Abstract. In games for which there exists a potential, the deviation-from-rationality dynamical model for which each agent’s strategy adjustment follows the gradient of the potential along with a normally distributed random perturbation, is shown to equilibrate to a Gibbs measure for a finite number of agents. A non-dynamic generalization of the Nash equilibrium is given which also yields the Gibbs measure. This Gibbs measure appears intrinsically in potential games: statistical mechanics is not “manufactured” around the economic model. Hence a static form of bounded rationality is stated for potential games. For a finite number of agents, there is always a unique Gibbs equilibrium. The extension to an infinite number of agents is done by taking the infinite-agent limit of the Gibbs measures for a finite number of agents. Upon taking the infinite-agent limit, more than one infinite-agent equilibrium measure may occur, which is the analogy of a phase transition in statistical mechanics. The control of globally acting parameters determine which equilibrium state is obtained, just as a global magnetic field can determine the low-temperature phase of a physical spin system. This is exactly the spirit of ‘Post Walrasian’ economics: bounded rationality is implemented, multiple equilibria are acceptable (only a single equilibrium occurs for almost all given temperatures, but different equilibria can occur at different temperatures), and institutions (i.e., globally acting parameters) can be used to determine equilibrium.

The standard Cournot model of an oligopoly is shown not to have a phase transition, as it is equivalent to a continuum version of the Curie-Weiss model. However, when there is increased local competition among agents, a phase transition will likely occur. In the case of a simple discrete model (Gibbsian form of the so-called ‘minority game’), if the oligopolistic competition has power-law falloff and there is increased local competition among agents, then the model has a rich phase diagram with an antiferromagnetic checkerboard state, striped states and maze-like states with varying widths, and finally a paramagnetic state. Such phases have economic implications as to how agents compete given various restrictions on how goods are distributed. The standard Cournot model corresponds to a uniform distribution of goods, whereas the power-law variations correspond to goods for which the distribution is more localized. The Gibbsian approach is very useful for the discretized model, since there are an uncountably infinite number of Nash equilibria in the infinite agent model.

JEL Classification: C65, C73, C79

Keywords: Potential Games, Bounded Rationality, Logit Equilibrium, Gibbs Equilibrium, Noisy Directional Learning, Fokker-Planck equation, Phase Transition, Entropy.
1. Introduction

Many economic models have recently been recast in the light of “Post-Walrasian” ideas [22, 39]. These models encode bounded rationality, may have multiple equilibria, and demonstrate complexity in the sense that there can be non-price coordinating mechanisms. “Institutions” are considered to impose restrictions on models, and may effect the outcome of equilibria. Certain models in game theory [1, 2, 6, 7, 26, 27, 18, 37, 38, 53, 54] analyze the dynamics of decisions made by agents who adjust their decisions in the direction of higher payoffs, subject to random error and/or information (deductive “deviations-from-rationality” models, cf. [8]). These errors, which are essentially failures to choose the most optimal payoff, are understood to be intrinsic to the agents, and can be due to stochastic elements such as preference shocks, experimentation, or actual mistakes in judgment. In all of these contexts, the error is assumed to be due to intrinsic properties of the agents; i.e., the error is due to the agents making decisions that deviate from the true, optimal decision. In some of the aforementioned cases, a connection to a thermodynamic formalism can be made. The connection is analogous to that of nonequilibrium statistical mechanics, where stationary states of a dynamical system is pursued. An ad-hoc, non-unique, free energy is introduced in the case of [18], and a dynamical system is derived to relax to the corresponding measure. The distinct feature of the Gibbsian approach introduced here is that a free energy is shown to exist for potential games, which is based on the notion of Gibbsian entropy and not dynamics. In this sense, potential games have an intrinsic notion of Gibbsian equilibrium that does not require dynamics. The maximization of entropy is a natural extension of the notion of Nash equilibrium to the case of bounded rationality. The static notion of bounded rationality is a restriction on agents to play mixed strategies with a fixed, non-maximal potential, and hence non-maximal utilities. This introduces a “temperature”. Maximum entropy amounts to a Jaynesian notion of unbiased estimation: agents should have maximum mobility over pure strategy space. Since agents are bounded rational, their mixed strategies should reflect a desire to search as much pure strategy space as possible in hopes of maximizing their utility. When there is a unique Nash equilibrium, then at zero temperature (the case of perfect rationality) the Nash equilibrium for a potential
game is recovered. Likewise, a compatible “deviations-from-rationality” model is introduced which has the same Gibbs equilibrium measure. All of these stochastic approaches commonly use a Langevin equation to deduce logit equilibrium measures for each individual agent.

The logit measures had been earlier discovered by different reasoning [32, 41]. Logit measures are utilized in [1, 2], where agents use a continuum of pure strategies with decisions perturbed by white noise, and additionally, agents can use a restricted form of mixed strategies which are absolutely continuous with respect to the Lebesgue measure. A purely dynamical approach is taken in [37, 38], where a continuum of pure strategies is assumed and the agents are restricted to using only these pure strategies with their decisions perturbed by white noise. If agents are restricted to play a single pure strategy at any given point in time as in [37, 38], mixed strategies in [1, 2] can be viewed as a time-average of the agent’s pure strategies. Since averages are effectively used in the stationarity equations of [1, 2], it is not surprising that the solutions for the logit measures are mean-field theoretic in nature insofar as they must find fixed points for these equations to solve them. The mean-field assumption requires players to track all other agent’s decisions in time. While this assumption has experimental validity in certain cases (a mean-field static equilibrium is also found for a discrete Ising-type logit model in [9]), we assume here that the number of agents is too large for this tracking to be accurate. We replace the mean-field concept of agents taking in information with the information theoretic approach where agents take in information about the game by maximizing entropy.

The dynamics of a random utility model are also analyzed in [9], and shown to have the same stationary state as with the mean-field analysis. The static equilibrium is that for a Curie-Weiss model. Large-deviation and mean-field theoretic treatments involving phase transitions of the Curie-Weiss model have also been used to illustrate problems in finance [10]. Such concepts will be examined below within the context of statistical mechanics. For the dynamics presented in this paper, we will assume that agents are myopic in pure strategy space; that is they play a single pure strategy at any point in time as in [37, 38],
and can only make infinitesimal adjustments in pure strategy space over infinitesimal time. The difference between the dynamical approach in this paper versus those in [1, 2, 8, 26, 27, 18, 37, 38] is that a global approach is used \(^1\), in full exploitation of potential games [47]. As a result, a single stationary measure results, instead of multiple coupled measures in [1, 2]. This makes computations easier, since an explicit form of the measure is obtained, in contrast to the aforementioned references. This measure turns out to be the Gibbs measure found in equilibrium statistical mechanics. \(^2\) The dynamics in this paper are purely local in space and time: agents adjust their present pure strategy based on the present pure strategy of the other agents. It is noted that allowing agents to adjust their pure strategy based on other agents’ mixed strategies (as in [1, 2]) assumes agents can track the behavior of all other agents’ pure strategy play over enough time to determine their mixed strategies. This approach could be taken a step further in the global direction by allowing players to adjust their mixed strategies based on the mixed strategies of other players. As a result of a “global” ability to see and play strategies (e.g., agents’ knowledge of utility functions), Nash equilibria could be found more efficiently. As an example, consider pure-strategy quantities \(q_1\), \(q_2\), and \(q_3\) which are positive real numbers. The dynamics of this paper does not allow a quick jump from \(q_1\) to \(q_2\) since \(|q_1 - q_2| > 0\), where \(|·|\) is the distance function on the line. However, with mixed strategies, an agent can shift from \(q_1\) to \((1 - \epsilon)q_1 + \epsilon q_2\) for small epsilon, and get a quick sense of the strategy \(q_2\) from \(q_1\) and shift towards \(q_2\) in one step if it is better. This can happen since \(|q_1 - [(1 - \epsilon)q_1 + \epsilon q_2]| < 2\epsilon\), where \(|·|\) is the distance function on the Banach space of Radon measures. Consequently, the requirement that the path of evolution of decisions only be continuous in Radon measure norm, as opposed to a noiseless myopic evolution, effectively allows for large unilateral shifts of decision. This is similar to classical, noiseless static potential game theory when the Nash equilibrium is quickly and efficiently found to be a pure state (i.e., the global interior maximum of the potential function) in the sense that agents can make large unilateral

\(1\)For a potential game, a single dynamical equation can track all agents, instead of one equation for each agent when an agent’s response is to the pure states being played by the other agents.

\(2\)Gibbs measures on path space resulting from stochastic dynamics are investigated in [5, 49], but the appearance of stationary Gibbs measures on phase space are not pursued.
changes in decision and have global knowledge of utility functions. This does not happen in the myopic, noisy dynamics presented here, as is evident from the resulting mixed strategy Gibbs/logit stationary state. It turns out that for a potential game, the classical game-theory equilibrium (i.e., Nash equilibrium) is attained from the Gibbs measure at zero temperature. A thorough analysis of types of equilibria that occur in potential games can be found in [53]. An interesting generalization towards more boundedness on rationality could be a response of agents based on partial knowledge of other agents’ pure strategies, such as following the gradient of a partially integrated potential function, but this will not be pursued here.

An alternative static approach to a bounded-rational equilibrium is proposed in this paper, in the context of potential games, which is a bounded-rational extension of the traditional static approach for finding the Nash equilibrium. The same Gibbs/logit equilibrium distribution that results from myopic, noisy dynamics can be derived statically by using a reinterpretation of the axioms of equilibrium statistical mechanics (which amounts to doing large deviation theory or maximizing entropy). The approach is macroscopic in that it avoids explicit reference to error in agents’ decisions (which is microscopic) and extends easily to games with discrete pure strategy spaces. The approach of statistical mechanics can be interpreted in different ways [29, 30]. The ensemble approach was traditionally considered empirical in nature: our model of agent behavior using Gibbsian statistical mechanics can be based on many independent observations rather than the intrinsics (i.e. dynamics) of the game. However, as mentioned in [29], an ensemble is no more than a mechanism to justify a probability distribution on the state space of agents’ decisions (i.e., a mixed, non-pure state on full strategy space). Such a probability distribution is well-grounded in game theory, since agents’ have ‘intelligence’ insofar as they can play randomly. Therefore, although only pure states are observed at a given time, they are the results of agents playing mixed strategies. That agents are intelligent and taking in information about the state of the game implies that they can arbitrage excess information in attempt to increase their utility with the constraint of bounded rationality.
If entropy is not maximal, there will be some “accessible states”\(^3\), which are pure states that are not played with as much probability. The agents who benefit the most from these states will alter their play to make these states more probable. Hence they have taken out information about the game, in the sense of Shannon’s information entropy, so that they will increase their utility. This is Jaynes’ information-theoretic approach to statistical mechanics [29], and it justifies the introduction of entropy maximization.

In statistical mechanics, entropy maximization is a result of assuming that all accessible states should occur with equal probability. For example, if the potential \(V\) is restricted to a specific value \(V_0\), then any probability density function for an equilibrium state should have a single value on the surface \(V = V_0\) in strategy space \(\Omega\). This assumption is sometimes labeled as the “ergodic hypothesis”, but it is emphasized that there is no assumption about dynamics here. In game theoretic terms, this assumption is based on agents’ making decisions that generally increase their utility/payoff functions. For a potential game, the average difference in payoff is proportional to differences in average potential, and a purely rational move by agents would be to make decisions in such a manner that increases average payoff. An equilibrium probability density with different values on a constant potential surface would suggest that agents prefer one point (pure state) more than another, even though the payoff difference to move unilaterally from one point to the other would be zero. Such asymmetry is unjustified for this model, since the decisions of agents are based on payoff alone.

It will be shown that the Gibbs “maximum entropy” approach to games with a continuum of strategies is equivalent to the aforementioned global, noisy, myopic deviations-from-rationality potential game. As in classical statistical mechanics, we will assume the observables (i.e., functions of strategies) to be \(C(\Omega)\)\(^5\). It follows that the general mixed strategies will be the probability states in the dual of \(C(\Omega)\), \(R_1(\Omega) = \{\mu \in C(\Omega)^*| \mu \geq 0, \mu(1) = 1\}\). That is to say the mixed strategies will be generalized to probability Radon

---

\(^3\)This constraint turns out to be a nonmaximal expected value of the potential and is outlined later.

\(^4\)This is precisely defined later.

\(^5\)\(C(\Omega)\) denotes the continuous functions on (pure) strategy space.
measures on $\Omega$, which can include density functions with Lebesgue measure (such as the Gibbs measure), and delta functions for pure states (zero-temperature/pure-rational limits of Gibbs measures).

Since we only use one dynamical equation, only one stationary logit measure is obtained and we will call this measure the *Gibbs measure* of the system, exactly as in statistical mechanics. This will also avoid confusion with the more general case presented in [1, 2] of multiple logits for each agent. The Gibbs measure here is one for the entire system of agents in the given game which results from the global dynamical equation. This is a very interesting feature of potential games with noisy, myopic dynamics. It is stated in [38] that “...in game theory, there is not a unique Hamiltonian, but rather each agent has her own Hamiltonian to minimize.” This is true in general, but we’ll show that we do have a unique Hamiltonian in the case of potential games. The idea of looking for something global to unify dynamics was touched upon in [11] with the use of a “global cost function” in the ‘minority game’, but the technique is through the use of another dynamical method called “inductive reasoning” [4], rather than errors to deductive reasoning. Within inductive reasoning, an explicit formula for the stationary measure in terms of the state of the agents does not appear. The equilibrium measures obtained here do have such an explicit formula: a Gibbs measure in terms of the potential. The potential was pointed out in [1] to be the common part of the payoff functions that includes the benefits or costs that are determined by each agent’s own decisions (e.g., the effort costs). Mathematically, the potential is just like the negative energy of all of the particles (i.e. agents) in a physical system (i.e. game) for a given pure state (i.e. point describing each agent’s decision).

The essence of the Gibbs approach is that agents have the ability to play mixed strategies, and hence as a whole, agents consider many cases of the same pure-strategy playing game. In classical game theory, agents have the ability to average results over these cases, which is called an *ensemble average*. The ‘ensemble’ is then the set of possible pure-strategy decisions considered by the collective of agents. The errors in decisions are not explicitly encoded at the (microscopic) level of individual agent decisions in
this approach. However, bounded rationality is implicitly assumed on a macroscopic level by requiring the ensemble average of the potential be constant. The ensemble-average values of observable quantities (e.g., payoff, output, cost, etc.) are due to averaging these quantities over the ensemble. Hence it’s assumed that we don’t know the details of probabilities of being in various states, but rather that we must deduce these probabilities. The size of the ensemble (i.e., the number of representative games we observe) must be very large so that statistical laws of large numbers hold, and that the ensemble probabilities reflect the true intrinsic probability distribution of a single game. It is important to note that an ensemble of games is in the spirit of (and equivalent to) introducing mixed strategies in pure strategy games, as is sometimes necessary to obtain a Nash equilibrium. In this context, an ensemble is a series of games such that averaging over the pure-states of the individual games represents, in a low-of-large numbers sense, the mixed strategy average. However, unlike the ideas proposed in [33, 37, 38], we do not need to assume that there are a large number of agents and we do not treat a single agent as though she is a system in a ‘heat bath’ of agents, which implies an ensemble of agents and that we are only looking at one game. Rather, we recognize that the ability of agents to play mixed strategies is equivalent to considering an ensemble of many identical pure-strategy playing games. This approach also allows an easy generalization to discrete/finite decisions. The partition function is introduced systematically and axiomatically, rather than as a (necessarily) post-hoc mechanism to solve a minimum free energy problem in inductive models as in [17, 36]. The logit measure follows very naturally from the framework presented here. The limitation is that, for now, a systematic introduction of a partition function (which yields an explicit equilibrium measure) is only justified for potential games, whereas [1, 2, 36] are more general since agents have individual measures.

