to submit a high bid in order to 'steal a win'. This member may succeed in beating the designated winner but would then have to pay the latter's high bid, which exceeds this member's own valuation.

Likewise, bidding rings can accommodate themselves to an English auction. The designated losers would agree to withdraw from bidding soon after the reserve price is reached. With their cooperation, the designated winner would be able to win the auction at a low price. Any member who attempts to 'steal a win' by raising the price substantially above the reserve would provoke the designated winner into posing further high bids that eventually drive up the sale price; as a result, whoever wins the auction would gain little from breaching the collusive agreement.

For both auction forms, collusive strategies enable inefficient firms to make direct gains from auctions rather than living off side payments from relatively efficient ring members. Without side payments, however, a bidding ring relies mainly on the prospect of a minimal or even negative payoff to discourage members from violating the ring rules. The ring becomes stable only if individual members are convinced of the long-term profit potential from collusion. In the case of repeated auctions, for example, ring members abide by the ring rules in anticipation of their turn as designated winner.

Combating collusion

The presence of noncollusive outsiders reduces but does not eliminate the impact of collusive bidding on auction outcomes. Ring members are forced to adjust their bidding strategies to counter competition from outsiders. If the number of outsiders increases relative to the number of ring members, it will be increasingly difficult to maintain a stable bidding ring; therefore, the auction price is likely to be raised above the reserve price.

In the face of possible bidder collusion, the seller should use specific auction rules — rather than a particular auction form — to prevent bidders from coordinating their bids and enforcing ring rules. Auction rules should be devised to enable individual ring members to gain from noncooperative bidding strategies (in other words, cheating the ring) without being detected or penalised. The following design features help curtail collusive bidding (Graham and Marshall 1987; Hendricks and Porter 1989; McAfee and McMillan 1987a, 1992; Robinson 1985).

- Announce a higher reserve price, the larger the number of potential ring members. A high reserve price limits the potential gain from collusion. Assuming that the ring cannot disguise its operation, bidders will recognise the link between the reserve price and the extent of bidder collusion. If bidders are few, then they are better off by staying out of the ring and taking advantage of a low reserve price. The threat of a high reserve price can therefore deter collusion, especially in repeated auctions.
- Keep the reserve price secret. Ring members need to know the reserve price to determine collusive bids. Without knowing the reserve price, ring members will find it hard to coordinate their bidding strategies. In this circumstance, members

are forced to communicate their intentions at auction (using bid signals, for example), which is easier to detect and address. A lack of crucial price information, coupled with the need for signalling, destabilises the bidding ring.

- Announce only the identity of the winner, not the winning bid or losing bids. This solution reduces the ring's ability to detect deviant behaviour and disrupts collusive arrangements that entail the submission of low bids.
- Adopt a secret allocation rule that does not depend on the highest bid. This solution confuses ring members' bidding agreements. The seller can occasionally choose someone other than the highest bidder as the winner. Provided actual bids are not disclosed, the ring would find it difficult to detect whether cheating has occurred.
- Sell several items in one auction instead of a series of auctions. This approach increases a bidder's potential gain from trade, raising the temptation to defect from a bidding ring. It also delays or prevents retaliation against defectors.
- Choose a sealed-bid auction over an open auction. In a sealed-bid auction, the bidding ring cannot react instantaneously to prevent its members from cheating; it must rely on the threat of future retaliation, which is a less effective way of bonding ring members.
- If an open auction is used, impose a time limit on the bidding process. A ring defector would be able to bid and win just before the auction closes. An oral auction with a time limit is called a Scottish auction.

4.4 Bidder participation

Not all potential bidders choose to enter an auction if they have to bear expenses for entry and bidding. They may also have an incentive to discourage others from participating. Participation costs and strategic motives both can affect bidders' entry in auctions. An auction with too few bidders is unlikely to succeed, in both revenue and efficiency terms.

Participation costs

Potential bidders choose not to enter an auction if entry or bidding is judged too costly. Participation costs include: (i) the cost of determining valuations; (ii) the cost of preparing bids; and (iii) any non-refundable entry fee imposed by the seller.[2]

[2] In government auctions, entry fees (if any) are charged generally for cost recovery purposes, rather than as a means of extracting revenues from bidders.

Different types of participation cost may affect bidders' entry in different ways (Chakraborty and Kosmopoulou 2001; Levin and Smith 1994; McAfee and McMillan 1987b; Menezes and Monteiro 2000).

- The *cost of valuation* is incurred before bidders obtain value estimates. It affects potential bidders with a low valuation and those with a high valuation in the same way.
- The *cost of preparing bids*, incurred after bidders determine their valuations, screens out low-valuation bidders.
- An *entry fee* affects entry in a similar way to that by which the cost of preparing bids affects entry. These two types of participation cost affect the auction outcome differently, however: an entry fee adds to the seller's expected revenue, whereas the bid preparation cost is part of the transaction costs of an auction.

Typically, potential bidders compare the costs of entry and bidding against their own valuations when deciding whether or not to enter an auction. Only bidders with a high valuation relative to those costs stand to gain from an auction, so decide to participate. As a result, entry decision screens out potential bidders with a relatively low valuation.

Participation costs diminish bidding competition but generally have little impact on the efficiency of allocations. Despite the exclusion of low-valuation bidders, the auction outcome may remain efficient because only high-valuation bidders have any prospect of winning. However, the revenue from auction is expected to fall with a reduced number of bidders. By containing the costs of entry and bidding, the seller can attract bidders, and thereby strengthen bidding competition and increase potential revenue.

Strategic motives

Potential bidders may start 'playing games' before the auction, when some of them act to deter entry of others. Bidders seeking to deter entry hope to gain directly or indirectly from a reduction in bidding competition. Direct benefits include a greater chance of winning and a lower expected price. Indirect benefits stem from particular allocation outcomes, such as certain rivals being unable to win any allocation or the auction being called off in the face of insufficient demand. Such indirect benefits are sometimes more significant for a bidder than the direct benefits that would accrue to this bidder through winning the auction. For example, a firm can preserve its monopoly position in a lucrative market if it succeeds in blocking the sale of an input that is vital to potential entrants.

The flow-on effects of auction allocations

Jehiel and Moldovanu (1996, 2000a) link the flow-on effects of auction allocations to the strategic motives behind bidders' entry. These effects arise in auctions that have repercussions on the way in which bidders interact in a downstream market, such as spectrum auctions. Restricted competition in an oligopoly market often underpins intricate entry strategies in an auction in which the number of potential bidders is limited.

An allocation has positive flow-on effects on third parties if it benefits someone who has not entered the auction. These positive effects motivate potential bidders to free ride by not participating in an auction. Consider a takeover battle between two firms that bid for another firm within the same industry. The winner expects to gain economies of scale or scope from its acquisition. Both firms expect to benefit from reduced competition within the industry, provided that one of them merges with the takeover target. A successful takeover will lead to a structural change in the industry that benefits both firms, no matter which one wins. Takeover decisions therefore depend on comparisons of the expected profit gains due to reduced competition and the cost savings associated with synergies between the merged firms; the more significant the indirect effect of reducing industry competition, the stronger the incentive for the firms to stay out of the bidding.

An auction allocation has negative flow-on effects if it adversely affects someone other than the winner. These negative effects motivate the affected bidders to block the entry of others. The affected bidders may strategically exclude themselves from the auction. In doing so, they forgo any direct benefit from acquiring the traded good; however, they can minimise the potential loss if they succeed in inducing others not to bid. The strategic reason is that their mere presence in the auction could influence the allocation and the price that they would have to pay for the good.

To illustrate, consider a few firms bidding for a patented innovation. With this patent, the winning firm could improve its productivity and market share, imposing negative flow-on effects on the other firms. The patent is more valuable to firms with below-average productivity than it is to firms with above-average productivity. The latter do not have as strong an interest in the patent because they already use a superior technology. Leading firms, however, may be willing to pay to block productivity improvements by others. To bid for the patent, therefore, lagging firms would face competition from 'blocking' firms and the prospect of paying a price higher than their own valuations. They may be better off not entering the auction in the first place and forgoing the patent.

Tactics to block entry

Bidders can use a variety of predatory tactics to discourage others from participating (Klemperer 2002). A common way of deterring entry is to create the impression that one values the traded good more highly than anyone else does. This tactic is particularly effective in common-value auctions in which an ascending-bid format is adopted. In such auctions, even a modest perceived difference in bidders' value estimates can dramatically sway bidding behaviour. With a 'strong bidder' signalling a relatively high valuation, 'weak bidders' may think that they either have no chance of winning or would fall victim to the winner's curse if they do win (section 4.1). Wolfstetter (2001), for example, discusses the 'bidder meltdown' in several European spectrum auctions held in 2000; these auctions, conducted with an ascending-bid format, saw many qualified bidders withdraw before the auctions, after it became clear with whom they would have to compete.

A bidder can reinforce an apparent value advantage by creating a reputation for aggressive bidding. This tactic is often observed in repeated auctions: a bidder bids aggressively in early auctions, hoping to intimidate potential rivals into not taking part in later auctions.

The 'packaging' of goods can affect auction outcomes, so bidders sometimes have an incentive to lobby the seller to define and divide the goods for auction in their favour. For example, potential bidders may want different amounts of a divisible good. Typically, the more subdivided the good, the more potential bidders are willing to participate in the auction. If the good is auctioned as a number of basic units, bidders would have the flexibility to aggregate a desired quantity of those units that meet their own demand. Bidders with a large demand, however, would prefer the good to be divided into a small number of bundled sets; that way, they would stand a greater chance of winning a large allocation and pay less for a given allocation compared with the sale of basic units.

Consequences of strategic entry behaviour

Auctions in which entry strategies are potentially important are prone to efficiency distortions. This is the case because bidders' valuations include not only the direct gains from trade but also the indirect, flow-on effects caused by bidders' interaction in downstream markets. Only the first of these value components is relevant to allocative efficiency; the second represents a transfer of income among bidders competing in a downstream market. However, both value components affect bidders' entry and bids, and therefore the auction outcome — for example, a firm's willingness to bid higher than competitors may reflect its concern for losing market share and price setting ability rather than its productivity advantage.

Efficiency distortions arise from the flow-on effects that tend to differ between bidders, leading to 'bidder asymmetry': some (strong bidders) are perceived to have a higher valuation than others (weak bidders). It may seem that weak bidders play a minor role in promoting allocative efficiency in this type of auction. Insufficient participation from them, however, can be dangerous for several reasons.

First, the seller cannot be absolutely certain about bidders' relative value advantages; otherwise, an auction would be unnecessary, at least for the purpose of efficient allocation. Before the auction, one may guess that certain bidders have a relatively high valuation and are in a strong position to win some allocations; however, such a forecast is subject to error. A strong bidder's valuation may be overestimated while a weak bidder's valuation may be underestimated. By not including the so-called weak bidders in the auction, the seller risks efficiency and revenue losses.

Second, bidders may appear to have a low valuation merely due to negative flow-on effects. One example of such effects is an incumbent's cost advantage over entrants in a downstream market. New entrants may decide against participating for strategic reasons. Mistaking this for low market demand or low bidder valuation can lead to revenue losses. As Wolfstetter (2001) points out, to establish market value, it is not sufficient that demand exceeds supply: demand must give rise to sufficient bidder participation and bidding competition.

Third, a lack of bidder participation due to strategic motives is a form of market failure. As a result, the auction price fails to approximate the traded good's opportunity cost. Furthermore, the allocation is inefficient and has adverse impact on market competitiveness. For example, an incumbent firm may use predatory tactics to pre-empt the participation of potential entrants to perpetuate its monopoly in a downstream market.

Design features to address entry-blocking behaviour

To address entry-blocking behaviour, auction design should be aimed at reducing the importance of flow-on effects in bidders' valuations. To that end, the following approaches can be adopted.

Allowing flexible allocations

Let an auction decide how the goods on offer are apportioned among an unspecified number of winners. This approach breaks the cycle of market domination by a few bidders, attracting entrants (Wolfstetter 2001).

In a spectrum auction, for example, the seller can divide and assign the available radiofrequencies in relatively small chunks, increasing the likelihood of bidders winning sufficient spectrum. The seller can also allow the spectrum on offer to be used for different services, such as mobile communications and broadcasting. This arrangement broadens bidding competition beyond different suppliers of a particular service, to include providers of different services.

Discount bidding

Discount bidding involves the use of a handicapping auction rule to provide selected bidders with a price advantage. Typically, small firms or potential entrants receive bid preferences so that they become competitive against large firms or incumbents in an auction (Ayres and Cramton 1996; appendix A).

Bid discounts assist low-valuation bidders in competing with high-valuation bidders, so can lead to inefficient allocations. Nevertheless, any increase in bidder participation may bring greater competitiveness for a downstream market and so justifies this approach. The efficiency distortions will not persist if new entry can stimulate competition in unsubsidised downstream markets. Moreover, any efficiency loss is negligible if low bids made by the assisted bidders mainly reflect negative flow-on effects from downstream markets rather than the assisted bidders' inability to provide profitable services.

Discouraging collusive behaviour

Bidders who wish to pre-empt entry would prefer others to assume the cost of blocking entry. To resolve this free-rider problem, bidders are tempted to collude. To discourage collusive entry strategies, Jehiel and Moldovanu (2000b) suggest the seller limit the amount of market access rights that are available for bidding (appendix A), or use sequential auctions to introduce uncertainty about the future availability of market access rights. These measures intensify bidding competition among incumbents and reduce their profit potential from collusion.

Klemperer (2002) proposes the English–Dutch design, which involves two stages of bidding: first, an English auction that raises price until all but a number of bidders have dropped out; second, a sealed-bid Dutch auction in which each remaining bidder makes a final bid not lower than the standing high bid. This hybrid auction form captures the useful feature of an English auction for mitigating the winner's curse, and that of a sealed-bid auction for attracting weak bidders who may not participate in an open auction.

4.5 Selling multiple items

The analysis so far has addressed selling a single item or, equivalently, assumed that each auction could be examined in isolation. This assumption is now relaxed to discuss design issues in selling multiple items with interdependent values.

Complements or substitutes

The value of a good to a bidder generally depends on the other goods the bidder acquires. A set of goods can be complements or substitutes. To illustrate, consider a sale of just two goods.

- The goods are complements if their joint value is greater than the sum of their stand-alone values. They have a synergy (or combinatorial) value because acquiring one of them would make a bidder willing to pay more for the other.
- The goods are substitutes if their joint value is equal to or less than the sum of their stand-alone values. Having acquired one good, a bidder would be willing to pay the same or less for the other. In other words, the bidder has a constant or diminishing valuation for an extra good.

Typically, identical items are substitutes because bidders care about how many items they win, not about which particular items they win. Non-identical items may be substitutes for one bidder but complements for another. Consider an auction of oil drilling rights on different land tracts: a firm may bid for any of these tracts as substitutes, merely seeking production capacity; another firm may bid for particular tracts as complements that harbour a certain mix of oil and gas reserves. Physical or environmental characteristics need not be the only source of synergies. A coordinated use of public resources can generate significant synergy values from these resources (box 4.6).

A multi-item auction achieves allocative efficiency if it allocates a set of items among bidders in such a way that the greatest combined value of those items is realised. In this context, the key design problem is to devise a mechanism that can reveal potential synergy values or diminishing marginal values of the items. Whether the items are complements or substitutes changes the nature of the design problem. Two types of model are used to analyse multi-item auctions.

- Auction models for identical items address design issues in allocating substitutes.
- Auction models for non-identical items address design issues in allocating complements.

Box 4.6 **Sources of synergy value in public resources**

For efficient allocation of public resources, governments commonly face the problem of determining the potential synergies from using these resources together.

- The effectiveness of conservation activities increases if nearby lands are conserved at the same time (chapter 5).
- The desire of telecommunications firms to provide their customers with mobile-phone roaming creates synergies in spectrum licences that cover adjacent spectrum bands or service areas (chapter 6).
- Electricity auctions create synergies by coordinating power supply over different hours of the day, from different generators, and through various ancillary services such as transmission and distribution.
- When allocating water rights in a stream system, the amounts of water available at different gauge points (adjacent or separated) are interdependent.
- When allocating airport time slots, for logistics management reasons, airlines' demand for take-off slots at flight-originating airports is related to their demand for landing slots at flight-destination airports.

Sources: Leautier (2001); Rassenti, Smith and Bulfin (1982); Saleth, Braden and Eheart (1991).

Selling identical items

In an auction of multiple identical items, if every bidder can bid for only one item, the auction outcome would have properties similar to those in a single-item auction. This is the case because any potential synergy between items is nullified. If bidders are allowed to bid for two or more of the available items, then the analogy between a single-item auction and a multi-item auction breaks down.

Bidders demanding a single unit

To acquire one of the available items, a bidder needs only to forecast the lowest winning bid and outbid all but a specific number of competitors (that number is one less than the number of items on offer). The condition for winning some item is similar to the equilibrium condition in a single-item auction, in which each bidder aims to win over the second-highest bidder. The revenue equivalence theorem (discussed in section 3.4 for single-item auctions) extends to multi-item auctions. All basic auction forms, when augmented with an appropriate reserve price, can yield the maximum expected revenue for the seller. In this case, the allocation of multiple items is efficient. Individual items may sell for the same price or different prices, however, subject to the pricing rule chosen (Maskin and Riley 1989; Weber 1983).

A multi-item auction can adopt either a uniform or a discriminatory pricing rule. In a uniform-price English auction, for example, the seller raises the price successively until the number of remaining bidders matches the number of items on offer. Each of these bidders wins and pays the same price, equal to the last announced price plus a specified bid increment. In a discriminatory English auction, bidders alternate in calling out higher bids until a bid is not topped. Items are sold in order of bids and winners pay their own bids, in which case prices may be different.

Sequential auctions sell multiple items one after another, so bids are determined in light of the value information revealed by the prices of previously auctioned items. Anticipating some chance of winning an item later, bidders discount their bids for earlier items. High-valuation bidders perceive a greater chance of winning an item later, and so discount their early bids by a greater proportion than the discounting by low-valuation bidders. Potential gains to bidders from this waiting strategy are arbitraged away, causing prices to drift close to a constant level throughout the sequence of auctions.[3]

Bidders demanding multiple units

To permit bidders to bid on both prices and quantities, the basic auction forms need to be modified. In an English auction, for example, the seller continuously raises the price while bidders indicate how many units they intend to buy at each price level. Bidding closes when the price is raised high enough such that total demand matches the number of items available. In a sealed-bid auction, bidders express their demand quantities at one or more price levels and the seller uses these bid functions to determine the clearing price and allocation. Under discriminatory pricing, winners pay their own bid prices. Under uniform pricing, all winners pay the same cut-off price for every unit they acquire.

Bidders' strategies for winning multiple items at auction inevitably involve guesswork, causing outcomes to detract from allocative efficiency (Ausubel and Cramton 1998; Maskin and Riley 1989; Menezes 2000). Each bidder has to forecast numerous winning bids of competitors and consider the implications for the number of items that can be won at different prices.

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[3] Risk-averse behaviour and common-value uncertainties render particular auction forms superior to others in revenue or efficiency terms; see Tenorio (1993) for a summary account of revenue comparisons. Risk and valuation uncertainty also can influence the trend of prices in sequential auctions; see Branco (1997), Bulow and Klemperer (1994), Gandal (1997) and McAfee (1993).

Demand reduction behaviour

A major source of inefficiency in multi-item auctions is related to bidders' strategy of holding back their demand. Bidders have the incentive to reduce demand in auctions whenever they expect the prices of individual items to converge, such as in uniform-price auctions.[4] In this situation, the price of every unit acquired by a bidder can depend on how much the bidder bids for the last few units included in an own demand schedule. This is the case because all units will fetch a similar price and that price could possibly equate to one of this bidder's bids on the last few items. The bidder will typically shade bids on the last units relative to the valuations of those units, so as not to drive up the average price of any acquired units. The bidder can, for example, bid an own valuation on only the first unit, then bid strictly less than own valuations on all other units. This strategy may enable the bidder to win a number of units at a reduced price, although this bidder may have to forgo part of the demand at that price.

At a given price, the larger the number of units that a bidder demands, the stronger the incentive for this bidder to shade bids at the margin. This implies differential bid shading: that is, bidders with the same valuation for an item shade their bids by different amounts. As a result, bids no longer correlate with valuations, leading to efficiency distortions. Kagel and Levin (2001) and Wolfram (1998) provide empirical evidence of demand reduction in uniform-price auctions.

By contrast, discriminatory pricing has the merit of inducing bidders to be truthful about their demand for multiple items, thereby avoiding the loss of allocative efficiency due to differential bid shading. Ausubel and Cramton (1998) suggest different ways in which to modify the Vickrey and English designs for determining discriminatory prices of identical items. The modified designs can promote allocative efficiency in general while maximising the seller's expected revenue in specified circumstances.[5] It is impossible to be definite, however, about the

[4] Besides uniform pricing, any auction that provides bidders with the opportunity for arbitrage of prices creates incentive for demand reduction. In sequential auctions, for example, bidders tend to reduce their demand provided that arbitraged prices are more or less constant over time.

