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Mechanism Design Theory

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1 Introduction

Economic transactions take place in markets, within firms and under a host of other institutional arrangements. Some markets are free of government intervention while others are regulated. Within firms, some transactions are guided by market prices, some are negotiated, and yet others are dictated by management. Mechanism design theory provides a coherent framework for analyzing this great variety of institutions, or "allocation mechanisms", with a focus on the problems associated with incentives and private information.

Markets, or market-like institutions, often allocate goods and services efficiently. Long ago, economists theoretically proved this efficiency under fairly stringent assumptions concerning, among other things, the nature of the goods to be produced and traded, participants' information about these, and the degree of competition. Mechanism design theory allows researchers to systematically analyze and compare a broad variety of institutions under less stringent assumptions. By using game theory, mechanism design can go beyond the classical approach, and, for example, explicitly model how prices are set. In some cases, the game-theoretic approach has led to a new appreciation of the market mechanism. The theory shows, for example, that so-called double auctions (where buyers and sellers post their bid- and ask-prices) can be efficient trading institutions when each trader has private information about his or her valuations of the goods traded. As the number of traders increases, the double-auction mechanism will more and more efficiently aggregate privately held information, and eventually all information is reflected by the equilibrium prices (Wilson, 1985). These results support Friedrich Hayek's (1945) argument that markets efficiently aggregate relevant private information.

Mechanism design theory shows which mechanisms are optimal for different participants, say sellers or buyers (e.g. Samuelson, 1984). Such insights have been used to better understand market mechanisms that we frequently observe. For example, the theory has been used to identify conditions under which commonly observed auction forms maximize the seller's expected revenue (Harris and Raviv, 1981; Myerson, 1981; Riley and Samuelson, 1981). The theory also admits detailed characterizations of optimal auction forms when these conditions do not hold (Myerson, 1981; Maskin and Riley, 1984a). Likewise, mechanism design theory has enabled economists to find solutions to the monopoly pricing problem, showing, for example, how the price should depend on quality and quantity so as to maximize the seller's expected revenue (Maskin and Riley, 1984b). Again, the theoretical solution squares well with observed practice.

In some cases, no market mechanism can ensure a fully efficient allocation of resources. In such cases, mechanism design theory can be used to identify other, more efficient institutions. A classic example concerns public goods, such as clean air or national security. Paul Samuelson (1954) conjectured that *no* resource allocation mechanism can ensure a fully efficient level of public goods, because "it is in the selfish interest of each person to give false signals, to pretend to have less interest in a given collective activity than he really has..." (page 388 op. cit.). Mechanism design theory permits a precise analysis of Samuelson's conjecture. More generally, the theory can be used to analyze the economic efficiency of alternative institutions for the provision of public goods, ranging from markets and consensual collective decision-making through majoritarian decision rules all the way to dictatorship. An important insight is that consensual decision-making is frequently incompatible with economic efficiency. The theory thus helps to justify governmental financing of public goods through taxation. Applications of mechanism design theory have led to breakthroughs in a number of other areas of economics as well, including regulation, corporate finance, and the theory of taxation.

The development of mechanism design theory began with the work of Leonid Hurwicz (1960). He defined a mechanism as a communication system in which participants send messages to each other and/or to a "message center," and where a pre-specified rule assigns an outcome (such as an allocation of goods and services) for every collection of received messages. Within this framework, markets and market-like institutions could be compared with a vast array of alternative institutions. Initially, much of the interest focussed on the informational and computational costs of mechanisms, while abstracting from the problem of incentives. An important contribution was Marshak and Radner's (1972) theory of teams, which inspired much subsequent literature (e.g. Groves, 1973). However, in many situations, providing incentives to the participating agents is an important part of the problem. Mechanism design theory became relevant for a wide variety of applications only after Hurwicz (1972) introduced the key notion of *incentive-compatibility*, which allows the analysis to incorporate the incentives of self-interested participants. In particular, it enables a rigorous analysis of economies where agents are self-interested and have relevant private information.

In the 1970s, the formulation of the so-called *revelation principle* and the development of *implementation theory* led to great advances in the theory of mechanism design. The revelation principle is an insight that greatly simplifies the analysis of mechanism design problems. In force of this principle, the researcher, when searching for the best possible mechanism to solve a given allocation problem, can restrict attention to a small subclass of mechanisms, so-called direct mechanisms. While direct mechanisms are not intended as descriptions of real-world institutions, their mathematical structure makes them relatively easy to analyze. Optimization over the set of all direct mechanisms for a given allocation problem is a well-defined mathematical task, and once an optimal direct mechanism has been found, the researcher can "translate back" that mechanism to a more realistic mechanism. By this seemingly roundabout method, researchers have been able to solve problems of institutional design that would otherwise have been effectively intractable. The first version of the revelation principle was formulated by Gibbard (1973). Several researchers independently extended it to the general notion of Bayesian Nash equilibrium (Dasgupta, Hammond and Maskin, 1979, Harris and Townsend, 1981, Holmstrom, 1977, Myerson, 1979, Rosenthal, 1978). Roger Myerson (1979, 1982, 1986) developed the principle in its greatest generality and pioneered its application to important areas such as regulation (Baron and Myerson, 1982) and auction theory (Myerson, 1981).

