

## Chapter 2

# Implementation Theory

In this section we present key ideas and results from implementation theory that are relevant to the topics of the thesis.

### 2.1 What is Implementation Theory?

#### 2.1.1 Preliminaries

Implementation theory is a component of mechanism design. It provides an analytical framework for situations where resources have to be allocated among agents/users but the information needed to make these allocation decisions is dispersed and privately held, and the agents/users possessing the private information behave strategically and are self-utility maximizers. In any situation where the information needed to make decisions is dispersed, it is necessary to have information exchange among the agents/users possessing the information. Allocation decisions are made after the information exchange process terminates. Implementation theory provides a systematic methodology for designing an information exchange process followed by an allocation rule that leads to allocation decisions that are “optimal” with respect to some pre-specified performance metric.

The objectives of implementation theory are:

- (1) To determine, for any given performance metric, whether or not there exists an information exchange process and an allocation rule that achieve optimal allocations with respect to that metric when the users possess private information and are strategic.
- (2) To determine systematic methodologies for designing information exchange processes and allocation rules that achieve optimal allocations with respect to performance metrics for which the answer to (1) is positive.

- (3) To determine alternative criteria for the design of information exchange processes and allocation rules that lead to “satisfactory” allocations for situations where the answer to (1) is negative.

The key concept in the development of implementation theory is that of game form or mechanism. A game form/mechanism consists of two components: (1) A message/strategy space, that is, a communication alphabet through which the agents/users exchange information with one another. (2) An allocation rule (called outcome function) that determines the allocations after the communication and information exchange process terminates. Most mechanisms employ monetary incentives and payments to achieve desirable resource allocations. In such cases, the outcome function specifies the resource allocations as well as the monetary incentives and payments.

A game form along with the agents’/users’ utilities defines a game. The allocations made (through the outcome function) at the equilibria of the game determine the result of the decentralized allocation problem. The key objectives in the design of a game form/mechanism are:

1. To provide incentives to the strategic agents/users so that they prefer to participate in the allocation process rather than abstain from it.
2. To obtain, at all equilibria of the game induced by the mechanism, allocations that are optimal with respect to some pre-specified performance metric (criterion). For example, it may be desirable that the allocations obtained by the game form/mechanism are the same as those obtained by the solution of the corresponding centralized allocation problem.
3. To obtain a balanced budget at all equilibria of the game induced by the mechanism. That is, at all equilibria, the money received by some of the system’s agents/users as part of the incentives provided by the mechanism must be equal to the money paid by the rest of the agents/users.

### 2.1.2 Game Forms/Mechanisms

In the implementation theory/mechanism design framework, a centralized resource allocation problem is described by the triple  $(\mathcal{E}, \mathcal{A}, \pi)$ : the environment space  $\mathcal{E}$ , the action/allocation space  $\mathcal{A}$  and the goal correspondence/social choice correspondence/social choice rule  $\pi$ . Below, we briefly describe each component separately. Let  $\mathcal{N} = \{1, 2, \dots, N\}$  be the set of agents/users.

*Environment Space ( $\mathcal{E}$ ):* We define the environment space  $\mathcal{E}$  of an allocation problem to be the set of individual preferences (or the set of utilities), endowments and the technology taken together. The environment  $\mathcal{E}$  is the set of circumstances that can not be changed either by the designer of the allocation mechanism or by the agents/users that participate in the allocation mechanism.

The environment space  $\mathcal{E}$  is the cartesian product of the users’ individual environment spaces  $\mathcal{E}_i$ , i.e.,  $\mathcal{E} := \mathcal{E}_1 \times \mathcal{E}_2 \times \dots \times \mathcal{E}_N$ . A realization  $e \in \mathcal{E}$  of the environment

is a collection of the users' individual realizations  $e_i$ ,  $e_i \in \mathcal{E}_i$ ,  $i = 1, 2, \dots, N$ , that is,  $e = (e_1, e_2, \dots, e_N)$ .

*Action Space ( $\mathcal{A}$ ):* We define the action space  $\mathcal{A}$  of a resource allocation problem to be the set of all possible actions/resource allocations.

