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Differential information economies: Introduction*

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1 Introduction

Since the Cournot-Nash and Arrow-Debreu-McKenzie contributions to equilibrium theory with complete information, two main advances in equilibrium theory with differential information appeared. The first one is by Harsanyi (1967), who introduces differential information into the Cournot-Nash model, and the second one is by Radner (1968), who introduces differential information into the Arrow-Debreu-McKenzie model. Those two papers generated a literature on Bayesian Cournot-Nash equilibrium and on Walrasian expectations equilibrium respectively.

In the seventies and eighties there was a growing literature on Rational Expectations Equilibrium (REE), which is a natural extension of the Arrow-Debreu-McKenzie deterministic model of Walrasian equilibrium to a differential information framework. This literature on REE (a non-cooperative equilibrium concept) didn't provide an adequate explanation as to how prices reveal the same information to agents who are differentially informed, or to put it differently, how agents who have different information obtain the same information from the equilibrium prices. In other words, prices don't reflect the informational asymmetries of agents and this can be a major criticism of the REE concept under full revelation.

A new literature emerges from two early seminal works on cooperative equilibrium concepts with differential information. The first one was by Wilson (1979), who considers the core of an economy with differential information,

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and the second one was by Myerson (1982), who considers the (Shapley) value of a game with differential information.

A basic problem with cooperative equilibrium concepts with differential information is how agents within a coalition share their information. Wilson considered two alternative scenarios – the coalition may either choose to pool its information (fine core) or the coalition may use its common information (coarse core). In either case, problems are associated with existence and incentive compatibility so that this work was viewed for some time as a dead end. Myerson considered coalitions where each individual member truthfully reports his/her own information. In other words, Myerson's analysis took into account the individual Bayesian incentive compatibility (IBIC) constraint of each member of a coalition.

In the early nineties, the core and the value were reconsidered. In particular, Yannelis (1991) introduced a new information sharing concept for a coalition based on measurability requirements, recaste the notions of Wilson, presented refinements and thus introduced the private core. This core concept not only exists under quite general assumptions, but as shown in Koutsougeras-Yannelis (1993), it is coalitionally Bayesian incentive compatible, takes into account the informational advantage of an individual, and also provides sensible outcomes in cases where REE fails (see Section 3) to exist. Allen (1991b, 1991c, 1994), generalizes this further by introducing a very general framework which encompasses the models of Wilson and Yannelis. Allen (1991a, 1992c) and Krasa-Yannelis (1994, 1996) study the value of an economy. This work indicates that the NTU value exists and has nice properties, i.e., it is coalitionally Bayesian incentive compatible (CBIC). Moreover, the equilibrium outcome is sensitive to the initial information of an agent (i.e., a change in information can result in a change of the NTU value). Recently, Einy-Shitovitz (2001) have proved a private value equivalence theorem.

The above solution concepts in a differential information economy framework explain how multilateral contracts are written in an incentive compatible way. It should be noted however, that Bayesian incentive compatibility here is coalitional and not simply individual (see Section 4). Indeed, contracts that are IBIC are not necessarily CBIC; i.e., a coalition of agents always has an incentive to cheat the complementary coalition of agents by misreporting the realized state of nature and making side payments to all members of the coalition in order to become better off. Therefore, this literature points out that for contracts to be "stable" or viable they must also be CBIC. The private core and private value do have these properties, thus providing a rigorous foundation for the analysis of contracts under differential information and a nice alternative to REE. Finally, it should be noted that the private core and the private value are not fully cooperative solution concepts in the presence of differential information. Indeed, despite the fact that the members of a coalition act in a CBIC way, they don't necessarily share their private information. Therefore, the private core and private value provide a framework to analyze simultaneously both cooperative and noncooperative behavior.

In the next sections we present the differential information economy framework. Then we provide examples and discuss some open problems in the area.

2 Differential information economy

Let Ω denote a finite set of states of the world, and let $\Re^\ell$ denote the Euclidian commodity space (whose positive cone is denoted by $\Re^\ell_+$). An *exchange economy with differential information* is a set $\mathscr{E} = \{(X_i, u_i, \mathscr{F}_i, e_i, \mu) : i = 1, 2, \ldots, n\}$, where

1. $X_i = \Re^\ell_+$ is the *consumption set* of agent i,
2. $u_i : \Omega \times X_i \to \Re$ is the (random) *utility function* of agent i,
3. $\mathscr{F}_i$ is a partition of Ω denoting the *private information* of agent i,
4. $e_i : \Omega \to X_i$ is the (random) *initial endowment* of agent i, where each $e_i(\cdot)$ is $\mathscr{F}_i$-measurable.
5. μ is the common *prior* of all agents.