[5] As Ausubel and Cramton (1998) and Menezes (2000) point out, uniform pricing in a multi-unit auction is not comparable to the second-price rule in a single-unit auction; nor is discriminatory pricing in a multi-unit auction comparable to the first-price rule in a single-unit auction. Such an erroneous analogy has previously misled comparisons of the efficiency property between discriminatory pricing and uniform pricing in a multi-unit auction (see, for example, Latacz-Lohmann and van der Hamsvoort 1997, p. 410). In a single-item auction, the first-price rule induces bid shading while the Vickrey or English format encourages demand revelation (section 3.4). In a multi-item auction, discriminatory pricing encourages demand revelation while uniform

comparative ranking in revenue terms between discriminatory pricing and uniform pricing in multi-item auctions; Menezes (2000), for example, reports mixed revenue comparison results from numerous auctions of financial instruments.

Selling non-identical items

Selling non-identical items is complicated by the fact that bidders may attach different synergy values to the same set of items. A sale can attract bidders seeking certain quantities of substitutes as well as bidders seeking particular sets of complements. For the latter bidders, some items are valuable only in combination with others. Auction outcomes are driven by an interplay of complex bidding strategies. This makes formal modelling and analysis of bidding behaviour a daunting exercise, which has only recently been attempted by auction theorists (Milgrom 2000).

The main design issue is to minimise bidders' guesswork in valuing complementary items. Bidders typically cannot decide how much a particular item is worth until they know which other items they will acquire. The seller can choose between item-by-item bidding and package bidding. For example, in a sequential auction, bidders have to choose between the risks of acquiring too few or too many items (box 4.7). By comparison, package bidding allows bidders greater flexibility in aggregating desired items and is therefore more likely to attain efficient or nearly efficient allocation. Appendix B discusses several sophisticated designs for selling spectrum licences that may be complements.

Box 4.7 **Sequential auctions of non-identical items**

Sequential auctions generally cannot support efficient allocation of multiple items with interdependent values because bidders face the problem of coordinating their own bids across auctions. Bidders cannot remake early bids in the light of later auction results. To improve allocative efficiency, the seller should sell first an item that:

- has the most dispersed valuations among bidders; and
- forms a core part of some identifiable packages.

These design features reduce bidders' dependence on early auction results. If the order of sales is reversed, then early bids on core items can be heavily marked down from true valuations. Moreover, bidders regret winning in early auctions if they subsequently fail to secure a key part of their targeted packages.

Source: Bernhardt and Scoones (1994).

pricing induces demand reduction, unless each bidder is restricted to only one item (then, no scope exists for differential bid shading).

4.6 Conclusion

A well-designed auction induces competitive bidding, attaining an efficient or nearly efficient allocation while enabling the seller and buyers to share the gain from trade. Particular market conditions and bidder profiles, however, can distort allocations away from efficiency. The winner's curse and bidder collusion give rise to inefficiencies. Bidders' efforts to avert risk affect the likelihood of efficient allocation in some auctions. A lack of bidder participation due to bidders' strategic motives leads to market failure. Selling related goods widens the scope for strategic bidding, possibly leading to efficiency distortions.

Environmental factors underlie many resource allocation problems in the public sector. When governments lack information on resource values or costs, individuals competing for public resources often have the incentive and ability to misrepresent their own valuations of these resources. Incomplete information and strategic motives restrict the effectiveness of any allocation method used by governments — not just auctions. A formal analysis of bidding behaviour has two important implications for governments' use of auctions.

First, in an auction, incentive problems are confined mainly to strategic bidding and entry deterring behaviour. These problems may lead to inefficient allocation but, to a large degree, can be addressed through careful design of auction rules to avoid unintended or adverse outcomes. Put differently, auction design is an important weapon for harnessing market forces. Compared with administrative allocations, the auction mechanism is generally effective in eliciting value information from resource users. The potential sources of inefficiency in auction allocations are likely to be more tractable than factors contributing to inefficient administrative allocations, such as political influence.

Second, in using auctions as a policy tool, governments need to understand the auction environment for a particular application and adapt auction design to that environment. An arbitrary choice of auction form is unlikely to work well. In particular, the basic auction forms may not cope with certain environments. Complex resource allocation problems require comprehensive solutions that depend on a good command of design intricacies. Careful design helps avoid dissipating the benefits of a market based approach to allocating public resources.

5 Auctions of conservation contracts

To meet environmental goals, governments may appropriate public funds for conserving natural resources on private lands. In implementing this type of policy program, governments need to motivate landholders to adopt specific land management practices and to do so at least cost. Auctions provide a means of improving the policy outcome in both respects. Under a conservation program, the administrative agency offers contracts for bidding in order to influence the type and amount of human activity on enrolled lands. These auctions involve landholders competing on not only price but also conservation outcome.

This chapter provides an economic framework for understanding bidding behaviour, efficient allocation of public funds and price determination in conservation contract auctions. The focus is on the issues that need to be addressed when designing this type of auction, rather than the performance of particular auctions or conservation programs. Section 5.1 explains the nature of conservation contracts. Section 5.2 discusses the role of auctions for conservation management. Section 5.3 describes auction markets established to allocate conservation funds in Australia and overseas. Section 5.4 discusses design issues in using a single auction to contract numerous landholders. Section 5.5 discusses design issues in comparing conservation costs and benefits within an auction.

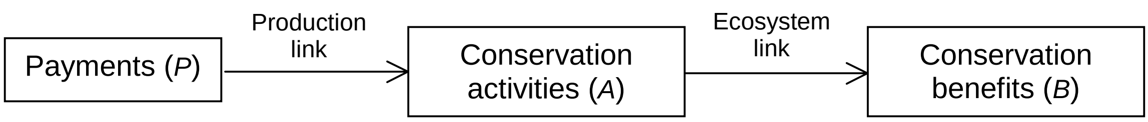
5.1 The nature of conservation contracts

The important goal of conservation management is to conserve biodiversity. Biodiversity can be broadly defined as the variety of life forms and ecosystems (an ecosystem is the community of creatures living in a specific environment such as a pond or a forest). Healthy ecosystems are essential for maintaining and regulating atmospheric quality, climate, fresh water, marine productivity, soil formation, cycling of nutrients, and waste disposal. Biodiversity therefore underpins effective use of natural resources for providing goods and services such as medicines, foods, timber and fibers. Conserving biodiversity enables ecosystems to become more resilient and life-supporting. DEST (1996) and SEAC (1996) discuss the aesthetic, existence, option and bequest values of biodiversity, which all add to the wellbeing of Australians.

Production and ecosystem links

An auction can be conducted to select those landholders who will receive government funds for activities designed to conserve biodiversity. To that end, the agency needs to set a budget, define objectives and adopt a bid selection method. Figure 5.1 shows the links between payment (P), conservation activity (A) and conservation benefit (B).

Figure 5.1 **Linking conservation payments to conservation benefits**



Examples of bid selection criterion: Minimise (i) $\frac{P}{A}$; or (ii) $\frac{P}{B}$ (that is, $\frac{P}{A} \times \frac{A}{B}$)

Once the budget, objectives and bid selection method are determined, owners of lands located within a defined area may submit bids to enrol their lands for conservation. Accepted bids constitute multi-year contracts with the agency, requiring landholders to adopt specific land management practices or undertake various conservation activities on their lands. These activities could include fencing, retaining standing trees and fallen timber, excluding stock from the site, and controlling pests and weeds. In exchange, landholders are paid an annual rent and, possibly, a share of their activity costs.

The agency selects bids by comparing payments to either activity levels or conservation benefits (illustrated in figure 5.1 as the ratio $\frac{P}{A}$ or $\frac{P}{B}$). Bid selection may or may not include an upper limit on the rental rate (called the reserve price). In a simple example where bids are compared in terms of payment per unit area of land, land area is taken to represent activity level, which is a proxy measure for the amount of conservation benefits. This method is often used when the relationship between conservation activities and outcomes (the ecosystem link) is not well known. This relationship could be site-specific and depend on geographic factors for which data are unavailable. In other cases, benefit indicators can be used to quantify site-specific effects of conservation activities.

The production link represents the cost aspect of conservation activities. Differences in land characteristics and productivity across landholders affect landholders' ability to select and perform effective conservation activities. Conservation decisions are influenced by numerous factors, including environmental awareness, income, land tenure, property size and technology. In deciding whether to conserve and, if affirmative, which part of their lands to conserve, landholders typically consider how conservation activities affect the profit potential of their land holdings. They may respond differently to economic incentives for adopting conservation practices. Lynne, Shonkwiler and Rola's (1988) empirical study of farmer attitudes confirms the positive yet varying influence of economic incentives on conservation efforts.

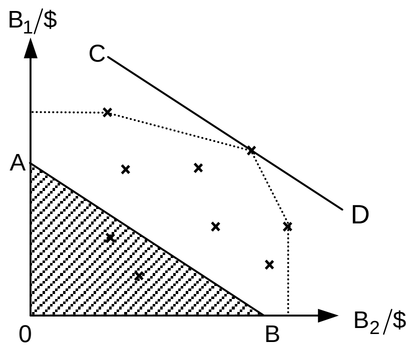
Attaining efficient allocation and payment savings

A conservation program yields the greatest amount of conservation benefits from a given budget if:

- selected landholders are productive and cost-efficient in performing conservation activities;
- selected conservation activities are effective in generating outcomes to meet the agency's conservation goals;
- selected conservation activities have low opportunity costs; and

Box 5.1 **Selecting productive, effective conservation activities**

Consider two types of conservation benefit, B_1 and B_2. The following figure measures these benefit variables divided by project cost along the corresponding axes. Each cross point represents a project of activities undertaken by a landholder.



The dotted envelope (called the frontier) indicates the most productive, effective projects in terms of achieving conservation benefits relative to activity costs. The agency applies a set of weights to derive an aggregate measure of the conservation benefits. Relative weighting is indicated by the slope of lines such as AB and CD, which gauge the agency's overall valuation of benefits for individual projects.

Line CD identifies project(s) that yield the highest level of conservation benefits per dollar of funding. Line AB eliminates projects within the shaded area that are deemed to provide too little conservation benefits relative to their costs. Line AB indicates the agency's reserve price for the conservation benefits, because public funds can be better spent elsewhere in pursuits other than conservation.

- selected landholders receive the smallest payments that are required to retain their participation in the program.

The first three conditions depend on the capacity of an auction to attain allocative efficiency in selecting winning bids (box 5.1). The fourth condition requires a procurement auction to minimise the total payment for a given level of conservation activities. (This corresponds to the property of maximising revenue in a selling auction.) The efficiency and payment properties jointly determine whether the greatest possible amount of conservation benefits is obtained with a given budget. Nevertheless, auction outcomes may involve tradeoffs between efficient allocation and payment savings.

5.2 The role of auctions in environmental management

Conservation management is hampered by a lack of information about the costs and benefits of different conservation activities. A conservation program may set the priority for conserving ecosystems in different regions on the basis of available ecological information. There are incentive problems, however, in eliciting private information on conservation costs and benefits from landholders.

An auction of conservation contracts can reconcile the interests of the agency and landholders in a coherent way. It enables the agency to accomplish conservation goals at least cost, while allowing landholders to establish their own prices for undertaking conservation activities (Latacz-Lohmann and van der Hamsvoort 1997, 1998). The ecosystem link is crucial to the agency's assessment of conservation benefits as well as to landholders' choice of cost-effective conservation activities. Depending on the production link, landholders require payments to cover activity costs and forgone incomes from land-based production; the agency pays to obtain conservation benefits.

The agency can tailor contract terms and bid selection methods for different regions, thereby accounting for regional variations in the potential of delivering conservation benefits (Stoneham et al. 2002). One limitation of auctions, however, is that bidding is voluntary whereas particular conservation goals may be achievable only through the conservation of ecosystems at specific sites. For example, a unique species or habitat with significant conservation value to the agency is found in one location only. In such a situation, the auction mechanism cannot guarantee successful outcomes because landholders located at the target sites may not participate in bidding and a lack of bidding competition may result in high contract prices that are beyond the agency's reserve. Instead of conducting an auction, the agency may have to either negotiate an agreement with landholders, or regulate land use, or assume public ownership and management of the land sites (for example, through the creation of a national park). These administrative measures, however, usually involve a costly, lengthy bargaining or legislative process (section 2.2).

5.3 Government auctions of conservation contracts

Governments increasingly recognise the potential of using auctions to allocate public funds for conservation. In Victoria, the Department of Natural Resources and Environment (DNRE) launched a pilot auction of conservation contracts (called the BushTender Trial) in 2001. In the United States, the Department of Agriculture has been running the Conservation Reserve Program (CRP) since 1986. These programs differ in their policy goals, their ways of setting the reserve price and their methods of assessing environmental benefits: for example, BushTender focuses on biodiversity conservation, while the CRP encompasses many more ecological aspects and distributes income assistance to farmers.

BushTender Trial

BushTender covers parts of the north east and north central of Victoria (DNRE 2001). DNRE officers visit landholders to assess the extent and quality of native vegetation on their lands and suggest land use options. Interested landholders bid for payments for undertaking conservation activities as promoted by the department officers. Bids are selected according to the department’s estimation of conservation benefits per dollar of payment. This criterion is established using a biodiversity quality index to weigh up activity levels, benefits and payments (box 5.2).

Each successful bidder enters a three-year land management contract with the department. As at February 2002, there had been 126 expressions of interest, 98 bid submissions and 73 accepted bids, accounting for $400 000 in payments (Stoneham et al. 2002).

Conservation Reserve Program

Under this program, landholders receive government funds for retiring their lands from farm production for a period of 10 to 15 years (FSA-USDA 1999). The program goals are to: (i) reduce water and wind erosion; (ii) improve water quality; (iii) reduce sedimentation; (iv) preserve soil productivity; (v) improve habitat for fish and wildlife; (vi) curb production of surplus commodities; and (vii) provide needed income support for farmers. These goals are subject to the enrolment of lands for specific environmental policy priorities and in specific regions (Reichelderfer and Boggess 1988).

Under this program, bid selection criteria have evolved over time (Amosson et al. 2000; Francis 2001; HRSCEH 2000; Osborn, Llacuna and Linsenbigler 1995). Before 1990, bids were compared in terms of dollars per hectare of conserved land. All eligible bids at or below a predetermined level were accepted. Such a payment cap was not made public until the auction was completed. Current CRP auctions employ an environmental benefit index to compare bids. This index weights various environmental objectives according to their relative importance (box 5.2).

Box 5.2 **Comparing environmental benefits**

Aggregate measures of land conservation value are constructed to account for an array of conservation benefits. These aggregate measures draw on environmental assessments conducted by ecologists and are limited by whatever data an agency is able to collect. Aggregation methods differ mainly in the choice of relative weights for individual benefit variables. Examples include the biodiversity quality (BQ) index used in BushTender and the environmental benefit index (EBI) currently used in the CRP.

The BQ index is the product of the biodiversity significance score and the habitat services score. The first factor measures current conservation value and the second measures activity level. Bids are ranked by the ratio of the BQ index to the payment.

The EBI employs a point-scoring method to measure six benefit variables: (i) wildlife; (ii) water quality; (iii) erosion; (iv) enduring benefits; (v) air quality; and (vi) state and national conservation priorities as specified by the US Department of Agriculture. Bids are compared in terms of EBI per dollar of payment.

Sources: Amosson et al. (2000); Stoneham et al. (2002).

In 1999, the program enrolled 36 million acres of land (equivalent to 10 per cent of farmland in the US). In 2001, the annual bill for the program was US$1.5 billion. The US Congress has planned to expand program enrolment by another 12 million acres in 2002 (Veneman 2002).

5.4 The contracting of numerous landholders

An auction of conservation contracts selects numerous landholders to take part in conservation. This type of auction is analogous to a multi-item auction, because each landholder can bid for a different activity level and because an unspecified number of landholders can win contracts in the same auction. This gives rise to the following design issues:

- the presence of synergies in conserving adjacent areas; and
- the choice of payment rules.

Synergies in conserving nearby areas

Conservation synergies are created from common borders for contiguous lands and connecting paths for separated conserved lands.

Sources of synergy

Conserving adjacent lands can increase the effectiveness of conservation efforts. Conservation benefits are derived mainly from the interior of conserved lands. For a specific land area, edges are where revegetated blocks interact with the surrounding environment, forming different vegetation and habitat from that at the interior. The higher the ratio of land area to land perimeter, the greater the potential for generating conservation benefits. Common borders reshape the entire conserved region, increasing that ratio and therefore the effectiveness of conservation efforts.

Box 5.3 **Boundary synergies in conservation activities**

Conservation values depend on the size and shape of lands, as illustrated by the following two examples.

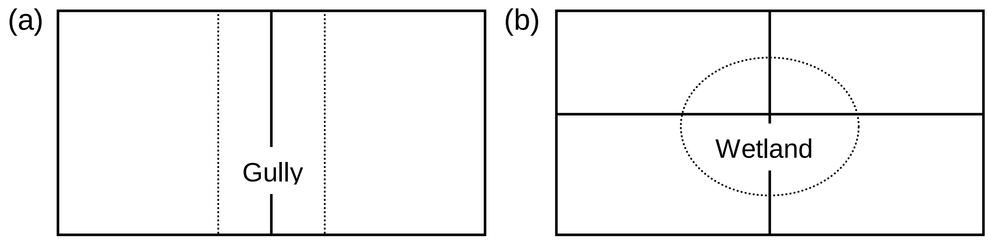


Diagram (a) represents two neighbouring landholders who bid for contracts to conserve the gully on a common edge of their lands. Conservation benefits are maximised if both bids are accepted, conserving both slopes of the gully to reduce soil erosion and improve water quality. One bid accepted in isolation would suffer adverse boundary effects from the neighbour’s side, reducing the area that can be effectively conserved.

Diagram (b) depicts a wetland located at the adjoining corners of four lands. The agency needs to engage all four landholders to conserve the entire wetland. For each of these lands, conservation benefits are affected by any adverse land use on the other three quadrants.

Source: Bennett, Kimber and Ryan (2000).

Bennett, Kimber and Ryan (2000) identify several sources of conservation synergy for contiguous lands, including reductions in: the exposure to wind and light that affect temperature and humidity; the invasion of weed species from surrounding land; the exposure to chemicals used on the surrounding land; and the incursions from human, domestic stock or feral animal pests (box 5.3).

Conservation synergies may also occur where habitat corridors link separate conservation areas (Bennett 1998). Such corridors help wildlife species move through surrounding lands. Conserving habitat corridors generates little stand-alone environmental value. Yet, by linking other conservation areas or joining together remnant vegetation, habitat corridors become valuable for supplementing conservation benefits from nearby areas.

The possibility of joint bidding

In the presence of boundary synergies, attaining allocative efficiency in an auction requires design refinements. The agency may wish to encourage all pertinent landholders to participate in an auction so that bids with synergetic values are accepted together. However, landholders face the double uncertainty of winning a contract and being able to realise the synergetic value (if any) of their lands; so they may not consider boundary synergies when determining their bids. Their bids depend not only on their own activity costs and benefit contributions, but also on expectations about neighbours' entry and bidding strategies.

These contingencies expose the agency to the risk of paying high rental fees without realising full synergy values from contiguous lands if neighbouring landholders do not all win in an auction — for example, where landholders owning habitat corridors do not bid for contracts because they are not aware of the synergies with surrounding lands or because high costs diminish their chance of winning.

To realise boundary synergies, the agency needs to look beyond the design that allows only separate bids from individual landholders. One possible solution is to allow neighbouring landholders to submit joint bids that cover adjoining sites as a whole. This solution makes bidding more flexible for landholders because they can choose to bid for conserving their own lands or make joint bids with others, or both. Landholders who submit a joint bid decide among themselves how to share costs and payments, therefore to a degree helping the agency with the funding decision.

The efficiency and payment properties of joint bidding are barely explored in the literature reviewed for this paper and detailed auction rules are yet to be developed. The feasibility of making a long-term contract with multiple parties is in question.

Theoretical and contractual issues need to be addressed before joint bidding can be put into practice.

The choice of payment rules

Payment rules specify the way of determining contract payments on the basis of bids. Different payment rules induce different bidding behaviour. Here, the payment rules compared are:

- *discriminatory pricing*, whereby landholders receive their own rental bids for accepted activities; and
- *uniform pricing*, whereby landholders receive the highest accepted, or lowest rejected, rental bid for accepted activities.

For uniform pricing, the choice between the highest accepted bid and the lowest rejected bid has implications for bidding strategies and auction outcomes (Hansen 1988; Milgrom 1989). Practical differences between these alternative rules depend on the degree of bidding competition, the agency's budget and landholders' cost profiles. The present discussion focuses on major differences between discriminatory pricing and uniform pricing, abstracting from the different ways of setting a uniform price.