The revelation principle is extremely useful. However, it does not address the issue of multiple equilibria. That is, although an optimal outcome may be achieved in one equilibrium, other, sub-optimal, equilibria may also exist. There is, then, the danger that the participants might end up playing such a sub-optimal equilibrium. Can a mechanism be designed so that *all* its equilibria are optimal? The first general solution to this problem was given by Eric Maskin (1977). The resulting theory, known as implementation theory, is a key part of modern mechanism design.

The remainder of this survey is organized as follows. Section 2 presents key concepts and results, Section 3 discusses applications, and Section 4 concludes.

2 Key concepts and insights

We begin by describing incentive compatibility and the revelation principle. We then discuss some results obtained for two main solution concepts, dominant-strategy equilibrium and Bayesian Nash equilibrium, respectively. We consider, in particular, the classic allocation problem of optimal provision of public goods. We also discuss a simple example of bilateral trade. We conclude by discussing the implementation problem.

2.1 Incentive compatibility and the revelation principle

The seminal work of Leonid Hurwicz (1960,1972) marks the birth of mechanism design theory. In Hurwicz's formulation, a mechanism is a *communication system* in which participants exchange messages with each other, messages that jointly determine the outcome. These messages may contain private information, such as an individual's (true or pretended) willingness to pay for a public good. The mechanism is like a machine that compiles and processes the received messages, thereby aggregating (true or false) private information provided by many agents. Each agent strives to maximize his or her expected payoff (utility or profit), and may decide to withhold disadvantageous information or send false information (hoping to pay less for a public good, say). This leads to the notion of "implementing" outcomes as equilibria of message games, where the mechanism defines the "rules" of the message game. The comparison of alternative mechanisms is then cast as a comparison of the equilibria of the associated message games.

To identify an *optimal* mechanism, for a given goal function (such as profit to a given seller or social welfare), the researcher must first delineate the set of feasible mechanisms, and then specify the equilibrium criterion that will be used to predict the participants' behavior. Suppose we focus on the set of "direct mechanisms", where the agents report their private information (for example, their willingness to pay for a public good). There is no presumption that the agents will tell the truth; they will be truthful only if it is in their self-interest. Based on all these individual reports, the direct mechanism assigns an outcome (for example, the amount provided of the public good and fees for its financing). Suppose we use the notion of dominant strategy equilibrium as our behavioral criterion.[1] Hurwicz's (1972) notion of incentive-compatibility can now be expressed as follows: the mechanism is *incentive-compatible* if it is a dom-

[1] A strategy is dominant if it is a agent's optimal choice, irrespective of what other agents do.

inant strategy for each participant to report his private information truthfully. In addition, we may want to impose a participation constraint: no agent should be made worse off by participating in the mechanism. Under some weak assumptions on technology and taste, Hurwicz (1972) proved the following negative result: in a standard exchange economy, no incentive-compatible mechanism which satisfies the participation constraint can produce Pareto-optimal outcomes. In other words, private information precludes full efficiency.

A natural question emanating from Hurwicz's (1972) classic work thus is: Can Pareto optimality be attained if we consider a wider class of mechanisms and/or a less demanding equilibrium concept than dominant-strategy equilibrium, such as Nash equilibrium or Bayesian Nash equilibrium?[2] If not, then we would like to know how large the unavoidable social welfare losses are, and what the appropriate standard of efficiency should be. More generally, we would like to know what kind of mechanism will maximize a given goal function, such as profit or social welfare (whether this outcome is fully efficient or not). In the literature that followed Hurwicz (1972), these questions have been answered. Much of the success of this research program can be attributed to the discovery of the revelation principle.

The revelation principle states that any equilibrium outcome of an arbitrary mechanism can be replicated by an incentive-compatible direct mechanism. In its most general version, developed by Myerson (1979, 1982, 1986), the revelation principle is valid not only when agents have private information but also when they take unobserved actions (so-called moral hazard), as well as when mechanisms have multiple stages. Although the set of all possible mechanisms is huge, the revelation principle implies that an optimal mechanism can always be found within the well-structured subclass consisting of direct mechanisms. Accordingly, much of the literature has focussed on the well-defined mathematical task of finding a direct mechanism that maximizes the goal function, subject to the incentive-compatibility (IC) constraint (and, where appropriate, also the participation constraint).

A rough proof of the revelation principle for the case with no moral hazard goes as follows. First, fix an equilibrium of any given mechanism. An agent's private information is said to be his "type". Suppose that an agent of type t sends the message $m(t)$ in this equilibrium. Now consider the associated direct mechanism in which each

[2] In a *Nash equilibrium*, each agent's strategy is a best response to the other agents' strategies. A *Bayesian Nash equilibrium* is a Nash equilibrium of a game of incomplete information, as defined by Harsanyi (1967-8).

agent simply reports a type t', where t' may be his true type t or any other type. The reported type t' is his message in the direct mechanism, and the outcome is defined to be the same as when the agent sends the message $m(t')$ in the equilibrium of the original mechanism. By hypothesis, an agent of type t preferred to send message $m(t)$ in the original mechanism (the agent could not gain by unilaterally deviating to another message). In particular, the agent preferred sending the message $m(t)$ to sending the message $m(t')$, for any for $t' \neq t$. Therefore, he also prefers reporting his true type t in the direct mechanism, rather than falsely reporting any other type t'. So the direct mechanism is incentive compatible: no agent has an incentive to misreport his type. By construction, the direct mechanism produces the same outcome as the original mechanism. Thus, any (arbitrary) equilibrium can be replicated by an incentive-compatible direct mechanism.[3]

As discussed below, the revelation principle can be used to generalize Hurwicz's (1972) impossibility result to the case of Bayesian Nash equilibrium. Thus, in settings where participants have private information, Pareto optimality in the classical sense is in general not attainable, and we need a new standard of efficiency which takes incentives into account. A direct mechanism is said to be *incentive efficient* if it maximizes some weighted sum of the agents' expected payoffs subject to their IC constraints. Armed with this definition, researchers have been able to answer many of the questions that emanated from Hurwicz's (1972) work. One of the key questions is whether market mechanisms can be incentive efficient. In partial equilibrium settings, Myerson and Satterthwaite (1983) and Wilson (1985) proved that so-called double auctions are incentive efficient. Prescott and Townsend (1984) characterized the information structures under which a competitive general equilibrium is incentive efficient.