*Goal Correspondence/Social Choice Rule/Social Choice Correspondence ( $\pi$ ):* Goal correspondence is a map from  $\mathcal{E}$  to  $\mathcal{A}$  which assigns to every environment  $e \in \mathcal{E}$  the set of actions/allocations which are solutions to the centralized resource allocation problem associated with/ corresponding to the decentralized resource allocation problem under consideration. That is,

$$\pi : \mathcal{E} \rightarrow \mathcal{A}.$$

The setting described above corresponds to the case where one of the agents (e.g. a network manager) has enough information about the environment so as to determine the actions according to the goal correspondence  $\pi$ . Generally this is not the case. Usually, different agents have different information about the environment. For this reason it is desired to devise a mechanism for information exchange and resource allocation that leads, for every instance  $e$  of the resource allocation problem, to an allocation in  $\pi(e)$ .

When the system's agents are strategic the resource allocation mechanism is described by a  $N$ -user/agent game form  $(\mathcal{M}, f)$ , where  $\mathcal{M} = \prod_{i=1}^N \mathcal{M}_i$  is the message space, specifying for each user  $i$ ,  $i = 1, 2, \dots, N$ , the set of messages  $\mathcal{M}_i$  that user/agent  $i$  can communicate to other users, and  $f$  is an outcome function that describes the actions that are taken for every  $m := (m_1, m_2, \dots, m_N) \in \mathcal{M}$ ; that is

$$f : \mathcal{M} \rightarrow \mathcal{A}.$$

The game form  $(\mathcal{M}, f)$  is common knowledge [1, 2] among all the  $N$  agents/users. Note that a game form is different from a game, as the consequence of a profile  $m$  of messages is an allocation (or a set of allocations if  $f$  is a correspondence) rather than a vector of utility payoffs. Once a realization  $e \in \mathcal{E}$  of the environment is specified, a game form induces a game.

Within the context of implementation theory, a decentralized resource allocation process proceeds in three steps:

1. The mechanism designer announces the game form  $(\mathcal{M}, f)$ .
2. An instance  $e \in \mathcal{E}$  of the environment is realized. The realization of environment  $e$  specifies, among other things, the utilities  $u_i$ ,  $i \in \mathcal{N}$ , of all agents. Depending on its utilities and the specified mechanism, each agent decides whether or not to participate in the mechanism. The agents that choose not to participate in the allocation process get some exogenously specified "reservation utility", which is usually a number independent of the environment  $e$ ; we set this number to be zero.
3. The agents who choose to participate in the allocation process play the game induced by the mechanism. In this game,  $\mathcal{M}_i$  is the strategy space of player  $i$ ,

and for every strategy profile  $m \in \mathcal{M}$ ,  $u_i(f(m))$  is the utility payoff of player  $i$ . We denote this game by  $(\mathcal{M}, f, e)$ .

The mechanism designer is interested in the outcomes that occur at the equilibria of the game induced by the game form.

### 2.1.3 Implementation in an Appropriate Equilibrium Concept

A solution/equilibrium concept specifies the strategic behavior of the agents/users faced with a game  $(\mathcal{M}, f, e)$  induced by the game form  $(\mathcal{M}, f)$ . Consequently, an equilibrium concept is a correspondence  $\Lambda$  that identifies a subset of  $\mathcal{M}$  for any given specification  $(\mathcal{M}, f, e)$ . We define for every environment  $e \in \mathcal{E}$ ,

$$\mathcal{A}_\Lambda(m, f, e) := \{a \in \mathcal{A} : \exists m \in \Lambda(\mathcal{M}, f, e) : f(m) = a\} \quad (2.1)$$

as the set of outcomes associated with the solution concept  $\Lambda$ , when the environment is  $e$ .