To simplify the analysis, activity levels can be expressed in terms of land area conserved and payments in terms of rental fee per hectare of land. Accordingly, payment rules are set for pricing activities rather than benefits. For uniform-price and discriminatory auctions alike, benefit prices may vary across landholders because the same activity performed on different parcels of land can deliver different conservation benefits. As such, contract payments do not directly vary with benefit contributions.

Similarities with a multi-item auction

Bidding for conservation contracts can be analysed as a multi-item auction, in which the seller has a number of contracts available for bidding and each bidder bids for conserving a land of certain area at one price (rental fee). In this type of auction, bids specify rental fees and land areas. Bids are 'lumpy', in the sense that each landholder nominates one rental rate for the whole land area included in an own bid. Under this approach, a landholder cannot divide a parcel of land into two or more bids in order to obtain different rental fees for different parts of that land. Pricing can be discriminatory only with respect to individual landholders, not individual land areas belonging to the same landholder.

Landholders can bid for conserving land of different areas, depending on their own cost considerations. From a landholder's perspective, the total opportunity cost of conservation includes the direct cost of conservation activity and the forgone income from production on a conserved land. In some cases, the income loss is more significant than the activity cost. The larger the land area conserved, the less is the input of land available for production. Land-based production typically exhibits economies of scale. Conserving a larger land area would increase the average cost and decrease the profit margin of land-based production. This cost pattern implies rising marginal costs of conservation, restraining landholders from conserving large land areas. It is evident that landholders, on cost grounds, tend to conserve only part of their land holdings:

> James Hamilton's 800 hectares of grazing land between Bendigo and Maldon have a few unusual features … Last year Mr Hamilton signed up to fence off 150 hectares of poor grazing land as part of the Victorian Government's BushTender program, which pays farmers not to farm some land to encourage biodiversity… [He said,] 'For us this was terrific. This was the icing on the cake, to put away 150 hectares which we can lock up for three years and during that time we'd still be developing the less significant areas that weren't as precious.' (Paxinos 2002)

To compare the pricing rules for their effects on auction outcomes, theoretical results are drawn from section 4.5, which discusses multi-item auctions with multi-unit bids, and Tenorio's (1999) analysis of lumpy bids. Box 5.4 explains the assumptions about landholders' behavioural characteristics.

Box 5.4 **Behavioural assumptions**

The standard behavioural assumptions adopted in auction theory (section 3.2) reasonably fit an auction of conservation contracts.

- It is typical for landholders to make independent, private estimates of conservation costs (Cason, Gangadharan and Duke 2002).
- The assumption of risk neutrality is applicable because, however risk averse landholders may be, the risk of winning or losing an auction is small relative to their assets. To some, the stakes are just 'the icing on the cake' (Paxinos 2002).
- Landholders may have different productivity and cost levels; however, this possibility does not violate the assumption of symmetric bidders. Bidders are *symmetrically informed* if their bases for costing are indistinguishable before auction, not if their cost estimates are comparable, which remains a matter of conjecture until the auction is completed. If a conservation program is implemented for a specific region or for lands with a specific ecological aspect, landholders competing in the same auction are likely to have symmetric cost information.

The impact on allocative efficiency

Under uniform pricing, landholders tend to shade bids, bidding above their costs of conservation. Moreover, landholders with a large land area tend to shade their bids by more than those with a small land area. This bidding behaviour reflects bidders' strategic motive to maximise potential profit from winning a conservation contract.

Landholders face a strategic tradeoff between an increase in the rental fee and a decrease in the area of land conserved. By proposing to conserve a smaller land area, a landholder is prepared to receive a reduced payment for winning a contract. This strategic move reduces the landholder's supply of land area for conservation, thus called 'supply reduction'. (It is analogous to 'demand reduction' in an auction selling multiple items; see section 4.5.) It allows high-cost competitors a greater chance of winning some contracts from a given conservation budget. As a result, the rental fee submitted by a marginal winner may increase, thereby raising the uniform rental fee for all winners.

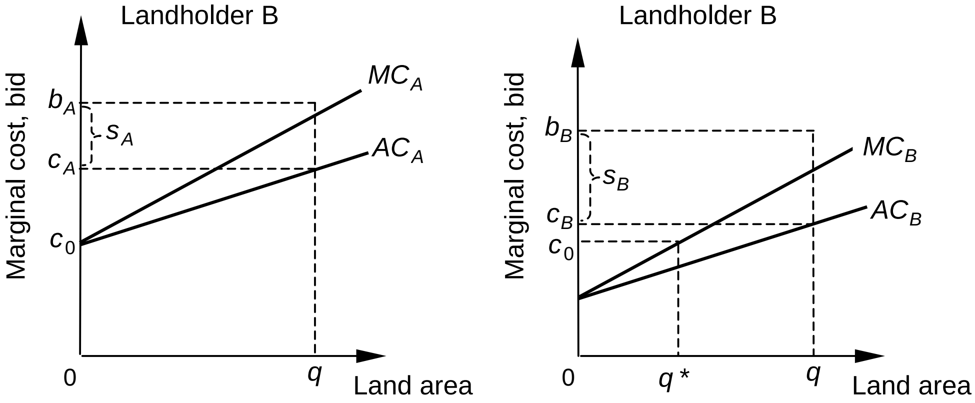
Large landholders can individually gain from conserving a reduced land area if the potential increase in rental fee more than offsets the reduction in land area conserved. They may be paid less from a contract; however, under the condition of rising marginal cost of conservation, the average cost is lower with a reduction in the land area conserved, actually yielding a greater profit. By comparison, supply reduction is less attractive as a bidding strategy for small landholders because their bids cover limited land areas and are unlikely to be influential in determining the marginal winner and setting the uniform price. Consequently, the incentive for this form of bid shading grows with land area, leading to different degrees of bid shading by landholders with different sizes of land holdings.

Auction outcomes are biased in favour of small landholders, yet not on the basis of superior productivity; their chance of winning a contract increases merely because, compared with large landholders, they do not have as strong an incentive to shade bids above costs. As a result, bids need not be aligned with costs, leading to efficiency distortions. Wolfram (1998) presents evidence of differential bid shading in a uniform-price procurement auction for electricity. From conducting selling auctions in a laboratory, Kagel and Levin (2001) obtain experimental data that confirm the adverse effects of demand reduction on allocative efficiency and revenue potential. Their results most likely apply to procurement auctions with uniform pricing.

Under discriminatory pricing, the incentive for differential bid shading disappears. Landholders' expected marginal profits from conservation do not depend on their land sizes because high-cost activities (if accepted) can earn high rental fees and

Box 5.5 **Efficiency distortions due to lumpy bids**

Funding allocation is efficient if contracts are awarded to whichever activities have relatively low costs per unit of land area conserved. Lumpy bids lead to inefficiencies, however, if marginal cost of conservation rises with land area. This effect is illustrated in the following example, where landholders A and B compete for a conservation contract. Their average costs AC_A and AC_B (and correspondingly their marginal costs MC_A and MC_B) rise at the same rate with land area but differ by a constant gap.



On efficiency grounds, the funding priorities are to first contract B for an area up to q* (because B has the lowest marginal cost at below c_0) and then contract A and B for additional, equal land areas as the program budget allows. Under this allocation, B conserves a larger land area than that conserved by A, while both of them carry out conservation at the same marginal cost. A genuine discriminatory pricing rule would achieve this outcome, with landholders each submitting a schedule of bids for different land areas (similar to a supply function). Assuming that the landholders apply the same proportional cost markup in their bids, bids would be consistent with relative marginal activity costs for *any* land size.

The 'all or nothing' nature of lumpy bids precludes contracting the landholders for up to the land areas at which they are relatively productive. Restricted by lumpy bids, they each bid one rental rate above their average costs. The cost markup now varies directly with the productivity level, which is the landholders' private information. Expecting to be relatively productive, one can afford to increase the cost markup and still maintain a perceived advantage in bid comparisons.

Accordingly, for a given land area q, A bids b_A and B bids b_B. (By design, these bids are shown to exceed the marginal costs, which need not be generally so.) B always outbids A (b_B lower than b_A) because B has a lower cost than A *if* they are to conserve the same area of land respectively (c_B lower than c_A). Their bids differ by less than the difference in their average costs, reflecting an incomplete offset due to the different amounts of bid shading (s_B greater than s_A). As a result, B wins over A to conserve a larger land area than justifiable on efficiency grounds. This source of inefficiency vanishes, however, if the landholders have constant (flat) cost functions.

Source: Adopted from Dasgupta and Spulber (1990).

vice versa for low-cost activities. Pricing for conservation contracts, however, is discriminatory only with respect to individual landholders as a result of the submission of lumpy bids. Lumpy bids conceal variations in the marginal cost over different land areas conserved by a landholder. The bid–cost correlation weakens as a result, contributing to efficiency distortions (box 5.5).

In summary, neither uniform pricing nor discriminatory pricing makes a perfect claim to allocative efficiency. On balance, a discriminatory auction is probably less prone to efficiency distortions because it provides landholders with fewer incentives for bid manipulation. Moreover, under uniform pricing, landholders would receive a rental fee in excess of their bid prices if they win, creating the impression that landholders are 'overpaid'. By contrast, discriminatory pricing has the popular appeal of not paying landholders more than what they bid at auction. This pricing feature, however, is not necessary for allocative efficiency and payment savings; these outcome properties can be achieved without using a 'pay your bid' rule (see box B.3 in appendix B).

The impact on payment

For a multi-item auction in which bidders are not restricted to one item, it is impossible to tell which of the alternative pricing rules can generally yield greater revenue (Tenorio 1993, 1999). Revenue comparisons are subject to allocation effects. A uniform-price auction and a discriminatory auction result in the same expected total payment if they select the same winning bids. Bid selections generally vary across auction formats, however; as a result, payment equivalence in multi-item auctions cannot be taken for granted.

Within the empirical literature reviewed, no study simulates landholders' cost structures in a way that adequately captures the complexity of a multi-item auction with multi-unit bids. Instead, lessons are drawn from numerous studies of auctions for selling financial instruments (for example, bonds). These studies provide mixed results on comparing revenues in multi-item auctions (which are taken here to imply mixed results on comparing payments in auctions of conservation contracts). The studies reviewed are limited by specific assumptions about bidders' behavioural characteristics. Revenue comparisons typically involve testing the *joint* hypotheses that particular behavioural assumptions apply *and* that either uniform or discriminatory pricing yields greater expected revenues under those behavioural assumptions.

Bidders' behavioural characteristics affect revenue comparison results. Goswami, Noe and Rebello (1996) explain that bidder communication before an auction facilitates collusive strategies under the uniform pricing rule, but competitive strategies under the discriminatory pricing rule. Their results show that uniform pricing is revenue inferior to discriminatory pricing. Tenorio (1993) obtains opposite comparison results, however: uniform pricing can attract more bidders to participate, thereby increasing bidding competition and auction revenue compared with discriminatory pricing.

The above empirical results, obtained from selling auctions, most likely apply to procurement auctions too. There is probably no clear-cut answer to the question about which pricing rule would lead to lower payments in conservation contract auctions. Tenorio's (1993) results highlight the positive effect of uniform pricing on bidder participation. This observation conforms with the supply reduction behaviour under uniform pricing, which provides small landholders with an increased chance of winning some contracts with a high rental fee. Small landholders may therefore prefer uniform pricing to discriminatory pricing.

5.5 Bidding on price and service quality

For cost–benefit comparisons of conservation activities, the question arises as to how an auction can incorporate the information on conservation benefits. The answer to this question depends on whether conservation benefits are private or public knowledge. On the one hand, landholders can have private information about the environmental impact of their production, such as the potential effects on rare or threatened species on particular lands. On the other hand, the agency can know better than landholders the ecological significance of their lands and the match of policy objectives with land characteristics. By weighting various components of an aggregate benefit measure, for example, the agency can determine the conservation values of those lands.

Conservation contract auctions have complex information settings: both the agency and landholders are likely to possess some private benefit information. Analysis of these auctions is possible only under certain modelling assumptions that impose a tractable structure on the benefit information held by the agency and landholders respectively. Analysis results are conditional, however, on those assumptions and may not be applicable more generally.

This section generically examines procurement auctions in which bidders compete in terms of price (payment) and service quality. Such auctions are called *multi-dimensional*, because bid selection involves two dimensions: price and quality. The quality dimension aggregates an array of service attributes according to a weighting scheme that reflects the buyer's preferences. In this context, quality corresponds to some aggregate measure of conservation benefits, such as the biodiversity quality index and the environmental benefit index (box 5.2).

Two scenarios of private information on service quality are considered. The first scenario is an auction in which bidders have private information on service quality. In the second scenario, the buyer has private information on service quality.

Bidders with private information on service quality

Bidders have private information about their costs of providing different levels of service quality. Bids specify prices and quality levels. By assumption, the service quality delivered can be verified afterwards. The buyer designs a scoring rule to combine price and quality into a score for each bid. The highest-score bidder wins the contract. The bid selection process, including the scoring rule and reserve price, is public knowledge.

Competing on quality-adjusted price

Thiel (1988) shows, under the standard behavioural assumptions, that the problem of designing a multi-dimensional auction is equivalent to the problem of designing an auction with only price competition — that is, allocating items or contracts with a pre-specified level of quality. For multi-dimensional auctions, auction design is aimed at attaining efficient service provision and relatively high expected scores. These objectives are the equivalent of attaining efficient allocation and relatively high expected prices in selling auctions. An analogous result to revenue or payment equivalence is that the basic auction forms, by incorporating a scoring rule, can determine the same quality-adjusted price. Introducing the quality dimension into an auction, therefore, does not change the nature of auction design; all it means is that quality-adjusted prices replace raw prices. By analogy with a first-price auction, a ‘first-score’ auction, for example, is one in which the winner delivers service quality and receives payment as specified in a sealed bid.

The choice of the scoring rule is the key design issue (Che 1993). The appropriate scoring rule is based on the buyer’s relative preferences for price and quality (which can be conceived as the buyer’s utility function) and includes an adjustment to limit the information rent accruing to relatively efficient bidders — that is, the cost that the buyer bears due to the information disadvantage regarding quality (section 3.5). The adjusted scoring rule puts less weight on quality than what the buyer’s price–quality tradeoff would warrant. Using that scoring rule, a first-score auction attains allocative efficiency by contracting someone who can deliver the chosen quality level at a lower cost than other bidders can.

Implications for auction design

Several observations are instructive. First, transparency in the bid selection process is essential for efficient contracting. Provided that the scoring rule is common knowledge, bidding competition effectively ranks bidders by their cost structures. The winning bids reflect the buyer's preference ordering, contributing to allocative efficiency. The buyer overpays for quality due to the information disadvantage but can curtail the loss of information rent to bidders with an appropriate adjustment in the scoring rule.

Second, if service quality cannot be precisely measured, then the buyer should require bidders to pass certain quality thresholds before submitting price-only bids (Cripps and Ireland 1994). This design suffers from potential efficiency losses, however, because outcomes can only approximate the buyer's preferences.

Third, if the buyer is unable to verify service quality after auction, then bidding behaviour is characterised by the problem of adverse selection: price competition at auction may lead to the selection of low-quality service. Manelli and Vincent (1995) recommend, in this situation, that the buyer sequentially makes credible, 'take it or leave it' offers until some bidder accepts the offer. Without any reliable prior information on service quality, the buyer cannot exploit price competition. Instead, the proposed contracting procedure allows a better chance of obtaining a relatively high level of service quality for the payment offered, improving allocative efficiency if the buyer values quality gains more than what they cost the potential bidders to produce.

Fourth, if bidders have little scope for varying their service quality, a first-score auction has the same outcome as that of a first-price auction (Che 1993). Bidders would adapt to the alternative auction forms, adjusting their bids for any perceivable quality differences in such ways that lead to the same auction outcome. In the case of allocating conservation funds, if lands have predetermined conservation benefits, then using either a first-price auction or a first-score auction would determine the same contract payment. This prediction contrasts with the empirical results obtained by Reichelderfer and Boggess (1988), who suggest that score based auctions determine lower contract payments than those determined by price based auctions. Their results, however, are affected by some invalid modelling assumptions (box 5.6).

Box 5.6 Comparing activity and benefit based bid selection methods

Ignoring shifts in bidding behaviour across different auction formats can lead to misleading results in empirical research. One example of this pitfall is the study by Reichelderfer and Boggess (1988), which compares the effectiveness of activity based and benefit based auctions in allocating conservation funding.

The researchers argue that the Conservation Reserve Program, if implemented with a benefit based bid selection method (comparing unit prices of conservation benefits), would have obtained greater conservation benefits from a given budget than under the adopted activity based method (comparing payments per unit of land area conserved).

The study uses actual bids and ecological data to calculate soil erosion reductions due to the 1986 program. A simulation model is used to predict benefit changes that would have occurred under the alternative bid selection method. The model assumes that bids exceed activity costs by a constant factor. This parameter represents the amount of bid shading and has an assumed value of 1.25. With activity costs of $100, for illustration, a landholder bids $125 for a conservation contract.

Simulation results suggest there is scope for reducing total erosion by about 18 per cent. This estimate, however, is affected by the following critical, yet apparently invalid modelling assumptions about bidding behaviour.

- The amount of bid shading is assumed to be invariant with respect to the bid selection methods. This implies that landholders ignore the public, ecological information that is used for comparing bids under the benefit based approach.
- Landholders competing in three program periods are assumed to shade bids by the same amount. This ignores the effect of bidding competition on bid shading. Under the first-price format, the amount of bid shading most likely varies inversely with the degree of bidding competition. The program periods have recorded acceptance rates that range from 23 per cent to 80 per cent of submitted bids, so the amount of bid shading should have changed across auctions.
- The study assumes landholders use dominant bidding strategies — that is, bids depend on only landholders' own cost variables. This assumption is hardly tenable in multi-item auctions.

Affected by these invalid assumptions, the simulation results are questionable and the study's general conclusions may not hold under a suitable theoretical framework of bidding behaviour.

Buyer with private information on service quality

Several contracting practices enable the buyer to keep private information on service quality from bidders for the purpose of determining bids. First, only the buyer has the know-how needed to measure quality. Second, an assessment of quality is feasible only after bid submission. Third, the buyer conceals quality assessment results. Fourth, bidders can evaluate their own service attributes but do not precisely know the buyer's relative preferences for these attributes. In these circumstances, the key design issue is the buyer's information policy: the decision to conceal or disclose information on service quality can crucially affect bidding behaviour and auction outcomes.

Bidding behaviour

Without the crucial information needed for evaluating service quality, bidders have an added incentive to shade their bids above costs, taking into account their own assessments of relative service quality. Relative service quality indicates the extent to which the buyer's preferences match the service attributes supplied by individual bidders. Particular service attributes may be costly to produce. Nevertheless, the higher the service quality in relative terms, the greater the scope for a bidder to raise contract price. Even if bidders each produce a fixed level of service quality, they would still have an incentive to shade their bids in line with any perceived differences between their own and competitors' service quality. Anticipating a quality disadvantage, for example, bidders tend to bid above their costs by less than they otherwise would. That way, bidders increase their chance of winning, albeit at the cost of reduced profits if they do win some contracts.

A lack of information on service quality compounds the guesswork that bidders face in making bid decisions. To maximise potential profits from an auction, apart from cost considerations, bidders have to individually predict the buyer's preferences for quality as well as their competitors' quality choices. As only the buyer has access to a precise measurement of quality for every bidder, all bidders alike face increased uncertainty in their own quality assessments. The greater the uncertainty affecting bidders in measuring their own quality levels, the less they are able to supply favourable but costly service attributes in order to increase their chance of winning a contract.

In repeated auctions, for example, the buyer can reweight various component attributes of an aggregate quality measure. This change may or may not be related to a shift in the buyer's preferences. Unless the buyer forewarns bidders of a change in the way of measuring quality, bidders are led to believe in the randomness of the buyer's preferences and therefore perceive increased uncertainty in their own quality assessments.

According to Moscarini and Ottaviani's (2001) theoretical analysis, bidding strategies are affected by bidders' expectations of: (i) competitors' quality levels and costs; and (ii) the buyer's way of measuring quality. The latter consideration refers, for example, to the weights that the buyer attaches to various service attributes for calculating relative quality, not to the results from that calculation (which remain unknown to bidders until the conclusion of the auction). By anticipating the buyer's preference weights, bidders attempt to determine how significantly various service attributes might affect their chance of winning a contract compared with some random effect.

Auction outcomes

Expectations based on incomplete information intricately drive the competition among bidders and the competition between the buyer and bidders. The interplay of such competition forces is illustrated by the following two stylised examples. These polar cases define a continuum of sophisticated bidding behaviours across different information settings.

Case 1: Symmetric bidders perceiving a strong impact of service attributes on bid selection

In this scenario, bidders are symmetrically (but not fully) informed of their relative service quality — that is, they know as much as their competitors know about the buyer's preferences for quality. Moreover, they are confident of predicting the buyer's quality assessment. In particular, each of them anticipates the buyer to select one specific mix of service attributes, so links the chance of winning a contract to the supply of that buyer favoured quality mix rather than any low-price service; however, they may make different predictions of the buyer's preferences.