We now discuss some results pertaining to economies with public goods, both for dominant-strategy equilibrium and for Bayesian Nash equilibrium.

[3]More formally, suppose there are n agents. The original (indirect) mechanism assigns an outcome x, say an allocation of private and/or public goods, to all message profiles $(m_1, ..., m_n) \in \times_{i=1}^{n} M_i$, $x = h(m_1, ..., m_n)$. A *pure strategy* for a agent i is a rule (function) s_i that specifies for each possible type $t_i \in T_i$ a message $m_i \in M_i$. Thus $m_i = s_i(t_i)$ for all agents i and types t_i. Suppose now that a strategy profile s^* is an equilibrium of the original mechanism. Then a direct mechanism can be defined in which each agent i announces a type $t_i' \in T_i$ and the outcome is given by $x = h^*(t_1', ..., t_n')$, where h^* is defined by $h^*(t_1, ..., t_n) = h(s_1^*(t_1), ..., s_n^*(t_n))$ for all type reports $(t_1, ..., t_n)$. No agent can gain by reporting his or her type falsely, for if this were possible, then it would also have been possible for that agent to improve his or her payoff in the original mechanism by way of a corresponding unilateral change of strategy.

2.2 Dominant-strategy mechanisms for public goods provision

As mentioned above, a classic problem concerns the optimal provision of public goods. When individuals have private information about their own willingness to pay for the public good, they may be tempted to pretend to be relatively uninterested, so as to reduce their own share of the provision cost. This problem is canonical and arises in virtually all societies: how should a group of farmers, say, share the cost of a common irrigation or drainage system; how should the countries in the world share the cost of reducing global warming; how should grown-up siblings share the burden of caring for their elderly parents?

Before 1970, economists generally believed that public goods could not be provided at an efficient level, precisely because people would not reveal their true willingness to pay. It thus came as a surprise when Edward Clarke (1971) and Theodore Groves (1973) showed that, if there are no income effects on the demand for public goods (technically, if utility functions are quasi-linear), then there exists a class of mechanisms in which (a) truthful revelation of one's willingness to pay is a dominant strategy, and (b) the equilibrium level of the public good maximizes the social surplus.[4] In the context of a binary decision (whether or not to build a bridge, for example), the simplest version of the Clarke-Groves mechanism works as follows. Each person is asked to report his or her willingness to pay for the project, and the project is undertaken if and only if the aggregate reported willingness to pay exceeds the cost of the project. If the project is undertaken, then each person pays a tax or fee equal to the difference between the cost of the project and *everyone else's* reported total willingness to pay. With such taxes, each person "internalizes" the total social surplus, and truth-telling is a dominant strategy. The main drawback of this mechanism is that the total tax revenue typically will not add up to the cost of the project: the mechanism does not in general satisfy budget balance (see Green and Laffont, 1979). Both too much funding and too little funding is problematic. For example, sharing surplus funds among the participants will destroy the participants' truth-telling incentives, while wasting surplus funds is inefficient.

Outside the quasi-linear economic environments studied by Clarke and Groves, not much can be achieved by way of dominant-strategy mechanisms. A result to this effect was given by Gibbard (1973) and Satterthwaite (1975). They showed that in quite general environments, the only dominant-strategy mechanism is dictatorship, whereby

[4] The basic intuition behind the Clarke-Groves mechanism was already present in Vickrey (1961), so this kind of mechanism is often referred to as the Vickrey-Clarke-Groves (VCG) mechanism. See Tideman and Tullock (1976) for a discussion of this type of mechanism.

one pre-selected agent, the "dictator", always gets his favorite alternative. Because of this and other negative results, the focus of the literature shifted from dominant-strategy solutions to so-called *Bayesian mechanism design.*

2.3 Bayesian mechanisms for public goods provision

In a Bayesian model, the agents are expected-utility maximizers. The solution concept is typically Bayesian Nash equilibrium. The general Bayesian mechanism design problem was formulated by Dasgupta, Hammond and Maskin (1979), Myerson (1979) and Harris and Townsend (1981). After the discovery of the revelation principle (see Section 2.1), the main development of the theory of Bayesian mechanism design came in a series of papers by Roger Myerson (Myerson, 1979, 1981, 1983, Baron and Myerson, 1982, and Myerson and Satterthwaite, 1983). In these papers, the set of possible allocations was unidimensional, and the agents had quasi-linear preferences that satisfied a single-crossing property, familiar from the work of James Mirrlees and Michael Spence. Myerson obtained elegant characterizations of the incentive constraints which admitted a particularly insightful analysis. The same machinery has subsequently been used in a large number of applications.