---

6If one game in the ensemble gains potential, another must lose potential which is counter to purely rational behavior, where agents would not consider strategies that would not maximize potential.

7Again, it is emphasized the ensemble it not connected to dynamics, but results from independent considerations of different strategies by the collective of agents.
An interesting aspect of this Gibbs approach is that the coefficient that determines the importance of errors in a stochastic potential game (the $\mu_i = 2/\sigma^2$ in [1, 2] or the $2/\nu^2$ in equation (6)) is directly proportional to the usual notion of temperature in statistical mechanics. This was also discussed in [33] for individual agents. In the kinetic theory of gases in equilibrium, the temperature $T$ is proportional to the average of the square of velocities $v$ of the gas particles ($T = k \cdot \langle v^2 \rangle$ for a constant $k$). If a game has a potential that is the mathematical equivalent of such a gas, this equilibrium ‘kinetic’ theory states that the ‘temperature’ of that game is proportional to the average of the square of the temporal rates-of-change of decisions ($T = c \cdot \langle (dx/dt)^2 \rangle$, where $x \in [x, \bar{x}]$ represents an agent’s decision). Hence larger instantaneous changes in decisions by agents correspond to higher temperatures of the game, and in general, temperature is a measure of the rate-of-change in decisions. In the dynamical sense [1, 2], temperature measures agents’ deviation from rationality. The more general association of temperature and agents’ deviation from rationality in the stochastic and Gibbsian models presented below is an example of the fluctuation-dissipation theorem.

A major application of statistical mechanics is to take infinite-agent limits from finite agent games. An example of this will be done to show the classical result of oligopolies approaching perfect competition as the number of agents goes to infinity. This requires some modest technical restrictions to be made on the potential function so that the finite-agent Gibbs measures will converge in the infinite-agent limit (c.f. [55]); however these restrictions also make clear economic sense. A major advantage with the Gibbs approach for potential games is that, for various potentials, all of the rigorous techniques for phase transitions can be implemented as well as the process of renormalization of infinite-agent games. Renormalization would allow us to look at behavior of aggregate blocks of agents at various scales. Dynamical renormalization is also very recently being done in economics [24, 25], where large numbers of small firms are “agglomerated” and the dynamics of the resulting “meta-firms” are examined via a sandpile model. It will only be mentioned in this paper that renormalization can be done. The standard real-space renormalization is applicable to any potential game with the imposition of a lattice dimension, since all agents interact uniformly in many
classic economic models. It would also be interesting to compare dynamical renormalization of the noisy myopic dynamics with the real-space renormalization of the Gibbs measure. Hopefully, the model shown here may be fruitful in understanding how local and global interactions between agents unify; that is to say a better understanding and more systematic treatment of economic interactions at small and large scales. Renormalization may link different economic scales as it does different scales in physics.

2. POTENTIAL GAMES AND AXIOMS FOR BOUNDED-RATIONAL EQUILIBRIA

Let us consider a game with a finite number of $n$ agents, and all of these agents belong to the set $\Lambda$. At any moment in time, agent $i \in \Lambda$ can select an action or strategy $x_i \in A_i$ and the $x_i$ are the decision variables. A configuration $\vec{x}$ of the system is any possible state of the system: $\vec{x} = (x_1, x_2, \ldots, x_n)$, where each $x_i \in A_i$. The set of all possible configurations of the game is $\Omega \equiv \prod_i A_i$, which is called (pure) state space. A typical example of $A_i$ is an interval of real numbers $A_i = [\bar{x}, \bar{x}]$. The development below is for continuum decisions, and discrete decisions will be accommodated later.

In this article, we will only consider potential games [47]. Let

$$V(\vec{x}) = V(x_1, x_2, \ldots, x_n) : \Omega \rightarrow (-\infty, \infty)$$

be the potential function for the game. Recall that a potential game is one such that every agent’s payoff function $u_i(\vec{x})$ satisfies

$$\frac{\partial u_i}{\partial x_i} = \frac{\partial V}{\partial x_i}$$

for some function $V(\vec{x})$.

Certain conditions must be imposed upon $V$ in order that probability distributions exist when the number of agents is taken to infinity in a limit. These conditions are well known functional-analytic restrictions to ensure that infinite-volume limits exist (c.f. [55]). Basic axioms for a game in equilibrium will be introduced (c.f. [52]). These turn out to be a reinterpretation of ideas from equilibrium statistical
mechanics to the very different situation of agents who consider mixed strategies, and the probability of finding the game in a particular state can be derived from these axioms. Recall a state of the system is an element of the state space $\Omega$. We consider an ensemble of identical games, each being in some arbitrary state. Likewise, it is assumed that the size of the ensemble is arbitrarily very large, so that a law of large numbers will yield the probability distribution for the game being in a given state. In the context of the stochastic dynamics in (4), an ensemble arises as an arbitrarily close approximation to a single stochastic path, where each member of the ensemble represents a point in phase space $\Omega$. It then follows that for ergodic stochastic dynamics that has a single stationary measure on phase space as an attractor, the ensemble average of a function on $\Omega$ is the average of the function with the stationary measure. There is a well-known problem with this interpretation (cf. [29, 30]). Namely, for a large number of agents, ergodicity arguments to justify constant-valued equilibrium density values on constant-potential surfaces are unrealistic, since it would take very large amounts of time (longer than the current estimated age of the universe) for agents to actually explore a dense set of points. These issues are reconciled below using the ideas of Gibbs and Jaynes.

**Axiom 1** (conservation of potential). *The game is isolated and agents act in such a way that the ensemble average of the potential converges to a constant as the size of the ensemble goes to infinity. The constant is independent of the choice of ensemble. We define the energy of a game to be the negative of the potential, so that this axiom can also be stated as conservation of energy.*

The ‘isolated’ requirement excludes outside sources from changing the potential for a given set of choices: the potential is function on state space $\Omega$. Even though agents in a specific game in the ensemble try to maximize potential, the deviations from rationality will introduce errors into agents' decisions such that an increase in potential in one game will correspond to a decrease in the potential in one or more other games in the ensemble. Since purely rational agents attempt to maximize potential, this axiom precludes
perfect rationality unless the ensemble average of the potential is the maximum potential (this is the zero-temperature case). In large deviation theory, the constraint of a constant average potential will specify the temperature of the system. Alternatively, the constraint of a fixed temperature will specify the average potential. Conservation of potential can then be interpreted as specifying the temperature of the system; i.e., how much the agents deviate from rationality.

**Axiom 2** (equilibrium/stationarity). *The game is in equilibrium. This is to say that the probability of finding the game in any one state (i.e., a single representative from the ensemble) is independent of ‘time’ or other non-specified parameters.*

This is the usual notion of stationarity. From Axiom 2, all *macroscopic* parameters (those that describe the system as a whole) are then also time-independent. Macroscopic parameters will be described in more detail later, but examples are the average output per agent, the average payoff, and the temperature.

**Axiom 3** (probability is determined by entropy and constraints). *The isolated ensemble in equilibrium is equally likely to be in any of its accessible states.*

An accessible state \((\vec{x}_1, \ldots, \vec{x}_g)\) in an ensemble of \(g\) games is a collection of configurations of decisions \(\vec{x}_k \in \Omega, 1 \leq k \leq g\), with \((\sum_k V(\vec{x}_k))/g = V_0\), given a fixed observed average potential \(V_0\) for the game. There is actually an ergodic interpretation of this axiom, in terms of the dynamics (4). However, this is incidental, and ergodicity does not justify this axiom in this non-dynamical context. If the potential for \(n\) agents is restricted to a constant value \(V_0\) (i.e., we look at a constant-potential surface in \(\Omega\)), then the

---

8The notion of time can be somewhat nebulous in statistical mechanics, especially for spin systems. The scale of time over which agents update decisions and that for stationarity to occur may or may not match the usual notion of time. Independence from time in this notion means the probability density function on state/strategy space only varies with points in \(\Omega\) and any other parameters are held constant. In economics, equilibrium may be what occurs for agents on a Sunday night, before the week starts (see [56] for an interesting discussion).
equilibrium measure of the dynamical system (4) is ergodic with respect to the time-translation semigroup generated by stochastic dynamics. Fluctuations will cause a system to move among its accessible states over time with equal frequency, and ergodicity means essentially that the system, over time, will visit almost all points on the constant potential surface (with respect to the Lebesgue measure). There are serious objections to the ergodic interpretation in statistical mechanics, namely that it would take an unrealistically large amount of time to trace out a dense path on a constant-potential surface in state space for a large number of players. However, it was already mentioned that the notion of ‘time’ in the dynamical system (4) does not necessarily reflect physical time. Furthermore, the assumption here is based on Jaynes’ notion of unbiased estimation (or Occam’s razor): unless there is any specified parameter to distinguish two accessible states, they should have the same probability (cf. [29, 30] for more details). If a potential game with potential $V$ has payoff functions $u_i(x)$ for each agent $i \in \Lambda$, then

$$\frac{\partial}{\partial x_i} u_i(x) = \frac{\partial}{\partial x_i} V(x).$$

(3)

The change in payoff for any player moving on a constant potential surface is thus zero, and there should be no rational motivation to change decisions (thus it is seen that motion on such a surface should be a result of bounded rationality). As such, we assume all points on the constant $V_0$ surface have “the same probability of being observed”, i.e., the density of any equilibrium measure will have a constant value on constant-potential surfaces in $\Omega$. Likewise, it is assumed that the games in an ensemble are independent considerations by the collective of agents. Agents would then consider playing an independent collection of decisions $(x_1, \ldots, x_g)$ with probability that is a function of the total potential $V(x_1) + \cdots + V(x_g)$. This happens if agents make decisions based on the ensemble average of the changes in utility, which is a very reasonable assumption. For potential games, this is the same as changes in the total potential above. Thus for two considerations, independence implies $P_2(V_1, V_2) = P_1(V_1)P_1(V_2)$, where $P_k$ is the joint probability for $k$ considerations by all agents. Since the probability should depend on total potential, $P_2(V_1, V_2) = P_2(V_1 + V_2)$. This alone (applied to $f = P_1/P_1(0)$) yields the exponential Gibbsian form for
a measure. However, introducing entropy in the discrete $\Omega$ case as $S[P] = \sum_i P(V_i) \ln(P(V_i))$ gives an understanding in terms of maximization. The Gibbs measure has maximum entropy, and entropy is a measure of how many ways the considerations in the ensemble can be distributed over accessible states in the ensemble. Hence agents, in this sense, have maximum mobility over $\Omega$. This is a static version of what diffusion does in the dynamical case: agents tend to want to explore state space. In the Shannon sense, the negative of entropy is a measure of information available to the agents about the state of the game itself. Individual agents would want to extract out as much information as possible, and maximum entropy implies that no more information is left for extraction. As an example, suppose agents play a pure strategy $\vec{x}_0$ of suboptimal potential (the restriction to constant average potential implies the average must be $V_0 = V(\vec{x}_0)$). At least one agent can obtain higher payoff by playing a different strategy with higher potential $V_a$. But bounded rationality (i.e., the average potential must be $V_0$) requires that this be balanced with a strategy having potential $V_b$ which is lower than $V_0$. It may be that some agents benefit from the higher potential and others do not. The possibility of improving can drive agents to try more possible combinations. Agents took away information from the system (the mixed state of $V_a$ and $V_b$ has higher entropy than the pure state $V_0$) by learning that there is a state of higher and lower potential. It is then seen that entropy can be interpreted as a non-dynamical notion for bounded rationality in the case of potential games. The probability measure with maximum entropy subject to a fixed average potential is stated in Proposition 5.

The approach to stochastic game theory in [1] produces a single Fokker-Planck equation that the joint probability distribution of decisions on $\Omega$ satisfies. There, the Langevin equations for the joint distribution

---

9 When strategy space $\Omega$ is a continuum, the sum is replaced with integration over the Lebesgue measure. Justification for using the Lebesgue measure is given in Appendix A: any dynamical solution will be absolutely continuous with respect to the Lebesgue measure when $\Omega$ is a nice space (no isolated points, connected, etc.)

10 This is similar to Maxwell’s demon.
\[ dx_i(t) = \frac{\partial}{\partial x_i} u_i(\vec{x}, t)dt + \nu dw_i(t), \quad 1 \leq i \leq n, \quad (4) \]

where the \( w_i \) are zero-mean, unit-variance normal random variables and \( \nu \) is a variance parameter.

The following result very similar to [1]. The major difference here is that we are looking at a dynamics for all agents who only use pure strategies, whereas in [1] single-agent dynamics are analyzed separately, and they use mixed strategies. The point of the following result is to show the stochastic dynamical approach in global form leads to the same Gibbs measure as that derived from Axiom 1, Axiom 2, and Axiom 3. The proof is in Appendix A. Again, it is important to note that the dynamics below assume agents only use pure strategies and can only make small-distance moves over pure strategy space within a small time period (myopic agents).

**Proposition 4.** Let \( f(\vec{x}) \) be the joint density over decision space \( \Omega \) for a potential game with a finite number of agents \( n \) and potential \( V \). Consider the dynamics

\[ d\vec{x} = \vec{\nabla}V dt + \nu d\vec{w}(t), \quad (5) \]

where \( x \in \Omega, \, d\vec{x} = (dx_1, \ldots, dx_n), \, \vec{\nabla}V = (\partial V/\partial x_1, \ldots, \partial V/\partial x_n), \) and \( \vec{w}(t) = (w_1(t), \ldots, w_n(t)) \) with the \( w_i(t) \) standard Wiener processes which are identical and independent across agents and time. Furthermore, the \( w_i(t) \) have mean zero and variance one and reflecting boundary conditions \(^{11}\) are used. Note that no conditional averages are done on \( V \) above, as opposed to [1, 2]. This indicates that only pure strategies are being played.

If the process \( \vec{x}(t) \) satisfies the dynamics of (4), then the joint density satisfies the Fokker-Planck equation

\[ \frac{\partial f(\vec{x}, t)}{\partial t} = -\vec{\nabla} \cdot [\vec{\nabla}V(\vec{x}(t))f(\vec{x}, t)] + \frac{\nu^2}{2} \nabla^2 f(\vec{x}, t) \quad (6) \]

\(^{11}\)This requires zero time derivatives on the boundary, specifically that (51) be satisfied for boundary points \( \vec{x} \).
and the corresponding equilibrium measure for variance $\nu^2$ is the Gibbs state

$$f(\vec{x}, t) = f(\vec{x}) = \frac{\exp\left(\frac{2}{\nu^2} V(\vec{x})\right)}{\int_{\Omega} \exp\left(\frac{2}{\nu^2} V(\vec{y})\right) d\vec{y}}.$$  \hspace{1cm} (7)$$

In statistical mechanics, the term in the exponent of (7) is $-E(\vec{x})/(kT)$, where $k$ is Boltzmann’s constant, $T$ is temperature, and $E(\vec{x})$ is the energy of configuration $\vec{x}$. Hence the analogy of a potential game to statistical mechanics is that $\nu^2$ (deviation from rationality; influence of the noise in dynamics (4)) is proportional to ‘temperature’ and the potential $V$ is the negative ‘energy’ of the system as defined in Axiom 1.