The solution/equilibrium concept appropriate for a decentralized resource allocation problem depends on the information that is available to the agents/users about the environment. For example, if agent  $i$ ,  $i \in \mathcal{N}$ , knows  $e_i \in \mathcal{E}_i$  and has a probability mass function on  $\mathcal{E}_{-i} = \prod_{j=1, j \neq i}^N \mathcal{E}_j$ , then an appropriate solution concept is a Bayesian Nash equilibrium (BNE) [3]. On the other hand, if agent  $i$ ,  $i \in \mathcal{N}$  knows  $e_i \in \mathcal{E}_i$ , and  $\mathcal{E}_j$ , for all  $j \neq i$ , then an appropriate solution concept is a Nash equilibrium (NE) [4], or a sub-game perfect NE or a sequential NE [5].

**Definition 2.1** A goal correspondence  $\pi : \mathcal{E} \mapsto \mathcal{A}$  is implemented (respectively, weakly implemented) by the game form  $(\mathcal{M}, f)$  in the equilibrium concept  $\Lambda$  if  $\mathcal{A}_\Lambda(\mathcal{M}, f, e) = \pi(e)$  (respectively,  $\mathcal{A}_\Lambda(\mathcal{M}, f, e) \subset \pi(e)$ ) for all  $e \in \mathcal{E}$ .

**Definition 2.2** A goal correspondence  $\pi : \mathcal{E} \rightarrow \mathcal{A}$  is said to be implementable (respectively, weakly implementable) in solution/equilibrium concept  $\Lambda$  if there exists a game form  $(\mathcal{M}, f)$  that implements (respectively, weakly implements) it.

Within the context of implementation theory there have been significant developments in the characterization of goal correspondences that can be implemented in the following solution concepts: dominant strategies [6, 7]; Nash equilibria [8–11]; refined Nash equilibria, such as sub-game perfect equilibria [12, 13], undominated Nash equilibria [14–17], trembling hand perfect Nash equilibria [18]; Bayesian Nash equilibria [19–22].

### 2.1.4 Implementation in Nash Equilibrium and Maskin's Mechanism

In the problems investigated in this thesis we consider Nash equilibrium (NE) as the solution/equilibrium concept. For any  $(\mathcal{M}, f, e)$ , a pure NE is a message/strategy

profile  $m^* := (m_1^*, m_2^*, \dots, m_N^*) \in \mathcal{M}$  such that for all  $i \in \mathcal{N}$ ,

$$u_i(f(m_i^*, m_{-i}^*)) \geq u_i(f(m_i, m_{-i}^*)), \quad (2.2)$$

for all  $m_i \in \mathcal{M}_i$ , where  $m_{-i}^* := (m_1^*, m_2^*, \dots, m_{i-1}^*, m_{i+1}^*, \dots, m_N^*)$  and  $u_i, i \in \mathcal{N}$ , are the utility functions of the agents under the realization  $e$  of the environment. Let  $NE(\mathcal{M}, f, e)$  be the set of NE of the game  $(\mathcal{M}, f, e)$  and

$$\mathcal{A}_{NE} := \mathcal{A}_{NE}(\mathcal{M}, f, e) := \{a \in \mathcal{A} \mid \exists m \in NE(\mathcal{M}, f, e) \text{ s.t. } f(m) = a\}. \quad (2.3)$$

The game form  $(\mathcal{M}, f)$  implements (respectively, weakly implements) a social choice rule  $\pi$  in Nash equilibrium if

$$\mathcal{A}_{NE}(\mathcal{M}, f, e) = \pi(e)$$

(respectively,  $\mathcal{A}_{NE}(\mathcal{M}, f, e) \subset \pi(e)$ ) for all  $e \in \mathcal{E}$ .

In his seminal paper [4], Maskin characterized social choice rules that can be implemented in NE, and constructed a mechanism that achieves implementation in NE. To state and discuss the main result in [4] we need to define the concepts of weak no-veto power and monotonicity.

**Definition 2.3** A goal correspondence/social choice rule  $\pi : \mathcal{E} \rightarrow \mathcal{A}$  satisfies weak no-veto power if for any  $e \in \mathcal{E}$ , any outcome  $a \in \mathcal{A}$  that is the top ranked alternative of at least  $N - 1$  agents under the given environment  $e$  (that is,  $a$  simultaneously maximizes individual utilities of at least  $N - 1$  agents) belongs to  $\pi(e)$ .

