Investments without Coordination Failures

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I study games in which agents must sink their investments before they are potentially matched into partnerships that generate value. I focus on competitive matching markets where there is a price to join any partnership. Despite the welfare theorems for competitive markets, because agents' investments are sunk—implying that markets are incomplete—inefficiencies can still arise that can be interpreted as coordination failures. Armen does not invest because Bengt does not invest, and visa versa. But should we predict these coordination failures? I argue no because the standard, Nash solution concept used for these types of games is too weak in the context of competitive markets. For an important class of matching with investment games—where investment is only valuable if matched—Nash equilibrium only restricts outcomes (in terms of utilities) to those outcomes that are individually rational and feasible. Therefore I argue we should replace the Nash solution concept in this context with a mild refinement: trembling-hand perfection. I then prove that every perfect equilibrium is efficient. Therefore, in the context of competitive markets, coordination failures are not robust, even though they are robust in markets that are not competitive.

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1 Introduction

Coordination failures would seem to be ubiquitous, at least if we look at the amount of game theory research devoted to them. Yet, when we look at actual markets, many investments are made in the face of incomplete markets, seemingly without much fear of

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those dreaded coordination failures. Entrepreneurs develop hardware before the matching software is available. College students invest in skills before looking for jobs. In both examples, the actors must trust that proper market forces will work things out. For coordination, two things must happen. First, to induce efficiently coordinated investment, people must trust that there will be ex post competition to avoid hold out problems. Second, to induce investment, people must trust that there will not be widespread miscoordination. This paper is focused on this second point.

In this paper, I proved that coordination failure equilibria are not robust when people act as price-takers. Formally, coordination failures do not survive a trembling-hand refinement, where equilibrium is seen as the limit of a sequence of mistakes that become small. When there is a chance that people experiment or make mistakes, markets with price-taking achieve efficiency. In a sense, the model is a formal argument of how Adam Smith's "higgling and bargaining of the market" can fix coordination failures.

To formally study the connection between market coordination and game coordination, I build on a series of papers that model players as playing a game before entering a market.[1] Makowski and Ostroy (1995) first reformulated a First Welfare Theorem without price-making and incomplete markets. They showed that two conditions were sufficient for markets to generate efficient outcomes:

- full appropriation: each individual's private benefit from any investment coincides with his/her social contribution;
- non-complementarity: different player's investments cannot be complementary.

As Makowski and Ostroy show, perfect competition gives full appropriation. However, when there are complementarities, game coordination problems can still arise. Per-

1. Brandenburger and Stuart (2007) called such games, with a non-cooperative game before a cooperative games, "biform games." Such games are grossly understudied.

fect competition alone is not sufficient for efficiency.[2] Further follow up papers, such as Makowski (2004) and most recently Nöldeke and Samuelson (2015) have further generalized results and clarified the connection between competition and efficiency. But the take-away is always the same: coordination failures will plague competitive markets. However, none of these papers examine whether these coordination failure equilibria are robust.

This focus on coordination problems and the sources of their resolution is central to economics. In his reinterpretation of F.A. Hayek's early work, Gerald O'Driscoll (1977) sees "economics as a coordination problem." Unlike in a standard Walrasian model of the world where everyone chooses their best action, given the objective facts of the work, for a real economy "It is not sufficient for an individual to have complete knowledge of all objective conditions (technology, resources, and so on)." Instead "the attainment of equilibrium is a coordination problem" (p. 23-4). For Hayek, the interesting question is how such coordination comes about, not simply the definition of equilibrium as when coordination occurs. This paper theoretically investigates when efficient coordination is likely within markets or when we can expect to find "coordination failures".

But "coordination problem" has come to mean something different today, especially within game theory. To differentiate the broader notion of coordination used by writers like Hayek and the game theory form of coordination, let me use the terms "market coordination" and "game coordination".[3] Unlike the market coordination in any equilibria, game coordination occurs in any situation where each player's best-response is to somehow match the other players' actions. Coordination games have multiple pure-strategy

2. Following up on Makowski and Ostroy (1995), two important papers Cole, Mailath, and Postlewaite (2001a, 2001b) find three different types of coordination problems can arise: (1) under-investment equilibria, (2) over-investment equilibria, and (3) mismatch equilibria, as first pointed out by Felli and Roberts (2016).

3. Klein and Orsborn (2009) make a similar distinction between "concatenate coordination" and "mutual coordination." Another paper of mine (Albrecht 2016) provides a model that ties together the two different forms of coordination through the effort of entrepreneurs.

equilibria. If equilibria can be Pareto-ranked, we will call any equilibrium that is not Pareto-optimal a coordination failure.[4] The coordination failure remains as a equilibrium because people cannot contract for “joint-deviations”; markets are incomplete.