To adopt the mutually profitable strategy, bidders avoid price competition and select their own service attributes in the hope of matching the buyer's preferences. For a given number of bidders, price competition would reduce bidders' expected profits without necessarily improving their chance of winning a contract. Bidders tend to bid close to the buyer's reserve price, expecting profits to vary inversely with costs. As long as bidders expect positive profits, they have little incentive to base prices on costs. Auction outcomes are characterised by subdued competitive pressure on price, high expected profits for bidders, and a large transfer of information rent from the buyer to the winner.

Case 2: Asymmetric bidders perceiving a weak impact of service attributes on bid selection

Bidders are asymmetric, in the sense that some are perceived to produce higher service quality than others. Nevertheless, bidders are uncertain about the buyer's way of determining relative quality and so cannot determine whether their own quality assessments match the buyer's preferences. The quality differences perceived by asymmetric bidders are therefore not a reliable forecast of bid selection results. Bidders anticipate their own quality assessments to be imprecise, and so emphasise price competition.

Strong bidders, who are distinguished by the perception of high-quality service, can pre-empt bidding competition by quoting low prices relative to their costs of supplying the perceived superior service quality. This cautious strategy allows them a better chance of winning a contract even if the buyer happens to make an unfavourable assessment of their service quality. Weak bidders, who are perceived to produce low-quality service, quote relatively low prices too. Consequently, price competition drives down the expected contract price, enabling the buyer to gain a large share of information rent.

Impact on payment

The key factor that affects contract price is the sharing of information rent between the buyer and bidders. If bidders have symmetric, incomplete information about the buyer's preferences for quality, they can strategically avoid price competition in order to increase their share of information rent. This strategic incentive is strong if bidders are confident of inferring the buyer's quality assessment. In a sense, each bidder chooses to supply a particular mix of service attributes based on an own guess of the buyer's preferences. They need only compete directly with those supplying the same quality mix, thus reducing price competition overall.[1]

To gain a greater share of information rent, the buyer can introduce uncertainties into the way of determining relative service quality. This tactic increases bidders' difficulty of predicting the buyer's preferences and thereby limits the scope for bid shading. Price competition strengthens as a result, reducing the expected contract price but (as discussed below) adding to efficiency distortions.

Impact on allocative efficiency

Allocative inefficiencies result from the combined effects of the buyer's exclusive information on service quality, bidders' dependence on guesswork in making bid decisions, and strategic pricing behaviour. The key to allocative efficiency lies in

[1] Similar incentive effects are present in markets for differentiated goods or services in which firms need to devise marketing and pricing strategies on the basis of limited information on customers' preferences for their products. In such a market, depending on their prior belief about the market demand, individual firms may target only those customers who are identified with certain preferences while giving up other customers to competitors; that way, firms can develop their own market niches and avoid price competition.

the correlation between prices and cost–quality ratios. A strongly positive correlation means a high probability of selecting low-cost, high-quality service in an auction.

If bidders are unable to assess their own service quality precisely, they have to guess the buyer's preferences and determine their bids on the basis of guesswork involving random choices. This aggravates strategic pricing, as opposed to cost-based pricing. Bid-shading behaviour is particularly sensitive to incomplete, imprecise information on service quality, limiting the revelation of costs in bids. The greater the uncertainty that bidders perceive in their own quality assessments, the more their bid decisions are driven by strategic motives and randomness, and the less they are driven by cost considerations, leading to greater efficiency distortions.

Empirical evidence

Cason, Gangadharan and Duke (2002) compare experimental data from quality-disclosed and quality-concealed auctions. According to their results, if the measurement of quality is disclosed to bidders, then the price–cost correlation is strong and positive. Furthermore, bid prices are strongly and positively correlated with quality measures. These relationships confirm the incentive for bidders to raise prices for high-quality items (proxy for contracts with high-quality service attributes).

Compared with quality-disclosed auctions, quality-concealed auctions increase the levels of quality for given contract budgets by 10 per cent on average. To properly interpret this result, one needs to decompose the estimated quality gains into: (i) payment savings due to reduced bid shading; and (ii) allocative efficiency gains due to the selection of high-quality, low-cost items. Unfortunately, the study does not directly address the sources of quality gains. Data analysis seems to suggest that payment savings are the main contributor. This effect is evident because the cost markups for high-quality items are significantly lower (implying smaller amounts of bid shading) in quality-concealed auctions than in quality-disclosed auctions. That observation does not suggest allocative efficiency gains, because high-quality service can have low or high costs.

Implications for auction design

If the buyer has the choice between disclosing and concealing the true assessment of relative quality, then an important question for auction design is whether the buyer should release such information before auction. With a degree of generalisation, several observations from the above analysis are instructive for answering that question.

First, by concealing the information on relative quality, the buyer may succeed in reducing contract payments and gaining a larger share of information rent. Any quality gains or payment savings for the buyer, however, are partly offset by allocative efficiency losses. It is the adverse effect on allocative efficiency that matters for overall economic wellbeing. In government auctions, information rent is an income transfer between governments and bidders in the private sector. Extracting information rent from bidders, by itself, achieves little in promoting productive, effective use of resources.

Second, in a quality-concealed auction, bidders have an incentive to ascertain the buyer’s preferences for quality, so that they can avoid price competition and increase profit for certain information settings. If bidders can infer quality measures from previous auction results or acquire the know-how needed to make their own quality assessments, then the buyer’s private information on quality degenerates. As a counter tactic, the buyer can secretly alter the way of determining relative quality in order to maintain an information advantage. A secret change in the measurement of relative quality may also reflect a genuine shift in the buyer’s preferences. Irrespective of the buyer’s motive behind such secret changes in the way of assessing quality, bidders will eventually perceive them to be a source of uncertainty in their quality assessments. Adding uncertainties to bidders’ quality assessments can lead to a reduction in the overall gain from trade that is available for sharing between the buyer and bidders.

Third, in a quality-concealed auction, bidders may face an incentive to not reveal their own service attributes to the buyer if such information is to become public before auction. Bidders have two strategic considerations behind this incentive: (i) they are unsure about the impact of those service attributes on the buyer’s quality assessment; and (ii) price competition among asymmetric bidders may intensify if the information on individual bidders’ service attributes is made public. This information enables the buyer to select high-quality service and gain a greater share of information rent. For bidders who supply buyer favoured service attributes, their revelation of private information on quality can lead to greater chances of winning a contract. These bidders become worse off, however, when the release of such information results in greater price competition, potentially reducing their profits if they win the auction. The nature of the auction shifts from a competition *among bidders* in which private information on their costs and quality is elicited, towards a contest *between the buyer and bidders* for information rent, which can adversely affect the revelation of socially beneficial information.

Fourth, using a quality-disclosed auction, the buyer can keep the expected contract price low without sacrificing allocative efficiency. The necessary conditions include: (i) a properly designed scoring rule to reveal the buyer's preferences and control the distribution of information rent; (ii) transparency of the bid selection process; and (iii) sufficient bidding competition. The buyer's disclosure of own quality preferences reduces bidders' strategic incentives for bid manipulation. Competitive pressure forces bidders to reveal private information on costs and service quality. Given the buyer's preferences for certain service attributes, bidders include those attributes in their service supply subject to cost considerations.

5.6 Conclusion

Auctions can provide an effective solution to the problem of allocating public funds for the conservation of biodiversity. By introducing competitive pressure among landholders, the auction mechanism helps reveal the cost and benefit information needed for sound conservation management decisions. Governments continue to play a role by identifying conservation priorities, and assessing and monitoring the benefits of conservation activities. Furthermore, auctions can be used to address other environmental problems, including the management of pollutant and saline discharges.

An auction of conservation contracts can involve complex design issues. Improved auction design enhances both government budgets and allocative efficiency. Auction theory provides the framework — that is, making strategic decisions under incomplete information — for developing and substantiating intuition behind various design features. A formal analysis is necessary because some intuition may fail for such a complex resource allocation problem. Empirical research confirms or rejects theoretical predictions and helps quantify potential efficiency and budget gains. A suitable theoretical framework can guide the conduct of empirical research and the interpretation of results. Ignoring behavioural shifts across different auction formats, for example, is a common pitfall in analyses of actual bid data.

In conclusion, theory, practical judgments and a policy perspective should guide auction design for allocating conservation funds so as to optimise the implications for government budgets and allocative efficiency.

6 Synergies in spectrum auctions — the Australian case

The assignment of licences to use the radiofrequency spectrum has proved to be a fruitful ground for advancing auction theory and practices since the early 1990s. The particular nature of the spectrum resource, along with the characteristics of the end markets that spectrum is used to satisfy, presents significant challenges to spectrum regulators and auction designers in devising appropriate selling procedures. Not least among these challenges has been the question of how best to account for potential synergies — that is, interdependent values — among licences.

This chapter provides evidence of synergies in spectrum licences in Australia and discusses the implications for auction design. Section 6.1 is an overview of spectrum auctions worldwide. Section 6.2 discusses design issues related to the presence of synergies and the impact on allocative efficiency at auction. Section 6.3 reviews the Australian experience with spectrum assignment. This review is followed by an attempt to ascertain the existence of spectrum synergies in Australia through circumstantial evidence (section 6.4) and an econometric study (section 6.5). Section 6.6 summarises the evidence and discusses the implications for designing spectrum auctions in Australia.

6.1 Spectrum auctions worldwide

In 1958, Ronald Coase posed to the US Congress the idea of selling the rights of access to the radiofrequency spectrum (Coase 1959). The first spectrum auction (in New Zealand) did not take place, however, until 1989. Australia soon after conducted its own spectrum auctions. Teething problems affected these early auctions, leading to progressive refinements in auction design that many countries subsequently adopted.

The era of spectrum auctions began in earnest in 1993, with the US Congress passing the legislation that authorised the Federal Communications Commission (FCC) to auction licences (McMillan 1994). The US regulator had previously relied on comparative hearings and, at one time, lotteries to assign licences (section 2.2).

Beginning in 1994, the FCC held a series of Personal Communications Services (PCS) auctions to assign thousands of spectrum licences for the provision of wireless telecommunications services such as mobile phones and pagers. These auctions were deemed to be successful because they quickly and transparently assigned thousands of interrelated licences, avoiding much of the delays, rent seeking and allocative inefficiencies that had accompanied other assignment methods.

The simultaneous ascending auction design, commissioned by the FCC and first used in the PCS auctions, was considered to be instrumental to the success of these auctions (see appendix B for design details). It is based on the English outcry format, which is the norm in real estate and art auctions. In the taxonomy of auctions, English auctions are described as *open* because bids are known to all bidders, *multi-round* because bidding is conducted over several rounds, *ascending* because a new bid must exceed the standing high bid, and *sequential* because several items are auctioned one at a time (unless pre-packaged).

Like English auctions, simultaneous ascending auctions are open, ascending and multi-round. Unlike English auctions for multiple items, however, they are not sequential; instead, bidders are free to bid on several items at the same time. Put differently, a simultaneous ascending auction is akin to running several English auctions in parallel, in which bidders can choose to enter particular auctions and, subject to specific auction rules, switch between auctions at any time.

Simultaneous ascending auctions are well suited to the assignment of spectrum licences because they:

- generate a great deal of common-value information about spectrum, promoting efficiency in its assignment and use;
- moderate the winner's curse;
- discourage collusive and predatory bidding behaviour; and
- more importantly, allow synergy values in spectrum use to be realised.

On the strength of these advantages, simultaneous ascending auctions have now become the preferred design for selling spectrum worldwide, including in Australia (section 6.3).

6.2 Synergies and licence aggregation

A bidder may view different spectrum lots (a lot is a single item of spectrum offered for sale) as complements or substitutes. If lots are complements, then they have a synergy value (section 4.5). Synergy value is measured by the difference between the joint value of lots and the sum of their stand-alone values. Synergies are likely to arise in spectrum use as a result of the following factors.

- *Seamless roaming*. With this facility, the same mobile phone can be used across different licence areas. Roaming is highly desirable for mobile phone users, so service providers can capitalise on it as a selling point. The demand for an extended coverage of mobile services creates geographic and population synergies in spectrum licences.
- *Guard bands*. These are part of the licence coverage that must be kept 'empty' to avoid creating unacceptable interference for adjacent licensees. Spectrum licences typically specify guard bands in both the geographic and frequency dimensions (PC 2002). By holding licences over adjacent areas or frequencies, fewer guard bands are required, thus raising spectrum productivity.
- *Spectrum–infrastructure tradeoff*. Spectrum and infrastructure are substitutable inputs to telecommunications services. If only a small amount of spectrum is available, then a relatively large investment in infrastructure is needed to support a given number of customers. More mobile phone base stations, for example, are needed to 'recycle' the spectrum. Moreover, some technologies require a minimum amount of spectrum to operate efficiently. By increasing the amount of spectrum input, positive synergies arise from reduced infrastructure costs and the use of more advanced technologies.
- *Economies of scale*. Cost savings result from operation in as many geographic areas as possible, although not necessarily contiguous ones.

Synergy values are idiosyncratic, based on a bidder's specific circumstances in terms of technology, business case, infrastructure base and commercial strategy. An established firm, for example, may be willing to pay a higher price than a new entrant for a particular licence that supplements its existing services.

Given positive synergies in various licences on offer, a bidder seeks to obtain preferred lots in aggregate. Compared with sequential English auctions, simultaneous ascending auctions permit more flexible licence aggregation. In an English auction, a bidder would have to bid on a synergetic lot while not being sure of winning other elements of a preferred aggregation. By contrast, in a simultaneous ascending auction, so long as bidding remains open for all lots, a bidder can add new lots to the ones already held or switch between equivalent lots if one becomes too expensive.

Simultaneous bidding cannot eliminate, however, the risk that a bidder may fail to win some of the complementary licences. Moreton and Spiller (1998, p. 689) explain this *exposure* problem as follows.

> [A]nytime a bidder submits a bid that exceeds the stand-alone value of a license, it runs the risk of paying a price for an individual license that is above its stand-alone value if it fails to win one or more of the complementary licenses.

The exposure problem occurs in licence-by-licence bidding, leading to inefficient assignment of spectrum because potential synergy values are not fully realised. This main drawback of simultaneous ascending auctions has led to proposals for ‘package’ (also called ‘combinatorial’) bidding (Bykowsky, Cull and Ledyard 2000). This alternative format allows bidders to bid on an ‘all or nothing’ basis: that is, a bidder chooses a preferred combination of lots on which to bid and submits a bid *for the set*. If a bidder does not win with a bid on a preferred combination, then no payment is required.

Laboratory experiments show that package auctions can attain a higher degree of allocative efficiency than that attained by simultaneous ascending auctions in selling items with positive synergies. Package bidding has not been used, however, for spectrum auctions anywhere in the world. Complicated auction rules are the major hurdle to acceptance by regulators and prospective bidders alike. Also, proposed designs lack theoretical support for the efficiency property. (Appendix B discusses the free-rider problem in package bidding.) Nonetheless, the FCC has scheduled its first package auction for January 2003 (FCC 2002). This auction of spectrum in the upper 700-megahertz band will use a restricted package bidding format, allowing bidders to bid on individual licences as well as on a number of pre-selected lot combinations.

6.3 Spectrum auctions in Australia

In Australia, spectrum auctions were conducted in the early 1990s as part of the sale of pay television and radio licences. Spectrum auctions remained relatively uncommon at that time and the first sale of spectrum for mobile phone services (in 1991 and 1992) used a mixture of comparative hearings and auctions.

This scene changed in 1992 with the passage of the *Radiocommunications Act 1992*, which introduced major reforms of the way in which to manage spectrum in Australia. Foremost among these reforms were the creation of property rights to spectrum (in the form of so-called ‘spectrum licences’) and the use of market based mechanisms to assign these rights (see PC 2002 for a detailed analysis of these reforms).

Under the Radiocommunications Act, the Australian Communications Authority (ACA) is the spectrum regulator and can choose any of the following types of market based mechanism to assign spectrum licences: (i) auctions; (ii) negotiated prices; and (iii) predetermined prices.

The ACA has always used auctions except when only one bidder registered for an auction, in which case licences were sold at predetermined prices. Since the introduction of the Radiocommunications Act, spectrum auctions have raised in excess of $3 billion. The Act does not specify the type of auction to use, other than allowing the use of first-price sealed-bid auctions among others. While many auction designs are available, the ACA has chosen only the English outcry format and the simultaneous ascending format. It has used the former only infrequently, when a small number of lots were for sale. Since 1997, the ACA has always resorted to simultaneous ascending auctions whenever it has had to assign a large number of spectrum licences (table 6.1).

Table 6.1 **Simultaneous ascending auctions for spectrum licences in Australia, 1997–2001[a]**

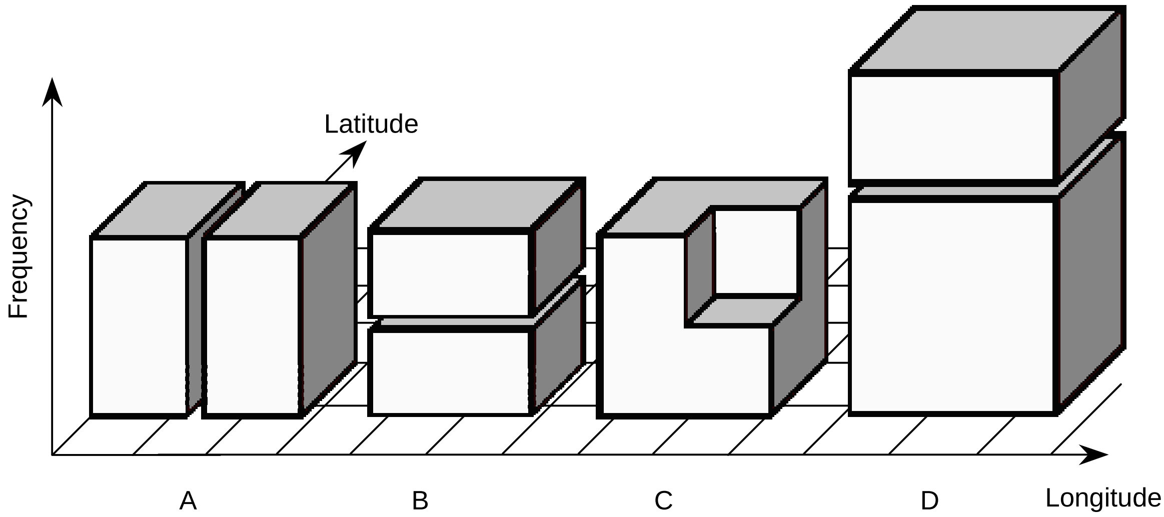
Auction	*Year*	*Service type*	*Number of lots*	*Total rounds*	*Number of bidders*	*Revenue raised*	*Revenue/ MHz/Population*[b]
						$m	cent
500 MHz	1997	Land mobile and point-to-point services	834	63	13	1.0	0.62
PCS (800 MHz and 1.8 GHz)	1998	2G mobile phones	230	89	9	347.4	1.13
28/31 GHz	1999	Fixed wireless	29	37	5	66.2	0.01
PCS (1.8 GHz)	2000	2G mobile phones	60	138	7	1 327.7	12.95
3.4 GHz	2000	Wireless local loop	482	53	8	114.8	0.40
27 GHz	2000	Fixed wireless	126	3	2	37.6	0.03
3G (2.1 GHz)	2001	3G mobile phones	58	19	7	1 169.0	6.27

a Excluding auctions of apparatus licences and re-auctions. **b** Based on an annual discount rate of 6 per cent. MHz = megahertz. GHz = gigahertz. 2G = second generation. 3G = third generation.

Source: PC (2002).

Unlike for licences auctioned elsewhere, the geographic and spectral coverage of Australian spectrum licences is not set before an auction. The ACA sells 'building blocks' consisting of a few megahertz in a region or capital city (except for a few national licences). Bidders may aggregate these building blocks up to a maximum they declare before auction, subject to pro-competition limits imposed by the Commonwealth Government for particular auctions. Figure 6.1 illustrates four spectrum (dis)aggregation scenarios. Scenario A is an aggregation of two geographically contiguous licences. Scenario B represents the aggregation of two licences covering adjacent spectrum bands. Scenario C shows a subdivided licence. Scenario D combines scenarios A and B.

Figure 6.1 **Examples of spectrum aggregation**



Source: Adapted from ACA (1998a).

The selling of basic spectrum blocks means that spectrum auctions in Australia are well suited to the exploitation of synergy values that differ across bidders. Firms can tailor licence aggregations to suit their particular needs in terms of both the combined market areas and populations, and the amounts of contiguous spectrum available. Firms with regional ambitions, for example, do not have to bid for national coverage, while large firms aimed at interstate markets can form nationwide aggregations. Similarly, firms that want niche technology markets can bid for small amounts of spectrum, while those interested in offering spectrum-intensive voice networks can secure large tracts of spectrum.