In words, a social choice rule satisfies weak no-veto power if, whenever all agents except possibly one agree that an alternative is *top-ranked*, (i.e. no other outcome is higher in their preference orderings), then that alternative is in the social choice set; the remaining agent can not veto it.

**Definition 2.4** A social choice rule  $\pi : \mathcal{E} \rightarrow \mathcal{A}$  is *monotonic* if for all  $e := (e_1, e_2, \dots, e_N)$ ,  $\hat{e} := (\hat{e}_1, \hat{e}_2, \dots, \hat{e}_N)$  and  $a \in \mathcal{A}$ ,  $a \in \pi(\hat{e}_1, \hat{e}_2, \dots, \hat{e}_N)$  whenever:

- (i)  $a \in \pi(e_1, e_2, \dots, e_N)$ ,
- (ii) for all  $b \in \mathcal{A}$  and  $i \in \mathcal{N}$ ,  $u_i(a) \geq u_i(b)$  implies  $\hat{u}_i(a) \geq \hat{u}_i(b)$ ,

where  $u_i, \hat{u}_i$  are utilities of agent  $i$  under  $e_i$  and  $\hat{e}_i$ , respectively.

In words, monotonicity of  $\pi$  says the following: Suppose that under a profile of utility functions  $u_1, u_2, \dots, u_N$ ,  $u_i \in e_i$ ,  $\forall i \in \mathcal{N}$ , the outcome  $a$  is in the choice set  $\pi(e)$ . Furthermore, suppose that the environment  $e$  is altered to  $\hat{e}$  so that under the new profile  $\hat{u} := (\hat{u}_1, \hat{u}_2, \dots, \hat{u}_N)$ ,  $\hat{u}_i \in \hat{e}_i$  for all  $i \in \mathcal{N}$ , the outcome  $a$  does not fall in any agent's preference ordering relative to any outcome in  $\mathcal{A}$ . Then, the outcome  $a$  must be in the choice set  $\pi(\hat{e})$ . Monotonicity is satisfied by many social choice

rules including the “social welfare maximizing correspondence” and the “Pareto correspondence” [8, 23–25].<sup>1</sup>

We can now state Maskin’s fundamental result on Nash implementation.

**Theorem 2.5** ([4]) *If a social choice rule  $\pi : \mathcal{E} \rightarrow \mathcal{A}$  is implementable in NE then it is monotonic. Furthermore, if the number of agents is at least 3 and  $\pi$  is monotonic and satisfies the weak no-veto power condition, then  $\pi$  is implementable in NE.*

The proof of the above theorem is constructive. Given a social choice rule  $\pi$  that satisfies monotonicity and weak no-veto power, Maskin constructs a game form that implements  $\pi$ . We present the construction of the game form in words. Such a presentation reveals the complexity of the mechanism and provides a justification as to why we pursue alternative approaches in this thesis. Before we proceed with the description of the game form we need to define the lower contour set of  $u_i$ ,  $i \in \mathcal{N}$ , at outcome  $a \in \mathcal{A}$ .

**Definition 2.6** For each  $a \in \mathcal{A}$  and  $u_i \in \mathcal{U}_i$ ,  $i \in \mathcal{N}$ , let

$$\mathcal{LC}(a, u_i) := \{b \in \mathcal{A} \text{ s.t. } u_i(a) \geq u_i(b)\} \quad (2.4)$$

$\mathcal{LC}(a, u_i)$  is the lower contour set of  $u_i$  at  $a \in \mathcal{A}$ .

In words, the lower contour set of  $u_i$  at  $a \in \mathcal{A}$  is the set of outcomes in  $\mathcal{A}$  that someone with utility function  $u_i$  does not prefer to  $a$ .