There is an entirely separate literature on adverse selection in Walrasian markets. As Gale (1992) points out, in these models there are many equilibria. However, some of those equilibria are sustained by unreasonable off-equilibrium beliefs, like the belief that other people will not best-respond if a deviation occurs. To discipline off-equilibrium beliefs, Gale uses a form of a trembling-hand refinement (Selten 1975). Whether the refinement leads to more or less efficient equilibria depends on the exact context. In Gale (1992), the refined equilibria are inefficient, while in Gale (1996) they are efficient. More recent studies have been done by Dubey and Geanakoplos (2002), Dubey, Geanakoplos, and Shubik (2005), Zame (2007), and Scheuer and Smetters (2018).

The result does not imply that coordination problems do not exist. However, we should instead think of them as arising in environments with *imperfect* competition, as is the common in the macro literature since Cooper and John (1988), for example.

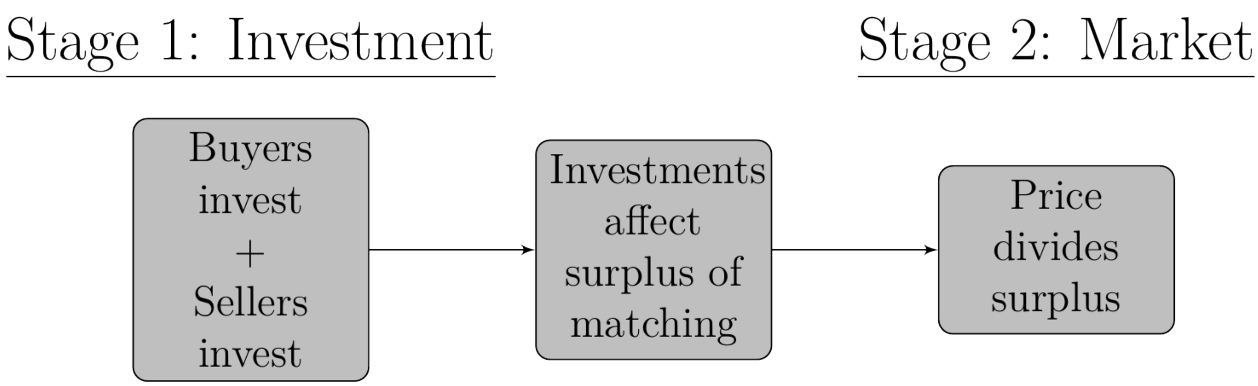
2 Example

Consider a simple example of a two-sided matching market. For consistent language, I talk about buyers and sellers. There are two stages to the game. First, before matching, buyers and sellers must invest in an attribute, $b \in \{0,1\}$ and $s \in \{0,1\}$. The cost to buyer is $\frac{1}{4}b$ and the cost to seller is $\frac{1}{4}s$. These investments generate a surplus for any match: $v(b,s) = bs$. Second, after buyers and sellers sink their investment, buyers and sellers enter a Walrasian market with prices, $p(s)$. Price is only a function of s because the seller does not care which b pays her. When buyers and sellers invest, they have some

4. A game like Battle of the Sexes does not have an equilibrium which is a coordination failure.

conjectures $p(\tilde{s})$ about the prices.

The payoff function for a buyer is $v(b,s) - p(b,s) - \frac{1}{4}b$ and for a seller is $W(b,s) = p(b,s) - \frac{1}{4}s$. The game is summarized in the figure below.



For an investment equilibrium, it must that

I. prices clear matching market,

II. each buyer i chooses b to maximize utility, given price conjectures: $\tilde{p}^i(s)$,

III. each seller j chooses s to maximize utility, given price conjectures: $\tilde{p}^j(s)$, and

IV. rational conjectures: conjectures are not contradicted by the data:

- If s exists in the economy, $\tilde{p}^i(s) = \tilde{p}^j(s) = p(s)$
- If s does not, conjectures are not pinned down

Because utility is quasi-linear (transferable), a profile of investments and matchings is efficient if and only if it maximizes $v(b,s) - \frac{1}{4}b - \frac{1}{4}s$. For this example, the efficient allocation is to maximize investment: $b = s = 1$.

However, there is also an equilibrium where no one invests: $b = 0, s = 0$, and $p(0,0) = 0$. This equilibrium is a coordination failure. However, this equilibrium is only sustained by certain conjectures of buyers and sellers. Buyers must conjecture that $p(1)$ is sufficiently high to rule out deviations and sellers must conjecture that the price is sufficiently low. The conjectures of markets that open in equilibrium are a free parameter that do not need to agree across agents.