The (ex-ante) *expected utility* of agent i is given by

$$V_i(x_i) = \sum_{\omega \in \Omega} u_i(\omega, x_i(\omega))\mu(\omega).$$

The (interim) *expected utility* of agent i is

$$V_i(\omega, x_i) = \frac{1}{\mu(E_i(\omega))} \sum_{\omega' \in E_i(\omega)} u_i(\omega', x_i(\omega'))\mu(\omega'),$$

where $E_i(\omega)$ denotes the event in $\mathscr{F}_i$ containing the realized state of nature.[1]

A possible interpretation of the above economy is the following: one may think that the economy extends over two periods. In the first period there is uncertainty over states of nature. In this period, agents make contracts (agreements) either before the state of nature is realized (ex ante) or after they have received a signal as to what is the event containing the realized state of nature (interim). In the second period, agents carry out the previously made agreements and consumption takes place.

The above differential information economy model is less general than the ones in Allen (1991b) and Yannelis (1991) among others. For simplicity of exposition we have chosen this less general model.

3 Private core versus rational expectation equilibrium

Below we define the private core of Yannelis (1991), (see also Allen (1992b)). An allocation $x : \Omega \to \Pi_{i=1}^n X_i$ is said to be a *private core* allocation for the economy $\mathscr{E}$, if the following hold:

[1] It is assumed that for all $i, \mu(E_i(\omega)) > 0$.

(a) each x_i is $\mathscr{F}_i$-measurable
(b) $\sum_{i=1}^{n} x_i(\omega) = \sum_{i=1}^{n} e_i(\omega)$ for all $\omega \in \Omega$,
(c) there does not exist a coalition S and a function $y : \Omega \to \Pi_{i \in S} X_i$ such that for each i, y_i is $\mathscr{F}_i$-measurable, $\sum_{i \in S} y_i(\omega) = \sum_{i \in S} e_i(\omega)$ for all $\omega \in \Omega$ and $V_i(\omega, y_i) > V_i(\omega, x_i)$ for all $i \in S$ and for all $\omega \in \Omega$.

By replacing the interim utility function in condition (c) above with the ex ante one, we obtain an ex ante version of the private core, i.e.,

(c') there does not exist a coalition S and a function $y : \Omega \to \Pi_{i \in S} X_i$ such that for each i, y_i is $\mathscr{F}_i$-measurable, $\sum_{i \in S} y_i(\omega) = \sum_{i \in S} e_i(\omega)$ for all $\omega \in \Omega$ and $V_i(y_i) > V_i(x_i)$ for all $i \in S$.

As was pointed out in Koutsougeras-Yannelis (1993, p.198) and Lefebvre (2001, footnote 11) the existence of the private core doesn't depend on the choice of either ex ante or interim utility functions. Moreover, one can allow for different priors.

The example below (see Koutsougeras-Yannelis (1993) and also Glycopantis-Muir-Yannelis (2001)) illustrates the private core. A comparison with the REE outcome is also given.

Example: Consider a differential information economy with three agents, one good, and three different equally-probable states, i.e., $I = \{1, 2, 3\}, X_i = \Re_+, i \in I, \Omega = \{a, b, c\}, \mu(a) = \mu(b) = \mu(c) = \frac{1}{3}$. The random initial endowments, the private information sets, and the utility function are given as follows:

$$\begin{aligned} e_1 &= (20, 20, 0), \qquad \mathscr{F}_1 = \{\{a, b\}, \{c\}\}, \\ e_2 &= (20, 0, 20), \qquad \mathscr{F}_2 = \{\{a, c\}, \{b\}\}, \\ e_3 &= (0, 0, 0), \qquad \mathscr{F}_3 = \{\{a\}, \{b, c\}\}, \end{aligned}$$

and $u_i : \Omega \times X_i \to \Re$ is given by $u_i(\omega, x) = \sqrt{x}$. It can be shown that an ex ante private core allocation for this economy is

$$\begin{aligned} x_1 &= (16, 16, 4) \\ x_2 &= (16, 4, 16) \\ x_3 &= (8, 0, 0). \end{aligned} \tag{3.1}$$