As mentioned in Section 2.2, the Clarke-Groves dominant-strategy mechanism for the provision of public goods violates budget-balance. Claude d'Aspremont and Louis-André Gérard-Varet (1979) showed that this problem can be solved in the Bayesian version of the model.[5] In a dominant-strategy mechanism, the IC constraints require that each agent's utility is maximized by reporting the truth, regardless of what the other agents might report. In the Bayesian model, agents are expected utility maximizers, and the IC constraints only have to hold in expectation. Accordingly, the IC constraints are easier to satisfy in the Bayesian model, and d'Aspremont and Gérard-Varet could obtain more positive results than is possible with dominant strategies. In fact, d'Aspremont's and Gérard-Varet's (1979) mechanism can be seen as an extension of the Clarke-Groves mechanism to the Bayesian context.

The d'Aspremont and Gérard-Varet (1979) mechanism produces outcomes which are fully Pareto efficient, but their mechanism violates (interim) participation constraints. Some individuals, having observed their own type but not yet taken their actions, would prefer not to participate, so this mechanism is feasible only if participation is mandatory. If participation is voluntary and decisions to start the project must be

[5] Arrow (1979) independently constructed a similar mechanism.

taken unanimously, then the problem of free-riding becomes severe. Using techniques developed by Myerson (1981), Mailath and Postlewaite (1990) show that the probability of funding a public-goods project tends to zero as the number of agents increases. They give an example where the asymptotic probability of funding the public project is zero despite everyone knowing that they can be jointly better off if the project is funded.[6]

These results provide a rigorous foundation for Samuelson's (1954) negative conjecture about public goods cited above (Section 1). They give a plausible explanation for observed failures to provide public goods. For example, the fact that English villages were much earlier than French villages in deciding on public goods such as enclosure of open fields and drainage of marshlands can arguably be ascribed to the fact that French villages required unanimity on such issues whereas the English did not. This may at least partially explain why the productivity growth in English agriculture outstripped that of French agriculture in the period 1600-1800 (Grantham, 1980; Rosenthal, 1992).

In a large class of models, classical Pareto efficiency is incompatible with voluntary participation, even if there are no public goods.[7] In these models, the classical notion of Pareto efficiency is usually replaced by the more relevant notion of incentive efficiency (see Section 2.1). Two fundamental "impossibility results" to this effect—showing the incompatibility of voluntary participation and classical Pareto efficiency—were proved by Laffont and Maskin (1979, Section 6) and Myerson and Satterthwaite (1983). In order to illustrate these results and to convey the flavor of the formal analysis of Bayesian mechanism design, let us consider in some detail the case of bilateral trade in private goods.

2.4 Example: bilateral trade

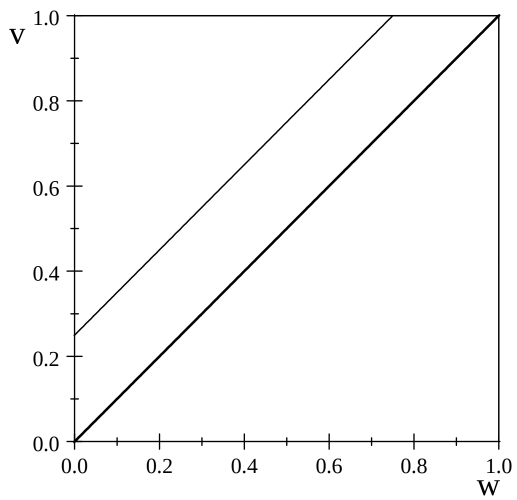
Suppose one individual, A, owns an indivisible object. A is considering selling this object to a prospective buyer, B. The object is worth w to A and v to B. Normalize both valuations v and w to lie between zero and one. If the object is sold at a price p,

[6] Similar results were obtained by Roberts (1976) and Rob (1989).

[7] The key difference between private and public goods is that in the former case, there are plausible assumptions under which problems of incentives and private information vanish as the economy becomes large. For example, Wilson (1977) and Milgrom (1979) found that if private goods are allocated via auctions, and there is a large numbers of potential buyers, then the equilibrium outcomes satisfy key properties of classic competitive equilibria (i.e. the price aggregates all privately held information and reflects the "true value" of the good, and the agents find it optimal to treat prices parametrically). In sharp contrast, if public goods are present, then incentive problems often become more severe as the economy gets larger (Mailath and Postlewaite, 1990).

then A's utility is $p - w$; she has to give up the object worth w to her but receives p in return. Similarly, B's utility from such a transaction is $v - p$. If no trade occurs, then each party obtains utility zero. Suppose that this is a truly bilateral situation; none of the parties can trade with a third party.

In such a situation, the classical notion of Pareto efficiency requires that the object be sold if $w < v$ and not if $w > v$. That is, all gains of trade should be realized. Geometrically, this means that trade occurs if and only if the valuation pair (w, v) lies above the diagonal of the unit square in the diagram below. Now suppose that B does not know A's valuation, so w is A's *private information*. Similarly, suppose that v is B's private information. To be more precise, suppose that the two individuals have been randomly drawn from a population of individuals with different valuations, in such a way that their "types", w and v, are statistically independent and identically distributed random variables with positive density on the whole unit square. What kind of mechanism could they use to trade with each other?