Although narrowly defined spectrum lots offer great flexibility for licence aggregation, they can exacerbate the exposure problem. This occurs because, in an auction of a large number of small lots, bidders may end up with disparate and fragmented holdings of spectrum. A firm seeking national coverage may miss out on an all-important capital city. Exposure risk of this kind has apparently affected some bidders in Australian spectrum auctions (PC 2002, p. 189).

Overseas, governments have sometimes pre-empted the risk of exposure in spectrum auctions by offering only national licences or by leaving the exact location of lots in the spectrum unspecified, so regulators can consolidate holdings after auctions. This approach, however, has the undesirable effect of limiting bidder participation to, for example, those firms that wish to offer national voice coverage. This could result in inefficient assignment of spectrum, because firms with high valuations but small spectrum needs are discouraged from entering an auction.

Secondary trading of licences is another way of alleviating the risk of exposure. If bidders are able to adjust their aggregations after auction by selling or swapping spectrum with competitors, then they may not be under as much pressure to 'get it right first time'. The greater flexibility of Australian spectrum licences, relative to their overseas counterparts, appears ideally suited to secondary trading. Licences can be bought and sold, subdivided, leased or swapped with minimal government intervention in Australia. Moreover, domestic spectrum licences are more technology neutral than their overseas counterparts, meaning that bidders can engage in secondary trades with a wide range of spectrum users, not just with their rivals in an auction.

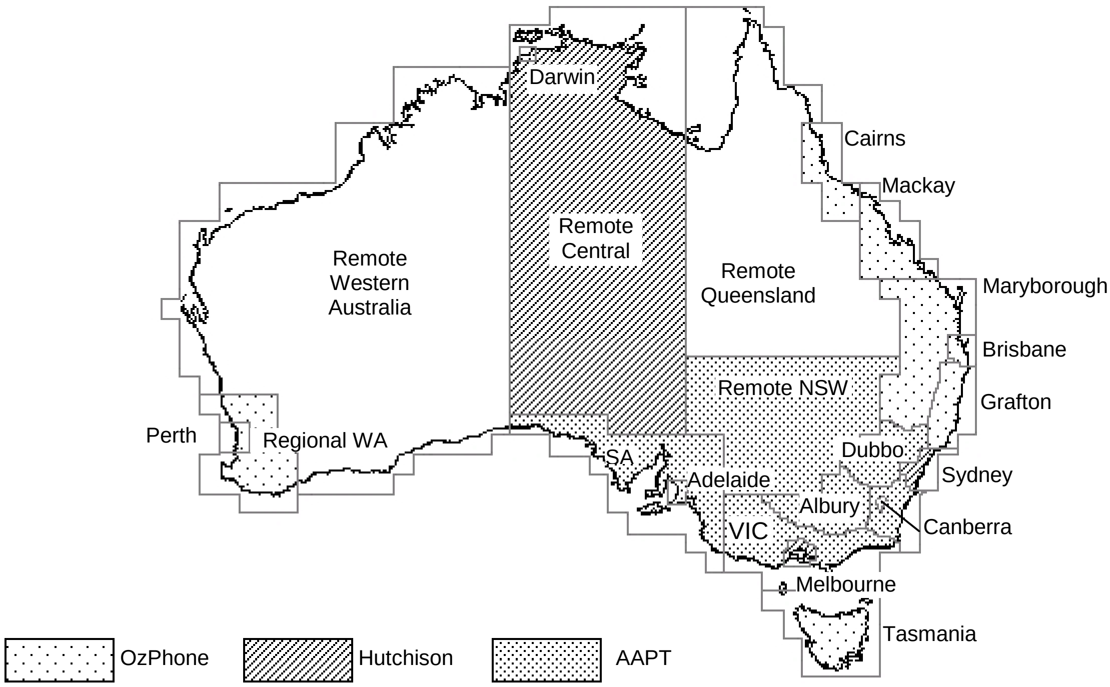
Despite these advantages, secondary trading of spectrum remains immature in Australia and elsewhere. Barriers exist, ranging from the small number of licences in circulation to the tax treatment of some spectrum trades (PC 2002). Moreover, some auction theorists assert that the secondary market is a poor substitute for auctions in terms of achieving efficient spectrum assignment (see, for example, Milgrom 2000). Their reasons include theoretical ones (such as information constraints on bargaining) as well as practical ones (such as transaction costs). Consequently, secondary trading does not yet offer a viable alternative to well-designed auctions for achieving efficient licence aggregations.

Without the possibility of secondary trading, package bidding could mitigate the exposure problem while preserving the inherent flexibility of Australian spectrum licences. A move to package auctions is not cost free, however. Both the ACA and telecommunications companies have invested in bidding software and know-how tailored to simultaneous ascending auctions. Moving to a new auction design after only five years means writing off that investment. To justify such costs, a new design must demonstrate the potential for efficiency gains compared with the current design. Large efficiency gains are likely in cases of strong, positive synergies in spectrum use and a high exposure risk of licence aggregation. Ascertaining the existence and strength of synergies is therefore crucial before contemplating a move to package auctions.

6.4 Indirect evidence of synergies

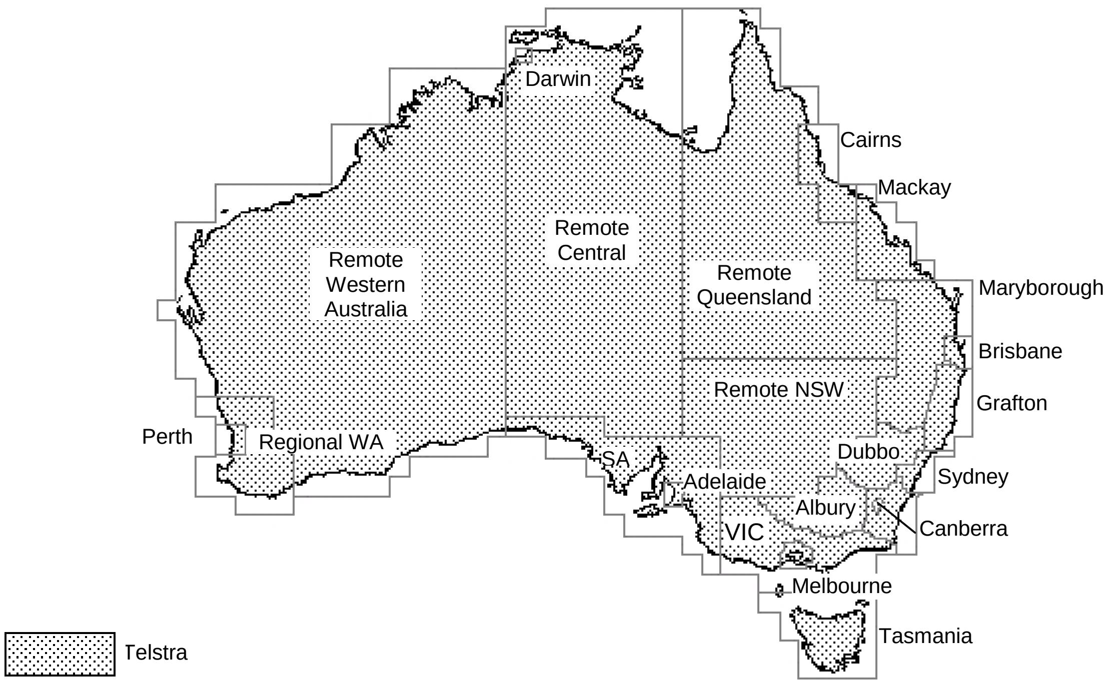
The allocation pattern in a spectrum auction can provide insights into the potential sources of inter-licence synergy. Here, selected results from the 1998 PCS auction in Australia are analysed. Licence aggregation has two dimensions — geographic and spectrum —and so is difficult to illustrate on a map. For ease of exposition, these dimensions are considered separately, bearing in mind that Australian licences can be aggregated across both geographic areas and frequency bands.

Figure 6.2 **Geographic aggregation of band-1 licences in 1998 PCS auction**



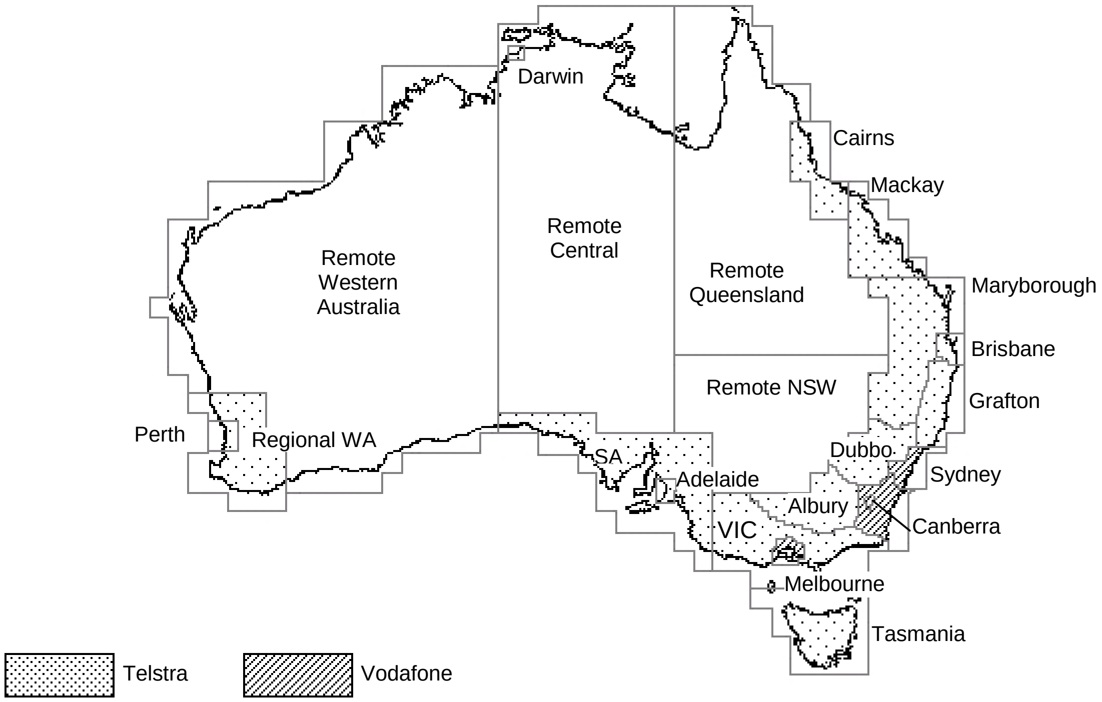
Source: Adapted from ACA (1998b) using ACA auction data.

Figure 6.3 **Geographic aggregation of band-3 licences in 1998 PCS auction**



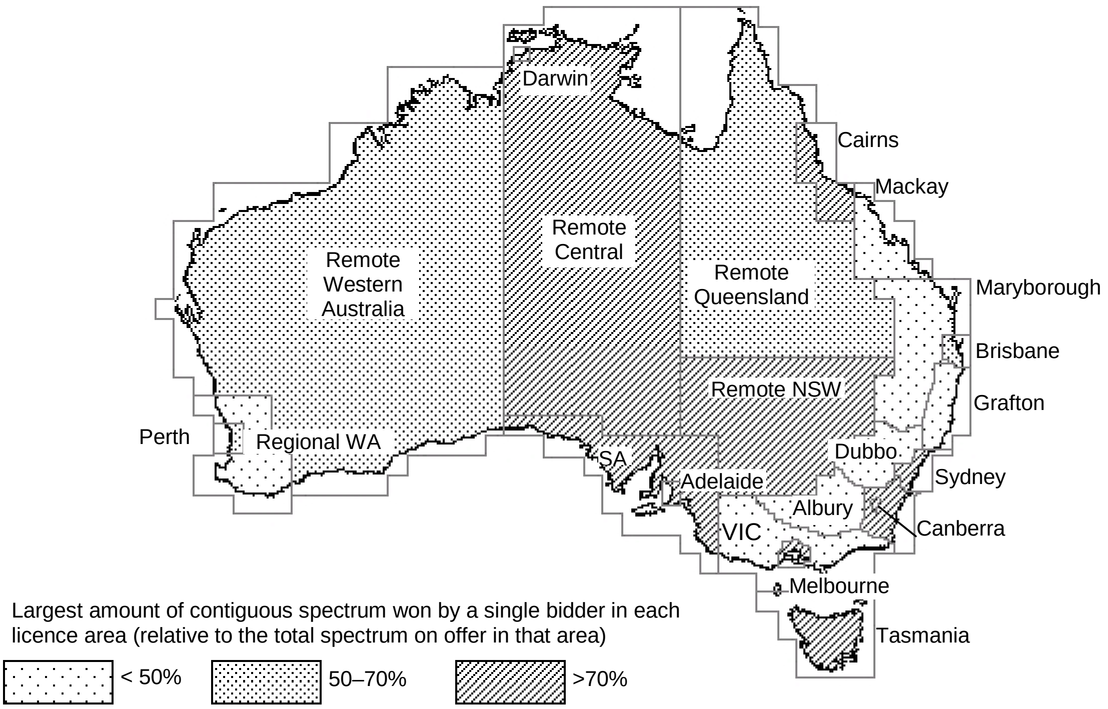
Source: Adapted from ACA (1998b) using ACA auction data.

Figure 6.4 **Geographic aggregation of band-9 licences in 1998 PCS auction**



Source: Adapted from ACA (1998b) using ACA auction data.

Figure 6.5 **Spectrum aggregation in 1998 PCS auction**



Source: Adapted from ACA (1998b) using ACA auction data.

Figures 6.2 to 6.4 show the identities of the winning bidders for three frequency bands (selected from a total of 22 bands) in various licence areas. From figure 6.2, it appears that OzPhone and AAPT did strive to win geographically contiguous lots needed for building regional markets. Nevertheless, population synergies are not the only possible explanation behind this allocation pattern; regional aggregations could result from tacit collusion among bidders. In figure 6.3, Telstra is shown to have achieved national coverage using numerous band-3 licences (no nationwide licence was offered in that auction). A similar plan for aggregating band-9 licences, however, might have been thwarted by Telstra missing out on some capital cities (figure 6.4).

Licence aggregation is apparent in the spectrum dimension too. In most licence areas, a single bidder (usually Telstra) was able to win contiguous lots that amounted to half or more of the total spectrum on offer in that area (figure 6.5). Spectrum aggregation may have been even more pronounced had competition limits not been in place. These limits restricted the amount of 800-megahertz spectrum that Telstra could win in non-metropolitan areas (and, for that matter, the amount of 1.8-gigahertz spectrum that any bidder could win in major capital cities from the 2000 PCS auction).

The use of particular bidding strategies is consistent with the existence of positive synergies for some bidders.

- The use of ‘jump bids’ (that is, bids that exceed the minimum acceptable price for a lot in a given round) is a sign that some bidders have preferred aggregations (Cramton 1997). By signalling to competitors that one has a high valuation for a lot, a bidder acts to keep others from bidding on that lot.
- An automatic re-bid facility is available to bidders in ACA spectrum auctions, enabling them to surpass any competitor’s bid during a round (up to a pre-specified limit). A large number of automatic re-bids used in an auction may reflect attempts by some firms to secure the ‘core’ licences in their aggregations.
- By withdrawing a standing high bid, a bidder may avoid unwanted exposure to an expensive, complementary lot. A large number of bid withdrawals raised in an auction suggest cases of failed aggregation (Cramton 1997).

Table 6.2 shows the incidences of jump bids, automatic re-bids and bid withdrawals for each of the simultaneous ascending auctions. On the whole, jump bids were more frequent than automatic re-bids, which were more frequent than bid withdrawals. This comparison might have been affected by the financial penalty imposed on the latter but not the former two bidding actions. Comparing auctions, these bidding facilities were most actively used in the 500-megahertz auction (although automatic re-bids were unavailable at this auction). Other auctions of note include the 2000 PCS auction of 1.8-gigahertz spectrum (at which jump bids were used at a rate of 7 per cent) and the 1998 PCS auction of 800-megahertz spectrum (at which automatic re-bids were used at a rate of 3 per cent).

Table 6.2 **Incidences of jump bids, automatic re-bids and bid withdrawals**
Share of total number of bids in a round

Auction	*Jump bids*	*Automatic re-bids*	*Bid withdrawals*
	%	%	%
500 MHz	17.5	..	1.4
3G (2.1 GHz)	4.3	2.6	0.0
28/31 GHz	5.5	1.2	0.0
PCS (1.8 GHz)	7.3	1.4	0.2
3.4 GHz	2.2	0.2	0.4
PCS (800 MHz and 1.8 GHz)	1.2	2.9	0.4
27 GHz	0.0	0.0	0.0

MHz = megahertz. GHz = gigahertz. 3G = third generation. **..** Not applicable.

Source: Authors' estimates based on ACA auction data.

6.5 Econometric estimation of synergies

Synergy value in spectrum use can be expressed in terms of the premium that a bidder is willing to pay to add to a set of contiguous lots. Estimating this value premium is typically not a simple matter because the auction format chosen affects the extent to which bid data reveal bidders' true valuations. Particular pricing rules discourage demand revelation in multi-item auctions (section 4.5).

However, the use of an open, ascending format for spectrum auctions presents an opportunity to quantify premia associated with inter-licence synergies. This opportunity is based on a hypothesised relationship between the winning bid and the valuation of the *marginal bidder* (that is, the bidder who, by making the *marginal bid* for a lot, just loses the bidding — box 6.1).

Under certain conditions, the marginal bidder's valuation of a lot is within one bid increment below or above the winning bid, which determines the licence price. (The smaller the minimum bid increment, the closer the licence price approximates a marginal bidder's valuation.) For this relationship to hold, bidders are assumed to bid straightforwardly, not strategically. For example, bidders do not make jump bids or pay a premium for a lots that have little intrinsic synergy value to them but represent a core piece in a competitor's intended aggregation. In the presence of positive synergies, a straightforward marginal bidder would bid higher for a given lot, other factors being equal, if that bidder holds other complementary lots. Positive synergies thus increase the winning bid under the above assumptions. By regressing winning bids against variables that represent the holding of contiguous lots by marginal bidders, one can therefore investigate the significance of synergies in an auction.

Box 6.1 **Marginal bid definition**

In general, the marginal bid is the second-highest bid for a given lot. That bid can occur in the same round as the winning bid or in an earlier round.

Occasionally, two or more equal-highest bids are recorded in the same round (as bidders do not know what their competitors are bidding during a round). In that event, the marginal bid is that which is recorded second in time.

Thus, the marginal bid must satisfy one of the following conditions in relation to the winning bid:

- it was placed in an earlier round;
- it was placed in the same round but was of a lower value; or
- it was placed in the same round, was of equal value, but was placed later.

Synergy variables

A variety of synergy variables can be constructed to indicate licence coverage. In their study of the US PCS auctions, Ausubel et al. (1997) define two measures of population coverage.

- *Absolute local synergy* measures the total population of all contiguous lots held by the marginal bidder.
- *Relative local synergy* is absolute local synergy expressed as a percentage of the maximum contiguous population that the marginal bidder can hold.

For each of these synergy measures, a variant is defined to include the population of any contiguous areas that the marginal bidder owns before the auction (called the 'cellular footprint').

Moreton and Spiller (1998) also define 'global' population synergy variables, measuring the size of the population serviced by the marginal bidder in all market areas, not only those markets located next to the licence area of interest. In effect, global variables emphasise economies of scale as a source of population synergy.

The present econometric study considers population synergies only in absolute, local terms. In addition, an absolute, local spectrum synergy variable is constructed, measuring the total bandwidth (in megahertz) of all contiguous bands held by the marginal bidder in one area. Given that the US PCS auctions did not allow spectrum aggregation, the two studies mentioned above did not consider spectrum synergies.

Another departure from the US studies is that the present study measures population and spectrum synergies *when a marginal bidder withdraws from bidding for the lot of interest*. This differs from the treatment in both Ausubel et al. (1997) and Moreton and Spiller (1998), which measure the synergy variables for a marginal bidder *at the end of an auction*. Their approach assumes that bidders' valuations of a spectrum lot *during an auction* are a function of the population coverage of the contiguous lots that these bidders *ultimately* win. In other words, throughout the auction, bidders would have anticipated the lots that they would win or, at least, the probability of winning these lots.

This assumption of perfect foresight does not affect the measurement of coverage before an auction, such as the 'cellular footprint' synergy variables. It appears unrealistic, however, for synergy variables that depend on a bidder's provisional holding of lots in a round. Bidders' valuations for a given lot are influenced by their holdings of other lots, which keep changing during the course of an auction. It makes sense, therefore, to synchronise the measurement of valuations and potential synergies.

Data

The ACA makes all bid data available to registered bidders during an auction and to the public after auction. Those data are largely unprocessed, except for the rounding of bid amounts to prevent bidders from using the last few digits of a bid to signal for collusive bidding (as has happened in some overseas auctions).

For the present study, bid data are drawn from the simultaneous ascending auctions between 1997 and 2001. This sample of data covers the sales of 1819 lots over a total of 402 rounds. The synergy variables are constructed by identifying lots that are contiguous geographically or spectrum-wise. For the 2000 PCS auction, contiguous areas are the closest neighbours of a capital city, because that auction offered only capital city lots.