Now the Gibbs measure above can be derived using only the axioms of equilibrium statistical mechanics: Axiom 1, Axiom 2, and Axiom 3. The proof is the standard proof of the ‘canonical distribution’ in any text on statistical mechanics, and is the one that finds a state (i.e. probability measure) that maximizes entropy under the condition of a constant ensemble-average energy. The variational form of this maximization problem is the Gibbs variational principle of finding a state that minimizes the Helmholtz free energy. It is interesting to note that the problem of finding a state that maximizes the Liapunov function (expected potential plus entropy) for dynamical equilibrium in [1] is identical to finding a state that minimizes the Helmholtz free energy (negative expected potential minus entropy) of a given potential game. This is exactly what the Gibbs variational principle accomplishes. It is no surprise that the Liapunov function in [1] is the negative Helmholtz free energy for corresponding potential game with no explicit noise. This fact is stated here as a contrast to Proposition 4:

**Proposition 5.** Let $f(\vec{x})$ be the joint density over decision space $\Omega$ for a potential game with a finite number of agents $n$ and a potential $V$. Suppose the three thermodynamic axioms Axiom 1, Axiom 2, and Axiom 3 hold. Then the equilibrium measure for this potential game is the Gibbs state at inverse-temperature $\beta \equiv (kT)^{-1}$:

$$f(\vec{x}, t) = f(\vec{x}) = \frac{\exp\left(\beta V(\vec{x})\right)}{\int_{\Omega} \exp\left(\beta V(\vec{y})\right) d\vec{y}}.$$  \hspace{1cm} (8)$$
Here the constant $\beta$ in $f(\vec{x})$ is determined so that the mean potential $\int_{\Omega} V(\vec{x})f(\vec{x})d\vec{x} = \bar{V}$, where $\bar{V}$ is the ensemble-average observed potential (i.e., the limit of the sum of the potentials of each game in the ensemble divided by the number of games $g$ in the ensemble $\lim_{g \to \infty}(V_1 + \cdots + V_g)/g$). This is equivalent to the notion of considering one game to reside within the ‘heat-bath’ of the other games in the ensemble with a fixed average potential $\lim_{g \to \infty}(V_1 + \cdots + V_g)/g$. Exchange of potential between members in the ensemble amounts to changing stochastic paths in the stochastic model. For all such paths, the temporal average of potential must be the same constant.

We consider equilibrium states of an infinite-agent game to be the measure(s) resulting from the appropriate infinite-agent/volume limit of the Gibbs state.

In the case of potentials that fit the usual notion of an ‘interaction’ \footnote{It is noted that the potential for a Cournot oligopoly is not such an ‘interaction’, and other techniques must be used. This is because of the $1/n$ factor; see Section 3 for the explicit potential.} in statistical mechanics (c.f. [55] for the appropriate machinery), the infinite-agent measures will be consistent with the finite-agent measures via the Dobrushin-Lanford-Ruelle equations. Such techniques can be used directly to analyze possible phase transitions for an infinite-agent potential games. We can then consider equilibrium states of an infinite-agent game to be the appropriate infinite-volume limit of the Gibbs measure.

3. Example: Cournot Oligopoly, Local Demand, Perfect Competition and Collusion

The simplest oligopoly model is due to Augustin Cournot (1838). There is one homogeneous good with demand function $p(Q)$, where $Q$ is the total quantity of the good produced. Given an oligopoly of $n$ firms, if each firm produces an amount $q_i$ of the good, then

$$Q = \sum_{1}^{n} q_i.$$  \hfill (9)
For the sake of later analysis, each firm’s production $q_i$ will be scaled between a minimum production $\underline{q} \geq 0$ and a maximum production $\bar{q} > q_i$. We will assume each firm produces a sufficiently large number of the good so that the $q_i$ can be regarded as continuum variables $\underline{q} \leq q_i \leq \bar{q}$, $1 \leq i \leq n$. For example, $q_i = 1$ can represent the production of a sufficiently large number of goods. It is noted that smaller production would be handled in the discrete case as in Section 4.

Each firm uses quantity $q_i$ as its strategy based on the payoff function

$$\Pi_i = q_i p(Q) - C_i(q_i), \tag{10}$$

where $C_i$ is the $i$th firm’s cost function. We will assume a linear (inverse) demand function

$$p(Q) = a - \frac{b}{n} Q, \tag{11}$$

with constants $a > 0$ and $b > 0$. Notice that $b$ is divided by $n$ so that demand is based on the average production. Thus demand stays nonnegative for large $n$. To illustrate this, if each firm were to produce $\bar{q}$, then $p(n\bar{q}) = a - \bar{b}$ is well-behaved and non-trivial (i.e., doesn’t go to negative infinity or zero).

Constant marginal costs (i.e., $C'_i = c$, for a constant $c > 0$) will also be assumed, so that $C_i(q_i) = cq_i + d_i$, and the payoff functions are now

$$\Pi_i = q_i \frac{-b}{n} \sum_{j=1}^{n} q_j + (a - c)q_i - d_i. \tag{12}$$

In the case of collusion, firms would try to maximize total industry profits

$$\Pi = \sum_{i=1}^{n} \Pi_i = -\frac{b}{n} \sum_{i,j=1}^{n} q_i q_j + (a - c) \sum_{i=1}^{n} q_i - \sum_{i=1}^{n} d_i. \tag{13}$$

Both of these cases constitute potential games. A potential for the oligopoly in equation (12) is

$$V_o = -\frac{b}{2n} \sum_{i,j=1}^{n} q_i q_j - \frac{b}{2n} \sum_{i=1}^{n} q_i^2 + (a - c) \sum_{i=1}^{n} q_i. \tag{14}$$
and a potential for collusion is the same as the collusion payoff function (except for the irrelevant constants $d_i$) in equation (13),

$$ V_c = -\frac{b}{n} \sum_{i,j} q_i q_j + (a - c) \sum q_i. $$

(15)

These two potentials are two cases of the potential

$$ V = -\frac{b}{n} \sum_{i,j} q_i q_j - \frac{\tilde{b}}{n} \sum q_i^2 + (a - c) \sum q_i. $$

(16)

To get the potential in equation (14), replace $b$ and $\tilde{b}$ in equation (1) with $b/2$. To get the collusion potential in equation (15), set $\tilde{b}$ to zero.  

The Nash equilibrium for the Cournot oligopoly with potential $V$ above is

$$ q_j^* = \frac{a - c}{2(b + \tilde{b}/n)}. $$

(17)

For non-collusion, $q_j^* = [n/(n + 1)][(a - c)/b]$, and for collusion $q_j^* = (a - c)/(2b)$ are the Nash equilibria.  

Note for collusion, the output is half of that for the non-collusive model, and hence firm profit (12) is less than it would be for the non-collusive equilibrium. These classical equilibrium solutions will be recovered in the perfectly rational case (zero temperature, $\beta = 0$) below, using the Gibbs approach.

The partition function for $n$ agents is

$$ Z_n = \int \prod_{i=1}^n dq_i \exp \left[ -\beta \frac{b}{n} \sum q_i q_j - \beta \frac{\tilde{b}}{n} \sum q_i^2 + \beta (a - c) \sum q_i \right]. $$

(18)

\[13\]It is interesting to note the effect of collusion pertaining to rationality. If $a - c = 0$ in (16), then collusion has the effect of doubling $\beta$ in the partition function (18). The collusive model is simply the non-collusive oligopolistic model at half the temperature $1/(2\beta) = T/2$. In the infinite-agent limit, the oligopolistic model is the same as perfect competition. Hence collusion is more “rational” behavior than perfect competition!

\[14\]These equilibria look like those for total industry output $Q = \sum q_i$ in the standard literature, but as described below (11), the scaling is at the level of firm production instead of industry production (where firm production would go to zero as $n$ increases).
The infinite-agent free energy

\[ F(\beta, a, b, \bar{q}, q) = \lim_{n \to \infty} \frac{1}{\beta n} \ln(\mathcal{Z}_{n,h}). \]  

is calculated in Appendix B to be

\[ F(\beta, a, b, c, q) = \frac{b(\bar{q} + q)[b(\bar{q} + q) - 2(a - c)]}{4\beta} - \ln(\bar{q} - q) - \frac{1}{\beta} \min_{y \in (-\infty, \infty)} -\beta by^2 + \ln \left( \sinh \left( \beta b(\bar{q} - q)y + \beta \frac{(\bar{q} - q)}{2} \{b(\bar{q} + q) - (a - c)\} \right) \right) \]  

where \( \sinhc(x) = \sinh(x)/x \), \( \sinhc(0) = 1 \), and it is noted that the free energy \( F \) is independent of \( \tilde{b} \), which can be set to zero. It is also shown in Appendix B that the expected value of any agent’s output is

\[ \langle q_i \rangle = \frac{\partial}{\partial a} F = \frac{a - c}{2b} + \frac{y_m(\beta, a, b, c, q) + y_m}{\beta Qb}, \]  

where \( |y_m| < |(\bar{q} + q)/2 - (a - c)/(2b)| \), \( y_m < 0 \) when \( (a - c)/(2b) > (\bar{q} + q)/2 \), and \( y_m > 0 \) when \( (a - c)/(2b) < (\bar{q} + q)/2 \). Hence the Gibbs equilibrium is always between the average \((\bar{q} + q)/2\) and the Nash Equilibrium \((a - c)/(2b)\). In the completely irrational limit

\[ \lim_{\beta \to 0} \langle q_i \rangle = \frac{\bar{q} + q}{2}, \]  

and the output is pushed to the average as would be expected for uniformly random behavior. In the completely rational limit,

\[ \lim_{\beta \to \infty} \langle q_i \rangle = \begin{cases} q & \text{if } \frac{a - c}{2b} < q \leq \bar{q} , \\ \frac{a - c}{2b} & \text{if } \frac{a - c}{2b} \leq q \leq \bar{q} , \\ \bar{q} & \text{if } \frac{a - c}{2b} > \bar{q} , \end{cases} \]  

which is the classical Nash equilibrium for an infinite number of agents in (17).

From the properties of \( y_m \), we see that agents adjust output down (up) from \( q^* \equiv (a - c)/(2b) \) towards the average output \( q_{av} \equiv (\bar{q} + q)/2 \) if \( q^* \) itself is larger (smaller) than \( q_{av} \). The magnitude of the adjustment increases as the deviation from rationality (i.e., temperature or \( 1/\beta \)) increases. This shows that a collusive-type behavior occurs insofar as agents produce less than the purely rational equilibrium.
output $q^*$ when $q^* > q_{av}$. When $q^* < q_{av}$, agents will produce more output than $q^*$, which is anticollusive/supercompetitive.

It is also shown in Appendix B that the volatility, which is $\chi \equiv \beta^{-1} \partial^2 F / \partial h^2$, is zero at zero temperature (as expected for perfect rationality) and goes to $(\bar{q} - \bar{q})^2/12$ as temperature goes to infinity (i.e., randomly acting agents have independent, uniformly distributed outputs $q_i$). An agent’s payoff can be computed using $\langle q \rangle$ and $\chi$. Since $\langle \Pi_k \rangle = \lim_{n \to \infty} q_k [-b/n \sum_{j=1}^{n} q_j + (a - c)]$ and $\langle \Pi_k \rangle = \langle \Pi_i \rangle$, $1 \leq i \leq n$, for all temperatures we have

$$\langle \Pi_k \rangle = \lim_{n \to \infty} -\frac{b}{n} \chi + \langle q_k \rangle (h - b \langle q_k \rangle) = \langle q_k \rangle (h - b \langle q_k \rangle).$$

(24)

The maximum payoff occurs at the Nash equilibrium $\langle q_k \rangle = q^*$. Furthermore, from the explicit formula for $\langle q_k \rangle$ it is evident that $\langle \Pi_k \rangle$ is an increasing function of $\beta$. Payoff increases as the deviation from rationality (i.e. temperature) decreases.

The model presented above is the standard Cournot model, which assumes the inverse demand is symmetric among the agents. In reality, this is not typically the case. As a specific case, water prices in parts of a city with higher elevation may have a higher price because of additional costs of pumping the water. Likewise, competition among agents may not be perfectly uniform. An example of this would be firms who are more competitive against neighboring firms than with those far away, such as a local restaurant. It draws customers from mostly one area, and would be in greater competition with other nearby restaurants. The success or failure of distant restaurants would not have any affect. A single member of a restaurant franchise competes with local restaurants, but colludes with other more distant members of the parent company. In contrast to this would be a type of regional collusion, where all of the firms in any given locale may work in collusion with each other in an attempt to outcompete distant firms.
To formalize these ideas, notice that an individual payoff function can be written as the collusion potential minus all other agents’ payoff functions:

\[ \Pi_k = V_c - \sum_{i \neq k} \Pi_i. \]  

(25)

This shows an agent in oligopolistic competition will offset the collusive potential by subtracting the gains made by all other agents. A smaller degree of competition would correspond to subtracting fewer of the other agents payoffs.

Example 1 (Local Collusion Within a Global Oligopoly). Suppose \( n \) agents are assumed to lie at integer points on the real line. If agents work collusively in disjoint groups of three, the payoffs are of the form

\[ \Pi_{lc}^{k\pm 1} = \Pi_{lc}^k = \sum_{i=k,k\pm 1} \Pi_i = \sum_{i=k,k\pm 1} \sum_{j=1}^n \left[ -\frac{b}{n} q_i q_j + (a - c) q_i \right], \quad k = 3m, \text{ for integer } m. \]  

(26)

A potential is \( V_{lc} = V_o - (b/n) \sum_{k=3m,i=k\pm 1} q_i q_k \), where \( V_o \) is the oligopolistic potential in (14). Although the potential is not translation invariant, if ‘block outputs’ \( Q_k \equiv (q_{k-1} + q_k + q_{k+1})/3 \), \( k = 3m \), are used along with periodic boundary conditions \( (q_n \equiv q_1) \) then a renormalized potential would be translation invariant.

Example 2 (Local Oligopoly Within Global Collusion). Suppose now that agents collude with non-neighboring agents and compete oligopolistically with neighboring agents within the same setting as Example 1. Here, however, the agents are competing oligopolistically with nearest neighbors, and not in disjoint groups of three. The payoffs are

\[ \Pi_{lo}^k = \sum_{i \neq k\pm 1}^{n-1} \Pi_i = V_c - \Pi_{k-1} - \Pi_{k+1}, \]  

(27)

where we define \( \Pi_0 \equiv 0 \) and \( \Pi_{n+1} \equiv 0 \) to get correct payoffs. The potential is

\[ V_{lo} = V_c + \frac{b}{n} \sum_{i=1}^{n-1} q_i q_{i+1} \]

(28)

\[ = -\frac{b}{n} \sum q_i q_j + (a-c) \sum q_i + \frac{b}{n} \sum q_i q_{i+1}. \]  

(29)
It is shown in Appendix B that the $\hat{b}$ term in the potential $V$ of (16) has no significance in the infinite-agent limit because the number of terms in the summand is of order $n$, and as such it can be set to zero. This is the case for the last nearest-neighbor sum in (29), and in the infinite-agent limit, the free energy is the same as the collusion model. To maintain local oligopolistic competition in the infinite-agent limit, the interaction term $b/n$ must be changed to a constant $\delta > 0$ that does not vanish as $n \to \infty$.