One possibility is that A makes a take-it-or-leave-it offer to B. Another possibility is that B makes such an offer to A. A third possibility would be a *double auction*, a mechanism in which both parties (simultaneously) announce a price and, if B's announcement exceeds A's, they trade at a price between the two announcement (for example, at the mid-point between the two announcements). It turns out that none of these mechanisms has the property that trade occurs in equilibrium whenever $w \leq v$. For example, if A makes a take-it-or-leave it offer p, then she will surely propose $p > w$, and B will accept only if $v \geq p$. So, trade does not occur if $w < v < p$, an event with positive probability. The argument is symmetric when instead B makes an offer. The mechanism would realize all gains of trade if the agents priced at their own valuations. However, this is not incentive-compatible. Agent A will benefit from pricing above her valuation (in order to obtain a higher selling price), and agent B will benefit from pricing below his valuation (in order to obtain the object at a lower price). Thus, each party will to try to improve his or her terms of trade by not pricing at their own true valuations. However, by doing this they will not realize all gains of trade.

If the population value-distribution is uniform, then the double auction has a linear Bayes Nash equilibrium, that is, one in which each party's (ask- and bid-) price is linearly increasing in the party's true valuation. More specifically, in this equilibrium, A's ask price is $p_A = 2w/3 + 1/4$, unless her valuation w exceeds 3/4, in which case she asks her true valuation, $p_A = w$. Likewise, B bids the price $p_B = 2v/3 + 1/12$, unless his valuation v falls short of 1/4, in which case he bids his true valuation, $p_B = v$. Notice that if $w < 3/4$, then $p_A > w$, that is, A asks for more than her own valuation. Similarly, if $v > 1/4$ then B bids below his valuation. Consequently, if v and w are too close to each other, no trade occurs even if $v > w$. Indeed, trade occurs if and only if B's valuation, v, exceeds A's valuation, w, by at least 1/4. This is the triangular area above the higher (and thinner) 45^o-line in the diagram. By contrast, no trade occurs in the central band between the two straight lines, that is, where the valuations are too close. Hence, for valuation-pairs falling in this area, no gains of trade are realized.

This situation is quite general. The impossibility results established by Laffont and Maskin (1979, Section 6) and Myerson and Satterthwaite (1983) imply that for bilateral trade no incentive compatible *direct* mechanism which satisfies (interim) participation constraints can have the property that trade occurs if and only if $w \leq v$. By the revelation principle, we can infer that no mechanism whatsoever can realize all gains from trade.[8] Classical Pareto efficiency, in other words, is incompatible with voluntary participation and free trade in this example. Indeed, although the above equilibrium outcome apparently violates classical Pareto optimality, further extraction of potential gains from trade cannot be achieved by any incentive compatible mechanism; it can be shown that the double auction is incentive efficient and that the linear equilibrium achieves this upper efficiency bound.

[8]Note that the double auction is mathematically equivalent to the direct mechanism in which each party announces its valuation and the object changes hands if and only if the owner's valueation is lower than the propspecitve buyer's, at a price between the announced valuations.

More exactly, using the revelation principle, Myerson and Satterthwaite (1983) established an upper bound for the gains from trade, $v - w$, that are realizable in any trade mechanism in situations like this. Their approach can be explained as follows. Consider a Bayesian Nash equilibrium of an arbitrary mechanism for bilateral trade. Suppose that when A's type is w and B's type is v, the object is sold with probability $q(w, v)$ at price $p(w, v)$, so A's payoff is $q(w, v)\,[p(w, v) - w]$, where w and v are statistically independent random variables. Since A knows her own type but not B's type, she calculates that her expected payoff is $\mathbb{E}_v\,[q(w, v)\,[p(w, v) - w]]$, where the expectation is with respect to B's type v. Now it must be the case that

$$\mathbb{E}_v\,[q(w, v)\,[p(w, v) - w]] \geq \mathbb{E}_v\,[q(w', v)\,[p(w', v) - w]]$$

for all w and $w' \neq w$. To see this, notice that the left-hand side is what A's type w obtains in equilibrium, while the right-hand side is what her type w would get if she behaved just like type w' (in which case the object would be sold with probability $q(w', v)$ at the price $p(w', v)$). The definition of Bayesian Nash equilibrium requires that the inequality holds, that is, type w should not be able to improve her payoff by mimicking type w'. By an analogous reasoning applied to B instead of A, we must have

$$\mathbb{E}_w\,[q(w, v)\,[v - p(w, v)]] \geq \mathbb{E}_w\,[q(w, v')\,[v - p(w, v')]]$$

for all v and $v' \neq v$. The two inequalities we have just derived are nothing but the IC constraints for the direct mechanism in which A announces w and B announces v, and where trade occurs with probability $q(w, v)$ at price $p(w, v)$. Thus, we may as well focus on such direct mechanism — this is the revelation principle. Moreover, if a trader's expected payoff is negative, he or she would refuse to participate. Therefore, the (*ex ante*) participation constraints are

$$\mathbb{E}_v\,[q(w, v)\,[p(w, v) - w]] \geq 0 \quad \text{and} \quad \mathbb{E}_w\,[q(w, v)\,[v - p(w, v)]] \geq 0.$$

Now, to establish an upper bound for the gains from trade that can be achieved in *any* mechanism, we need only consider the well-defined mathematical problem of maximizing the expected gains from trade, $\mathbb{E}\,(v - w)$, subject to the above IC and participation constraints. A mechanism which achieves this upper bound (in some equilibrium) is incentive efficient. The upper-bound result in Myerson and Satterthwaite (1983) implies that the double auction, first studied in detail by Chatterjee and

Samuelson (1983), is incentive efficient.