With a free parameter, many equilibrium can be sustained. In this simple example in particular, notice also that this coordination failure *minimizes* total value. However, this means that there is little predictive power from a Nash-style equilibrium since we cannot rule out any utility outcome.

To try to pin down the equilibrium more, I consider a mild refinement: trembling hand perfection. For now, assume there is only a simple type of tremble: a uniform trembling hand, where each attribute must be chosen with positive probability $\epsilon > 0$ by each buyer and seller. Since there is a continuum of buyers and sellers, I will assume that in the aggregate each attribute must be chosen by a positive mass of players. A perfect investment equilibrium is the limit of some sequence of ϵ that goes to zero.

With trembling hand, each b and s are played, so that the actual prices are pinned down and players cannot have contradictory beliefs: $\tilde{p}^i(s) = \tilde{p}^j(s) = p(s)$. If $p(1) > \frac{1}{4}$, sellers want to choose $s = 1$ as much as possible: $1 - \epsilon$. If $p(1) < \frac{3}{4}$, buyers want to choose $b = 1$ as much as possible: $1 - \epsilon$. For any perturbation, equilibrium requires $p(1) \in \left[\frac{1}{4}, \frac{3}{4}\right]$. As perturbations go to zero, $(1, 1)$ is the unique equilibrium strategy profile. However, the prices are not necessarily unique.

This example highlights three important features of such markets. First, even with price-taking, coordination failures can exist. Second, coordination failures are sustained by off-path conjectures that are contradictory across buyers and sellers. Third, the possibility of mistakes/trembles is one justification to rule out such contradictions, which therefore rules out coordination failures. The next section extends these three features to a more general model.

3 Model

There are a continuum of buyers, indexed by $i \in I$, and a continuum of sellers, indexed by $j \in J$. There are functions that specify an endowed *type* for each agent: $\beta : I \to \mathcal{B}$ and $\sigma : J \to \mathcal{S}$. A generic type is given by $t \in T = \mathcal{B} \cup \mathcal{S}$. An economy is defined by a positive measure on the set of types,

$$E \in M_+(T).$$

There are two stages to the model. In the first stage, each individual must acquire/invest in one *attribute*, A. There exists a function of acquiring attribute an

$$c : A \times T \to \mathbb{R} \cup \infty,$$

so that $c(a,t)$ is the cost of acquiring a for type t. Individual investments lead to distribution of attributes $\mu \in M_+(A)$. For any Borel subset $E \subset A$, $\mu(E)$ is the mass of individuals with attributes in E.

The second stage involves an market that assignment of buyers to sellers,

$$x \in M_+(B^0 \times S^0),$$

where $B^0 \equiv B \cup 0$ and $S^0 \equiv S \cup 0$. An assignment x is *feasible* for μ if $x(0,0) = 0$, and for all Borel subsets, $E \subset B$ and $F \subset S$,

$$x(E, S^0) = \mu(E)$$

$$x(B^0, F) = \mu(F).$$

We can think of a matching, (b,s), as a market for a good sold by a seller of type s to buyer of type b. A market is open if that pair is part of an equilibrium. A market is closed if it is not open. While in the formulation here, players act like price-takers, players know they can affect the set of markets when they deviate. They are therefore "market-makers".

The value generated by an assignment is given by a bounded continuous value function: $v : B^0 \times S^0 \to \mathbb{R}$. In general, I will impose no further assumptions, but sometimes I will be interested in cases where v is not submodular so that coordination problems are possible.

Social assignment gains function is given by μ

$$g(\mu) \equiv \sup \int v dx \quad s.t. x \text{ is feasible given } \mu.$$

An allocation that attains $g(\mu)$ is *conditionally efficient*.

The second-stage assignment is coordinated by done through prices. To focus on coordination under perfect competition, I assume "naive" perfect competition in the continuum through price-taking. Everyone acts like price-takers, even if they do not face perfectly elastic demand and supply curves.[5] A price system is $p : B^0 \times S^0 \to \mathbb{R}$.

