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ON PARTICLES IN EQUILIBRIUM ON THE REAL LINE

AGELOS GEORGAKOPOULOS AND MIHAIL N. KOLOUNTZAKIS

ABSTRACT. We study equilibrium configurations of infinitely many identical particles on the real line or finitely many particles on the circle, such that the (repelling) force they exert on each other depends only on their distance. The main question is whether each equilibrium configuration needs to be an arithmetic progression. Under very broad assumptions on the force we show this for the particles on the circle. In the case of infinitely many particles on the line we show the same result under the assumption that the maximal (or the minimal) gap between successive points is finite (positive) and assumed at some pair of successive points. Under the assumption of analyticity for the force field (e.g., the Coulomb force) we deduce some extra rigidity for the configuration: knowing an equilibrium configuration of points in a half-line determines it throughout. Various properties of the equilibrium configuration are proved.

1. INTRODUCTION

A seminal question in the study of crystals, that dates back to Wigner [?], is whether an infinite system of identical particles, acting on each other with pairwise forces such as the Coulomb forces, will have a ground state (where energy is minimized) in which the locations of the particles form a lattice (i.e. a discrete subgroup of isometries of the space of full rank or dimension); see [?] for more precise formulations and for a review of the large literature on the topic. Rigorous results exist mostly in dimension one, and often under assumptions (such as a potential which is integrable at infinity) which make it possible to say precisely what a ground state is [?, ?, ?, ?, ?, ?, ?]. In this paper we consider variants of this question for 1-dimensional systems that are based on the forces exerted on the particles rather than energy minimisation. We prove ‘crystalisation’ in certain setups with elementary arguments.

The *force* between two particles, as a function of their distance, can be defined as the derivative of their contribution to the energy of their system whenever the latter is given by a differentiable function. Thus at the ground state the total force on each particle is 0 by elementary calculus. A system may have a state of *unstable equilibrium* though, where the total force on every particle is 0 but the energy is not minimised globally.

In this paper we study precisely such states of equilibrium, making no claim that these states minimize energy (to the best of our knowledge though, our results are new even when restricted to ground states). This is clearly a more general situation than a ground state, yet we prove, under very mild assumptions, that an equilibrium implies equispaced particles, either in the real line or on the circle. Our main assumption is that the force between two particles is a strictly monotone decreasing function of their distance. This is equivalent to assuming that the corresponding potential is strictly convex when it is differentiable. In finite setups, convexity often implies that every critical point is a global minimum, hence the only equilibria are the ground states. In an infinite system though it makes no sense to talk about a ground state unless one makes a periodicity assumption. By working with forces rather than potentials, we are able to work with infinite systems without making such an assumption.

Our first result is that for every strictly monotone decreasing function $F : \mathbb{R}_+ \rightarrow \mathbb{R}_+$, the only configurations of infinitely many particles on \mathbb{R} which are in mechanical equilibrium when the (repelling or, equivalently, attractive) force between any two particles at distance d is $F(d)$, are obtained when the distance between any two consecutive particles is constant, unless the distances between consecutive particles are unbounded above and below (Theorem 1). By (*mechanical*) *equilibrium* we mean that the net force exerted on each particle is zero. In particular, the only periodic configurations of particles on \mathbb{R} in equilibrium are obtained by equally spacing the particles.

Problem 1. If a configuration of particles on \mathbb{R} is in (mechanical) equilibrium, do all distances between subsequent particles have to be equal?

Here we are assuming that $F : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ is strictly monotone decreasing, and it is such that the total force exerted on each particle from each side is finite when we place a particle at each integer, say. The latter assumption is important, as it allows us to directly work with configurations of infinitely many particles without any periodicity assumption, and without having to consider limits of finite configurations, which are standard approaches in the ground state literature.

The above problem is open for all such force functions F , and we find it interesting that, although it is not clear that the answer is positive for e.g. $F(d) = d^{-2}$, it is also not clear whether there exists F for which the answer is negative. We prove however that if we nail one of the particles at a fixed position, then we can obtain non-trivial equilibrium configurations for continuous F (Theorem 7).

We also obtain the following result about the Coulomb force (or somewhat more general analytic forces). A configuration in equilibrium with bounded distances between consecutive particles is uniquely determined by any of its *tails* (i.e. co-final subsequences); see Theorem 4.