2.5 Implementation theory

Incentive compatibility guarantees that truth-telling is *an* equilibrium, but not that it is the only equilibrium. Many mechanisms have multiple equilibria that produce different outcomes. For instance, Leininger, Linhart, and Radner (1989) found that the double auction (see Section 2.4) has infinitely many (indeed uncountably many) non-linear equilibria, the welfare of which ranges from incentive efficiency to zero. Clearly, this multiplicity of equilibria reduces the appeal of the double auction.

Wilson (1979) analyzed uniform-price auctions for divisible goods and uncovered equilibria where the bidders divide up the good in question at a very low price. In these "collusive" equilibria, each bidder bids aggressively for anything less than his anticipated equilibrium share, which deters other bidders from trying to acquire more than their (implicitly agreed upon) shares. Such implicit collusion is highly detrimental to the seller. According to Klemperer (2004, Chapter 3), precisely this kind of implicit collusion has plagued many real-world auctions, including the U.K. market for electricity.

Multiple-equilibrium problems are also endemic in social-choice theory. Voters who are to select one out of many candidates face, in effect, a coordination problem. To vote for a candidate who has little chance of winning means "wasting one's vote". Accordingly, if there is a commonly held belief in the electorate that a certain candidate has no chance of winning, then this expectation can be self-fulfilling. Such phenomena easily generate multiple equilibria, some of which lead to suboptimal outcomes (see Section 3.3 for further discussion of voting mechanisms).

In view of these difficulties, it is desirable to design mechanisms in which *all* equilibrium outcomes are optimal for the given goal function. The quest for this property is known as *the implementation problem*.[9] Groves and Ledyard (1977) and Hurwicz and Schmeidler (1978) showed that, in certain situations, it is possible to construct mechanisms in which all Nash equilibria are Pareto optimal, while Eric Maskin (1977) gave a general characterization of Nash implementable social-choice functions. He showed that Nash implementation requires a condition now known as *Maskin monotonicity* (see Section 3.3 for an illustration of this property). Maskin (1977) also showed that

[9] Formally, "weak" implementation requires that every equilibrium is optimal, while "full" implementation in addition requires that every optimum be an equilibrium.

if Maskin monotonicity and a condition called *no-veto-power* are both satisfied, and if there are at least three agents, then implementation in Nash equilibrium is possible.[10]

Maskin considered Nash equilibria in games of complete information, but his results have been generalized to Bayesian Nash equilibria in games of incomplete information (see Postlewaite and Schmeidler, 1986, Palfrey and Srivastava, 1989, Mookherjee and Reichelstein, 1990, and Jackson, 1991). For example, Palfrey and Srivastava (1991) show how the double auction can be modified so as to render all equilibria incentive efficient.

Maskin's results have also been extended in many other directions, such as virtual (or approximate) implementation (Matsushima, 1988, Abreu and Sen, 1991), implementation in renegotiation-proof equilibria (Maskin and Moore, 1999) and by way of sequential mechanisms (Moore and Repullo, 1988). Implementation theory has played, and continues to play, an important role in several areas of economic theory, such as social choice theory (Moulin, 1994) and the theory of incomplete contracts (Maskin and Tirole, 1999).

3 Applications

In many cases, mechanism design has modernized and unified existing lines of research. For example, while the *revenue equivalence* of well-known auction formats was known already to Vickrey (1961), the mechanism-design approach entailed a more general revenue-equivalence theorem. By contrast, the *optimality* of the most common auction formats (within the class of all possible selling mechanisms) could only be established by mechanism-design techniques. In still other cases, mechanism-design theorists have developed entirely new research avenues. We are in no position to discuss all applications of mechanism design but will try to give a flavor of a few important ones.[11]

3.1 Optimal selling and procurement mechanisms

Auctions and auction-like mechanisms are an important part of modern economic life. Myerson's (1981) seminal analysis of optimal auctions and the large subsequent litera-

[10] In Maskin's original manuscript, the proof of this result was incomplete. Complete proofs of Maskin's theorem were later provided by Williams (1986), Repullo (1987) and Saijo (1988).

[11] An interesting research area not discussed here is the analysis of competing institutions, which studies the equilibrium allocation of buyers across competing trading mechanisms and price formation in these (see McAfee, 1993, Peters, 1997, and Ellison, Fudenberg and Möbius, 2004).

ture (see Krishna, 2002) have helped economists understand these important real-world institutions.[12] In a typical scenario, an economic agent has an object to sell, but does not know how much the prospective buyers (bidders) are willing to pay for it. Which mechanism will be optimal in the sense of maximizing the seller's expected revenue? This problem was analyzed by Myerson (1981). Appealing to the revelation principle, Myerson studied incentive-compatible direct mechanisms, where the bidders report their willingness-to-pay. The mechanism specifies who will get the object and at what price, as a function of these reports. Incentive-compatibility guarantees that truth-telling is a Bayesian Nash equilibrium. Since participation is voluntary, the equilibrium must also satisfy an (interim) participation constraint: each bidder who participates in the auction must be at least as well off as if he or she had abstained. For this scenario, Myerson proved a general *revenue-equivalence* theorem. This theorem establishes conditions, such as risk neutrality and uncorrelated types, under which the seller achieves the same expected revenue from any auction in which the object goes to the bidder with the highest valuation (in equilibrium). In particular, four well-known auction forms (the so-called English and Dutch auctions, and first-price and second-price sealed bid auctions, respectively) generate the same expected revenue. Myerson (1981) showed that if the bidders are "symmetric" (drawn from one and the same type pool) and if the seller sets an appropriate *reserve price* (a lowest price below which the object will not be sold), then all of the four well-known auction formats are in fact optimal.[13] For example, if the bidders' types are independently drawn from a uniform distribution on the interval from zero to one hundred, then the optimal reserve price is 50, independently of the number of bidders. This reserve price induces bidders whose valuations exceed 50 to bid higher than they would otherwise have done, which raises the expected revenue. On the other hand, if it so happens that no bidder thinks the object is worth 50, then the object is not sold even if it has a positive value to some bidder and no value at all to the seller. This outcome is clearly not Pareto efficient in the classical sense. Nevertheless, the above-mentioned auction forms are incentive efficient in the sense defined above.