Definition 1. Fixing attribute investment, a pair (x, p) is an (ex post) *Walrasian equilibrium* for μ if x is feasible for μ, $p(0) \equiv 0$,

- For each $b \in \text{supp } \mu$ and each $(s) \in \text{supp } x$,

$$v(s) - p(s) = v_b^*(p) \equiv \max_{s' \in S^0} v(b, s') - p(b, s')$$

- for each $s \in \text{supp } \mu$ and each $(s) \in \text{supp } x$,, $b \in B$ implies

5. In this, I follow most of the related matching literature, such as Cole, Mailath, and Postlewaite (2001b) and Nöldeke and Samuelson (2015). However, see Gretsky, Ostroy, and Zame (1999) and Makowski (2004) for a rigorous analysis of when the price-taking assumption is justified in an assignment model.

$$p(s) = v_s^*(p) \equiv \max\{p(s), v(0,s)\}.$$

The equilibrium requires that when players are deciding whether to form a match given prices, they are optimizing.

However, the equilibrium price is not unique. Consider the above bargaining game, but only after buyers and seller have both chosen the maximum investment. There is a pie $v(b,s) = 1$ to divide by $p(b,s)$. The division which occurs is indeterminate, even though the optimal "quantity traded" is when all buyers and sellers match. This is exactly the setup and outcome in Figure 4 of Smith (1982, p. 171). As Smith finds, even though the number of trades is the efficient and equilibrium amount, the price moves between each round of play.

Even though prices are not unique, because of price-taking, we immediately have a "Conditional First Welfare Theorem": If a pair (x, p) is Walrasian for μ, then it is conditionally efficient. It is conditional because maximization only holds within the support of attributes.

However, even though all equilibria are Walrasian, they are not all efficient in the ex ante sense. In particular, investment coordination failures can arise. In the example, $b = 0, s = 0$ and $p(0,0) = 0$ can be part of an ex post contracting equilibrium. Suppose buyers conjecture that $p(b,s) > 1$ for all other levels of investment they could choose. They would not want to deviate, because any other investment is too costly. Similarly, if sellers conjecture that the price is zero, they will not make a return on their positive investment. Since only the price for $p(0,0)$ is observed in equilibrium, both sides' conjectures are rational; there is no feedback that tells the buyers and sellers they should revise their conjectures. Even though there is competition, players are stuck in a coordination failure.

However, the set of attributes chosen may be inefficient; μ may be missing the efficient

b and s. The next section asks, given the choice in a non-cooperative setting, do people choose the efficient b and s?

4 Investment Equilibrium

Fix the investment population E. An allocation of attributes is a measure $\nu \in M_+(A \times T)$, where ν_A and ν_T are the respective marginal distributions and $\mu = \nu_A$. An allocation ν is *feasible* for E if $\nu_T = E$.

Definition 2. A pair (ν, p) is an (ex ante) *investment equilibrium* for E if ν is feasible, p is a Walrasian price for μ, and for all $(a, t) \in \text{supp } \nu$,

$$v_a^*(p) - c(a, t) \geq v_{a'}^*(p) - c(a', t) \quad \forall a' \in A.$$

Note that an investment equilibrium does not involve the standard Nash equilibrium epistemic justification; people are not best-responding to actions. Instead, they are best-responding to expected prices. Beyond a Walrasian equilibrium, when players are deciding how much to invest, they must form conjectures about what prices will be in the future. The equilibrium disciplines those conjectures, as Hayek (1937) p. 41 pointed out, "the concept of equilibrium merely means that the foresight of the different members of the society is in a special sense correct." I will further discipline conjectures below when I consider refinements.

There is a total cost of attributes in the economy, ν is $\int c d\nu$, and a total surplus from ν,

$$G(\nu) = g(\nu_A) - \int c d\nu.$$

Definition 3. The allocation ν is unconditionally *efficient* for E if it is feasible and $G(\nu) \geq G(\nu')$ for all other feasible allocation ν'.

Returning to the example, we showed that investment equilibria need not be unconditionally efficient. For all buyers, $b = 0$, for all sellers $s = 0$, and $p(s) = 0$ is an investment equilibrium. There are no profitable deviation:

$$\underbrace{0}_{\text{Surplus}} - \underbrace{0}_{\text{Transfer}} - \underbrace{0}_{\text{Cost of } b=0} \geq \underbrace{0}_{\text{Surplus}} - \underbrace{0}_{\text{Transfer}} - \underbrace{\frac{1}{4}b}_{\text{Cost of } b>0} .$$

4.1 Weak Predictions with Unconstrained Beliefs

<To Be Completed>

5 Disciplined Beliefs and Perfect Equilibrium

One issue with the equilibrium concept is that off-path beliefs are a free parameter. As Robert Lucas taught us, "beware of theorists bearing free parameters." In related papers of adverse selection mentioned about, economists have recognized this issue in other Walrasian contexts. For example, Zame (2007) notes that "imposing no discipline would admit equilibria which are *viable only because different agents hold contradictory beliefs*."