We now proceed with the description of Maskin’s game form. The message space for each agent  $i \in \mathcal{N}$  is  $\mathcal{M}_i := \mathcal{U}_1 \times \mathcal{U}_2 \times \cdots \times \mathcal{U}_N \times \mathcal{A} \times \mathbb{Z}_{++}$ , where  $\mathbb{Z}_{++}$  is the space of positive integers. That is, each agent’s message/strategy is a profile of the agents’ utilities, an outcome  $a \in \mathcal{A}$ , and a positive integer. The outcome function is defined as follows:

- (i) If all agents announce the same message/strategy  $m_i = (u_1, u_2, \dots, u_N, a, K)$ ,  $i \in \mathcal{N}$ , and  $a \in \pi(e_1, e_2, \dots, e_N)$ , ( $u_i \in e_i \forall i \in \mathcal{N}$ ), then  $f(m_1, m_2, \dots, m_N) = a$ . That is, if all agents are unanimous in their strategy, and their proposed outcome is in the choice set  $\pi(e)$ , then the outcome is  $a$ .
- (ii) Suppose all agents  $j \neq i$  announce the same strategy  $m_j = (u_1, u_2, \dots, u_N, a, K)$  and  $a \in \pi(e_1, e_2, \dots, e_N)$ . Let  $m_i = (u'_1, u'_2, \dots, u'_N, a', K')$  be the  $i$ th agent’s message/strategy. Then,

$$f(m_1, m_2, \dots, m_N) = \begin{cases} a' & \text{if } a' \in \mathcal{LC}(a, u_i) \\ a & \text{if } a' \notin \mathcal{LC}(a, u_i). \end{cases} \quad (2.5)$$

That is, suppose all players but one propose the same strategy and the proposed outcome  $a \in \pi(e_1, e_2, \dots, e_N)$ . Then, agent  $i$ , the odd-agent out, gets his pro-

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<sup>1</sup> In Chaps. 3 and 5, the social choice rule/goal correspondence is the social welfare maximizing correspondence and in Chap. 4 the goal correspondence is the Pareto correspondence.

- posals  $a'$ , provided that  $a'$  is in the lower contour set of  $a$  of the ordering that the other agents proposed for him. Otherwise, the outcome is  $a$ .
- (iii) If neither (i) nor (ii) applies, then  $f(m_1, m_2, \dots, m_N) = a^i$ , where  $i := \max\{i \mid k^i = \max_{j \in \mathcal{N}} k^j\}$ . In words, when neither (i) nor (ii) applies, the outcome is the one proposed by the agent that has the highest index among those whose proposed integer is maximal.

Maskin proved in [4] that the above-described game form/mechanism implements  $\pi$  in NE.

From the above description it is clear that Maskin's mechanism requires, in general, an infinite dimensional message space. That is why in this thesis we do not follow Maskin's approach. We follow a different approach, outlined in Chaps. 3–5, which requires a finite dimensional message space and a particular interpretation of NE. Below we present this interpretation of NE.

### 2.1.5 Interpreting Nash Equilibrium

We present two interpretations of Nash equilibrium which appear in Nash's original work [24]. The first is the “mass-action” interpretation of NE points. According to this interpretation, it is unnecessary to assume that agents participating in the game have full knowledge of the structure of the game, or the ability to go through any complex reasoning process. But it is assumed that the participants have the ability to accumulate empirical information, obtained through repeated plays of the game and to evaluate, using this empirical information, the relative advantage of the various pure strategies they have at their disposal. The evaluation of empirical information determines, as the number of repeated plays of the game increases, the agents' NE strategies. Quoting Nash,

*It is unnecessary to assume that participants have full knowledge of the total structure of the game... but the participants are supposed to accumulate empirical information on the relative advantages of the various pure strategies at their proposal, J. Nash, PhD thesis ([24] p. 21).*

Implicit in this interpretation of NE is the assumption that the game's environment  $e$  is stable, that is, it does not change before the agents reach their equilibrium strategies. Nash's “mass-action” interpretation of NE has also been adopted by Reichelstein and Reiter [26], and Groves and Ledyard [27]. The authors of [26, 27] consider resource allocation problems with strategic agents who have private information, adopt NE as the solution concept and state,