In the above discussion the particles are tacitly assumed to have equal masses. If we allow them to have different masses, then non-equally-spaced stable configurations do exist as observed by Ulam [?, Chapter VII, §4].

Stable particle configurations for generic force functions are also considered in [?], although with a different focus. For an analogue of Proposition 1 in higher dimensions see [?].

2. NO EXTREMAL GAPS

By an *equilibrium configuration* we mean a bi-infinite sequence of real numbers such that a configuration of particles positioned at those numbers is in equilibrium in the sense defined above. An equilibrium configuration is *trivial*, if it is an arithmetic progression, or in other words, if consecutive particles have equal distances.

For a pair of real numbers x, y , we write xy for the absolute value of the force between a particle at x and a particle at y . By a *gap* we mean the distance (i.e. difference) between two consecutive members of an equilibrium configuration.

Theorem 1. *If an equilibrium configuration has a gap of maximal or minimal length, then it is trivial.*

Proof. Suppose there is a non-trivial equilibrium configuration $\dots, w_2, w_1, x, y, z_1, z_2, \dots$, where the gap $[x, y]$ is maximal (see Fig. 1), i.e. $|x - y| \geq |p - q|$ for any two (consecutive) members p, q of the sequence. Since the equilibrium configuration is not trivial, we may assume without loss of generality that $|x - y| > |x - w_1|$. Writing $F^-(x)$ for the force exerted on a particle at x from the left, we have

FIGURE 1. The points around a gap of maximum length (x, y) .

$$(1) \quad \begin{aligned} F^-(x) &= xw_1 + xw_2 + xw_3 + \dots, \text{ and} \\ F^-(y) &= yx + yw_1 + yw_2 + \dots \end{aligned}$$

Let us compare the j th summand of the first line to the j th summand of the second one: since $|x - y| > |x - w_1|$, we have $yx < xw_1$ by the strict monotonicity of the forces.

Moreover, we have $|y - w_i| = |y - x| + |x - w_i| \geq |x - w_{i+1}| = |x - w_i| + |w_i - w_{i+1}|$. Thus $yw_i \leq xw_{i+1}$. Combining these inequalities we obtain $F^-(y) < F^-(x)$.

By repeating the argument for the forces $F^+(y), F^+(x)$ exerted at y, x from the right, the only difference being that $|y - z_1|$ might equal $|x - y|$, we obtain $F^+(y) \geq F^+(x)$, reaching a contradiction.

If the gap $[x, y]$ is minimal, then the same argument applies with all inequalities reversed. \square

As an immediate corollary of Theorem 1, we obtain

Corollary 2. *If an equilibrium configuration is periodic, then it is trivial.*

Next, we adapt this to configurations on the circle S^1 .

Corollary 3. *Let $\{x_1, \dots, x_n\}, x_i \in S^1$, be a configuration of particles constrained on S^1 in equilibrium. Suppose that the (tangential) force they exert on each other is a strictly monotone decreasing function of their distance. Then the distance $d(x_i, x_{(i+1) \bmod n})$ of any two consecutive particles is constant.*

Distance here can be taken to mean either euclidean distance or geodesic distance along S^1 , and the same proof applies in both cases; thus the result holds when we replace S^1 by any rectifiable simple closed curve as considered e.g. in [?]. When restricted to ground states this fact is well-known [?, Proposition 1.1. (A)] (a strictly monotone decreasing force is equivalent to a decreasing, strictly convex potential) and is usually attributed to Fejes Toth [?]. With a little bit of more work it is also possible to deduce Corollary 3 from this using the fact that every critical point of a convex function is a global minimum.

Proof. Suppose, to the contrary, that $d(x_i, x_{(i+1) \bmod n})$ is not constant. Then there are two consecutive particles x, y maximising that distance, such that the distance between x and its other neighbouring particle w_1 is strictly less than $d(x, y)$. We proceed as in the proof of Theorem 1, the only difference being that now $F^-(x)$ denotes the force exerted on a particle at x by particles lying on one of the two half circles S_x^- between x and its antipodal point x' on S^1 .

FIGURE 2. The points around an arc of maximum length (x, y) .

Thus the sums in (1) have finitely many summands. Since the i th summand of the first sum is greater than the i th summand of the second one by the same argument, it suffices to show that the first sum has at least as many summands as the second. This is indeed true, for if yw_k is the last summand of the second sum, then the particle $w_{(k+1) \bmod n}$ lies in S_x^- because $d(w_k, w_{(k+1) \bmod n}) \leq d(x, y)$ by the choice of x, y .