Notice that the above allocation is measurable with respect to the partition of each agent. It is feasible and it cannot be improved upon by any coalition by redistributing their initial endowments based on net trades which are measurable with respect to agents' private information; the allocation is in the private core. Observe that agent 3 plays the role of an intermediary; she uses her private information to execute the trades that make everybody better off (Pareto improvement relative to the initial endowment) and she is rewarded for doing so. Notice that any REE notion gives zero to agent 3, since her budget set is zero in each state. In sharp contrast, the private core takes into account the fact that agent 3 can

play the role of an intermediary by using her "superior" private information to make a Pareto improvement for the whole economy. It should also be noted that if the private information set of agent 3 changes from $\mathcal{F}_3 = \{\{a\}, \{b, c\}\}$ to $\mathcal{F}'_3 = \{\{a, b, c\}\}$, then the private core allocation is the initial endowment (i.e., no trade). Hence, contrary to REE, the private core in this example is sensitive to information changes; a change in the private information of an agent can change the core allocation here. Clearly this is not the case for REE and this may be considered a drawback of REE in this example, which may make it unsuitable to capture informational asymmetries.

The above example demonstrates that any Walrasian expectations equilibrium notion may not be in the private core. This is in sharp contrast to the complete information case where any Walrasian equilibrium allocation is also a core allocation. It is also important to notice (see also Koutsougeras-Yannelis (1993, p. 208)) that by adding a fourth agent identical to agent 3 one can easily show that the private core lacks the *equal treatment property*. In addition one can easily check that replication of the economy doesn't restore equal treatment.

Indeed, one can verify that the allocation

$$\begin{aligned} x_1 &= (16, 16, 4) \\ x_2 &= (16, 4, 16) \\ x_3 &= (\delta_3, 0, 0) \\ x_4 &= (\delta_4, 0, 0) \end{aligned}$$

(where δ_3 and δ_4 are nonnegative numbers such that $\delta_3 + \delta_4 = 8$), is a private core allocation that treats agents 3 and 4 in an unequal manner. Observe that whenever $\delta_4 = 0$, player 4 becomes a "dummy" player and one can introduce an infinite number of dummy players identical to agent 4 and still maintain unequal treatment. Since any Walrasian expectations equilibrium will treat *all* agents with zero endowments as dummies, one can conclude that even in "large" differential information economies, no Walrasian expectations equilibrium notion may be a subset of the private core allocation. The version of the coarse core of Wilson (1978) introduced in Yannelis (1991) doesn't converge since it contains the private core. Hence, the private core in general *doesn't converge* to any Walrasian expectations equilibrium. However, by imposing a stronger set of assumptions, Aliprantis-Tourky-Yannelis (2001) have shown a Debreu-Scarf analogue for the private core, settling a conjecture made in Yannelis (1991, p. 196). Einy-Moreno-Shitovitz (2001) prove an equivalence theorem for the private core and Serrano-Vohra-Volij (2000) present counter-examples to the core convergence theorems whenever expected utilities are interim. An early core convergence result for a pooled information core was obtained by Srivastava (1984). A discussion of core convergence and equal treatment can be found in Kwasnica (1999). Moreover, Forges-Heifetz-Minelli (2001) obtain a Debreu-Scarf analogue for a type-model where allocations are defined as incentive compatible state contingent lotteries over consumption goods.

4 Transfer coalitional Bayesian incentive compatibility

Note that in the above example, the resulting private core allocation (3.1) is incentive compatible in the following sense: In an interim stage when the realized state of nature is a, agent 1 sees the event $\{a, b\}$ and she cannot distinguish a from b, while agent 2 cannot distinguish a from c. The question which arises is whether or not agent 3 (who is the only one who knows a) has an incentive to misreport the realized state of nature a in view of the fact that the other agents are confused and benefit from misreporting. If this cannot happen, we can say that the resulting allocation is incentive compatible. Indeed, notice that in state a, agent 3 receives 8 units of the good and she gets zero in every other state. Hence, agent 3 has no incentive to misreport the realized state of nature. Indeed the private core is incentive compatible.