To discipline beliefs, I follow Gale (1992), who argued that "*some refinement of the equilibrium concept is required to give the theory predictive power*. One such refinement is based on the notion of the 'trembling' hand."

Therefore, we will consider a perturbed strategy vector for all buyers $i \in I$, $\epsilon_B = (\epsilon(b))_{b \in B}$, satisfying $\epsilon(b) > 0$ for all $b \in B$ and

$$\int_B \epsilon(b) db \leq 1.$$

For all sellers $\epsilon_S = (\epsilon(s))_{s \in S}$, satisfying $\epsilon(s) > 0$ for all $s \in S$ and

$$\int_S \epsilon(s) ds \leq 1.$$

A perturbed games is index by the set of perturbed strategy vectors $\epsilon = (\epsilon_B, \epsilon_S)$. An allocation $\nu(\epsilon)$ is ϵ-feasible for E if $\nu_T = E$ and for all $a \in A$

$$\nu_A(\epsilon(a)) \geq \epsilon(a).$$

The allocation $\nu(\epsilon)$ is ϵ-efficient for E if it is feasible and $G(\nu(\epsilon)) \geq G(\nu'(\epsilon))$ for all other ϵ-feasible allocation ν'

Definition 4. A pair $(\nu(\epsilon), p)$ is an ϵ-investment equilibrium for E if ν is ϵ-feasible, p is a Walrasian price for μ, and for all (a, t) such that $\nu_A(\epsilon) > \epsilon$,

$$v_a^*(p) - c(a, t) \geq v_{a'}^*(p) - c(a', t) \quad \forall a' \in A$$

Note that by construction, with a trembling hand, $\text{supp } \nu_A(\epsilon) = A$.

Before getting to the perfect equilibria, I prove that in the game with trembles is ϵ-efficient.

Lemma 1. *If $(\nu(\epsilon), p)$ is an ϵ-investment equilibrium, then it is ϵ-efficient.*

Proof. Let $Q(\epsilon)$ be the utility generate by the trembling actions

$$Q(\epsilon) = \int \int [v_a^*(p) - c(a, t)] \, \epsilon(a) da \, d\nu_t$$

$$\underbrace{\left(\int\left[\max_b v(s)-\tilde{p}^i(s)-c(b,i)\right]di+\int\left[\max_s \tilde{p}^j(s)-c(s,j)\right]dj\right)\left(1-\int\epsilon(a)da\right)}_{\text{Optimized Choice}}$$

$$+\quad\underbrace{Q(\epsilon)}_{\text{Constrained Choice}}\quad.$$

But since all actions are played by trembles, $\tilde{p}^i(s)=\tilde{p}^j(s)$. Therefore they optimize the entire left expression. It is looks exactly like a static problem, which we know is efficient. ■

Therefore, the possibility of mistakes actually rules out coordination failures. Now we can consider the limit of trembles.

A pair (ν,p) is a *perfect investment equilibria* if there exists a sequence of ϵ, such that $\lim_{k\to\infty}M(\epsilon^k)=0$ such that $(\nu(\epsilon^k),p)\to(\nu,p)$.

Theorem 2. *If (ν,p) is a perfect investment equilibrium, then it is efficient.*

Proof. The theorem is immediate from Lemma 1 snce $\underbrace{Q(\epsilon)}_{\text{Constrained Choice}}\to 0.$

■

The theory's predictive power comes from imposing more restrictions on beliefs than just rational expectations. The trembling with a large number of agents rules out contradictory beliefs, as in Zame (2007), and ensures "price consistency", as in Makowski and Ostroy (1995). However, instead of assuming price consistency, the tremble gives a justification for sure price consistency in terms of the stability of the equilibria considered.

There are other justifications for non-contradictory beliefs. For example, Dubey and Geanakoplos (2002) consider fictitious seller who contributes an infinitesimal to each health insurance pool. Dubey, Geanakoplos, and Shubik (2005) assume that the government intervenes to sell infinitesimal quantities of each asset and fully delivers on its promises.

The usual examples of perfect equilibria actually show that the perfect equilibra are the inefficient ones. See a textbook example in Maschler, Solan, and Zamir (2013, p. 263) .

6 Conclusion

In this paper, I argue that, with price-taking, coordination failures rely on using beliefs as a free parameter and constructing overly pessimistic conjectures. If we want predictive power, we must use a refinement, such a trembling hand perfection.

When we consider perfect equilibrium in an Walrasian assignment model with investment, every perfect equilibrium is efficient. The mathematical mechanism is that the mistakes caused by trembles generate complete markets, even though in equilibrium, markets are endogenous and incomplete.

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