Example 3 (True Local Oligopoly Within Global Collusion). As mentioned in Example 2, an appropriate potential that maintains local competition in the infinite-agent limit is

$$V_{lo} = -\frac{b}{n} \sum q_i q_j + (a - c) \sum q_i + \delta \sum_{i=1}^{n-1} q_i q_{i+1},$$

(30)

where $\delta > 0$.

The $\delta$ term in (30) only involves local interactions, that is, only terms within a fixed distance (of one) appear in the summand. Such terms in the potential are also called local interactions.

Example 4 (Oligopoly With Stronger Local Competition). It is noted that in the infinite-agent limit, replacing $b$ with $b/2$ in (30) is equivalent to changing the collusive potential component $V_c$ to the standard oligopoly potential $V_o$. We can then interpret the (infinite-agent) free energy generated by the potential $V_{lo}$ to be oligopolistic competition with increased local competition.

The potential in (30) is also generated by payoff functions

$$\hat{\Pi}_k^{lo} = q_k \left( -\frac{2b}{n} \sum q_j + (a - c) + \delta \left[ q_{k-1} + \frac{b}{\delta n} q_k + q_{k+1} \right] \right),$$

(31)

where $q_0 \equiv q_{n+1} \equiv 0$ applies. The dynamics generated by the $\hat{\Pi}_k^{lo}$ in (31) and the $\Pi_k^{lo}$ in (27) are identical, since they generate the same potential. Likewise, the infinite-agent free energies are the same, and as argued previously, the term $bq_k/(\delta n)$ will have no effect in the infinite-agent limit.
What is interesting about (31) is that an inverse demand function appears:

\[ p_k(q_1, \ldots, q_n) = p(Q) + \delta \left[ q_{k-1} + \frac{b}{\delta n} q_k + q_{k+1} \right], \quad (32) \]

where \( p(Q) \) is a standard linear inverse demand as in (11). The remaining term only involves terms local to agent \( k \), and is called a local (inverse) demand function. Also notice that payoffs cannot be described by a single global demand \( p(Q) \), and each agent has her own demand function \( p_k \).

The reason for the consideration of the addition of local demand as with (30) is that a phase transition is possible in contrast to the lack of one for the standard Cournot oligopoly. This will be shown in Section 4 for a discrete model which is a version of the Cournot model with local demand.

Finally, we consider a situation where local demand for an agent’s good is less affected by more distant firms.

**Example 5 (Power-Law Falloff of Local Demand).** Imagine agents residing at integer coordinates in a box in \( d \)-dimensional space; call this set \( Q \subset \mathbb{Z}^d \). Consider the local inverse demand functions

\[ p_k(q_1, \ldots, q_n) = -2b \sum_{j \in Q, j \neq k} \frac{q_j}{|k - j|^w} + (a - c) + 2\delta \sum_{i : |i - k| = 1} q_i, \quad (33) \]

where \( |i - j| \) is the distance between agents \( i \) and \( j \), and \( w \geq 1 \). Here, the \( \delta \)-term again represents heightened local competition, but the \( b \)-term is in a different form. The output of agents more distant from agent \( k \) has less of an effect on the inverse demand of agent \( k \). This can be due to a variety of issues. Local agents may have more of a local market share because more distant agents could have to pay more for shipping, which can increase the price of their good in more distant regions. A variation of that is the good is primarily bought and not shipped, with customers preferring to travel less distance to purchase the good. This is in contrast to the previous term \( p(Q) \) in (11) which assumes goods are circulated uniformly in a global market, with no barriers that would put more emphasis on local output.
A potential for payoffs $\Pi_k = q_k p_k$ is

$$V_w = -b \sum_{(i,j)} \frac{q_i q_j}{|i - j|^w} + (a - c) \sum q_i + \delta \sum_{(i,j)} q_i q_j,$$

(34)

where $(i, j)$ indicates a sum over distinct pairs of sites in $Q$ and $\langle i, j \rangle$ indicates a sum over nearest neighbors $|i - j| = 1$.

It has been shown that a very interesting phase transition occurs for a discrete version of (34) above, which will be outlined in Section 4. This phase transition is very distinct from the phase transition speculated for the discrete version with the standard $p(Q)$ term. We then see that an interesting feature of the Gibbs model of Cournot competition among an infinite number of agents is that it distinguishes between models with uniform and nonuniform distribution of goods for certain ranges of parameters $\beta$, $b$, and $\delta$.

4. Example: Gibbsian Minority Game

The inductive minority game (cf. [19, 34]) is a version of the El Farol bar problem [4, 36] that was introduced to analyze cooperative behavior in markets. It is introduced in the context of inductive reasoning and non-equilibrium statistical mechanics, but we will look at it in another way since the utility functions can be derived from a potential. An interesting point is that the dynamical equations in the inductive reasoning view do not satisfy detailed balance and there is a dynamical phase transition separating an ergodic from a non-ergodic process (c.f. the discussion in [21]). Similarly, there are Glauber dynamics for the Ising model which use sequential site updating and do not in general satisfy detailed balance, but nevertheless do converge to the appropriate Gibbs measure by stationarity (see [58] for an example). The lack of detailed balance usually suggest a study of dynamics, but the advantage of a Gibbs approach is that the dynamics yield an explicit stationary equilibrium state. The approach to information is different for each model. In the inductive reasoning model, agents make decisions based on external information. In
the Gibbsian model, entropy can be interpreted as information about the state of the game, and entropy maximization implies agents act in such a way as to take/arbitrage all of the available information about the game itself. The internal information about the Gibbsian game can be made to have random external dependence by using a “quenched model” \(^1\), but that will not be pursued.

In equilibrium analysis, many models exhibit a unique translation invariant infinite-volume state (hence ergodicity) at high temperature, while at lower temperatures there are multiple states and non-ergodic translation invariant limiting states exist (c.f. [55] for details). As such it seems reasonable to consider a Gibbs model of the minority game. First, for the sake of background, we will introduce the inductive reasoning form of the game as presented in [21], and then contrast it with the Gibbsian version.

The inductive game consists of \(n\) agents, labeled \(i = 1, \ldots, n\). For simplicity, we can picture these agents lined up at integers on a one-dimensional axis, hence the agents are situated at sites \(\Lambda \subset \mathbb{Z}\). \(^{16}\) At each discrete time step \(t\), each agent \(i\) must make a decision \(\sigma_i \in \{-1, 1\}\) (such as to ‘buy’ or ‘sell’). The agents decide to buy or sell based on public information \(I(t)\) that is available to all agents at time \(t\) (c.f. the discussion in [21]). Note that at a given time, all agents receive the identical piece of information. Examples of such information could be the state of the market (decisions off all agents, the decisions of agents on odd sites, the block/regional-averages of decisions on blocks of length \(n/100\), etc.), the weather forecasts, change in government regulations, etc.

Profit, or utility, is made at time step \(t\) by agents according to the formula

\[
 u_i(t) = -\frac{b}{n} \sigma_i(t) \sum_{j=1}^{n} \sigma_j(t) \tag{35}
\]

\(^{15}\) It would be interesting to see if replica symmetry breaking would occur in a quenched Gibbsian model, as it does in the inductive reasoning model.

\(^{16}\) Because of the form of the potential, this model is not a \(d\)-dimensional lattice model for any \(d\). We have chosen to use \(d = 1\) for visualization, and later, a true \(d\)-dimensional term will be added to the potential.
with $b > 0$. Because the coefficient $-b < 0$, the profit $u_i(t) \geq 0$ when $\sigma_i(t) = -\text{sgn}\left[\sum_{j=1}^{n} \sigma_j(t)\right]$. The justification is that in a market, if the majority is selling it is profitable to buy and vice-versa. Further notice the payoff function is scaled by $1/n$. It is mentioned in [21] to exist for mathematical convenience, but we will see later that it is needed for stability of the thermodynamic limit. Economically it makes sense to scale this way so that the inherent inverse demand function stays finite (see Section 3).

Now the element of public information will be introduced. It is noted in [34] that a phase transition occurs without the element of information, and all that is needed is stochastic mixed strategies. In [21], information is randomly drawn at time $t$ from a set $\{I_1, \ldots, I_p\}$. For example, at time $t$ a number $\mu(t) \in \{1, \ldots, p\}$ is drawn randomly and the information $I_{\mu(t)}$ is given to all agents, so that $I(t) = I_{\mu(t)}$ with $1 \leq \mu(t) \leq p$. The information will have relative size $\alpha \equiv p/n$.

The information $I(t)$ is converted into a configuration of $n$ trading decisions $\sigma(t) = (\sigma_1(t), \ldots, \sigma_n(t))$. These are determined using ‘response strategies’, which are look-up tables or functions $R_{i,s} = (R^{1}_{i,s}, \ldots, R^{p}_{i,s}) \in \{-1, 1\}^p$. Each agent $i$ has $S$ decision making strategies $R_{i,s}$ with $s \in \{1, \ldots, S\}$. The strategy that each agent $i$ plays depends on the public information $I(t)$. If $I(t) = I_{\mu(t)}$, agent $i$ will choose a strategy $s$ and then lookup the decision $R^{\mu(t)}_{i,s} = \pm 1$ in the vector $R_{i,s}$. Agent $i$ will then make the decision $\sigma_i(t) = R^{\mu(t)}_{i,s}$, which depends on her choice of strategy and public information.

Finally, the last ingredient is for agents to evaluate strategies based on the market performance of the strategies. At time $t$, strategy $R_{i,s}$ is profitable if and only if $R^{\mu(t)}_{i,s} = -\text{sgn}\left[\sum_{j=1}^{n} \sigma_j(t)\right]$. Each agent $i$ will then measure the cumulative performance of each strategy $R_{i,s}$, $1 \leq s \leq S$ by a profit-indicator $p_{i,s}$ which is updated at each time step $t$ by

$$
p_{i,s}(t+1) = p_{i,s}(t) - \frac{b}{n} R^{\mu(t)}_{i,s} \sum_j \sigma_j(t).
$$

Note that at time $t$, all strategies are updated for each agent. Likewise note that the above is an evaluation scheme of strategies, and the strategies $R$ are coupled to the actual decision $\sigma_i(t)$ (since $\sigma_i(t)$ appears in the
Additionally, these hypothetical decisions are being tracked in time, even though some aren’t actually made. At time $t$, each agent $i$ now chooses strategy $s_i(t)$ which has the best cumulative performance $p_{i,s}(t)$ up to that time.

Given the external information $\mu(t)$, the dynamics of the minority game are given by

$$p_{i,s}(t + 1) = p_{i,s}(t) - \frac{b}{n} R_{i,s}^{\mu(t)} A(t),$$

$$A(t) = \sum_j R_{j,s}^{\mu(t)},$$

$$s_i(t) = \arg\max_{s \in \{1, \ldots, S\}} p_{i,s}(t).$$

Some interesting observations about the above approach need be made. Firstly, a phase transition occurs in the above inductive model even though the model is a totally frustrated one. The fact that something stochastic is what introduces the phase transition makes sense since this is what happens in the setting of spin glasses and replica symmetry breaking (c.f. [21, 35, 11]). It has been shown in [12, 45, 16] that the minority game achieves more coordination (i.e., less frustration) when the payoff functions are localized in space (short-ranged interactions). If the payoffs only depend on the difference between the number of agents buying and selling (which is global and long-ranged in nature), then the inductive reasoning model appears to retain the same phase properties independent of whether the payoff is some power or an exponential of that difference [31, 50]. Speculatively, it seems that the global nature of public information can outweigh the interactions among agents, just as a global magnetic field can alter the susceptibility/volatility in a fully frustrated model. However, there are some fundamental economical differences between long-range and short-ranged interactions, which are made lucid in a supply-demand model. In [12] frustrated domained phases and frustrated striped phases occur for short-ranged models. Such phases have also been shown in standard/Gibbsian Ising models (cf. [13]). The economical differences were described in Section 3 as local versus global inverse demand and/or availability of goods. The physical differences between such interactions are significant. As will be shown below, the Gibbsian approach to the minority game results
in a Cournot oligopoly. The Gibbsian approach is thus a supply-demand approach to the market where agents arbitrage all of the information about the game itself. Supply-demand analysis of markets can also be found in [17, 57]. This motivates us to study the minority game in a different light than the inductive approach above and to see what properties appear in the Gibbsian supply-demand model.

Now we will introduce the Gibbs model of the minority based on statistical observation of deductive reasoning and show how this model distinguishes local and global demand. The Gibbs approach is not inductive: only the values of the agents’ decisions are considered. Which inductive strategy an agent may be using is irrelevant. In other words, we do not distinguish inductive strategies $R_i^s$ that an agent may be considering, but only look at her final decision $\sigma_i$ to buy or sell. The supply and demand of the market is the primary influence on such decisions, and these decisions are offset by the temperature of the system (or, in the stochastic model, the Brownian motion).

In the simplest Gibbs model, there is no phase transition, but the infinite-volume volatility (c.f. Appendix B for the continuum version) does display nonrandom behavior at finite temperature. There are phase transitions in the Gibbs model if local interactions among agents are added which represent greater competition among local firms. This will be pursued below.

Notice that the utility functions in (35) can be deduced in the sense of (2) from the potential

$$V(\sigma) = \frac{-b}{n} \sum_{i,j} \sigma_i \sigma_j,$$

where $b > 0$ and there are $n$ agents. The agents can be pictured to lie on integer points of some lattice, but dimensionality of the lattice is irrelevant since all agents interact. If short-range perturbations are added, the dimensionality of the lattice is then relevant. In any case, the potential function $V$ can have a maximum value of zero when equal numbers of agents independently play pure strategies $\sigma = 1$ and $\sigma = -1$, and the remaining agents play mixed strategies of $\sigma = 1$ half the time and $\sigma = -1$ the other half. Thus it is seen that an infinite number of Nash equilibria will occur in the infinite agent limit. In the
basic model presented here, the volatility is differentiable in the global field (i.e., no phase transition; see below). However, we will momentarily digress from the basic model in (38) and look at variations in an attempt to determine what may cause a phase transition.

Consider this new model (in (38) below) to lie in two dimensional space, and the addition of nearest neighbor ferromagnetic/aligning interactions. These local aligning interactions correspond to the (local) inverse demand for an agent

\[ p_i(\sigma) = \frac{-b}{n} \sum_j \sigma_j + \delta \sum_{j:|j-i|=1} \sigma_j, \quad (39) \]

where \( b > 0 \) and \( \delta > 0 \). When \( n \) is large, the local aligning interactions having coefficient \( \delta \) correspond to the \( i \)th agent’s inverse demand function increasing in response to local supply increase (i.e. selling, or the \( \sigma_j \) changing from +1 to −1 for \( |j-i|=1 \)). On the surface, this seems contrary to usual supply and demand, since inverse demand should be a decreasing function of supply variables \( \sigma_j \). ¹⁷ Mathematically, these interactions give more probability weight in the Gibbs measure to configurations with more alignments between local agents. This could be interpreted as a reward when nearest agents to do the same thing (i.e., align: all buy or all sell). It could be a purely psychological reward for “following the herd”, and not part of the monetary economic demand function, since utility or payoff functions need not be based on monetary payoff alone. It could also be a form of monetary influence where agents are willing to pay other agents to go along with their ideas. Since an agent only has a relatively small amount of money, they would only be able to payoff several agents. However, it is important to note that the first term of (39) may penalize the agent for alignment. Ultimately, whether or not an agent benefits from aligning depends on the phase of the system.