The above example suggests the following definition of incentive compatibility:

A feasible[2] allocation $x : \Omega \to \Pi_{i=1}^{n} X_i$, is said to be *Transfer Coalitionally Bayesian Incentive Compatible* (TCBIC) if the following is not true: There exist a coalition S, states a, b with $a \neq b$ and $a \in E_i(b)$ for all $i \notin S$, and a net trade vector $(m_i)_{i \in S}$, such that $\sum_{i \in S} m_i = 0$, $e_i(a) + x_i(b) - e_i(b) + m_i \in \Re_+^{\ell}$ for all $i \in S$, and

$$\frac{1}{\mu(E_i(a))} \sum_{c \in E_i(a)} u_i(c, e_i(c) + x_i(b) - e_i(b) + m_i)\mu(c)$$
$$> \frac{1}{\mu(E_i(a))} \sum_{c \in E_i(a)} u_i(c, x_i(c))\mu(c) \text{ for all } i \in S.$$

When the transfers are zero (i.e., $m_i = 0$ for all $i \in S$) the above notion reduces to *Coalitional Bayesian Incentive Compatibility* (CBIC). Furthermore, when $S = \{i\}$, CBIC reduces to *Individual Bayesian Incentive Compatibility* (IBIC).

This notion of incentive compatibility (see also Krasa-Yannelis (1994) and Hahn-Yannelis (1997)) is stronger than the Harsanyi-type concept. Moreover, it is more appropriate if one considers multilateral contracts as is the case with the private core. Indeed, one can easily show that contracts that are IBIC need not be TCBIC. The fact that the private core and private value are TCBIC is shown in Krasa-Yannelis (1994) and Koutsougeras-Yannelis (1993).

The following example which is a modification of the one in Barseghyan-Bulu-Yannelis (1998), demonstrates that IBIC allocations need not be TCBIC.

Example: Consider a differential information economy with three agents $I = \{1, 2, 3\}$, three equally-probable states ($\Omega = \{a, b, c\}$) and two goods (denoted by x and y). All agents have the same utility function $u_i : \Omega \times \Re_+^2 \to \Re$ given by

[2] An allocation $x : \Omega \to \Pi_{i=1}^{n} X_i$ is said to be *feasible* if $\sum_{i=1}^{n} x_i(\omega) = \sum_{i=1}^{n} e_i(\omega)$ for all $\omega \in \Omega$.

$u_i(\omega, x, y) = \sqrt{xy}$, $i = 1, 2, 3,$ and the random initial endowments and private information sets are as follows:

$$\begin{aligned} e_1 &= ((10,0),(10,0),(10,0)), & \mathcal{F}_1 &= \{\{a,b,c\}\} \\ e_2 &= ((0,5),(0,5),(0,2.5)), & \mathcal{F}_2 &= \{\{a,b\},\{c\}\} \\ e_3 &= ((5,5),(5,5),(10,15)), & \mathcal{F}_3 &= \{\{a\},\{b\},\{c\}\}. \end{aligned}$$

The allocation,

$$\begin{aligned} x_1 &= ((5,2.5),(5,2.5),(6.25,3.75)) \\ x_2 &= ((5,2.5),(5,2.5),(1.25,1.25)) \\ x_3 &= ((5,5),(5,5),(12.5,12.5)) \end{aligned}$$

is IBIC and CBIC but not TCBIC. To see this, note that if state c occurs, the coalition $S = \{2,3\}$ has an incentive to report state b and instead of the 13.75 units of each good that they have together, they now obtain (15, 15) in total by giving agent 1 the allocation he would receive in state b. Indeed, the coalition $S = \{2,3\}$ can redistribute 1.25 units of each good among themselves so as to become better off, i.e., the vectors[3] $e_2(c) + x_2(b) - e_2(b) + m_2 = (2,2)$ and $e_3(c) + x_3(b) - e_3(b) + m_3 = (13,13)$ make agents 2 and 3 better off since $u_2(2,2) = 2 > u_2(1.25,1.25) = 1.25$ and $u_3(13,13) = 13 > u_3(12.5,12.5) = 12.5$.

The above example demonstrates that for multilateral contracts, one should impose a coalitional notion of incentive compatibility rather than an individual one, because otherwise contracts need not be viable. Indeed, core concepts with individual incentive constraints may not be appropriate multilateral contracts. Note that the private information measurability of net trades implies TCBIC (see Krasa-Yannelis (1994)). It is exactly for this reason that we believe that the private information measurability of allocations is a useful assumption.