The rest of the proof is identical to that of Theorem 1. \square

3. UNIQUENESS OF CONTINUATION UNDER ANALYTIC FORCES

Definition 3.1. *Call an increasing sequence $x_n \in \mathbb{R}, n \in \mathbb{Z}$, uniformly discrete if there are constants $0 < c \leq C < \infty$ such that*

$$c \leq x_n - x_{n-1} \leq C, \quad \forall n \in \mathbb{Z}.$$

We show the following.

Theorem 4. Let $x_n \in \mathbb{R}$, $n \in \mathbb{Z}$ be a uniformly discrete configuration of particles subject to repellent Coulomb forces

$$F(d) = \frac{1}{d^2}.$$

Suppose that the particles at the set $\{x_n \geq 0\}$ are in equilibrium. Then the locations $\{x_n < 0\}$ are uniquely determined.

Proof. Suppose not, and suppose that the two sets of points $X, Y \subseteq (-\infty, 0)$ (each of them uniformly discrete, in the obvious way) can both cause the electrons at the points $W = \{x_n \geq 0\}$ to experience zero total force. In other words, the two systems of electrons, at $X \cup W$ and at $Y \cup W$ are such that the electrons at W are in equilibrium. It follows that for each $w \in W$ the force exerted on w due to electrons at X is the same as the force exerted on w due to electrons at Y .

The Coulomb force exerted at a point w on the nonnegative real semi-axis by the electrons at X is given by

$$f_X(w) = \sum_{x \in X} \frac{1}{(x - w)^2},$$

up to redefining the physical constants, and similarly for the force $f_Y(z)$ due to electrons in Y . Since these must be the same at each $w \in W$ we deduce that the function

$$(2) \quad f(w) = f_X(w) - f_Y(w) = \sum_{p \in X \Delta Y} \frac{\epsilon_p}{(p - w)^2},$$

where $X \Delta Y$ is the symmetric difference of X and Y and $\epsilon_p = \pm 1$ depending on whether $p \in X$ or $p \in Y$, vanishes at each $w \in W$. It is easy to see that $f(w)$ is well defined (the series at (2) converges) at every point of the complex plane except at $X \Delta Y$, at each point of which it has a pole of order 2, and is an analytic function in $\mathbb{C} \setminus (X \Delta Y)$. Since, for $\Re w \geq 0$ we have

$$|f(w)| \leq \sum_{p \in X \Delta Y} \frac{1}{|p - w|^2} \leq \sum_{p \in X \Delta Y} \frac{1}{|p|^2} < \infty,$$

it is clear that f is bounded on the closed right half plane. Our plan is to use Theorem 5 below to show that f is identically 0.

We write, as we may,

$$W = \{w_0 = 0 < w_1 < w_2, \dots\}$$

for the points of W and we assume that $c \leq w_n - w_{n-1} \leq C$ for all $n > 0$. This implies that

$$(3) \quad cn \leq w_n \leq Cn, \quad (n \geq 0).$$

Define the linear fractional transformation

$$z = z(w) = \frac{w - 1}{w + 1}, \quad w = w(z) = \frac{1 + z}{1 - z}$$

and note that $z(w)$ maps the open right half plane $\{\Re w > 0\}$ bijectively to the open unit disk $\{|z| < 1\}$ (with $1 \rightarrow 0, 0 \rightarrow -1, i \rightarrow i$).

The function $f(w)$ vanishes at all points of W and therefore the analytic function on the unit disk $\{|z| < 1\}$

$$g(z) = f(w(z))$$

vanishes at all (real) points $z_n = z(w_n) = 1 - \frac{2}{w_n + 1}$, $n \geq 0$, of the open unit disk. Since f is bounded on the open right half plane so is g on the open unit disk.

Because of (3) we have

$$(4) \quad 1 - z_n = \frac{2}{1 + w_n} \geq \frac{2}{1 + Cn}$$

and hence

$$(5) \quad \sum_n (1 - |z_n|) = \infty.$$

We now use the following result.

Theorem 5 ([?], Theorem 15.23). *If a function g is analytic and bounded in the open unit disk U and vanishes at points $z_n \in U$ satisfying (5), then g is identically 0 in U .*

(This is a rather simple consequence of Jensen’s formula.)