A potential for the model with payoffs in (39) is

\[ V(\sigma) = \frac{-b}{n} \sum_{i,j} \sigma_i \sigma_j + \delta \sum_{\langle i,j \rangle} \sigma_i \sigma_j, \quad (40) \]

¹⁷One interpretation in Section 3 is that such aligning terms are due to heightened local competition. Aligning terms result from agents subtracting the utility/payoff of nearest-neighbor agents from their own utility functions.
where \( b > 0, \delta > 0, i, j \in \mathbb{Z}^2 \), and the last sum is over nearest neighbors \(|i - j| = 1\). It has been speculated that the model in (40) has a transition as \( T = 1/\beta \to 0 \) from a fully frustrated state to a ferromagnetic, or fully aligned, state provided \( b < 4\delta \) [13]. If \( b > 4\delta \) there would likely be no transition and only full frustration as with (38) [13]. Completely aligned states should occur in some cases, and there should not always be only fully frustrated states.

In the case of overhyped introductory price offerings, essentially everyone is in a frenzy to buy and we would see the configuration of \( \sigma_i = -1 \) for all \( i \). If news got out that a company lost all of its worth, everyone would sell and we would see the configuration of \( \sigma_i = +1 \) for all \( i \). The aligning interactions are the only way to support such states without the addition of a field term \((a - c) \sum \sigma_i\), as the model in (38) has no phase transition (cf. Appendix B). The addition of such a ‘field’ term, which has demand and cost components, will support such states in the absence of a phase transition. The demand/cost component should be able to support such states, since such extreme market reactions result in pricing adjustments (changes in \( a \)). However, it was shown in Section 3 that the aligning terms can be interpreted as increased local competition. Such effects can become large in such a frenzied environment, and large alignments may occur no matter how small the demand/cost term \( a - c \) may be if the temperature is low enough (i.e., agents are not deviating much from “rational” behavior).

The model in (40) is similar to the models studied and summarized in [40, 14, 43]. The salient difference is that [40, 14, 43] study a long-range ‘Coulomb’ \((w = 1)\) or ‘dipole’ \((w = 3)\) on the two-dimensional square lattice

\[
V(\sigma) = -b \sum_{i,j} \frac{\sigma_i \sigma_j}{|i - j|^w} + \delta \sum_{\langle i,j \rangle} \sigma_i \sigma_j,
\]

(41)

where the \( i, j \in \mathbb{Z}^2 \) are two-component vectors with integer coordinates. These models are very rich, and interesting in an economic sense: the local demand functions should depend more strongly on local agents, and not depend significantly on distant agents. This suggests that output of goods local to an agent has more of an affect on that agent than goods that are distant from the agent, i.e., that local inverse demand...
(cf. Section 3) depends more on local supply. The model in (40) assumes that local inverse demand is identical for each agent, and that distant goods are equally accessible to an agent as local goods. There is a fundamental difference between these interactions. An important difference in two dimensions between (40) above and models with falloff potentials where \( n \) is replaced with \( |i - j|^w \), \( w = 1, 3 \), is that the latter models can have a phase transition to an antiferromagnetic phase at low temperatures and the former model has no such phase transition and only totally frustrated ground states. Antiferromagnetic phases correspond to a checkerboard of +1’s and −1’s in the plane, which is ordered behavior of agents. The agents with potential (40) have no such ordered behavior: +1’s and −1’s are seen equally but in a random unordered fashion, which reflects that supply is equally accessible to everyone.

There are four types of phases in the dipolar model (cf. [14] for details and references). The first two occur below a critical temperature \( T_c(\Delta) \) that depends on \( \Delta = \delta/b \). When \( \Delta \) is smaller than \( \Delta_a \approx 0.425 \), the ground state is the antiferromagnetic one, consisting of a checkerboard of +1 and −1 values of the \( \sigma \). When \( \Delta > \Delta_a \), the transition is from the antiferromagnetic state to a state consisting of antialigned stripes of width one, representing large areas of buyers and large areas of sellers that persist in some direction. As \( \Delta \) gets larger, the stripes grow in width. Stripes of widths two, three, and four appear at \( \Delta_k \approx 1.26, 2.2, 2.8 \), respectively.

The other two phases occur when \( T \geq T_c(\Delta) \). There is a transition to a disordered tetragonal phase above and near the \( T_c(\Delta) \), and this phase is not paramagnetic. There are extended ferromagnetic domains characterized by predominantly square corners, and a typical configuration looks like a maze of +1 trails and −1 walls. For larger temperatures, the transition is to a paramagnetic phase. Similar phase behavior occurs for the \( w = 1 \) Coloumb model in (41) [43].

The antiferromagnetic phase is one with buyers and sellers in a checkerboard pattern. This happens when the demand \( p(Q) \) is mostly due to nearest-neighbor oligopolistic competition; i.e., the terms
\[-b \sum_{i:|i-k|=1} q_k q_i\] dominate agent \(k\)'s demand function. When there are stripes there are large areas persisting in some direction that are buying and other such areas that are selling. In this case, agent \(k\) has localized oligopolistic competition in one direction and heightened local competition in the other direction.

As the stripes widen, there is heightened local competition within the stripes, and a localized oligopolistic competition among the groups of agents in the stripes. In the tetragonal phase, there are large unordered areas of buyers and sellers that look like a maze. In the paramagnetic phase, buyers and sellers tend to appear at random, and this corresponds to the standard Cournot model of nonlocalized oligopolistic competition.

It seems intuitive that (40) would not display stripes, but rather be fully frustrated or completely aligned; that is, if supply is globally accessible and local prices are essentially the same for all agents (such as a homogeneous market with no trade barriers and uniform distribution of goods) then there should not be large clumps of buyers and sellers. On the other hand, if there are no local interactions as in (38), then there should only be antiferromagnetic states or fully frustrated states with high probability, and no large clumps of buyers or sellers.

The stochastic nature of public information in the inductive model does induce a phase transition. It would be interesting to determine if the deductive model presented here with a random field component, which could be represented by random marginal cost fluctuations (cf. Section 3), will yield a phase transition. Such random costs could represent the fees, which vary from agent to agent, charged to each agent per buy/sell. In [51], the addition of demand into a model of stock trade is analyzed by introducing an effective field as mentioned above.

Evidence is found in [50] that the dynamics of the inductive minority game is intrinsic to resource allocation. The view of the minority game as a potential game makes clear why this is the case, in the sense that all potential games are isomorphic to congestion problems [47], and the potential for the minority game is a specific, discrete case of a supply-and-demand potential (c.f. Section 3).
5. Conclusion

We have seen that potential games (with nice potentials), when coupled with deviations-from-rationality, result in models for which equilibrium values of all relevant (macroscopic) quantities such as output per agent, payoff per agent, etc., are determined by averaging over a Gibbs measure with the given potential at inverse temperature $\beta$. The introduction of temperature in economics simply corresponds to the assumption that players deviate from the purely rational behavior of producing output in the direction of maximum increasing payoff.

A very nice feature of the Gibbs approach is that it is accessible and demonstrates different patterns of behavior among agents for different types of distribution of goods. This is desirable when modeling trade barriers, shipping costs, and real-life models such as restaurants, where demand is localized. It can also be used in conjunction with renormalization techniques, which could model large-scale behavior of ‘agglomerated’ agents, analogous to block spins for physical systems.

It would also be of interest to pursue more depth insofar as the economic implications of different types of phases for the different models presented here. Since the author is not an economist, such an endeavor will be left to the experts.

Acknowledgments. I wish to thank Alexander Chorin for exposing me to fascinating ideas, which ultimately led to this paper.
Here we will show the derivation of a vector Fokker-Planck equation for the joint distribution given the Langevin dynamics in [1]. This proof is just a slight modification of the proof in [1], and rigorous grounding for reflecting Brownian motion with a drift can be found in [23, 60, 61, 62]. We only consider a finite number of agents $n < \infty$.

In a potential game, the Itô equation for dynamics is $d\vec{x} = \vec{\nabla}V dt + \sigma d\vec{w}(t)$ as in (4). For a small change in time $\Delta t$, the dynamics can be written

$$\Delta \vec{x}(t) \equiv \vec{x}(t + \Delta t) - \vec{x}(t) = \vec{\nabla}V \Delta t + \sigma \Delta \vec{w}(t) + \vec{o}(\Delta t),$$

(42)

with $\sigma \Delta \vec{w}(t)$ a normal random variable of mean zero and variance $\sigma^2 \Delta t$, and $\vec{o}(\Delta t)$ is the usual vector ‘little order’ notation. Technically, there are also boundary terms that should be included in (42). However, the boundary terms will have no effect on any (finite-player) computations in this paper since only averages of quantities with respect to the equilibrium measure are used and the boundary has Lebesgue measure zero.  

The configuration of decisions $\vec{x}(t)$ at time $t$ is hence a random variable with time-dependent joint density $f(\vec{x}, t)$. Let $h(\vec{x}) : \Omega \rightarrow ( -\infty, \infty)$ be an arbitrary twice differentiable function such that $h$ and $\vec{\nabla}h$ vanish on the boundary $\partial \Omega$ of decision space $\Omega$. Note $h$ does not explicitly depend on time. Then the expected value of $h(\vec{x})$ (over phase space) at time $t + \Delta t$ is

$$E[h(\vec{x}(t + \Delta t))] = \int_\Omega h(\vec{x})f(\vec{x}, t + \Delta t)d\vec{x},$$

(43)

$^{18}\vec{v}(\Delta t)$ is $\vec{o}(\Delta t)$ if $\lim_{\Delta t \to 0} v_i(\Delta t)/(\Delta t) = 0$ for each component $v_i$ of $\vec{v}$.  

$^{19}$Since the time evolution operator $L^*$ appearing below is (hypo)elliptic, any stationary solution will be smooth and absolutely continuous with respect to the Lebesgue measure on $\Omega$.  

36
where $d\vec{x}$ is the product measure $dx_1dx_2\cdots dx_n$ on $\Omega$. Note above that $\vec{x}(t+\Delta t)$ on the left side represents the random variable over which the expected value $E$ is to be taken, whereas the $\vec{x}$'s on the right side are the points in $\Omega$. Equation (42) can be used to express (43) in its dual form:

$$E[h(\vec{x}(t+\Delta t))] = E[h(\vec{x}(t) + \vec{∇}V(\vec{x}(t))\Delta t + \sigma\Delta w(t)) + \vec{o}(\Delta t)].$$  \hspace{1cm} (44)

The expression on the right hand side of (43) will be subtracted from the Taylor expansion of the right side of (44) to yield the Fokker-Planck equation. We will proceed as follows.

Let $g(\vec{y})$ be the (joint) density of $\sigma\Delta w(t)$, which is an $n$-dimensional normal density with mean zero and variance $\sigma^2\Delta t$. The left side of (44) is in terms of the random variables $\vec{x}(t + \Delta t)$, and the right side is in terms of the variables $\vec{x}(t)$ and $\vec{y}$ with respective densities $f(\vec{x}, t)$ and $g(\vec{y})$. Accordingly, the right side of (44) can be written as an integral over these densities:

$$E[h(\vec{x}(t+\Delta t))] = \int_{\mathbb{R}^n} \int_{\Omega} h(\vec{x}(t) + \vec{∇}V(\vec{x}(t))\Delta t + \sigma\vec{y}) f(\vec{x}, t)g(\vec{y})d\vec{x}d\vec{y},$$  \hspace{1cm} (45)

where $\mathbb{R} = (-\infty, \infty)$.

The Taylor expansion of the right side of (45) yields

$$\int_{\mathbb{R}^n} \int_{\Omega} \left\{ h(\vec{x}(t)) + \vec{∇}h(\vec{x}(t)) \cdot [\vec{∇}V(\vec{x}(t))\Delta t + \vec{y}] + \frac{1}{2} [\vec{∇}V(\vec{x}(t))\Delta t + \vec{y}]^T \cdot D^2 h(\vec{x}(t)) \cdot [\vec{∇}V(\vec{x}(t))\Delta t + \vec{y}] + \vec{o}(\Delta t) \right\} f(\vec{x}, t)g(\vec{w})d\vec{x}d\vec{y},$$  \hspace{1cm} (46)

where $D^2 h$ is the second-derivative matrix for $h$ (i.e., the $ij$ entry is $\partial^2 h/\partial x_i\partial x_j$) and the transpose of a row vector $\vec{v}$ is the column vector $\vec{v}^T$.

---

\textsuperscript{20}Rigorously, the map $\vec{x}(t) \rightarrow \vec{x}(t+\Delta t)$ generates a differentiable global (stochastic) semiflow \cite{46} on decision space $\Omega$ for nice potentials, and the global semiflow has a semigroup generator which will be shown below. The dual of this generator advances $f$ in time.

\textsuperscript{21}For simplicity, we use the formal notation of differential stochastic calculus. In (43), the dual of the semigroup generator is applied to $f$. 

37
Integrating (46) over the $\vec{y}$ eliminates terms linear in $y_i$ as well as the mixed second-order terms since the $y_i$ have mean zero and are independent. The expected value of $w_i^2$ is $\sigma^2 \Delta t$, hence (46) reduces to

$$
\begin{align*}
\int_{\Omega} h(\vec{x}(t))f(\vec{x}, t)dx + \Delta t \int_{\Omega} \vec{\nabla} h(\vec{x}(t)) \cdot \vec{\nabla} V(\vec{x}(t))f(\vec{x}, t)d\vec{x} \\
+ \Delta t \frac{\sigma^2}{2} \int_{\Omega} \nabla^2 h(\vec{x}(t))f(\vec{x}, t)d\vec{x} + o(\Delta t),
\end{align*}
$$

(47)

where $o(\Delta t)$ is the one-component version of $\vec{o}(\Delta t)$ and $\nabla^2$ is the Laplacian. Thus the generator for the Langevin dynamics $\vec{x}(t + t_0) = \mathcal{L}^t \vec{x}(t_0)$ is $\mathbb{L} = (\vec{\nabla} V) \cdot \vec{\nabla} + (\sigma^2/2)\nabla^2$, where $\mathbb{L}$ acts on twice-differentiable functions on $\Omega$ that vanish on the boundary. It is easy to show $\mathbb{L}$ is closed and the domain of its adjoint is the Sobolev space $H^2(\Omega)$ for a well-behaved potential $V$. We view its adjoint $\mathbb{L}^*$ as a densely defined unbounded operator in $L^2(\Omega, d\vec{x})$. The idea is apparent from the following.