5 The symposium

The papers in the present volume address different issues arising in differential information economies. In particular, Yazar examines the core by endogenizing the private information. Serfers presents a dynamic differential information economy and examines the private core by introducing non-myopic learning. The papers of Forges-Heifetz-Minelli and Einy-Moreno-Shitovitz present results on the equivalence of core notions and Walrasian expectations equilibrium. Moreover, Einy-Moreno-Shitovitz provide an equivalence theorem for the bargaining set. Hahn-Yannelis present coalitional Bayesian implementation results for the private core and private value. Glycopantis-Muir-Yannelis present an extensive form interpretation of the private core. Hellwig analyses a debt contract model

[3] Note that $m_2 = (-3,2), m_3 = (3,-2)$.

by introducing risk aversion. Gale considers a two-sided adverse selection economy and adopts an equilibrium refinement based on strategic stability. Demange-Guesnerie examine the stability of mechanisms with respect to coalitional deviations. Krasa-Shafer examine whether or not the private core (as well as other core concepts) converges to a complete information core. Finally, Lefebvre presents an alternative proof of the nonemptiness of the private core.

6 Conclusions and main open questions

The work on differential information economies has definitely enriched and advanced our knowledge of how contracts under differential information are written.[4] Yet many interesting open questions remain.

Despite the fact that the core, the value and the bargaining set do provide alternatives to REE, at this stage there is no cooperative solution concept which is universally applicable to all situations. Since the solution concepts which have been introduced are different, they generally provide different outcomes in the same situation and therefore they should be judged on the properties of the outcomes that they generate as well as the intuitive economic plausibility of their definitions. If one thinks that the best properties for a solution concept are incentive compatibility, individual rationality, and full Pareto optimality (pooled information Pareto optimality), then it is well known that this is impossible. Yet, this can be achieved in a dynamic setting by means of learning, as the work of Koutsougeras-Yannelis (1999) and Serfes (2001) indicates. Moreover, Allen (1995, 1999) shows that positive results can be obtained for the incentive-compatible cores of large economies.

There are several important unresolved issues in economies with differential information. In particular, the issue of enforceability of contracts is one of them. Although a contact may be coalitionally or individually incentive compatible, this doesn't necessarily mean that ex post all agents will fulfill their promises. Indeed, in the example of Section 3, the private core is coalitionally Bayesian incentive compatible but nonetheless, if in state a agent 1 reneges, there is no enforceable way to prevent this behavior. As in Krasa-Villamil (2000) and Krasa-Yannelis (1996), part of the contract should be a penalty (or an exogenous enforcer like the court) in case an agent or a coalition of agents reneges. Alternatively, one may be able to introduce a coalition proof mechanism in order to prevent agents from reneging. We think that the issue of contract enforcement in differential information economies is important and that it should be incorporated in the new equilibrium concepts. See also the recent work of Koeppl-MacGee (2001).

Despite the fact that in the symposium, equivalence results are presented for the private core and Walrasian equilibrium for differential information economies with a continuum of agents (Einy-Moreno-Shitovitz), the problem of modeling perfect competition remains open. In particular, in the Aumann model, agents

[4] The reader may want to consult the survey paper of Forges-Minelli-Vohra (2000) for additional references and discussion of different core concepts.

are negligible in terms of their initial endowments and therefore take prices as given. However, in a differential information economy with an atomless measure space of agents, traders are indeed negligible in terms of their initial endowments but not with respect to their private information. Consequently, an agent with non-negligible private information may be able to influence prices.

It appears that the lack of an "exact" law of large numbers in the standard measure theoretic framework (see, for example, Sun (1999)) may be a major obstacle in tackling this problem. For example, imagine a continuum of random variables satisfying the (probability) independence assumption; we know that randomness may remain because of the lack of law of large numbers! Hence, in "large" differential information economies, we shouldn't expect to have perfect competition. However, with a Loeb measure space (Loeb (1975)), the exact law of large numbers becomes true (see Sun (1999)) and the use of Loeb measure-theoretic arguments seems to be a promising way to proceed to formalize the idea of perfect competition in differential information economies.[5]

Finally, we believe that it is of interest to present a non-cooperative (extensive form) interpretation of the Shapley value, the bargaining set, and the Walrasian expectations equilibrium concepts (i.e., REE and Radner equilibrium, as analyzed in Einy-Moreno-Shitovitz). In the spirit of the Nash programme one should examine whether or not the above concepts can be supported as a perfect Bayesian equilibrium. This will provide not only a deeper understanding of these solution concepts but also a dynamic interpretation of static equilibrium allocations.

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