Thus Theorem 5 implies that $g \equiv 0$ on U , hence $f \equiv 0$ on the open right half plane, and by analytic continuation f is 0 on $\mathbb{C} \setminus (X \triangle Y)$. So f has no singularities at all, a contradiction, unless $X = Y$, as we had to prove. \square

Corollary 6. *Let S be a uniformly discrete equilibrium configuration such that some tail of S is periodic. Then S is trivial.*

Proof. Let T be such a tail, and let T' be the subsequence of T obtained by omitting the first period. By Theorem 4, T can be brought to equilibrium by a unique sequence preceding it. We claim that this sequence must start with the period of T . Indeed, applying Theorem 4 to T' , and noting that T is a shifted copy of T' , we see that the two unique continuations coincide.

This easily implies that the whole sequence S is periodic, and by Corollary 2 trivial. \square

Generalization. The proof of Theorem 4 and Corollary 6 is valid for more general forces than the Coulomb forces. The force function $F(d)$ needs to be an analytic function on the open right half complex plane, whose values on the positive real axis are positive and satisfies

$$\int_1^{+\infty} F(x) dx < \infty.$$

Such functions are, for instance, the functions

$$F(d) = \frac{1}{d^k}, \quad (k \geq 2),$$

and

$$F(d) = e^{-d^k}, \quad (k \geq 1).$$

4. OTHER REMARKS

The following facts are easy to check

Proposition 1. *If x, y, z are consecutive points in an equilibrium configuration, then $|x - y|/|y - z|$ is bounded.*

Proposition 1 is an easy consequence of

Proposition 2. *If S is a finite set of consecutive particles in an equilibrium configuration, then the (signed) forces exerted on S by particles in S only are monotone.*

Proof (Sketch). If they are not, then the other forces only make the situation worse. \square

FIGURE 3. Why Proposition 2 implies Proposition 1.

To see why Proposition 2 implies Proposition 1 let $x < y < z$ be three consecutive points in an equilibrium configuration, hold the points x, y fixed and let z move far to the right (see Fig. 3). Observing the inner forces of the triple we see that if z is far

enough to the right then the force on x is negative (it is mostly affected by y), the force on y is positive (it is mostly affected by x) and the force on z is positive but very small, violating the monotonicity proved in Proposition 2.

In fact, the particles in Proposition 2 do not have to be part of an equilibrium configuration; the statement holds for any finite set S of consecutive particles that are in equilibrium inside some configuration. Even stronger, the first particle in S does not have to be in equilibrium.

Proposition 3. *Suppose that the force function F is strictly monotone decreasing and continuous, and $\int_1^\infty F(x)dx < \infty$. For every uniformly discrete sequence of particles $S_- = \{x_{-1}, x_{-2}, \dots\}$ with $x_i < x_{i-1} < 0$, there is a sequence of particles $S_+ = \{x_0, x_1, x_2, \dots\}$, $x_i > x_{i-1} > 0$, such that each particle in S_+ is in equilibrium in the configuration $S_- \cup S_+ = \{x_i\}_{i \in \mathbb{Z}}$. Moreover, x_0 can be chosen arbitrarily.*

Proof. For $n = 1, 2, \dots$, let x_n be any positive real. Then there are $x_1^n, \dots, x_{n-1}^n \in (0, x_n)$ such that the particles at $\{x_1^n, \dots, x_{n-1}^n\}$ are in equilibrium in the configuration $S_- \cup \{x_1^n, \dots, x_{n-1}^n\} \cup \{x_n\}$: we claim that the positions in $(0, x_n)$ minimising the energy of the particles at $\{x_1^n, \dots, x_{n-1}^n\}$ have this property. To make this argument precise, define the energy $E(x, y)$ contributed by a pair of particles at positions x and y by $E(x, y) := \int_{z=|x-y|}^\infty F(z)dz$. Note that this is finite by the choice of F and the fact that S_- is uniformly discrete.

For $m \in \mathbb{N}_{>0}$, let S_-^m be the subsequence $\{x_{-1}, \dots, x_{-m}\}$ of S_- . In order to obtain the desired configuration $\{x_1^n, \dots, x_{n-1}^n\}$ we will consider a sequence of configurations $C^m = \{x_1^{n,m}, \dots, x_{n-1}^{n,m}\}$, where $x_i^{n,m} \in (0, x_n)$, such that the particles in C^m are in equilibrium in the configuration $S_-^m \cup C^m \cup \{x_n\}$ and use compactness to take a limit.