Using Green’s identities, the integrals containing the terms $\vec{\nabla} h$ and $\nabla^2 h$ can be integrated by parts, and the boundary integrals vanish on the boundary $\partial\Omega$ (since $h$ and $\vec{\nabla} h$ do) leaving a new expression for (47):

$$
\begin{align*}
\int_{\Omega} h(\vec{x}(t))f(\vec{x}, t)dx - \Delta t \int_{\Omega} h(\vec{x}(t))\vec{\nabla} \cdot [\vec{\nabla} V(\vec{x}(t))f(\vec{x}, t)]d\vec{x} \\
+ \Delta t \frac{\sigma^2}{2} \int_{\Omega} h(\vec{x}(t))\nabla^2 f(\vec{x}, t)d\vec{x} + o(\Delta t).
\end{align*}
$$

(48)

This shows that the adjoint of $\mathbb{L}$ operates as $\mathbb{L}^*(f) = -\vec{\nabla} \cdot (f \vec{\nabla} V) + (\sigma^2/2)\nabla^2 f$. Equations (43) and (48) are identical, hence subtracting them yields

$$
\int_{\Omega} h(\vec{x}(t))[f(\vec{x}, t + \Delta t) - f(\vec{x}, t)]dx = \Delta t \int_{\Omega} h(\vec{x}(t))[-\vec{\nabla} \cdot [\vec{\nabla} V(\vec{x}(t))f(\vec{x}, t)] + \frac{\sigma^2}{2}\nabla^2 f(\vec{x}, t)]d\vec{x} + o(\Delta t).
$$

(49)

Dividing (49) by $\Delta t$, taking the limit $\Delta t \to 0$ results in the Fokker-Planck equation (6) since the set of all such $h$’s described are a separating set for continuous probability densities on $\Omega$ (i.e., these $h$’s can weakly approach delta functions on $\Omega$).
Let $h(\vec{x})$ be an observable (i.e. function) on $\Omega$ that is differentiable, vanishes on $\partial\Omega$, and doesn’t depend explicitly on time. For a stationary state $f$, the average of $h(\vec{x})$ is constant in time:

$$0 = \frac{\partial}{\partial t} \int_{\Omega} h(\vec{x}) f(\vec{x}, t) d\vec{x}$$

$$= \int_{\Omega} h(\vec{x}) \vec{\nabla} \cdot \left\{ -[\vec{\nabla} V(\vec{x}(t))] f(\vec{x}, t) + \frac{\sigma^2}{2} \vec{\nabla} f(\vec{x}, t) \right\}$$

$$= - \int_{\Omega} \vec{\nabla} h(\vec{x}) \cdot \left\{ -[\vec{\nabla} V(\vec{x}(t))] f(\vec{x}, t) + \frac{\sigma^2}{2} \vec{\nabla} f(\vec{x}, t) \right\}. \quad (50)$$

Since $h$ was arbitrary and $\vec{\nabla} h$ can be made to approach delta functions, for a stationary state

$$- [\vec{\nabla} V(\vec{x}(t))] f(\vec{x}, t) + \frac{\sigma^2}{2} \vec{\nabla} f(\vec{x}, t) = 0. \quad (51)$$

We then see that the Gibbs state in (7) is the unique solution to (51), and is the equilibrium state for the potential game. The negative of the Helmholtz free energy is in fact a Liapunov function for the dynamics and it can be used to show (see [1]) that the unique finite-agent solution equation (7) of equation (51) is attained in the long run.
Appendix B. Solution of the Cournot Free Energy

The free energy for the Cournot oligopoly and collusion is obtained from the partition function in equation (18)

\[ Z_n(\tilde{b}) = \int \exp \left[ -\beta \frac{b}{n} \sum_{j,k=1}^{n} \tilde{q}_j \tilde{q}_k - \beta \frac{\tilde{b}}{n} \sum_{j=1}^{n} \tilde{q}_j^2 + \beta(a-c) \sum_{j=1}^{n} \tilde{q}_j \right] \prod_{j=1}^{n} d\tilde{q}_j. \] (52)

The limit of the free energy

\[ F_n(\tilde{b}) = \frac{1}{\beta n} \ln \left( Z_n(\tilde{b}) \right) \] (53)

will be shown below. First note that the limit does not depend on the value of \( \tilde{b} \), since

\[ -\frac{\tilde{b}q^2}{n} + F_n(\tilde{b}) \leq -\frac{\tilde{b}q^2}{n} + F_n, \] (54)

where \( F_n \equiv F_n(0) \). It then suffices to set \( \tilde{b} \) to zero in equation (52), which will be done below to simplify a limit. For further manipulation, changing variables to \( q = \tilde{q} - \gamma, \ \gamma \equiv (\bar{q} + q)/2, \ h \equiv a - c \), results in

\[ Z_n = \exp \left[ -\beta b\gamma^2 n - \beta b\gamma^2 + \beta hv_n + \beta \frac{n}{b} \left( \gamma b + \gamma \frac{\tilde{b}n}{2} - \frac{h}{2} \right)^2 \right] \]

\[ \times \int_{[-Q/2,Q/2]^n} \exp \left[ -\beta \left( \sqrt{\frac{b}{n}} \sum q_j + \sqrt{\frac{n}{b}} \left( b\gamma + \bar{q} - \frac{h}{2} \right) \right)^2 - \beta \frac{\tilde{b}}{n} \sum q_j^2 \right] \prod_{j=1}^{n} dq_j, \] (55)

where \( Q \equiv \bar{q} - q \).

The solution can be found using a saddle point method, and the key is to use the identity

\[ e^{-\beta p^2} = \frac{1}{\sqrt{\pi \sqrt{4\beta}}} \int_{-\infty}^{\infty} \exp \left( -\frac{1}{4\beta} t^2 + ipt \right) dt \] (56)

as with the simplest case in [28]. Using the above in (55) and setting \( \eta \equiv b\gamma + \bar{b}/n - h/2 \) results in

\[ Z_n = \frac{1}{\sqrt{\pi \sqrt{4\beta}}} \exp \left[ \frac{3h^2 n}{4b} + b\gamma \left( \frac{b\gamma}{bn} + \gamma - \frac{h}{b} \right) \right] \int_{-\infty}^{\infty} \exp \left[ -\frac{1}{4\beta} t^2 + i \sqrt{\frac{n}{b}} \eta t \right] \]

\[ \times \left\{ \int_{-Q/2}^{Q/2} \exp \left[ -\beta \frac{\tilde{b}q^2}{n} \right] \exp \left[ i \sqrt{\frac{b}{n}} qt \right] dq \right\} \prod_{j=1}^{n} dq_j, \] (57)
where the order of integration was changed via Fubini’s theorem. Consider part of the integrand above

\[ g_n \left( \sqrt[Q/2]{\frac{b}{n}} t \right) = \frac{1}{Q} \int_{-Q/2}^{Q/2} \exp \left[ -\beta \frac{b}{n} q^2 \right] \exp \left[ iq \sqrt[Q/2]{\frac{b}{n}} t \right] dq = \text{sinc} \left( \frac{Q}{2} \sqrt[Q/2]{\frac{b}{n}} t \right) , \]  

(58)

where sinc \((x) \equiv \sin(x)/x \) (sinc \((0) \equiv 1\), \(\tilde{b}\) was explicitly set to zero, and a normalizing factor was added so that \(g_l(0) = 1\). Changing variables to \(\hat{t} = t/\sqrt{n}\), the partition function can then be written

\[ Z_n = \exp \left[ -\beta \gamma (b \gamma - h) n \right] \frac{Q^n \sqrt{n}}{\sqrt{\pi} \sqrt{4\beta}} \times \int_{-\infty}^{\infty} \left\{ \exp \left[ -\frac{1}{4\beta} \left( \hat{t} - i \frac{2\beta}{\sqrt{b}} \eta \right)^2 \right] \right\} \frac{Q}{2} \sqrt{\frac{b}{n}} \hat{t} \}^n \right\} d\hat{t}. \]  

(59)

Now a basic fact is needed to determine the limit of the free energy.

**Lemma 6.** Let \(f(x)\) be a bounded, continuous, real-valued, integrable function on the real line \(\mathbb{R}\) and let \(G\) be an open set. Suppose there is a point \(x_0 \in G\) for which \(|f(x)| < f(x_0)\) for all \(x \neq x_0\) and \(\limsup |f(x)| < f(x_0)\) for all \(x\) outside of some neighborhood of \(x_0\) contained in \(G\). Then

\[ \lim_{m \to \infty} \left\{ \int_G |f(x)|^{m+k} \, dx \right\}^{1/m} = f(x_0) \]  

(60)

for any fixed integer \(k\). Furthermore, for a function \(g(x)\) that is continuous at \(x_0\) with \(gf^k \in L^\infty\),

\[ \lim_{m \to \infty} \frac{\int_{-\infty}^{\infty} g(x) |f(x)|^m \, dx}{\int_{-\infty}^{\infty} |f(x)|^m \, dx} = g(x_0) . \]  

(61)

**Proof.** First, by factoring \(\|f\|_\infty\) out of the integral in (60), we may assume \(f(x_0) = 1\) by considering the function \(f/\|f\|_\infty\). Choose a number \(\epsilon_0 > 0\) so that \(\limsup |f(x)| < 1 - 2\epsilon_0\) for all \(x\) outside of a neighborhood \(\mathcal{N} \subset G\) of \(x_0\) and \(f > 0\) on \(\mathcal{N}\). Let \(S_{1-\epsilon_0} = \{x \in G | f(x) \geq 1 - \epsilon_0 \}\), and \(I_m = (\int_G |f(x)|^{m+k} \, dx)^{1/m}\). Since \(I_m \leq f(x_0)^{(m+k-2)/m} (\int_G f^2(x) \, dx)^{1/m}\) for large \(m\), \(\limsup_{m \to \infty} I_m \leq f(x_0)\). The inequality

\[ (I_m)^m \geq (1 - \epsilon)^{m+k-2} \int_{S_{1-\epsilon}} f^2(x) \, dx - (1 - 2\epsilon_0)^{m+k-2} \int_{G-\mathcal{N}} f^2(x) \, dx \]  

(62)
holds for all $\epsilon \leq \epsilon_0$. Upon factoring out $(1 - \epsilon)^{m+k-2}$, it is seen that $\liminf_{m \to \infty} I_m \geq f(x_0)$. To prove (61), the following is needed:

$$\lim_{m \to \infty} \left| \frac{\int_{S_{1-\epsilon}} g(x)[f(x)]^m \, dx}{\int G[f(x)]^m \, dx} \right| \leq \|gf^k\|_{\infty} \lim_{m \to \infty} \frac{\int_{S_{1-\epsilon}} |f(x)|^{m-k} \, dx}{\int G[f(x)]^m \, dx} = 0,$$

where the last equality follows from the root test for convergence since the hypothesis implies the limit of the ratio on the right side of (63) to the power $1/m$ is less than one. With this, (61) reduces to

$$\int_{S_{1-\epsilon}} g(x)[f(x)]^m \, dx \int G[f(x)]^m \, dx .$$

(64)

By the continuity of $g$ and (63) again with $G = S_{1-\epsilon}$, it is seen that (61) holds. \square

To apply Lemma 6 to the partition function in (59), the integration path along the real line must be deformed in the complex plane to a path on which the integrand is real-valued. As such, consider the function $f(z) = \exp[-k(z + i\eta_0)^2] \text{sinc}(z)$, where $\eta_0 = -\beta Q \eta$ and $1/k = \beta b Q^2$ (changing variables $t = Q\sqrt{b} t/2$ in (59); note $\eta_0$ is increasing in $h$).

Let $z = x + iy$, and $f(z) = R(x, y) + iI(x, y)$, where $x, y, R, I$ are real-valued. Then we are interested in the paths $(x(s), y(s))$ in the complex plane $\mathbb{C}$ on which $I = 0$. Since $f$ is holomorphic and not identically zero, the gradient of $I$, $\nabla I$, can only vanish on a closed set of isolated points in $\mathbb{C}$. Thus $I^{-1}(0)$ consists of various differentiable paths in $\mathbb{C}$. The imaginary part can be expanded

$$I(x, y) = \frac{e^{-kx^2 + k(y + \eta_0)^2}}{x^2 + y^2} \left\{ \sin(-2kx(y + \eta_0))[x \sin x \cosh y + y \cos x \sinh y] \right\} \right.$$  

$$+ \cos(-2kx(y + \eta_0))[-y \sin x \cosh y + x \cos x \sinh y].$$

(65)

**Lemma 7.** There is a piecewise differentiable path $z(s)$ such that $I(z(s)) = 0$. In addition, $z(s)$ can be written $(x, y_z(x))$ for small and large $|x|$, with $\lim_{x \to \pm \infty} y_z(x) = C_1$ and $\lim_{x \to 0} y_z(x) = C_2$ for constants $C_1$ and $C_2$.

**Proof.** Consider fundamental domains in the $z$-plane of $w = \text{sinc}(z)$. The fundamental domains $D_j, D'_j$ shown in figure 1 are then separated by curves satisfying $y = 0$ and $\tan x/x = \tanh y/y$, with $x \neq 0$. If...
$x > 0$, the implicit function theorem implies the latter curves can be written $x = c_j(y)$ with $c_j$ differentiable and $j\pi < c_j(y) < (2j+1)\pi/2$, $j = 1, 2, \ldots$. Let $c_0(y) = 0$ and for $x < 0$, the curves are reflected: $c_{-j} = -c_j$.

The branch cuts in the $w$-planes are then the images of $c_{2j+1}$. The logarithm $\ln(\text{sinc } z)$ will now map two interior points in the $z$ plane to a complex number since $\text{sinc}(-z) = \text{sinc}(z)$. Branch cuts at $|x| > 0$ are added in the $z$-plane on the $x$-axis to avoid discontinuities in $\alpha$. The fundamental domains $D_j$ lie below the $x$-axis between the curves $c_{2j-1}$ and $c_{2j+1}$, whereas the $D'_j$ lie above the $x$-axis between $c_{-2j-1}$ and $c_{-2j+1}$.

The shaded regions of the $D_j$ and $D'_j$ in the figure below correspond to the lower half of the $w$-planes.

Let $\alpha = \alpha(x, y)$ be the angle of $\text{sinc}(z)$ (i.e., the imaginary part of $\ln(\text{sinc } z)$). Figure 1 shows that in the lower half of the $z$-plane, $\alpha$ increases in $x$ and is of order $x$.

**Figure 1.** $\ln(\text{sinc } z)$ values
Differentiating the identity for $\tan \alpha$,

\[
\frac{\partial \alpha}{\partial x} = \frac{2y \left( \sin^2 x + \sinh^2 y \right) - (x^2 + y^2) \sinh 2y}{2 (x^2 + y^2) \left( \sin^2 x + \sinh^2 y \right)} \tag{66}
\]

\[
\frac{\partial \alpha}{\partial y} = \frac{-2x \left( \sin^2 x + \sinh^2 y \right) + (x^2 + y^2) \sin 2x}{2 (x^2 + y^2) \left( \sin^2 x + \sinh^2 y \right)} \tag{67}
\]

and it is seen that $\frac{\partial \alpha}{\partial x} > 0$ ($< 0$) when $y < 0$ ($> 0$).

The part in braces in (65) can be written

\[
\sqrt{x^2 + y^2} \sqrt{\sin^2 x + \sinh^2 y} \sin(-2kx(y + \eta_0) + \alpha), \tag{68}
\]

and this is zero if and only if $\mathcal{I}$ is zero. For the case $\eta_0 = 0$, the integral in (59) can be evaluated using Lemma 6, with the maximum of the integrand occurring at zero. In the case $\eta_0 \neq 0$, the paths in $\mathbb{C}$ on which $f(z)$ is real-valued is precisely where

\[
-2kx(y + \eta_0) + \alpha = m\pi, \tag{69}
\]

where $m$ is an arbitrary integer.