Table 6.3 summarises the sample data for each of the auctions studied. In line with the adopted approach to detecting synergies for marginal bidders, only those lots that have attracted more than one bidder are considered. In effect, the sample data are purged to exclude unsold lots and lots sold at reserve price.[1] The proportion of

[1] Information on synergies can be lost in the regression analysis by excluding data on non-sales or sales at reserve price. By definition, reserve prices contain no synergy premium. That a lot is sold at all, however, can indicate synergies. If, for example, the probability of selling a lot at reserve

lots thus discarded ranges from zero per cent for the 2000 PCS auction to 100 per cent for the 27-gigahertz auction. Among those auctions that are identified as having marginal bidders, the 28/31-gigahertz auction generated virtually no potential synergies, while the 3G auction yielded only spectrum synergies. The other auctions yielded sizeable population and spectrum synergies. Take the 500-megahertz auction to illustrate: marginal bidders held the standing high bids on contiguous licences that covered, on average, over one million persons and 0.19-megahertz of spectrum at the time they withdrew from bidding for complementary lots.

Table 6.3 **Summary statistics of sample data**

Auction	*Number of lots*	*Lots with marginal bidders*	*Average population synergy*	*Maximum population synergy*	*Average spectrum synergy*[b]	*Maximum spectrum synergy*[a,b]
			Persons	Persons	MHz	MHz
500 MHz	918	287	1 101 349	5 231 400	0.19	3.93
PCS (800 MHz and 1.8 GHz)	230	133	556 158	6 274 900	2.48	25.00
28/31 GHz	29	5	–	–	–	–
PCS (1.8 GHz)	60	60	2 247 880	5 360 400	5.42	30.00
3.4 GHz	482	285	737 114	6 080 438	0.47	17.50
27 GHz	126	0	..	..	..	..
3G (2.1 GHz)	58	23	–	–	5.22	30.00

[a] Maximum spectrum synergy may exceed the competition limit imposed on a particular auction, because bidders can aggregate adjacent areas over which different competition limits apply. [b] Including paired channels. MHz = megahertz. GHz = gigahertz. 3G = third generation. – Negligible. .. Not applicable.

Source: Authors' estimates based on ACA auction data.

Model specification

A reduced-form equation can be formulated to relate auction prices to spectrum synergies. Subject to the price–value approximation and the assumption of straightforward bidding, this equation explains bidders' valuations in terms of their perceived synergies. Specifically, the regression model tested is:

$$\ln(WB_i) = \beta_0 + \beta_1 \ln(1 + PopSyn_i) + \beta_2 \ln(1 + SpecSyn_i) + u_i$$

where:

WB_i = winning bid for lot i

price to a bidder (instead of remaining unsold) increases with this bidder's holding of contiguous lots, other factors equal, then that sale implies positive synergies.

$PopSyn_i$ = combined population of licence areas that are contiguous to lot *i* and held by the marginal bidder at the time of withdrawal from bidding for lot *i*

$SpecSyn_i$ = total amount of spectrum that is contiguous to lot *i* and held by the marginal bidder at the time of withdrawal from bidding for lot *i*

u_i = random disturbance

$\beta_0, \beta_1, \beta_2$ = coefficients to be estimated.

The log-linear functional form captures the diminishing effects of synergies on valuations. Moreton and Spiller (1998), for example, calculate that bidders in the A–B block PCS auctions would have initially been willing to pay a premium equal to 25 per cent of the licence price to increase the size of their contiguous geographical coverage by the equivalent of an average area's population, but a premium of just 2 per cent for a further increase of the same magnitude.

Winning bids are expressed in dollars per megahertz per head of population to account for different sizes of the licence coverage. They are annualised to account for different licence tenures (ten or fifteen years). The explanatory variables are logged after adding one to avoid the numerical problem of taking the log of zero.

Apart from the synergy variables, other potential determinants of licence value are omitted from the equation. Such omitted factors relate to the demographic characteristics, the degree of bidding competition, and the regulatory and other aspects of the auction environment. Ausubel et al. (1997) and Moreton and Spiller (1998) confirm the impact of these factors in the US PCS auctions they studied. For this study, such control variables are excluded because of data limitations; instead, either the intercept term (β_0) or the disturbance term (u_i) is assumed to absorb technical and environmental differences between licences. This treatment involves detailed testing for data heterogeneity in determining the appropriate estimation method (as explained below).

Estimation method

The large number of data observations available makes several estimation methods possible. Ordinary least squares (OLS) regression on pooled data would yield the maximum degree of freedom and thus explanatory power of the equation estimated. However, this method results in biased coefficient estimates if data observations are heterogeneous (that is, characterised by differing statistical distributions). As this is most likely the case here, the OLS method is not adopted for this study.

Data heterogeneity can result from the omission of auction-specific variables from the equation. One such omitted variable relates to the changing climate of telecommunications investment over the study period. The sudden transformation of the 'dot.com' boom into a 'tech-wreck' in 2000 is widely thought to have had an adverse impact on spectrum prices. Another source of variability between auctions relates to the characteristics of the spectrum comprised in the licences being auctioned. Different parts of the spectrum attract greater or lower values, contributing to data heterogeneity if such value differences are not explicitly modelled.

As well as being present *between* auctions, data heterogeneity is also almost certainly present *within* auctions. As shown by Ausubel et al. (1997) and Moreton and Spiller (1998), numerous factors influence bidders' valuations for a particular lot. In addition to synergy potential, licence value is a function of characteristics of the pertinent licence area. By ignoring the commercial potential or profitability of an area, the regression equation is misspecified and leads to biased coefficient estimates.

To confirm differential synergy effects within and between auctions, preliminary regressions of the dependent price variable are run on a series of dummy variables for separate auctions and licence areas (results not shown). All the auction-specific dummies are found to be statistically significant at the 1 per cent level, as are the majority of area-specific dummies. Given this diagnostic result, the question arises of how best to account for both types of data heterogeneity in the regression. One option is to estimate the model with the pooled data set and rely on dummy variables to differentiate between auctions and between licence areas.

Using dummies to identify individual auctions within pooled data means sorting observations into various groups, each of which represents an auction. Following this classification, a number of binary variables are created to identify the auction to which a given observation belongs. Regressing the dependent variable on both the synergy and binary variables allows the effects of any unspecified, omitted variables to be captured as differences in the intercepts estimated for the various groups. This approach is equivalent to a panel regression with fixed effects (see Greene 2000 for details). A drawback, however, is that the coefficients for respective explanatory variables are assumed to be identical across auctions. This restrictive assumption is not supported by the evidence from Ausubel et al. (1997) and Moreton and Spiller (1998), which shows that a particular variable (including synergies) does not necessarily influence to the same extent the licence prices fetched in different auctions. It is desirable, therefore, to allow the coefficients to vary across auctions. This can be achieved by dividing the data among auctions and estimating a separate equation for each auction that provides sufficient data points.

Little information (except population size) is available about the characteristics of various licence areas. To account for the omission of relevant demographic and other market factors, the intercept term is modelled to vary across areas, through the inclusion of an area identifier as a group variable (as described in the previous paragraph), while the other coefficients remain invariant to a shift between licence areas. This is again akin to a fixed effects panel regression, whereby repeated measures occur for each area. An alternative panel estimation technique — the random effects model — assumes that group effects are unsystematic, affecting the disturbance term of the equation. The latter approach, however, is not supported by a Hausman test and provides a less satisfactory fit of data compared with the fixed effects model.

Consequently, the proposed regression model is estimated using a fixed effects panel regression on data collected from individual auctions. This method is judged to best represent auction specificities while controlling for omitted area characteristics.

Results

Table 6.4 presents estimation results for the four auctions that have sufficient data points for fixed effects panel regression. Subject to the adequacy of addressing bias from spatial correlation (box 6.2), significant positive population synergies are detected for the 1998 and 2000 PCS auctions, while spectrum synergies are operative in none of the auctions analysed. Further, F-statistic tests confirm the overall goodness-of-fit in the equation estimated for the PCS auctions.

Box 6.2 **Unbiased estimation in the presence of spatial correlation**

To ensure the coefficient estimates are unbiased, a diagnostic test is performed to identify any correlation of the disturbance term across licence areas. Such spatial correlation arises if licence value is a continuous function of some omitted geographic factors, such as terrain.

The diagnostic test involves estimating a generalised least squares (GLS) version of the price equation for the 2000 PCS auction, which is the only auction with the same number of observations for each licence area. That GLS regression specifies a heteroscedastic covariance structure for the disturbance term, allowing for the correlation of licence value across areas. The GLS results (not shown) are qualitatively similar to those obtained from the fixed effects panel regression.

This result accords with those of Ausubel et al. (1997) and Moreton and Spiller (1998), which show little evidence of spatial correlation in the A–B block PCS auctions over licence areas (called major trading areas) that are similarly sized to the licence areas defined in Australia.

Table 6.4 **Fixed effects panel regression results for selected auctions**[a]

Explanatory variable[b]	*Coefficient estimate*	*Standard error*	*t-value*	*P>|t|*
500-MHz auction (1997)				
Intercept	-5.698*	0.114	-50.059	–
ln(1 + *PopSyn*)	-0.007	0.010	-0.714	0.476
ln(1 + *SpecSyn*)	0.115	0.158	0.730	0.466
Number of observations = 256				
Number of area groups = 15				
Observations per group: minimum = 4; maximum = 44; average = 17				
F(2, 239) = 0.520				
Prob > F = 0.596				
PCS 800-MHz and 1.8-GHz auction (1998)				
Intercept	-4.383*	0.051	-86.269	–
ln(1 + *PopSyn*)	0.012*	0.006	1.990	0.049
ln(1 + *SpecSyn*)	-0.040	0.036	-1.122	0.264
Number of observations = 132				
Number of area groups = 18				
Observations per group: minimum = 1; maximum = 22; average = 7				
F(2, 112) = 2.610				
Prob > F = 0.078				
PCS 1.8-GHz auction (2000)				
Intercept	-2.947*	0.051	-57.277	–
ln(1 + *PopSyn*)	0.015*	0.005	2.745	0.008
ln(1 + *SpecSyn*)	0.019	0.029	0.645	0.522
Number of observations = 60				
Number of area groups = 5				
Observations per group: minimum = 12; maximum = 12; average = 12				
F(2, 53) = 7.210				
Prob > F = 0.002				
3.4-GHz auction (2000)				
Intercept	-5.596*	0.025	-219.727	–
ln(1 + *PopSyn*)	-0.005	0.005	-1.096	0.274
ln(1 + *SpecSyn*)	-0.026	0.034	-0.761	0.447
Number of observations = 285				
Number of area groups = 18				
Observations per group: minimum = 6; maximum = 20; average = 16				
F(2, 265) = 0.860				
Prob > F = 0.424				

a Excluding the 2.1-GHz, 28/31-GHz and 27-GHz auctions due to insufficient observations. **b** The dependent variable is ln(*WB*). MHz = megahertz. GHz = gigahertz. ***** Statistically significant at the 5 per cent level. – Negligible.

Source: Authors' estimates based on ACA auction data.

Insignificant spectrum synergies

The absence of significant spectrum synergies seems to indicate that bidders regard different bands of spectrum in the same area as perfect substitutes, such that contiguous bands attract little premium over non-contiguous bands. That is not to say that bidders are not concerned with acquiring sufficient spectrum to allow them to deploy cost-effective technologies.

Population synergies in PCS auctions

The coefficient estimates of the population synergy variable for the two PCS auctions are statistically significant at the 5 per cent level. These are auctions for which there have been suggestions that some bidders were unable to build efficient geographic aggregations at auction and have since needed to trade or swap spectrum (PC 2002). An estimated positive coefficient on the population synergy variable confirms bidders' willingness to pay a price premium for a lot that is geographically contiguous to other lots held at the time of bidding. Measured at the sample mean, such a premium amounted to 18 per cent of the licence price in the 1998 PCS auction and 25 per cent in the 2000 PCS auction. These calculations are based on population synergies equal to the average population size per licence area in respective auctions.

The findings of this study are generally consistent with the evidence available elsewhere. For the 2000 PCS auction, the estimated premium coincides with that obtained by Moreton and Spiller (1998) for the US A–B block auctions. For the 1998 PCS auction, the estimated premium is reasonably close to the average figure of 12 per cent calculated by Sutherland (1998) for the same auction. The present study and Sutherland's use the same approach to specifying and estimating the price equation. Sutherland's results, however, are difficult to generalise because the analysis, unlike this study, examined only a small subset of lots, did not consider spectrum synergies, used data from only a single auction and did not account for area characteristics.

Explanations

The question arises about why population synergies exist in some auctions but not in others. Several explanations are possible. First, as table 6.1 shows, the two PCS auctions achieved higher spectrum prices than the 500-megahertz and 3.4-gigahertz auctions. On a comparable basis, licence prices in the PCS auctions were two to 25 times those in the other two auctions. The auction price, as a fixed cost of production, eats away at the winning firm's profits. The higher the average price paid at auction, therefore, the more important it is for firms to realise potential synergy values in order to operate profitably. Presumably, the higher the prices, the more crucial a successful aggregation becomes for making a profitable use of the spectrum acquired.

A related explanation is that only the two PCS auctions were for the sale of mobile phone spectrum, whereas the other auctions were for spectrum suitable for fixed and land mobile services. The main driver of positive population synergies is probably mobile phone roaming; roaming is unimportant for fixed services, although economies of scale and scope may still drive aggregation. The latter source of synergy would not be detectable, however, through the local absolute synergy variable used here. Land mobile radio services are typically used by taxi fleets and ambulance services, and so are area specific. Population synergies are generally not expected in the 500-megahertz and 3.4-gigahertz auctions, whereas securing as many adjacent areas as possible in the PCS auctions could have been a major consideration for some providers of mobile phone services.

These are not the only possible explanations of the existence of synergies (or lack thereof). The size of licence areas, the feasibility of bidders forming alliances after auction, the prospect of secondary trades and the type of technology deployed are factors that might have played a part.

6.6 Conclusion

This chapter provides empirical evidence of the existence of positive population synergies in some recent Australian spectrum auctions. This finding accords with overseas evidence and limited domestic evidence, some of it anecdotal. By contrast, no sign of spectrum synergies is detected.

Given the use of simultaneous ascending auctions in Australia, the estimation of positive synergy values implies that bidders may risk paying too much for some lots if they fail to achieve their preferred aggregations. Such risk exposure is naturally undesirable from a bidder’s point of view. It is undesirable from an efficiency point of view too, because those who value spectrum most may end up with an insufficient assignment.

Package auctions have the potential to mitigate the exposure problem, allowing firms an ‘all or nothing’ bid for the exact package of geographic coverage and bandwidth they require. Package auctions are yet to be conducted for selling spectrum, however, and they have shortcomings: they involve complicated auction rules; they are costly to implement; and they lack a theoretical support for allocative efficiency in general circumstances.

Nevertheless, the evidence of significant spectrum synergies strengthens the case for package bidding in Australia. A 25 per cent price premium for licence synergies equates to a 25 per cent ‘exposure penalty’ for a bidder who fails to acquire preferred lots in aggregate. Based on the average price paid for a Sydney lot in the

2000 PCS auction, this exposure penalty translates into an overpayment of $13.4 million. This amount is not inconsequential for a firm, as borne out by part of the telecommunications industry calling for the adoption of package auctions to sell spectrum.

Beyond the cost to prospective licence buyers, exposure on such a scale also means that the benefit to the community from spectrum use would fall well short of the full potential. The concern about efficiency is presumably behind the FCC's decision to run its first package auction in 2003. Just as the US PCS auctions did in promoting simultaneous ascending auctions in the early 1990s, the use of package bidding in the US opens an opportunity for the ACA and bidders for Australian spectrum licences to gauge the worth of this design in a real-life setting.

A Enhancing market competitiveness

Government auctions can have implications for market structure and competitiveness. A comprehensive analysis of such implications is beyond the present paper's scope. Instead, this appendix introduces some key references for designing auctions to:

- adjust market values for externalities;
- promote market entry; and
- create competitive markets.

A.1 Adjusting market values for externalities

Discount bidding offers a way of realigning private values with social values. It is implemented through a handicapping rule that gives bid preferences to selected bidders. Under this rule, bids are treated unequally; a designated bidder can win the auction by making a bid that is within a price range lower than a nondesignated winner's bid. With a 10 per cent discount, for example, a designated bidder's bid at $90 has the same rank as a nondesignated bidder's bid at $100.

Discount bidding induces nondesignated bidders to bid higher than they otherwise would, thereby promoting bidding competition. Designated bidders have an increased chance, yet no guarantee, of acquiring the good on offer. As a policy tool, discount bidding requires governments to set appropriate price discounts so that designated bidders become competitive with nondesignated bidders. This is not always feasible, however, given governments' information gap. Moreover, price discounts may cause inefficiencies in resource use, such as excessive investment by designated bidders. In the context of spectrum auctions, Ayres and Cramton (1996), McAfee and McMillan (1989) and McMillan (1994) discuss the design details of discount bidding.

A.2 Promoting market entry

Market entry holds the key to a competitive structure of industries. Governments can use auctions to promote market entry, allocating 'production capacity' to small firms or potential entrants so that they can compete with incumbent firms in end markets. In this context, production capacity conveys market access rights. Governments sell vital inputs, such as spectrum licences, as a way of allocating production capacity.

Using auctions, governments can influence the allocation of production capacity in two ways. The first way is to impose allocation limits on individual firms. The second, less prescriptive way is to manoeuvre auction design for achieving particular allocation outcomes. In the absence of allocation limits, incumbent firms can bid for production capacity to exclude entry and increase their monopoly power. To counteract incumbents' incentive to pre-empt market entry, governments need to carefully consider the way of dividing production capacity into separate resource items that are available for bidding. The rights of access to spectrum, for example, can be offered for sale as a single licence or several licences.

As Jehiel and Moldovanu (2000b) analyse, an increase in capacity supply (in terms of the number of resource items offered) need not imply greater chances for potential entrants to gain market entry. Rather, the supply of production capacity should be *restricted*. This means that the number of resource items offered for sale should be limited, depending on the numbers of incumbents and potential entrants.

With excessive capacity supply, the pressure for competitive bidding diminishes. In this circumstance, incumbents can adopt bidding strategies by which they tacitly share the cost of dividing up a market. For example, they can purchase among them all of the available capacity, even though they may have to pay more than the expected profits from such additional capacity. Under specific cost conditions, a reduction in capacity supply makes tacit collusion difficult for incumbents, thereby raising the prospect of new market entry.

McAfee (1998) supports this analysis, pointing out that excessive capacity supply undermines a viable business. By increasing capacity supply, governments risk efficiency distortions at auction because bidding competition would then be driven by bidders' capability to endure unprofitable production until some winner is forced out of business.

A.3 Creating competitive markets

Markets are created as a result of governments privatising public-sector services or deregulating industries. These industrial policies affect the number of market operators and therefore the competitive structure of a new market.

In implementing a particular industrial policy, governments may want to determine the appropriate market structure but know little about the costs and revenues of individual firms. A firm's ability to make profit depends on the degree of market competition. To overcome the information gap, governments can design auctions to determine both the numbers and the identities of prospective producers in new markets. These auctions would induce bidders to reveal their expected profits for some resultant market structure. The auction outcome determines, for example, whether a government producer should retain production or contract out to a single firm or several firms.

Dana and Spier (1994) and Milgrom (1996) design auctions to allocate production capacity, linking the number of winners to the distribution of bids. Their design includes a minimum (reserve) price and a few threshold prices above the minimum price. These prices are associated with different numbers of winning bids that are selected according to the following rules.

- If all bids are below the reserve price, then the government seller retains production.
- If all bids are lower than the threshold prices but exceed the reserve price, then the firm that makes the highest bid acquires all production capacity.
- If a number of firms bid higher than a particular threshold price while no firm bids above the next higher threshold price, then a specified number of highest bidders among these firms each win some capacity to share production. For this outcome to occur, several firms expect to remain profitable while competing with others in the output market; with this expectation, each of them makes a sufficiently high bid to win some production capacity.

A properly designed auction can lead to greater economic benefits compared with an *ad hoc* administrative decision on market structure. However, a lack of information on the profit conditions of individual firms can constrain policy efforts to create viable, competitive markets. Reflecting this constraint, auction outcomes are biased towards either monopoly or government production.

- The threshold prices for shared production are set to rise with the number of winners. This design feature increases the likelihood of a monopoly outcome. To gain market shares, firms need to bid high relative to their potential profits. Yet, sharing production by several firms restricts their profit potential and therefore their ability to simultaneously make high bids. As a result, only one firm that is the most profitable may likely win.
- The reserve price is set at a relatively high level to discourage high-profit firms from bidding low. This design feature increases the likelihood of no sale. As a result, the government seller may likely retain production.

B Spectrum auctions

This appendix compares three multi-item auction formats that have been proposed for selling spectrum licences:

- simultaneous ascending auctions;
- Vickrey package auctions; and
- simultaneous ascending package auctions.