Myerson (1981) assumed the seller's objective was to maximize the expected revenue. But when the government is privatizing an asset, such as the radio spectrum or a

[12] Harris and Raviv (1981) and Riley and Samuelson (1981) independently analysed the problem of optimal auctions and reached some of the same conclusions, but it was Myerson's methods that provided the foundation for much future work.

[13] If the bidders are "asymmetric", then the optimal auction format enhances competition by discriminating in favor of the "weaker" bidders (those drawn from pools with lower willingness-to-pay).

publicly-owned production facility, revenue maximization may not be the only (or even the most important) motive. A bigger concern may be social-welfare maximization: the asset should go to the individual or firm that values it the most.

Maskin (1992) found that, under certain conditions, an English auction maximizes social welfare even if each bidder's valuation depends on other bidders' private information. One might be tempted to discount the need for the government's auction to maximize social welfare, for the following reason. Suppose there are two potential bidders, A and B, and B values the asset more than A. Then, even if the government allocates the asset to the "wrong" person, A, would not then B simply buy the asset from A (assuming it can be traded)? If so, then B (who values the asset the most) would always get the asset in the end - so the government should not worry too much about getting the initial allocation right. However, this argument is incorrect, because it does not take informational constraints into account. The Laffont-Maskin and Myerson-Satterthwaite impossibility results (see Section 2.4) imply that B may not buy the asset from A even if B values it the most. Therefore, getting the initial allocation of ownership right may be of the utmost importance. Indeed, there is no presumption that the initial allocation should be to one individual, since joint ownership may generate higher social welfare (see Cramton, Gibbons and Klemperer, 1987).

If the seller can produce additional objects at constant cost, it is not important for buyers to compete with each other directly. Mussa and Rosen (1978) and Maskin and Riley (1984b) derived the optimal selling mechanism for a monopolist who does not know its customers' types (i.e. their taste parameters). The optimal mechanism involves quantity discounts (rather than a fixed price per unit). Stole (1995) extends the theory to the case of oligopoly. Other important extensions concern multi-product monopolies and multi-dimensional types (see Armstrong, 1996). Turning from revenue to social-welfare maximization, Maskin's (1992) efficiency result does not generalize to the case of multi-dimensional types. For this case, Jehiel and Moldovanu (2001) found that there is in general no incentive-compatible mechanism which always allocates the object to the person who values it most.

3.2 Regulation and auditing

The regulation of monopolies and oligopolies is an old and important topic in economics. As discussed by Laffont (1994), the older literature made rather arbitrary assumptions about the regulatory process. The regulator was assumed to face certain constraints, such as a requirement that the monopolist must earn a return above the market rate. This rate was not derived from an underlying optimization process but was simply imposed *ad hoc*. Within such loosely grounded frameworks, it is hard to make sound normative judgements about regulatory processes. The situation changed dramatically with the pioneering contributions of Baron and Myerson (1982) and Sappington (1982, 1983), building on work by Weitzman (1978) and Loeb and Magat (1979). In these papers, the regulatory process was modelled as a game of incomplete information. The regulator did not have direct access to information about the monopolist's true production costs. Using the revelation principle, Baron and Myerson (1982) and Sappington (1982,1983) derived the optimal regulatory scheme, without resorting to *ad hoc* assumptions. In the optimal mechanism, the regulator (usually a government agency) trades off its objective to extract rents from the monopolist (revenue to the government) against its objective to encourage an efficient output level. In addition, the monopolist must be given sufficient incentive to participate (i.e. to stay in the market).

A surge in the literature on regulatory economics followed the Baron-Myerson and Sappington contributions. This literature has provided a solid theoretical foundation for evaluations of alternative regulatory mechanisms, such as price caps versus cost- and profit-sharing schemes. Economists have used the Baron-Myerson model to empirically estimate the effect of regulation on firms' behavior (see Wolak, 1994). The original static model was extended in many directions. The problem of optimal time-consistent mechanisms, in particular the "ratchet effect," when information is gradually revealed over time, was analyzed by Freixas, Guesnerie, and Tirole (1985) and Laffont and Tirole (1988), among others. Papers by Laffont and Tirole (1987), McAfee and McMillan (1986) and Riordan and Sappington (1987) have produced a synthesis of theories of optimal auctions and of optimal regulation. Baron and Besanko (1984) and Laffont and Tirole (1986) introduce the possibility of *ex post* audits of firms' costs. Many other topics, such as collusion between the regulated firm, its auditor and even the regulatory agency, have been extensively analyzed in the literature on optimal regulation. For a comprehensive and unified treatment, see Laffont and Tirole (1993).