Since $y + \eta_0 = \alpha/(2kx) - m\pi/(2kx)$ and $\alpha$ is of order $x$, it is evident that $|y| \to \infty$ as $x \to 0$ on such paths unless $m = 0$. This is not surprising, since large $|z|$ behavior of $f$ is dominated by the $z^2$ term in the exponential (thus giving hyperbolae-type curves). We will single out the $m = 0$ curve $z(s) = (x(s), y(s))$ satisfying

\[
y + \eta_0 = \alpha(x, y)/(2kx) \tag{70}
\]

for reevaluating the integral in (59). Since $\alpha$ is of order $x$, the $y$-component of $z(s)$, $y(s)$, is bounded and has finite limits as $x \to \pm \infty$. The location of the curve depends on $\eta_0$. To see this, note that $\alpha(x, y) < Dx$ for a constant $D$ with $|D| \leq 1$, and the sign of $D$ is negative in the upper-half and positive in the lower-half of the $z$-plane. If $\eta_0 > 0$ and the curve $z(s)$ were in the upper-half of the $z$-plane, then $y = \alpha/(2kx) - \eta_0 \leq D/(2k) - \eta_0 < 0$, which is a contradiction. Hence if $\eta_0 > 0$ ($< 0$), then the curve $z(s)$ is in the lower (upper) half of the $z$-plane.
The \(y\)-intercept of \(z(s)\) can be found using \(\lim_{x \to 0^+} \alpha = 0\) and \(\lim_{x \to 0} \sin(\alpha)/\alpha = 1\). Near \(x = 0\), \(z(s)\) can be written \(z = (x, y_z(x))\), from which

\[
y_z(0) + \eta_0 = \lim_{x \to 0} \frac{\alpha}{2kx} = \lim_{x \to 0} \frac{-y_z \sin x \cosh y_z + x \cos x \sinh y_z}{2kx \sqrt{x^2 + y_z^2} \sqrt{\sin^2 x \cosh^2 y_z + \cos^2 x \sinh^2 y_z}}
\]

\[= -\frac{y_z(0) \cosh y_z(0) + \sinh y_z(0)}{2ky_z(0) \sinh y_z(0)}. \tag{71}\]

The solutions of the above equation in \(y_z(0)\) are the same as the solutions in \(y\) to the equation \(y/[1 - 2k(y + \eta_0)y] = \tanh(y)\), except for an extraneous root of \(y = 0\) in the latter (since \(\eta_0 \neq 0\)). The solution for the \(y\)-intercept is unique, and this will be shown later. \(\square\)

With the above, the integral in (59) can be deformed onto the curve \(z(s)\). To apply Lemma 6, it is necessary to find the maximum of \(|f|\) on the full curve where \(I = 0\), and to also show it occurs at a single point \(z_m\) such that \(f(z_m) > 0\).

Equivalently, it will be easier to find the maximum of

\[|f|^2 = \exp \left[-2kx^2 + 2k(y + \eta_0)^2\right] \left(\sin^2 x \cosh^2 y + \cos^2 x \sinh^2 y\right) /(x^2 + y^2)\]

\[= \exp[-2x^2 + 2(y + \eta_0)^2] \left(\sin^2 x \cosh^2 y + \cos^2 x \sinh^2 y\right) / (x^2 + y^2) \tag{72}\]

on the full \(I = 0\) curve \(z(s) = (x(s), y(s))\). Since \(\lim_{s \to \pm \infty} f(z(s)) = \lim_{s \to \pm \infty} f(x, y_z(x)) = 0\), a maximum occurs and is greater than zero. On the curve near this maximum, say at \(s_m\), the argument of \(f\) is constant (either \(\text{Arg}(f) = 0\) or \(\text{Arg}(f) = \pi\)) hence \(\tan(\text{Arg}(f)) = I/R\) is constant. Since \(\tan(\text{Arg}[f(x(s), y(s))])' = 0\), the tangent vector \(\vec{v}(s)\) to the curve \((x(s), y(s))\) is orthogonal to \(\vec{V}(I/R)\) near \(s_m\).

Any maximum point of \(|f|^2\) on the curve \(z(s)\) must satisfy

\[0 = \frac{\partial}{\partial x} |f|^2 = \exp[-2x^2 + 2(y + \eta_0)^2] \left(\sin^2 x \cosh^2 y + \cos^2 x \sinh^2 y\right) / (x^2 + y^2)^2 \]

\[\times \left\{ -2x(2kx^2 + 2ky^2 + 1) \left(\sin^2 x \cosh^2 y + \cos^2 x \sinh^2 y\right) + (x^2 + y^2) \sin 2x \right\} \tag{73}\]
and
\[ 0 = \frac{\partial}{\partial y} |f|^2 = \frac{\exp[-2x^2 + 2(y + \eta_0)^2]}{(x^2 + y^2)^2} \]
\[ \times \left\{ (4k(y + \eta_0)(x^2 + y^2) - 2y) \left( \sin^2 x \cosh^2 y + \cos^2 x \sinh^2 y \right) + (x^2 + y^2) \sinh 2y \right\}. \]  
\[ (74) \]

**Lemma 8.** The conditions in (73) and (74) imply that the maximum of $|f|^2$ on the curve $z(s)$ occurs at $(0, y_z(0))$, the $y$-intercept of the curve $z(s)$.

**Proof.** Without loss of generality it can be assumed that $\eta_0 \geq 0$, since the integral in (59) is an even function of $\eta_0$.

For the case $\eta_0 = 0$, the curve $z(s)$ is the $x$-axis and $|f|^2(z(s)) = e^{-2kx^2} \text{sinc}^2 x$. Clearly $(0, 0)$ is a global maximum of $|f|^2$ on $z(s)$. Hereon, the case $\eta_0 > 0$ is considered.

We will consider the case $x \neq 0$, and $x = 0$ will be dealt with subsequently. Then (73) is equivalent to
\[ 1 > \text{sinc}2x = \frac{2kx^2 + 2ky^2 + 1}{x^2 + y^2} (\sin^2 x + \sinh^2 y) \geq 0. \]  
\[ (75) \]

The inequality $\text{sinc}2x \geq 0$ implies $x \in [-\pi/2, \pi/2]$ or $x \in \pm[m\pi, (m + 1)\pi/2]$ for positive integers $m$. In order for (75) to hold, $\sin^2 x + \sinh^2 y \leq \text{sinc}(2x)(x^2 + y^2)$, which is impossible for $|x| \leq \pi/2$. Any extreme points of $|f|^2$ for which $x \neq 0$ must therefore satisfy $|x| \geq \pi$.

From the above argument, maximum points of $|f|^2$ in the set $S_0 = \{(x, y) : |x| \leq \pi/2\}$ must satisfy $x = 0$. Any maximum point $(x, y) \notin S_0$ will then satisfy $|x| \geq \pi$. It is seen from (70) that $y + \eta_0 < 0$ when $x > 0$ and $y < 0$, which along with (74), implies that $|y| > (\pi^2 + y^2) \tanh |y|$ at an extreme point. That this is impossible shows the largest value of $|f|^2$ on the curve $z(s)$ will occur at $x = 0$.

It only remains to show the intersection of $z(s)$ with the $y$-axis is unique and is also a maximum point of $|f|^2$. Note that (73) is satisfied when $x = 0$. Also note that (74) reduces to the condition $[4k(y + \eta_0)y^2 - 2y] \sinh^2 y + y^2 \sinh 2y = 0$ As described by (71), $y = 0$ is an extraneous root since $\eta_0 > 0,$
and (74) is satisfied if and only if
\[
\frac{y}{\beta} = \frac{bQ^2}{2} \left( -\coth y + \frac{1}{y} \right) + Q \left( b\gamma - \frac{h}{2} \right) \equiv g(y). \tag{76}
\]

As was mentioned in Lemma 6, any solution \( y_0 \) must be negative since \( \eta_0 > 0 \). The function \( g(y) \) on the right side of (76) decreases from \( \frac{bQ^2}{2} + Q(b\gamma - h/2) \) to \( Q(b\gamma - h/2) < 0 \) as \( y \) increases from \(-\infty\) to zero. Therefore \( g(y) \) intersects \( h(y) = y/\beta \) at exactly one point \( y_0 < 0 \). This shows that there is a unique solution \( y_0 < 0 \) to (76). Consequently, the global maximum of \(|f|^2\) on \( z(s) \) occurs at \((0, y_z(0))\), the \( y \)-intercept of the curve \( z(s) \).

Combining the result of Lemma 8 with Lemma 6, it is seen that
\[
F(\beta, a, b, c, q, \bar{q}) = \lim_{n \to \infty} \frac{1}{\beta n} \ln(Z_{n, \beta, a, b, c, q, \bar{q}}) = -\gamma(b\gamma - h) + \frac{\ln Q}{\beta} + \frac{1}{\beta} \ln |f(0, y_z(0))|, \tag{77}
\]
and the unique global maximum of \(|f|\) at \((0, y_z(0))\) on the curve \( z(s) \) excludes any phase transition for this antiferromagnetic model.

Finally, notice that Lemma 8 shows that the only extreme point of \(|f|^2\) on the \( y \)-axis is at the \( y \)-intercept of the curve \( z(s) \). This extreme point must be a saddle point of the holomorphic function \( f(z) \), hence \((0, y_z(0))\) is a global minimum of \( v(y) = f(0, y) \). An explicit formula for the Cournot free energy can then be written
\[
F(\beta, a, b, c, q, \bar{q}) = -\frac{1}{4}(\bar{q} + q)[b(\bar{q} + q) - 2(a - c)] + \frac{\ln(\bar{q} - q)}{\beta}
\]
\[
+ \frac{1}{\beta} \min_{y \in (-\infty, \infty)} -\beta by^2 + \ln \left( \sinhc \left[ \beta b(\bar{q} - q)y + \beta \frac{\bar{q} - q}{2} \left(b(\bar{q} + q) - (a - c)\right) \right] \right), \tag{78}
\]
where \( y \) was translated and rescaled (this does not alter the result since \( y \) ranges over all real numbers) to get rid of square roots, and \( \sinhc(u) = \sinh(u)/u \) with \( \sinhc(0) = 1 \).

Now for a final note on the expected value of the variable \( q_i \). The minimum value in (78) occurs when the derivative of the smooth function within the minimum is zero, which is at \( y_m = y_z(0) \). Since the minimum is a global minimum, the second derivative with respect to \( y \) is nonzero. By the implicit function theorem,
the minimum point $y_m$ is locally a smooth function of $h = a - c$. As a result, the partition function in the form (77) is seen to be a smooth function of $h$.

The function $F_n(h)$ in (53) is convex in $h$ via Holder’s inequality, and as a result

$$\frac{F_n(h) - F_n(h - \delta)}{\delta} \leq F_n'(h) \leq \frac{F_n(h + \delta) - F_n(h)}{\delta}$$

(79)

where $\delta > 0$. Since $F(h)$ is a smooth function of $h$, taking the limit of (79) as $n \to \infty$ results in

$$F'(h) = \lim_{n \to \infty} F_n'(h).$$

Using (59)

$$F_n'(h) = \gamma - \eta/b - i\langle \hat{t} \rangle_n^\wedge/(2\beta\sqrt{b}),$$

(80)

where $\langle \cdot \rangle_n^\wedge$ is a (one-dimensional) Fourier transform of the Gibbs measure for $n$ agents, $\langle f \rangle_n = (\int f e^{\beta V})/Z_n$, which is generated by (52). The measure $\langle \cdot \rangle_n^\wedge$ is generated by the form of the partition function in (59). Taking the limit of (80) as $n \to \infty$,

$$F'(h) = h/(2b) + \lim_{n \to \infty} (2t/(Q\sqrt{b}))_n^\wedge/(2\beta\sqrt{b}).$$

(81)

The latter limit can be evaluated by deforming the integral in the complex plane as before (change $t$ to $z$), and using Lemma 6. The sequence $\langle \cdot \rangle_n^\wedge$ of measures converges to a ‘delta function’ or evaluation measure at $(0, y_m)$. Such measures are precisely the characters, meaning they are homomorphisms on the ‘algebra of observables’ and as such are extreme points. This also shows that there is no phase transition in this antiferromagnetic model. It is worthwhile to elaborate on such technicalities to show that the weak convergence of the Fourier transformed measures implies that the sequence of measures $\langle \cdot \rangle_n$ converges weakly. With Lemma 9, this implies the Gibbs measures $\langle \cdot \rangle_n$ converge weakly to the infinite-agent measure $\langle \cdot \rangle$.

Lemma 9. The weak convergence of the sequence $\langle \cdot \rangle_n^\wedge$ of measures \(^22\) implies the weak convergence of the sequence of Gibbs measures $\langle \cdot \rangle_n$.

\(^{22}\)This is the one-dimensional Fourier transform of the Gibbs measures $\langle \cdot \rangle_n$ in the variable $s_n \equiv (q_1 + \cdots + q_n)/\sqrt{n}$ that is generated by the partition function in (59)
Proof. Let $\mathfrak{A}_n$ be the algebra of observables for $n$ agents, which is simply the continuous functions $\mathcal{C}([q, q^n])$.

The algebra of observables (functions) for an infinite number of agents, $\mathfrak{A}_\infty$, is the inductive limit ($C^*$ algebra sense) of the finite-agent algebras $\mathfrak{A}_n$. As a result, the $\mathfrak{A}_n$ can be considered subalgebras of $\mathfrak{A}_\infty$ and any weak limit of finite-agent measures is defined on $\mathfrak{A}_\infty$.

Consider two distinct limit points $\langle \cdot \rangle, \langle \cdot \rangle' \in \mathfrak{A}_\infty$ which are limits of subsequences $\langle \cdot \rangle_{n_1}$ and $\langle \cdot \rangle_{n_2}$, respectively. There is a function $g \in \mathfrak{A}_\infty$ on which $\langle \cdot \rangle$ and $\langle \cdot \rangle'$ differ. By approximating $g$ closely enough with a function in some $\mathfrak{A}_{n_0}$ we may assume $g \in \mathfrak{A}_{n_0}$.

The integral $\langle g \rangle_{n_i}$ over the $q_j$, $1 \leq j \leq n_i$ can be manipulated into an integral over the variable $\hat{q}$ as was done with (59), upon which it becomes an integral $\langle G \rangle_{n_i}$, where $G = G(\hat{q})$ is a function independent of $n_i$. This shows $\langle g \rangle = \lim_{n_1} \langle G \rangle_{n_1}$ and $\langle g \rangle' = \lim_{n_2} \langle G \rangle_{n_2}$, which implies the assertion. $\square$

Remark. With $\vec{q} = (q_1, \ldots, q_n), g = g(\vec{q})$, note that (56) inserts the Fourier transform $\hat{g}$ (of the Gibbs measure) into the $\langle g \rangle_n$ integral, and (57) shows what the dual of the Fourier transform, $\hat{g}^*$ does to $g$. 23

The Fourier transform of the Gibbs measures need only converge on the subalgebra of functions generated by the $\hat{g}^* [\mathfrak{A}_n]$ in order for the sequence of Gibbs measures to converge.

The expected value $\langle q_i \rangle$ is then

$$F'(h) = \frac{h}{2b} + \frac{y_m(\beta, b, h)}{\beta Qb}, \quad (82)$$

From (76), we can see that

$$\lim_{\beta \to 0} F'(h) = \frac{h}{2b} + \left( \gamma - \frac{h}{2b} \right) = \gamma, \quad (83)$$

23In particular, $\hat{g}^*[\sqrt{bt}] = \int \exp(i\sqrt{bt}s_n)E[g(s_n, s^+_n)]\chi_Q(s, s^+_n)|s_n]ds_n$, where $s^+_n$ are integration variables orthogonal to $s_n$, $\chi_Q$ is the indicator function on $\vec{q} \in [-Q/2, Q/2]^n$, and $E[\cdot|s_n]$ is the conditional expectation over the subalgebra of functions in the variables $s^+_n$. 49
which simply reflects that for completely irrational behavior (i.e., ‘high temperature’), the agents will act randomly, and the Gibbs-Cournot measure will be uniform. As such, the expected value $⟨q_i⟩$ over the interval $[\bar{q}, \bar{q}]$ is the average $\gamma = (\bar{q} + \bar{q})/2$.