Section B.1 describes the auction mechanisms and explains their theoretical properties. Section B.2 assesses simultaneous ascending auctions through the evidence of practical applications. Section B.3 presents experimental results comparing the efficiency property of multi-item auctions in different controlled environments.

B.1 Multi-item auctions

Multi-item auctions in two categories are proposed for selling spectrum licences. The first category accepts bids on individual licences only, not allowing bidders to directly express synergy values. The simultaneous ascending format designed by Milgrom (2000) and associates belongs to this category. The second category provides bidders with a choice of licence packages on which to bid, thereby directly linking auction outcomes to synergy values. Examples include the Vickrey package bidding design (Forsythe and Isaac 1982) and the modified simultaneous ascending design with package bidding (Ausubel and Milgrom 2001; Charles River Associates and Market Design 1998).

Simultaneous ascending auctions

A simultaneous ascending auction is similar to a traditional English auction, except that all the licences are available for bidding throughout the auction rather than in sequence. Bidding proceeds in a series of rounds. In each round, bidders can bid on any individual licence on offer. The provisional winner for each licence at the end of a round is the one who makes the highest bid up to that point of time. Round results are announced before the next round. Between rounds, a new bid must beat the standing high bid by at least a specified bid increment. Several proposals have been made to specify the rule for closing the auction. Bidding on all licences can close at the same time when there is no further bidding on any licence. Alternatively, bidding can close progressively for licences that receive no new bid for a number of rounds. When the auction is closed, licences are assigned respectively to the highest bidders at prices equal to the last standing high bids.

The auction is executed with an array of procedural rules that govern deposits, payment terms, bid increments, information releases and so on. Particularly important are the activity rule and the closing rule, which control the pace of bidding and limit the scope for strategic manipulation by bidders.

The activity rule

The activity rule determines a bidder's eligibility to make bids during an auction. Eligibility is defined in terms of a bidder's active bids in a round. To be 'active' on a licence at a round, a bidder must make an eligible new bid for the licence or own the standing high bid from the previous round. A bidder can hold active bids on numerous licences. Current eligibility depends on the number of licences on which the bidder has active bids in a previous round. The measure of eligibility sets a limit to the number of licences on which a bidder can bid in a round as a function of its previous bidding activity. A bidder must remain active on some licences to maintain eligibility for bidding.

For licences covering different market areas, a weighted measure of eligibility is used. Licences are weighted by a quantity index that correlates with the licence value, such as the bandwidth (in megahertz) multiplied by the population in a licence area. At the outset of an auction, bidders each establish an initial eligibility by making a deposit covering the largest quantity of licences in which they have an interest. The deposit is not licence specific; it simply determines the limit to a bidder's total bidding activity in any round. A bidder must use at least a specified proportion of the assigned eligibility at a round; otherwise, eligibility is reduced at the next round. One version of the activity rule includes a sliding scale of fractions at 80 per cent, 90 per cent and 98 per cent of eligibility in various rounds divided in three bidding stages.

Bidders are each given a number of activity rule waivers, allowing them to preserve current eligibility even if activity in the current round falls below the required minimum level. An activity rule waiver applies to an entire round of bidding, not to a particular licence. By using a waiver, bidders avoid losing their bidding eligibility when not wanting to make bids in a round.

The activity rule includes provisions for bidders to withdraw bids after the close of each round, allowing them to avoid unintended reductions in eligibility in the event of mistakes or other problems in bid submission. Nevertheless, bid withdrawals expose a bidder to penalties (taken from the deposit payment) if another bidder does not subsequently pick up the withdrawn high bids. Despite the risk of penalty, bidders are able to make strategic use of bid withdrawals. When a withdrawn bid is counted as bidding activity, a bidder can switch licences without losing current eligibility. Bid withdrawals can be exploited for making insincere bids to maintain eligibility or to communicate bid signals in a collusive arrangement among bidders.

The activity rule has two functions. First, through the announcement of bids and eligibility, it conveys price information to bidders, which is particularly useful at a late stage in the auction. Second, it expedites the bidding process by requiring active bidding. Bidders have strategic incentives to delay making serious bids in an auction, such as a gain from concealing the ability or willingness to pay a high price until competitors have committed most of their budgets to acquiring other licences. Budget-constrained competitors respond with own delay tactics, hoping to learn more about others' bids on their most valued licences before bidding for other licences. Such 'wait and see' strategies hold back the pace of the auction. By inducing bidders to make active, serious bids, the activity rule helps ensure the completion of bidding within a reasonable amount of time and the steady convergence of bids towards equilibrium prices.

The closing rule

Two factors influence the choice between a simultaneous closing rule and a progressive, licence-by-licence closing rule. The first factor concerns the flexibility for bidders to switch among licences in response to relative price changes. The second factor concerns the possibility of collusive bidding.

A necessary condition for allocative efficiency is bidders' ability to switch to bidding for substitutes and to back out of a failed aggregation of complementary licences in response to price changes during an auction. With a simultaneous close of bidding for all licences, if a licence changes hands at some round, the losing bidder can react by bidding for a substitute or withdrawing a bid for a complement, and the winner can react in a reverse way. This situation creates opportunities for bidders to collude, because they can strategically bid on different licences to avoid direct competition that would drive up the prices of their targeted licences. The collusive outcome is supported by a bidder's threat to behave combatively in subsequent rounds if a competitor does not refrain from bidding on a particular licence. So long as all licences remain open for bidding, bidders can easily detect noncooperative bidding behaviour and make retaliatory bids.

With a licence-by-licence close of bidding, the scope for bidders to switch between licences is reduced. Collusive arrangements are disrupted because a defector can bid high and win some licences without facing the risk of retaliation. To balance the need to increase bidding flexibility and prevent collusive strategies, auction design can arrange for bidding to close on a licence only after several rounds in which no new bid is raised. It can also require the total number of new bids on all licences during a series of rounds to be less than some trigger value. Such rules allow for flexible shifts in a bidder's strategy until late in the auction, while still deterring some of the most obvious opportunities for collusive bidding.

Potential deficiencies of the auction outcome

By accepting simultaneous ascending bids, an auction improves efficiency in assigning multiple licences over sequential English sales. Ascending bids reveal value information between rounds, allowing bidders to adjust demands for price changes during the course of an auction. In auction environments characterised by common-value uncertainties, the effect of the winner's curse is reduced (section 4.1). With a collection of licences open for bidding at the same time, bidders enjoy a high degree of flexibility in aggregating licences and switching to another set of licences if price changes render a previous choice too expensive. Despite these advantages, simultaneous bidding has limitations in the context of both bidding for substitutes and bidding for complements.

Bidding for substitutes

In bidding for substitutes, a bidder may adopt either a straightforward or a sophisticated strategy. Only the former leads to an efficient assignment, which also generates the maximum expected revenue for the seller. A bidder often has an incentive for demand reduction, however, withholding bids for some licences to depress prices.

Straightforward bidding is when bidding behaviour follows a number of conditions.

- The bidder demands a set of licences only if this bidder's valuation of these licences as a whole exceeds the total amount of bids.
- The bidder bids on only licences in demand at the current prices.
- The bidder makes bids at any round as if the auction were to end after that round.

Together, these conditions imply that bidders determine their bids by comparing their own valuations with price changes between two consecutive rounds. If, at the end of a round, a bidder holds the standing high bids for a subset of desired licences, then this bidder will make minimum bids at the next round for additional licences that are part of the desired package.

Assuming that all bidders regard the licences as substitutes and that they bid straightforwardly, a simultaneous ascending auction would attain an efficient assignment that maximises expected revenue for the seller. In this circumstance, a bidder would never wish to withdraw bids at the end of a round. Furthermore, by winning some licences in the auction, a bidder would always make some gain from trade because the acquired licences would be priced below the winner's valuations.

Bidders face incentives to adopt a demand reduction strategy (unless each bidder is restricted to a single licence at most). Consider a firm with two conflicting concerns in bidding for spectrum licences. It does not wish to be completely shut out of the market and therefore must win some licences; yet, it does not wish to win too many licences, for which it has diminishing marginal values. A strategic option for the firm is to enter high bids on some licences but low bids on others. This makes room for other firms to make low bids. If a low-valuation firm wins an assignment, then the high-valuation firm can expect to win additional licences at bargain prices. As a result, the assignment is not strictly consistent with bidders' relative valuations, resulting in allocative inefficiencies.

To discourage demand reduction, the auction design must include a pricing rule that allows for differential prices for substitutes. An example is the pricing rule used in a Vickrey package auction (discussed below).

Bidding for complements

Bidding for complementary licences establishes a theoretical limit to the efficiency property of a simultaneous ascending auction. If the traded licences have positive synergies for any bidder, then equilibrium prices may not even exist to support an efficient assignment. This problem is potentially present in any auction that sells individually a set of non-identical items. Unlike the problem of demand reduction, the failure to achieve efficiency due to the presence of positive synergies cannot be addressed by designing an auction to counteract strategic manipulation. The nonexistence of equilibrium prices is related to the profile of bidder valuations. A typical example is one in which the traded licences are complements for one bidder but substitutes for another. Another example is where licences are complements for all bidders, yet by varying degrees. Box B.1 illustrates these auction environments.

Box B.1 Nonexistence of equilibrium prices for complements

Example 1

Consider the competition between bidders A and B for two licences that cover the market areas East and West respectively. For A, the licences are complements yielding a positive synergy value in the formation of a combined network. For B, the licences are substitutes. Their valuations are as follows:

Bidder	*East*	*West*	*Pair*
A	$40	$20	$80
B	$52	$32	$72

In the efficient assignment, A acquires both licences. For B to not win either licence, the price of East must be over $52 and that of West must be over $32. At such prices, however, A is unwilling to buy both licences because total payment at over $84 exceeds A's combined valuation for both licences. Consequently, no equilibrium prices exist in any auction that excludes package bidding.

Example 2

An auction sells separately the outbound and return communication channels for a two-way wireless service. Four bands are on offer, numbered as 1, 2, 3 and 4 in the waveband order. Each bidder is allowed one pair of channels. Bidders A, B and C use alternative technologies: A and B require adjacent outbound and return bands, while C requires that the bands be separated by one band. Their valuations for various licence pairs are as follows:

Bidder	*Bands 1 and 2*	*Bands 3 and 4*	*Bands 1 and 3*	*Bands 2 and 4*
A	$10	$10	$0	$0
B	$10	$10	$0	$0
C	$0	$0	$15	$15

The efficient assignment is for A and B to acquire either of the licence pairs (1, 2) and (3, 4), yielding a total value of $20. To exclude C from the assignment, the total price of licences 1 and 3 has to be at least $15 and the same is required for licences 2 and 4. Together, the four licences must be priced at above $30. However, this total price is outside the acceptable price range for A and B. This example therefore has no equilibrium prices despite the presence of complementary licences for all bidders.

Source: Charles River Associates and Market Design (1997).

In relation to the nonexistence of equilibrium prices for complements, a bidder may face the exposure problem in an auction. A straightforward bidder is exposed to the risk of failing to win some of the complementary licences in a desired package. The bidder may end up paying more than the combined valuation of the licences won, because the potential synergy for such licences are not realised in full.

The exposure problem creates an incentive for strategic bidding, which undermines the potential for raising revenue and leads to efficiency distortions. A bidder facing the exposure problem tends to bid cautiously in early rounds of the auction, seeking to assess the chance of winning a desired package before making high bids that reflect the full value of that package. Anticipating this strategy, a competitor makes high bids on some licences early in the auction, to discourage the bidder from bidding on the other desired licences. In that way, the competitor seeks to reduce bidding competition and acquire some licences at low prices.

Tensions exist in a simultaneous ascending auction in which the licences for sale are complements or substitutes for different bidders. Allocative efficiency requires that bids reflect positive synergy values for complements and diminishing marginal values for substitutes. With diverging synergy values among bidders, however, compatible equilibrium prices may not exist and straightforward bidding by all bidders is unlikely. The closer the bidders' valuations for particular licences (possibly due to some common-value elements in their valuations), the more serious is the exposure problem. Consequently, auction design is more complicated for closely contested auctions of complementary licences than for similar auctions of substitutes. The weaknesses of licence-by-licence bidding provide ample reason to investigate package bidding.

Vickrey package auctions

A Vickrey package auction adopts a one-shot, sealed-bid format. Each bidder makes a separate bid for every feasible package of the licences for sale. For a sale of n licences, a complete list of bids contains $2^n - 1$ packages. The seller searches across all feasible combinations of bids to determine the assignment that maximises the total value of the licences based on the bids. Each winner pays an amount equal to the sum of the lowest bid(s) that could have been made to win that part of the assignment, given the others' bids. The required payment is specific to each winner. There may be no single price for a licence as in a licence-by-licence auction. Until the assignment is decided, a bidder does not know the exact payment for any particular package that may be won. This differs from the 'pay your bid' pricing rule used in a simultaneous ascending auction (box B.2).

Desirable theoretical features

The interest in the Vickrey package design stems from its distinct theoretical features of auction outcomes and bidding behaviour. Each bidder adopts a dominant strategy, bidding an own valuation for every package regardless of how others bid. Because the payment required of a winner depends on others' bids rather than own bids, bidders bid their actual valuations. This bidding behaviour is called demand revelation. The auction achieves efficient assignment and maximises total expected revenue, resolving the exposure problem and the demand reduction problem. By virtue of its desirable properties, the Vickrey design is often used as a performance benchmark for assessing other auction forms.

Practical limitations

This auction form is seldom applied in practice for a variety of reasons. First, large differences between high bids revealed and payments required can be seen as a loss of revenue for the seller — that is, too much money is left on the table. Second, bidders may pay different amounts for identical assignments, even if they make the same bids on those packages. While these two situations may embarrass the seller, they do not indicate any fundamental deficiency of the auction outcome. The possibility that winners pay less than what they bid in a Vickrey package auction does not imply the possibility of using other auction forms to increase revenue. Bidding behaviour changes with the auction form chosen. Likewise, the phenomenon of differential prices is consistent with an efficiency outcome of a Vickrey auction. Any other auction design able to yield efficient outcomes must establish the same pattern of payments as in a Vickrey auction. Boxes B.3 and B.4 present examples to illustrate the efficiency property of a Vickrey pricing rule.

Box B.2 **Payment rule used in a Vickrey package auction**

For each bidder, the payment is computed as the difference between two terms: (i) the sum of the other bidders' winning bids; and (ii) the sum of the winning bids when own bids are disregarded. For an illustration, the following table shows the valuations for bidders A, B and C who compete for the two regional licences East and West. The licences are sold either separately or in a pair.

Bidder	*East*	*West*	*Pair*
A	$5	$10	$16
B	$12	$6	$21
C	$2	$3	$17

Through a Vickrey package auction, B acquires licence East while A acquires licence West. The combined value of $22 is the greatest among all of the feasible allocations. To compute the payment required of A, the first term in the payment formula is $12 (B's bid on East) and the second term is $21 (disregarding A's bids, B would win the Pair). The difference between these two terms is $9, which is A's payment (relative to a valuation of $10 for West). The payment for B is $7 (compared with a valuation of $12 for East). The seller's total revenue is $16.

Source: Ausubel and Milgrom (2001).

Box B.3 **Revenue comparison for a Vickrey package auction**

This example compares the capability of raising revenue between a Vickrey package auction and a simultaneous ascending auction. The setting is similar to box B.2. To simplify the analysis, suppose that each bidder in a Vickrey package auction makes only a package bid and a bid for an individual licence. The valuations are as follows:

Bidders	*East*	*West*	*Pair*
A	$10	$10	$19
B	$8	$8	$12
C	$5	$5	$10

In a simultaneous ascending auction, A and B have incentives for demand reduction. They avoid competition against each other by bidding on different licences. As a result, the equilibrium price for each licence is just above $5, which is high enough to deter further bidding by C and allows A and B to each win one licence. Any attempt by A or B to acquire a second licence would either fail or drive the price up to $8. Either outcome means a lower profit compared with winning a single licence for a price of $5. The auction generates a total revenue of $10 and the assignment is inefficient.

In a Vickrey auction, A wins both licences because all bidders bid according to a dominant strategy. A's payment is given by the difference between (i) the maximum total value of the licences acquired by the other bidders without A's participation (which is $13) and (ii) the value of the licences other bidders actually win (which is zero). Accordingly, A's payment for the licence pair is $13. The Vickrey auction is efficient, generating greater revenue than that of a simultaneous ascending auction.

Source: Charles River Associates and Market Design (1997).

Box B.4 **Price discrimination in a Vickrey package auction**

The following table shows the valuations of bidders A and B for the two regional licences East and West:

Bidder	*East*	*West*	*Pair*
A	$12	$12	$13
B	$12	$12	$20

As in box B.3, each bidder makes only a package bid and a bid for an individual licence. The assignment is for each bidder to acquire a licence, with A paying $8 and B $1. A has a smaller marginal value than B's for the second licence, so the only way to stop B from winning both licences is for A to pay an amount equal to B's marginal value. Consequently, A pays more than B despite their identical bids on both licences.

Source: Isaac and James (2000).

An inherent problem of this auction form is bidders' uncertainty about the payment for any assignment that they may win. To the extent that price uncertainty is high, which is likely in a spectrum auction, budgets can limit bidders' ability to express valuations in a Vickrey package auction. This problem has no simple solution. Bidding against a budget constraint is one of the most difficult areas in auction theory. Some remedial measures — such as the arrangements for bid withdrawals and for setting maximum budget exposures — not only complicate the auction rules but also introduce incentives for bidders to deviate from dominant strategies, depriving auction outcomes of the desirable properties due to the Vickrey design.

Another objection to this auction form relates to the information cost imposed on bidders. Without any package restriction, a large number of package bids are required. Bidders may be unable or reluctant to reveal valuations for every possible package. It is costly for bidders to investigate the technological attributes and costs of new services, and to create business plans for projecting future demand.

Simultaneous ascending auctions with package bidding

Given that it is not feasible to express all relevant package bids in advance, one solution is to allow bidders to select particular packages on which to bid as the auction progresses. The simultaneous ascending package bidding mechanism is one such proposal. It modifies and extends the original licence-by-licence bidding format to make package bidding possible.

Auction rules

The auction proceeds through a series of rounds in which bidders bid on allowable packages of licences or individual licences. In a round, standing high bids are chosen to maximise the total bid among all of the compatible combinations of packages in demand. Such standing high bids determine a provisional assignment, in which the component packages do not overlap but exhaust the available licences. If the auction ends in that round, then this is the final assignment and the standing high bids are the payments for the assigned packages. Bidding continues until a closing rule takes effect to end the auction.

Successful execution of an ascending package auction relies on carefully designed auction rules to manage the complex bidding process. Beyond the necessary modifications in the procedural rules (such as those for round structure, bidding activity, eligibility, bid increments, the withdrawal of bids and the closure of an auction), novel design features distinguish this auction form from its predecessor.

Restrictions on allowable packages

Some restrictions on the set of packages on which bidders can bid are needed to limit the computational burden in determining a feasible assignment. Package restrictions are designed primarily to mirror potential synergies among the licences on the basis of geographic coverage and spectrum use. The general principle is to allow for aggregation of licences with strong, positive synergies. Spectrum users and auction specialists advise on the estimation of bidders' demand for particular licence packages. Licence packages are restricted, for example, to subsets of regional licences such that one subset is contained within another. This way of packaging licences helps aggregate spectrum for contiguous service areas. Licence packaging also can be based on technological requirements of combining spectrum.

Restrictions on package bids

Within the set of allowable packages, further restrictions are imposed on the maximum number of packages on which a bidder can bid in a round and on the structure of package bids.

Restrictions on the package *number* are aimed at limiting computational complexity and reducing the scope for strategic manipulation and collusive agreements among bidders. The freedom to specify any division of licences offers bidders the opportunity to signal their intentions for dividing markets.

Restrictions on the *structure* of package bids are enacted through the provisions for contingent bidding, which allow bidders to specify the conditions under which they wish to win a bid. Contingent bids submitted by a bidder are treated as mutually exclusive and excluded from any feasible package combination used for determining assignments. Contingent bidding provides bidders with increased flexibility in bidding on substitutable licences, thus reducing the incentive for demand reduction. The use of 'or' bids, for example, allows a bidder to indicate an intention to win a licence for any region but not for more than one region.

Several factors affect the ruling on contingent bids. First, a large variety of allowable contingent bids can pose a computational problem. Second, through an iterative package bidding process, the auction form already provides bidders with considerable flexibility in making mutually exclusive bids. Third, contingent bidding introduces a bias towards the assignment of large-size packages, although it reduces the risk of bidders winning more licences than they demand.

Bulletin board

The bulletin board is a publicly observable electronic device for receiving and posting bids throughout the course of bidding. It has a dual role: first, it discloses standing high bids and provisional assignments; and second, it enables bidders to identify other bids that they can combine into packages to displace a provisional assignment. These functions are accomplished as follows.