3.3 Social Choice Theory

In the axiomatic social-choice theory pioneered by Kenneth Arrow (1951), there is a set X of feasible alternatives and n individuals who have preferences over these. A *social choice rule* is a rule that selects one or several alternatives from X on the basis of the individuals' preferences, for any given such preference profile. Arrow's seminal work was mainly concerned with the normative issue of how a social choice rule can represent the general "will of the people". In the 1970s, attention shifted to the positive question of strategic behavior of voters under alternative voting procedures. Is it possible to design a mechanism, that is, a voting procedure, such that voters are induced to reveal their true preferences over the set X? The impossibility results of Gibbard (1973) and Satterthwaite (1975) gave a negative answer. They showed that if X contains at least three alternatives, then there does not exist any non-dictatorial social choice rule that can be implemented in a mechanism in which revealing one's true preferences is a dominant strategy. The proof of the Gibbard-Satterthwaite theorem can be directly translated into a proof of Arrow's (1951) celebrated impossibility theorem for normative social choice (see Muller and Satterthwaite, 1985). This confirms Arrow's conjecture that his axiom of *Independence of Irrelevant Alternatives* is closely related to the notion of dominant-strategy mechanisms. Thus, the Gibbard-Satterthwaite theorem provides a bridge between normative and strategic analyses. The next step was to relax the requirement of dominant strategies. The resulting literature was greatly influenced by Maskin's (1977) work on Nash implementation. For a survey of the strategic aspects of social choice theory, see Moulin (1994).

An early insight of this literature was that if social choice rules are required to be singleton-valued, that is, if a unique alternative must always be selected, then the Gibbard-Satterthwaite impossibility result also holds for Nash implementation. To understand this negative result, recall that a necessary condition for Nash implementation of a social choice rule is a condition called *Maskin monotonicity*. This condition says that, if initially an alternative $a \in X$ is selected by the social choice rule and a does not fall in rank in any voter's preference ordering, then a must still be selected.

To illustrate the strength of this condition, consider a specific social choice rule, namely, *the plurality rule*. An alternative in X is said to be the *plurality alternative* if it is top-ranked by the greatest number of voters. The plurality rule simply states that the plurality alternative should always be selected. Now suppose there are 7 voters, and X contains three alternatives, a, b and c. Suppose that the voters' preference orderings are as follows. Voters 1, 2 and 3 think a is the best alternative, b the second best, and c is worst: $a > b > c$. Voters 4 and 5 think b is the best alternative, a the second best, and c is worst: $b > a > c$. Voters 6 and 7, finally, think c is the best alternative, b the second best, and a is worst: $c > b > a$. Clearly a is the plurality alternative, since it is top-ranked by three voters, while b and c are each top-ranked by only two voters. Now suppose voters 6 and 7 change their minds: they decide that alternative c is, after all, worse than a and b. In their new preference orderings, b has risen to the first place and a to the second: $b > a > c$. If the other voters' rankings remain as before, then alternative a did not fall in anyone's preference ordering, but it is no longer the plurality alternative since b is now top-ranked by four voters while a is still top-ranked by only three. Hence, the plurality rule is not Maskin monotonic.

By Maskin's (1977) theorem, there is no decision mechanism that Nash-implements the plurality rule.[14] In a similar fashion, other social choice rules that have been proposed in the literature, such as the well-known Borda rule (proposed by J.C. de Borda in 1781), also fail Maskin monotonicity. More generally, Muller and Satterthwaite (1977) showed that no single-valued social choice rule can be Maskin monotonic. This means that voters' strategic behavior will lead any conceivable voting mechanism to produce Nash equilibria that are suboptimal according to the given social choice rule.

One way out of this dilemma is to drop the requirement that the social choice rule be single-valued. Many interesting multi-valued social choice rules (such as the one that always selects all Pareto-efficient alternatives) are Maskin monotonic and can be Nash-implemented. The drawback is that we are forced to accept a fundamental indeterminacy: with some preference-profiles, more than one alternative should be acceptable to society. Therefore, more than one Nash equilibrium exists. This indeterminacy might be an unavoidable aspect of non-dictatorial systems. The final outcome can then depend on negotiations and bargaining among the voters. In the terminology of Thomas Schelling, voters may coordinate on a "focal point" equilibrium, an equilibrium that appears natural given their cultural background, history, or other social and psychological factors. An alternative path toward more positive results is to assume the voters' behavior can be captured by way of refinement of Nash equilibrium, such as trembling-hand perfect Nash equilibrium (Selten, 1975); see Maskin and Sjöström (2002).

4 Conclusion

Mechanism design theory defines institutions as non-cooperative games, and compares different institutions in terms of the equilibrium outcomes of these games. It allows

[14] More precisely, the plurality rule is not Maskin monotonic as long as X contains at least three alternatives. By contrast, it is easily verified that if X has only two alternatives, then the plurality rule is Maskin-monotonic.

economists and other social scientists to analyze the performance of institutions relative to the theoretical optimum. Mechanism design has produced a large number of important insights in a wide range of applied contexts, influencing economic policy as well as market institutions. We have discussed here some of the most important results and applications.

For introductory surveys of mechanism design theory, see Baliga and Maskin (2003) and Serrano (2004). The revelation principle is discussed in chapter 2 of Salanié (1997). For more on Bayesian mechanism design, see chapter 7 in Fudenberg and Tirole (1993), chapter 5 in Krishna (2002), chapter 23 in Mas-Colell, Whinston and Green (1995), and Myerson (1989). For the implementation problem, see Corchón (1996), Jackson (2001), Maskin and Sjöström (2002), Moore (1992), chapter 10 in Osborne and Rubinstein (1994), and Palfrey (2001).

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