In the completely rational limit (i.e., ‘zero temperature’), if $Q/2 + \gamma - h/(2b) > 0$ and $\eta \leq 0$ (equivalently, if $\gamma \leq h/(2b) < \bar{q}$), then the curve $g(y)$ which equals the right side of (76) has a positive limit as $y \to -\infty$. In this case, the line $h(y) = y/\beta$ intersects $g(y)$ at a point with $y$-value $y_m$ which has a finite limit as $\beta \to \infty$. Thus $y_m/\beta \to 0$ as $\beta \to \infty$ and

$$\lim_{\beta \to \infty} F'(h) = \frac{h}{2b} \quad \text{for } \gamma \leq h/(2b) < \bar{q}. \tag{84}$$

In the case when $h/(2b) \geq \bar{q}$, the curve $g(y)$ is always negative-valued. As a result, $y_m \to -\infty$ as $\beta \to \infty$. In this case, $g(y)$ can be used to evaluate $y_m/\beta$ and

$$\lim_{\beta \to \infty} F'(h) = \frac{h}{2b} + \left(\frac{Q}{2} + \gamma - \frac{h}{2b}\right) = \bar{q} \quad \text{for } h/(2b) \geq \bar{q}. \tag{85}$$

Since the integral in (59) is even in $\eta = b\gamma - h/2$, $\lim_{\beta \to \infty} F'(h) = \bar{q}$ when $h/(2b) \leq \bar{q}$. If $b\gamma - h/2 > 0$, then $g(y)$ in (76) is shifted up and $g(0) > 0$. With this, $g(y)$ can only intersect the line $y/\beta$ at positive $y_m$. It is then seen that $y_m > 0$ when $h/(2b) < \gamma$ and $y_m \leq 0$ when $h/(2b) \geq \gamma$.

In summary, we see that the expected value $⟨q_i⟩$ in the irrational case is the average value $(\bar{q} + \bar{q})/2$. In the completely rational case, we recover the classical Nash equilibrium value $⟨q_i⟩ = h/(2b)$ when $\bar{q} \leq h/(2b) \leq \bar{q}$. When $h/(2b) < \bar{q} (\geq \bar{q})$ then $⟨q_i⟩$ will be $\bar{q} (\bar{q})$. For finite $\beta$, the equilibrium $⟨q_i⟩$ will be smaller (larger) than $h/(2b)$ if $h/(2b)$ itself is larger (smaller) than the average $\gamma = (\bar{q} + \bar{q})/2$. Furthermore the graphical analysis below (76) shows that $|y_m|/\beta$ is a decreasing function of $\beta$, and $y_m < 0(> 0)$ when $h/(2b) > \gamma (< \gamma)$. As a result, the agents deviate farther from the Nash equilibrium $h/(2b)$ and closer to the average $\gamma$ as $\beta$ decreases (i.e., as deviations from rationality increase).
The volatility (i.e., susceptibility)

$$\chi = \frac{1}{\beta} F''(h) = \lim_{n \to \infty} \frac{1}{n} \sum_{i,j=1}^{n} \langle q_i q_j \rangle - \langle q_i \rangle \langle q_j \rangle$$

(86)

can be evaluated in a similar manner. Let

$$G(h, y) = \frac{bQ^2}{2} \left( -\coth y + \frac{1}{y} \right) + Q \left( b\gamma - \frac{h}{2} \right) - \frac{y}{\beta},$$

(87)

which equals zero at points $\left(h, y_m(h)\right)$. Then

$$\frac{1}{\beta} \frac{dy_m}{dh} = \frac{Q}{\beta bQ^2 (\sinh^{-2} y_m - y_m^{-2}) - 2}.$$  

(88)

In the irrational limit, $\lim_{\beta \to 0} y_m = 0$ and $\lim_{\beta \to 0} = (\sinh^{-2} y_m - y_m^{-2}) = -1/3$. Differentiating (82) results in

$$\chi = \frac{Q^2 (\sinh^{-2} y_m - y_m^{-2})/2}{\beta bQ^2 (\sinh^{-2} y_m - y_m^{-2}) - 2},$$

(89)

and as a result

$$\lim_{\beta \to 0} \chi = \frac{Q^2}{12}. \quad (90)$$

In the completely rational limit, either $y_m$ converges to a finite value (when $(\bar{q} + \bar{\bar{q}})/2 < h/(2b) < \bar{q}$) or goes to $-\infty$ (when $h/(2b) \geq \bar{q}$). If $y_m$ converges to a finite limit, then the denominator of (89) goes to $-\infty$ and $\lim_{\beta \to \infty} \chi = 0$. If $y_m$ goes to $-\infty$, then $\chi \leq (Q^2/4) |\sinh^{-2} y_m - y_m^{-2}|$ and $\lim_{\beta \to \infty} \chi = 0$. Using that (59) in even in $\eta$ as before,

$$\lim_{\beta \to \infty} \chi = 0. \quad (91)$$

In summary, when agents behave randomly in the irrational limit, the volatility is simply the variance of a uniform random variable. Each agent becomes decorrelated from the other agents and the volatility is the limiting-average of the volatility of each agent. When agents are completely rational they all output at the Nash equilibrium values and do not deviate from that, which is reflected by zero volatility.
REFERENCES

[1] S. P. Anderson, J. K. Goeree, and C. A. Holt: Stochastic Game Theory: Adjustment to Equilibrium Under Noisy Directional Learning, under revision for Review of Economic Studies, 1997

[2] S. P. Anderson, J. K. Goeree, and C. A. Holt: The Logit Equilibrium: A Perspective on Intuitive Behavioral Anomalies, Southern Economic Journal, July 2002, 69(1), p.21-47

[3] H. Al-Wahsh, M. Urb’an, A. Czachor: Exact solutions for a model antiferromagnet with identical coupling between spins, J. Magn. Mater., 1998, 185, p.144-158

[4] W. B. Arthur: Inductive Reasoning and Bounded Rationality, American Economic Review (Papers and Proceedings),1994, 84, p.406-411

[5] V. Betz, J. Lorinczi, H. Spohn: Gibbs measures on Brownian paths: Theory and Applications, Stoch. Sys., Eds. J-D, Deuschel and A. Greven, Springer, 2005.

[6] K. Binmore and L. Samuelson: Muddling Through: Noisy Equilibrium Selection, J. Econ. Theory, 1997, 74, p.235-265

[7] K. Binmore, L. Samuelson, R. Vaughan Musical Chairs: Modeling Noisy Evolution, Games and Econ. Behavior, 1995, 11, p.1-35

[8] L. Blume: Population Games, Working Papers, Santa Fe Institute, 1996, 96-04-022

[9] L. Blume, S. Durlauf: Equilibrium Concepts for Social Interaction Models, Working Papers 7, Wisc. Mad. - Soc. Sys., 2002

[10] W. A. Brock: Pathways to Randomness in the Economy: Emergent Nonlinearity and Chaos in Economics and Finance, Estudios Economicos, 1993, 8 no. 1, and SSRI reprint 410 (http://www.ssc.wisc.edu/econ/archive/ssriwp.htm)

[11] E. Burgos, H. Ceva, R.P.J. Perazzo: Thermal Treatment of the Minority Game, Phys. Rev. E, 2002, 65, p.36711

[12] E. Burgos, H. Ceva, R.P.J. Perazzo: The evolutionary minority game with local coordination, Physica A, 2004, 337, p.635-644

[13] Sergio Cannas, private communication.

[14] S. Cannas, P. Gleiser, F. Tamarit: Two dimensional Ising model with long-range competing interactions, preprint cond-mat/0502403. To appear.

[15] A. Cavagna: Irrelevance of memory in the minority game, Phys. Rev. E, 1999, 59, R3783-R3786

[16] H.F. Chau, F.K. Chow, K.H. Ho: Minority game with peer pressure, Physica A, 2004, 332 (1-4), p.483-495

[17] A. Cavagna, J. P. Garrahan, I. Giardina, and D. Sherrington: A thermal model for adaptive competition in a market, Phys. Rev. Lett., 1999, 83, p.4429-4432
[18] H. A. Ceccatto and B. A. Huberman: Persistence of Nonoptimal Strategies, Proc. Natl. Acad. Sci., 1989, 86, p.3443-3446
[19] D. Challet and Y.-C. Zhang: Emergence of Cooperation and Organization in an Evolutionary Game, Physica A, 1997, 246, p.407
[20] D. Challet, M. Marsili, G. Ottino: Shedding Light on El Farol, submitted to Physica A (2003), preprint cond-mat/0306445. To appear.
[21] A. C. C. Coolen: Non-equilibrium statistical mechanics of Minority Games, for Proceedings of Cergy 2002 Conference
[22] David Colander: Post Walrasian Macro Policy and the Economics of Muddling Through, Middlebury College Economics Working Paper, 2003, 03-22R.
[23] J. Dai: Steady-State Analysis of Reflected Brownian Motions: Characterization, Numerical Methods and Queueing Applications, Ph.D. Dissertation, Stanford University, 1990
[24] E. Friedman, S. Johnson, A. S. Landesberg: The Emergence of Correlations in Studies of Global Economic Interdependence and Contagion, Quantitative Finance, 2003, 3, p.296
[25] E. Friedman and A. S. Landesberg: Large-Scale Synchrony in Weakly Interacting Automata, Phys. Rev. E, 2001, 63, p.051303
[26] J. Hofbauer and W. Sandholm: On the Global Convergence of Stochastic Fictitious Play, Econometrica, 2002, 70, p.2265-2294
[27] J. Hofbauer and W. Sandholm: Evolution in Games with Randomly Disturbed Payoffs, preprint
[28] M. Kac in: M. Chretien, E.P. Gross, S. Deser (editors) Statistical Physics, Phase Transitions, and Superfluidity, vol. 1, Gordon and Breach, New York, 1968, p. 241
[29] David A. Lavis Equilibrium and (ir)reversibility in classical statistical mechanics, to appear in the Proceedings of the 5th International Symposium on the Frontiers of Fundamental Physics, Hyderabad, India, January 2003
[30] David A. Lavis Is equilibrium a useful concept in statistical mechanics?, ESF Conference on Philosophical and Foundational Issues in Statistical Physics, Utrecht, November 2003
[31] Y. Li, A. VanDeemen, R. Savit: The Minority Game with Variable Payoffs, http://arxiv.org/abs/nlin/0002004
[32] D. Luce: Individual Choice Behavior, New York, Wesley, 1959
[33] M. Marsili: On the multinomial Logit model, Physica A, 1999, 269, p.9
[34] M. Marsili and D. Challet: Trading Behavior and Excess Volatility in Toy Markets, Adv. Complex Systems, 2001, 3 p.1-14
[35] M. Marsili and D. Challet: Phase Transition and Symmetry Breaking in the Minority Game, Phys. Rev. E, 1999, 60, R6271

[36] M. Marsili, D. Challet, and Y.-C. Zhang: Exact solution of a modified El Farol’s bar problem: Efficiency and the role of market impact, Physica A, 2000, 280, p.522

[37] M. Marsili and Y.-C. Zhang: Stochastic Dynamics in Game Theory, Proceedings of the Budapest conference ECONOPHYSICS, Kluwer, 1998

[38] M. Marsili and Y.-C. Zhang: Fluctuations around Nash Equilibria in Game Theory, Physica A, 1997, 245, p.181

[39] Peter Hans Matthews: Who is Post-Walrasian Man?, Middlebury College Working Paper Series, 2004, 0412

[40] A.B. MacIsaac, J.P. Whitehead, M.C. Robinson, K. De'Bell: Striped phases in two-dimensional dipolar ferromagnets Phys. Rev. B, 1995, 51, p.16033

[41] D. McFadden: Conditional Logit Analysis of Qualitative Choice Behavior, Frontiers of Econometrics (P. Zarembka Ed.), New York, Academic Press, 1973

[42] E. Milotti: Exactly solved dynamics for an infinite-range spin system. II. Antiferromagnetic interaction, Phys. Rev. E, 2002, 65, p.027102

[43] Y. Mu and Y. Ma: Self-organizing stripe patterns in two-dimensional frustrated systems with competing interactions, Phys. Rev. B, 2003, 67, p.014110 (6 pages)

[44] R. D. McKelvey and T. R. Palfrey: Quantal Response Equilibria for Normal Form Games, Games and Economic Behavior, 1995, 10, p.6-38

[45] S. Moelbert and P. De Los Rios: The local minority game, Physica A, 2002, 303, p.217-225

[46] S. A. Mohammed and M. K. R. Scheutzow The stable manifold theorem for non-linear systems with memory: I. Existence of the semiflow Jour. Func. An., 2003, 205, p.271-305

[47] D. Monderer and L. S. Shapley: Potential Games, Games and Economic Behavior, 1996, 14, p.124-143

[48] J. F. Nagle: Ising Chain with Competing Interactions, Phys. Rev. A, 1970, 2 no.5, p.2124-2128

[49] H. Osada and H. Spohn: Gibbs Measures Relative to Brownian Motion, Ann. Probab., 1999, 27, p.1183-1207

[50] H. V. D. Paranuk, R. Savit, S. A. Brueckner, J. Sauter: A Technical Overview of the AORIST Project, preprint

[51] V. Plerou, P. Gopikrishnan, X. Gabaix, H. Stanley: Quantifying Stock Price Response to Demand Fluctuations, Phys. Rev. E, 2002, 66 p.027104-1–027104-4

[52] F. Reif Fundamentals of Statistical and Thermal Physics, McGraw-Hill, Inc., 1965

[53] W. Sandholm: Potential Games with Continuous Player Sets, J. Econ. Theory, 2001, 97 p.81-108
[54] W. Sandholm: Excess Payoff Dynamics, Potential Dynamics, and Stable Games, Working Papers 5, Wisc. Mad. - Soc. Sys., 2003

[55] B. Simon The statistical mechanics of lattice gases, vol. 1, Princeton University Press, Princeton, N.J., 1993

[56] D. E. Smith and D. K. Foley: Is Utility Theory so Different from Thermodynamics?, Santa Fe Institute Working Papers, 2004, 02-04-016

[57] E. Smith, J. D. Farmer, L. Gillemot, S. Krishnamurthy, Statistical theory of the continuous double auction, Quantitative Finance, 2003, 3 no.6, p.481

[58] A.D. Sokal: Monte Carlo Methods in Statistical Mechanics: Foundations and New Algorithms, Lectures at the Cargese Summer School on Functional Integration: Basics and Applications, 1996

[59] A. P. Vieira and L. L. Gonçalves: One-dimensional Ising model with long-range and random short-range interactions, J. Magn. and Magn. Mater., 1999, 192, p.177-190

[60] P. Dupuis and R. J. Williams: Lyapunov functions for semimartingale reflecting Brownian motions, Annals of Probability, 1994, 22, p.680-702

[61] J. G. Dai and R. J. Williams: Existence and uniqueness of semimartingale reflecting Brownian motions in convex polyhedrons, Theory of Probability and Its Applications, 1995, 40, p.1-40

[62] J. M. Harrison and R. J. Williams: Multidimensional reflected Brownian motions having exponential stationary distributions, Annals of Probability, 1987, 15, p.115-137