*We interpret our analysis as applying to an unspecified (message exchange) process in which users grope their way to a stationary message and in which the Nash property is a necessary condition for stationarity, Reichelstein and Reiter ([26] p. 664).*

and,

*We do not suggest that each agent knows  $e$  when he computes  $m, \dots$  We do suggest, however, that the ‘complete information’ Nash equilibrium game-theoretic equilibrium messages may be the possible equilibrium of the iterative process—that is, the stationary messages—just as the demand–equal–supply price is thought of the equilibrium of some unspecified market dynamic process, Groves and Ledyard ([27] pp. 69–70).*

In the second interpretation of NE, it is assumed that the agents know the full structure of the game in order to be able to predict the equilibrium strategies. This interpretation of NE is rationalistic and idealizing.

In this thesis, we will adopt the “mass-action” interpretation of NE. In the problems we investigate in Chaps. 3 and 5 the environment is stable (as the network where the network is wireless, the environment is assumed to be stable (i.e. it does not change) during the allocation process).

### 2.1.6 Desirable Properties of Game Forms

In addition to implementation in an appropriate equilibrium concept, the mechanism designer should try to achieve the other objectives mentioned in Sect. 2.1.1. We formally define the properties of a mechanism associated with those objectives in this section.

#### 2.1.6.1 Individual Rationality

One of the objectives in the design of a game form is to incentivize all the agents to voluntarily participate in the allocation process under any possible environment. Consider any environment  $e \in \mathcal{E}$ . If under  $e$ , agent  $i$  decides not to participate, its overall utility is zero (see Sect. 2.1.2). If agent  $i$  decides to participate in the game induced by the mechanism, its utility is  $u_i(f(m^*))$  where  $m^*$  is an equilibrium of the game  $(\mathcal{M}, f, e)$  induced by the mechanism. Under  $e \in \mathcal{E}$ , an agent participates in the allocation process if at all equilibria  $m^*$  of the game  $(\mathcal{M}, f, e)$ ,  $u_i(f(m^*)) \geq 0$ . We can now define individually rational mechanisms as follows:

**Definition 2.7** A mechanism/game form  $(\mathcal{M}, f)$  is individually rational if for all  $e \in \mathcal{E}$ , for all equilibria  $m^*$  of the game  $(\mathcal{M}, f, e)$  and for all  $i \in \mathcal{N}$ ,  $u_i(f(m^*)) \geq 0$ , where  $u_i$  is the utility function of agent  $i$  in the environment  $e$ , and 0 is the reservation utility a user receives if it decides not to participate in the allocation process (cf. Sect. 2.1.2).

#### 2.1.6.2 Budget Balance

Strategic agents are often incentivized to follow the rules of the mechanism through monetary tax or subsidy. Some agents are induced to accept allocations that may



not be their most preferred ones (under the realization  $e$  of the environment) by receiving money (subsidy). Conversely, some agents are induced to pay money (tax) for receiving their most preferred allocations. It is desirable that for any environment  $e \in \mathcal{E}$ , at every equilibrium of the game  $(\mathcal{M}, f, e)$  the sum of taxes paid by some agents should be equal to the sum of subsidies received by the rest of the agents. Any mechanism  $(\mathcal{M}, f)$  that possesses the above property is said to be *budget balanced at equilibrium*. Budget balance is also desirable at all out of equilibrium messages that result in feasible allocations (i.e. allocations that satisfy the problem's constraints) for the following practical reason. Suppose the mechanism designer specifies, along with the mechanism, an iterative message exchange process (tâtonnement process) which for any environment  $e \in \mathcal{E}$  is guaranteed to converge to an equilibrium of the game induced by the mechanism. In practice, the message exchange process may terminate when it reaches sufficiently close to the equilibrium (but not the equilibrium). If the mechanism is not budget balanced at these out of equilibrium terminal messages, then possible large amounts of unclaimed money may be left.

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Resource Allocation in Decentralized Systems with  
Strategic Agents

An Implementation Theory Approach

Kakhbod, A.

2013, XVII, 88 p., Hardcover

ISBN: 978-1-4614-6318-4