In each round, eligible new bids are tested against the standing assignment to determine whether any bid, in combination with other standing high bids or bids posted on the bulletin board, results in an increase in total revenue. If so, that new bid becomes part of the new provisional assignment. The new assignment is then announced on the bulletin board and the bids making up this assignment are posted as the standing high bids. If the new bid is insufficient to be a standing high bid, then it may be posted as a retained bid on the bulletin board. Bidders can subsequently use such a retained bid to construct a new assignment that dominates the standing assignment. A bid that loses at a round can thus become a winning bid at a later round.

The bulletin board provides bidders with a means of communication to exchange information on feasible packages to displace the standing high bids. It generates the necessary information for guiding the auction to achieve an efficient assignment and for directing bids to converge towards equilibrium prices. A bid is retained on the bulletin board only if it can potentially contribute to a new standing assignment subject to subsequent bids. The bulletin board needs to exclude low bids that have little chance of winning; otherwise, it can be exploited for collusive communications.

Discount bids

Reflecting the free-rider problem associated with package bidding (discussed on the next page), this auction form is biased towards package bids and against individual licence bids, causing a loss of assignment efficiency. To reduce such bias in auction outcomes, winning bids on single licences are given a discount. With a discount of 10 per cent, for example, a bid on an individual licence of $100 is counted as a bid of $100 for the purposes of the eligibility rule and the assignment rule, but the bidder is obliged to pay only $90.

Discount bids open the opportunity for strategic manipulation or collusive bidding. This problem necessitates the provision that disqualifies a bidder who has made a package bid from receiving a discount for a subsequent bid on any individual licence within that package. Package bidding is discouraged in early stages of the auction, because a package bid limits the options available to a bidder as the auction progresses. On efficiency grounds, it is desirable to activate package bidding only in later stages of the auction when the exposure problem facing package bidders becomes increasingly severe as bids approaching final prices.

Theoretical properties

Theoretical analyses of ascending package bidding remain sparse but are accumulating, with research in this area getting under way. Auction theory identifies a particular kind of bidding behaviour — that is, straightforward bidding — that leads to some unambiguous outcome for a simultaneous ascending package auction in a specific class of auction environment. By bidding straightforwardly in an ascending package auction, a bidder bids at each round on only the package(s) that generate the highest profits (that is, the bidder's valuations minus the required minimum bids) and makes the minimum bids on those packages. Between rounds, a bidder first bids on the most valued packages and, after acquiring such packages, proceeds to bid on other less valued packages.

Model results are derived for a class of auction environment in which the licences being auctioned are substitutes for all bidders. Under such assumptions, straightforward bidding in a simultaneous ascending auction with package bidding largely replicates the outcome of a Vickrey package auction: the final assignment is efficient and generates maximum expected revenue.

In the presence of complements, the analysis of bidding strategies remains intractable and outcome properties are mostly unclear. Ascending package bidding corrects the exposure problem. The effect of package restrictions is not accounted for, however. Such restrictions may remove desirable licence combinations that have idiosyncratic synergies not known to the auction designer.

Free-rider problem

This auction form admits bidding strategies that are far from straightforward bidding. Bidders have incentives to postpone making serious bids until late in the auction. Activity rules provide a partial solution to this problem. Furthermore, the auction outcome is biased, such that a package bidder can win even when allocative efficiency dictates that a set of licences should not be aggregated. This is known as the free-rider problem (or the threshold problem).

A group of bidders seeking single licences or small-size packages face an incentive problem in coordinating their bids against competition from a bidder for a relatively large package containing the same licences. This relates to the case in which the multiple bidders' total valuation for a set of licences exceeds the package bidder's valuation of the whole set. Former bidders want to hold back, hoping that some other bidders will increase their bids sufficiently for the collective bids on the pieces to beat the package bid. This motive leads to bidders' inaction in raising their individual bids by enough to beat a package bid.

To take advantage of package bidding, a bidder can strategically submit a package bid to win multiple licences even when perceiving little synergy value in these licences. Package bids, especially for relatively large packages, are more likely to

Box B.5 **Free-rider problem in package bidding**

Below are the valuations of bidders A, B and C for the two regional licences East and West. Bidders A and B are each eligible to acquire only one licence. Bidder C has the lowest valuations for the licences but wants to acquire both.

Bidder	*East*	*West*	*Pair*
A	$4	..	..
B	..	$4	..
C	$1	$1	$2

.. Not applicable.

The sole efficient assignment has A and B acquiring East and West respectively. This outcome is achievable in a simultaneous ascending auction, with C giving up bidding at just above $1, while A and B make minimum bids at each round as necessary to respectively acquire their licences of interest.

In a simultaneous ascending auction with package bidding, A and B can defeat C only by paying prices that add up to over $2. In response, C can refrain from bidding for individual licences and instead make a package bid. To illustrate the free-rider problem facing A and B, consider bids that are restricted to whole numbers. The bidders adopt the following strategies. In a round, C bids $2 for the Pair. Bidder A raises its bid for East by $1 whenever not holding the standing high bid for that licence. Otherwise, if at any time the standing high bids are $1 for East, $1 for West and $2 for the Pair, then A may or may not raise a high bid on East by $1, subject to A's expectation of B's strategy. B's strategy is symmetrical to that of A.

The auction outcome is indeterminate, depending on whether A or B raises the single licence bid above $1. Based on the bidders' expected profits under the conditions that they do and do not respectively raise the high bid, there is a probability of one-ninth that neither A nor B will raise the high bid, thus allowing C to win the Pair even though C's total valuation for both licences is just one quarter of A's and B's valuations combined. Such an inefficient assignment is avoidable by disallowing package bids in a simultaneous ascending auction.

Source: Milgrom (2000).

win licences at lower average prices. The resulting assignment is inefficient and does not maximise the seller's expected revenue. The use of discount bids in a package auction alleviates but does not overcome the free-rider problem, because such a remedy involves uncertainties in determining the appropriate discounts without knowing bidders' valuations. Box B.5 illustrates the free-rider problem.

B.2 Simultaneous ascending auctions in practice

The simultaneous ascending design (without package bidding) was first introduced in 1994 to sell spectrum licences in the United States. It has since been extensively used by spectrum regulators in Europe and Australia. Various reviews suggest that such auctions realised at least some of the theoretical advantages claimed for this auction form. The following discussion draws on the US experience over the period mid-1994 to mid-1996 as assessed by Cramton (1997, 1998), McAfee and McMillan (1996), Milgrom (1995) and Weber (1997).

Auctions of PCS licences

The US Federal Communication Commission (FCC) used simultaneous ascending auctions to assign thousands of personal communications service (PCS) licences. These licences were defined for different frequency bands and geographic areas. To test and refine the auction design, the FCC began with the sale of 10 nationwide narrowband PCS licences. The auction was relatively simple, partly due to the small number of licences and partly due to the absence of geographic aggregation issues. Licence aggregations were possible, however, because a firm was allowed to acquire up to three narrowband licences in any area. Narrowband licences are used to provide paging and data services and, as a result of the narrow bandwidth, are not suitable for commercial real-time voice services. The auction lasted 47 rounds over five days in July 1994 and raised US$617 million.

Next for sale were 30 regional narrowband licences, which comprised six licences in each of five regions. Geographic aggregations played a limited role compared with their role in later auctions, which split each of the regions into numerous major trading areas (MTAs) or further divided basic trading areas (BTAs). In October–November 1994, the auction took 105 rounds to complete. It assigned most of the licences as nationwide aggregations, raising a total of US$395 million.

The third auction was the largest simultaneous auction ever, offering 99 MTA broadband licences — a pair of 30-megahertz (AB-block) licences in each of the 51 major trading areas, bar a few exceptions in some areas. The auction raised over US$7 billion after 112 rounds of bidding from December 1994 to March 1995.

The fourth PCS auction assigned the third 30-megahertz (C-block) licence in each of the 493 basic trading areas. The auction was open for small firms only, raising US$10.2 billion in 184 rounds of bidding that ended in May 1996.

Indirect evidence of allocative efficiency

Bidders' actual valuations are indiscernible, so it is impossible to assess directly the efficiency property of the PCS auctions. Nevertheless, the observed bidding behaviour and bid data support the claim that the licences were efficiently assigned.

High revenues

Adjusted for population and bandwidth, high licence prices were obtained amid intense bidding competition. In the auction context, revenue maximisation and allocative efficiency are closely aligned goals. Only bidders with high valuations are willing to pay high prices. To reduce the chance that high valuations are derived from a non-competitive industry structure, the FCC limited the amount of spectrum that a firm could hold in any market. This helped ensure high valuations reflected a firm's advantage at providing better services at lower prices, rather than an advantage in restricting market entry. The iterative bidding process reduced the winner's curse and induced bidders to bid close to their valuations.

Extensive bid information

The PCS auctions revealed useful information on bidder valuations, contributing to an efficient assignment of the licences and a rapid convergence of the licence prices. Several sources of information assisted bidders in adjusting their bidding strategies. The first source was bidders' upfront payments, which suggested their bidding intentions. Strong correlation was found between the upfront payments and the amounts of spectrum won by different bidders. Statistically, the association was most significant in the MTA auction (measured at 93 per cent), followed by the regional auction (83 per cent), the nationwide auction (78 per cent) and the BTA auction (64 per cent). Bidders with small upfront payments tended to win nothing.

Second, current bids could be used to predict final assignments. Much about the final outcome was determined long before the auction closed. In the nationwide auction, the identities of high bidders were virtually unchanged during the last 19 rounds. In the regional auction, the assignment settled even sooner, with the final winners emerging as high bidders by round 10 while the auction was to close 95 rounds later. In the MTA and BTA auctions, over 70 per cent of the high bidders at the end of stage 2 (that is, rounds 64 and 58 respectively) eventually won the final assignments in their current markets.

Third, current high bids gave reliable information about relative prices at the end of auction. In the MTA auction, while initial high bids were modestly correlated with final prices (statistically measured at 30 per cent), the correlation increased sharply to 62 per cent by round 21. In the other auctions, the bid–price correlation was strong from early in the bidding.

Bidders were able to act on the information. The eligibility rule did not seriously constrain their responses by the time they could make sense of the bid information. This was clearly the case in the narrowband auctions, because the assignments and prices were settled early. In the broadband auctions, firms maintained adequate eligibility during most of the last bidding stage to shift among licences.

Similar prices for substitutes

Evidence of arbitrage bidding is important because it indicates whether bidders are able to switch between close substitutes in response to relative price changes until late in the auction. Arbitrage bidding also is consistent with strategic manipulation and collusive bidding, however. It is a necessary but not a sufficient condition for this auction form to achieve efficient assignments. Demand reduction strategies were detected in the nationwide auction, in which the largest bidding firm reduced its demand from three to two licences while prices were still well below the firm’s plausible valuation for the third unit. An examination of bid data from the MTA auction suggests that some of the largest bidding firms dropped out of certain markets at prices well below plausible valuations.

The PCS auctions exhibited clear evidence of arbitrage bidding. In the nationwide auction, licence prices differed by less than a few percentage points. In the regional auction, price differences increased but remained insignificant. Bidders’ interests in forming nationwide aggregations within the same band probably explained the increased price gaps between similar licences. In the MTA auction, prices for A-licences and B-licences differed by less than one bid increment in most markets.

Sensible aggregations

To a degree, bidders were able to piece together sensible licence aggregations without the aid of package bidding. The exposure problem was not severe in the PCS auctions because licence synergies were limited. This obviated the use of bid withdrawals to address failed aggregations.

Bidders had modest synergies for adjacent licences. In the nationwide auction, all bidders for multiple licences were able to acquire adjacent bands, which slightly increased spectrum capacity overall. In the regional auction, several bidders with nationwide interests were successful in acquiring licences over all five regions within the same band, which provided the only important source of inter-licence synergy. In the MTA auction, it appears that the defined areas were sufficiently large to capture most local synergies. As a result, bidders had little difficulty in acquiring adjacent licences. Compared with the other licences, BTA licences cover smaller geographic areas and have greater synergies. These licence features did not, however, prevent a number of firms from acquiring clusters of adjacent licences in the BTA auction.

Further evidence of efficient aggregations comes from the rare use of bid withdrawals. No withdrawal was made in the nationwide auction. Two withdrawals were raised in the regional auction as a result of strategic bidding rather than failed aggregation. Likewise, withdrawals in the MTA auction did not suggest aggregation failures. In the BTA auction, about 50 withdrawals were made out of nearly 30 000 bids; at least some of these withdrawals were made as bid signals.

Limited bidder collusion

There was no definitive evidence of collusion in the narrowband auctions. To encourage small firms to participate, the FCC allowed the formation of alliances for joint bidding. From the bidders' perspective, alliances help reduce the risk of mutually destructive bidding. Alliances were unimportant in the nationwide auction, because the successful firms mostly bid on their own. Alliances were formed in the regional auction but did not make a major impact on the auction outcome. Bidding was competitive and resulted in licence prices that were higher than many predicted.

Collusive behaviour was suspected in the MTA auction, in which major alliances were formed and altered the strength of bidding competition in different market areas. The bidding record reveals bidding behaviour consistent with tacit collusion or demand reduction. For some markets, there was virtually no bidding competition. A comparison of adjusted price data for the AB-licences and C-licences suggests that licence prices in the MTA auction were considerably lower than those for the same market area in the BTA auction. One plausible explanation is that the former auction, with fewer bidders, presented more opportunities for collusive agreements among bidders.

Timely completion of auction

Much of the benefit of multi-round bidding is lost if the auction does not come to a natural end according to the closing rule. In that case, the FCC would have had to declare a final round of bidding, resulting in inefficiencies in the assignment as high bids failed to converge to equilibrium prices. The PCS auctions were all completed in a timely manner, however. The nationwide auction took one week and the regional auction took two weeks. The short duration was possible as a result of the small number of licences up for auction. The MTA and BTA auctions concluded in three to four months. This is a modest duration, given the large number of licences being sold and the high stakes involved. Bidders needed time to digest bid information and make important decisions during an auction.

B.3 Experimental evaluation of auction designs

Building on auction theory and practical experience, experimental studies compare the performance of various auction designs in specific testing environments. Controlled auction environments are created to represent a varying profile of bidder valuations. Bidding behaviour and auction outcomes are observed to determine the sensitivity of performance to changes in value parameters and auction rules. Experimental studies explicitly measure the efficiency of an auction mechanism by comparing the assignment and the prior setting of valuations, which would not be possible with an analysis of field data.

Two studies are reported here. The first study, conducted by Isaac and James (2000), tested the Vickrey package auction design against a class of assignment method, including a simultaneous auction. The second study, sponsored by the FCC and conducted by Cybernomics (2000), compared the performance of the simultaneous ascending designs with and without package bidding.

Experimental design

Each experiment included a series of auctions using different formats to assign a set of items to subjects (that is, experimental bidders) who were each given a set of valuations for these items. Before the experiments, subjects received training with the bidding protocol and procedural rules; they were not instructed to employ any particular bidding strategy. Valuation models were devised to simulate the demand for the available items. The structure of synergy values differed across, but not within, the auctions. By changing the parameters included in such valuation models, the researchers generated the payoffs to winning subjects for different valuation environments. Bidder valuations were systematically simulated to adjust the strength of synergies, ranging from a negative synergy value for partial substitutes to a positive synergy value for strong complements.

Cybernomics conducted 49 auctions in which six to nine subjects (from different groups) bid for 10 available items. Two auction mechanisms were tested:

- the simultaneous ascending auction; and
- the simultaneous ascending package auction.

Isaac and James conducted 12 auctions, each involving a different group of three bidders in a sale of two items. Test results were obtained for two auction forms:

- the Vickrey package auction; and
- the simultaneous sealed-bid second-price auction.

The latter is a one-shot rather than ascending auction. It generated results comparable to those obtained by Cybernomics using the ascending design. As such, the second-price auction provides a common basis for comparing results across the two studies.

To gauge auction performance in relative terms, Isaac and James considered two assignment methods that are alternatives to auctions:

- random assignment, whereby each of the possible assignments is equally likely; and
- worst assignment, whereby the assignment is selected to generate the lowest possible level of efficiency given the bidders' valuations.

Experimental results

Allocative efficiency is the primary performance indicator used in evaluating the auction forms. It is measured by the ratio of (i) the realised value of the items as assigned, to (ii) the maximum value among all possible assignments. This ratio is expressed as an index number between zero and one; an index of one indicates full efficiency.

Table B.1 shows the relative measures of efficiency for the various auction forms or assignment methods tested. Results are obtained for a variety of value settings. The table presents average efficiency estimates for two classes of auction environment in which the auctioned items are characterised as substitutes and complements respectively. These results illuminate several features of the auction mechanisms being compared.

Table B.1 **Relative efficiency measures for multi-item auctions under different valuation environments**

	Substitutes	*Complements*
Cybernomics (2000)		
Simultaneous ascending auction	0.97[b]	0.84
Simultaneous ascending package auction	0.99[b]	0.97
Isaac and James (2000)		
Simultaneous sealed-bid second-price auction	0.92[c]	0.85
Vickrey package auction	0.96[c]	0.97
Random assignment	0.62[c]	0.60
Worst assignment	0.28[c]	0.17

[a] Full efficiency equals one. [b] The auctioned items are perfect substitutes (with zero synergy value) for all bidders. [c] The auctioned items are partial substitutes (with negative synergy value) for all bidders.

Sources: Cybernomics (2000); Isaac and James (2000).

Improved efficiency due to package bidding

Package bidding improved the efficiency of assignment in all of the auction environments tested. The measured increases in efficiency were notable in the auctions for complementary items. Detailed results (not shown here) indicate that varying the strength of synergy values did not affect the efficiency of package bidding. The efficiency of the nonpackage auctions declined markedly, however, as synergies grew. This finding supports the use of package bidding to sell multiple items with strong synergies. In the auctions for substitutable items, the improvements in efficiency due to package bidding were modest. The small changes in efficiency are consistent with the theoretical analysis that bidders have incentives to deviate from a straightforward strategy in bidding for multiple substitutes.

The Vickrey package auction as a performance benchmark

The Vickrey package auction design, serving as a performance benchmark, did not achieve full efficiency in all the testing sessions. This result may reflect a statistical discrepancy in the experimental results. A detailed analysis of the bid data suggests that subjects took time to adapt to a dominant strategy whereby they bid their valuations. Bidders' propensity to reveal true valuations increased with the repetition of bidding with this auction form.

Cross-study comparisons

Another observation is related to design comparisons across the studies. For complements, the two package auctions produced comparable average efficiency measures, as did the two nonpackage auctions. For substitutes, however, the two simultaneous ascending designs yielded higher efficiency measures than yielded correspondingly by the Vickrey package design and the simultaneous second-price design.

Different ways of defining substitutable items affected cross-study comparisons. Cybernomics simulated perfect substitutes that had a constant marginal value (or, equivalently, zero synergy value). In this auction environment, item aggregation would not severely complicate a bidder's strategy. By contrast, the other study tested the auction forms using partial substitutes, which were simulated with diminishing marginal values (or, equivalently, negative synergy values). This approach increased the environment's complexity relative to the case of perfect substitutes, because bidders faced an increased exposure risk in bidding for a particular numbers of items.

Instead, the results pertinent to complements provide a sound basis for integrating results across the studies. Both studies considered a wide range of synergy variations in simulating complementary items. Design-specific results can be compared by averaging the different profiles of positive synergy values simulated in each study. On this basis, the design for simultaneous ascending package bidding seems to perform as well as the Vickrey benchmark.

A yardstick for comparing efficiency

The results for random assignment and worst assignment provide a yardstick to calibrate the efficiency improvements due to the auction forms tested. The worst assignment measured a lower bound of efficiency at levels much higher than zero. By not requiring any auction, random assignment is a virtually cost-free method of achieving efficiency measures at over 0.6. Using this efficiency level as a starting point, simultaneous auctions without package bidding increased efficiency by about 48 per cent for substitutes (based on the study by Isaac and James) and 42 per cent for complements. Package bidding further increased efficiency by up to 4 per cent in bidding for substitutes and 14 per cent in bidding for complements. The use of a simultaneous auction, even without the aid of package bidding, appears to be the most important contributor to allocative efficiency.

Reservations with experimental results

Caution must be exercised in interpreting the experimental results.

- The findings based on laboratory simulations may not apply to real spectrum auctions. Field environments can be far more complicated and far less understood than those tested in controlled experiments. The two studies reported here have not examined, for example, the environment in which the traded items are substitutes and complements for different bidders.
- The scope for strategic manipulation of the auction rules is more restricted in experiments than in a real auction.
- Some experimental conditions are not typical of a spectrum auction: the subjects knew little about other bidders' valuations and the time allowed for bidding was relatively short, affording little opportunity to evaluate bid information and make strategic decisions.
- The trial stakes in the two experimental studies were only a fraction of the potential profit from acquiring a licence.

Together, these factors favour straightforward bidding over sophisticated strategies and lead to a potentially biased assessment of relatively high efficiency. In a spectrum auction, firms have access to advice of auction consultants, so are likely to bid differently from experimental subjects. Consequently, success of any auction form in laboratory may not occur in a real, high-stakes auction.

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