For this, given m we define the energy $E = E(x_1^n, \dots, x_{n-1}^n)$ of the configuration $S_-^m \cup \{x_1^n, \dots, x_{n-1}^n\} \cup \{x_n\}$ to be

$$E := \sum_{i=0}^{n-1} \sum_{j=-1}^{-m} E(x_i^n, x_j) + \sum_{i=0}^{n-1} \sum_{j=0}^{n-1} E(x_i^n, x_j^n),$$

i.e. the energy contributed by all pairs involving at least one of the particles $\{x_1^n, \dots, x_{n-1}^n\}$. It is not hard to see that there are $x_1^{n,m}, \dots, x_{n-1}^{n,m} \in (0, x_n)$ minimising E by the continuity of F and the fact that E increases if a particle gets too close to x_{-1} or x_n . Note that the partial derivative of E with respect to x_i^n equals the total force exerted on the particle at x_i^n by the definition of E , and by Fermat's theorem this has to vanish at any configuration minimising E . Thus each particle in $\{x_1^{n,m}, \dots, x_{n-1}^{n,m}\}$ is in equilibrium as claimed. By a standard compactness argument, there is a sequence m_1, m_2, \dots such that the position of x_i^{n,m_j} converges, for each i , as m_j goes to infinity. Define the limit configuration by $x_i^n := \lim x_i^{n,m_j}$. It now follows easily from the continuity of F that the particles at $\{x_1^n, \dots, x_{n-1}^n\}$ are in equilibrium in the configuration $S_- \cup \{x_1^n, \dots, x_{n-1}^n\} \cup \{x_n\}$ as desired.

Moreover, by the monotonicity and continuity of the forces, choosing x_n appropriately we can ensure that x_0 equals any predetermined constant greater than x_{-1} .

By a compactness argument like the one used above, there is a sequence n_1, n_2, \dots such that the position of $x_i^{n_j}$ converges (possibly to infinity), for each i , as n_j goes to infinity. By Proposition 1 (see also the remark after Proposition 2), the limit of $x_i^{n_j}$ is finite. Then defining $S_+ = \{\lim_j x_i^{n_j}\}_{i \in \mathbb{Z}}$ satisfies our requirements (here, we use the continuity of the forces again). \square

Proposition 4. *If the gaps of S_- in Proposition 3 are bounded between real numbers $0 < b < B$, then S_+ can be chosen so that its gaps are bounded between $\min(b, x_0 - x_{-1})$ and $\max(B, x_0 - x_{-1})$.*

Proof. We repeat the proof of Proposition 3, except that we replace the particle at x_n with an 1-way infinite arithmetic progression $x_n, x_n + a, x_n + 2a, \dots$, where a is any real in (b, B) .

We claim that, for every $n \in \mathbb{N}$, the resulting gaps of $\{x_1^n, \dots, x_{n-1}^n\}$ are bounded between $\min(b, x_0 - x_{-1})$ and $\max(B, x_0 - x_{-1})$. Indeed, let x, y be the particles spanning the largest (respectively smallest) gap of $\{x_1^n, \dots, x_{n-1}^n\}$. If this gap is longer than $\max(B, x_0 - x_{-1})$ (resp. smaller than $\min(b, x_0 - x_{-1})$), then we can repeat the main argument of the proof of Theorem 1 to obtain a contradiction, since such a gap cannot involve any particle in S_- , and in that proof we only used the equilibrium for the particles x, y . \square

We remark that we do not know if Proposition 4 is true for every equilibrium configuration S_+ . (We only proved it for one equilibrium configuration.)

Finally, we adapt the proof of Proposition 3 to obtain the main result of this section

Theorem 7. *For every strictly monotone decreasing and continuous force function $F : \mathbb{R}_+ \rightarrow \mathbb{R}_+$, there is a configuration $\{\dots, x_{-2}, x_{-1}, x_0, x_1, x_2, \dots\}$ of particles on \mathbb{R} in which all particles except $x_0 = 0$ are in equilibrium, and x_{-1} and x_1 can be chosen arbitrarily.*

Proof. We use the strategy of the proof of Proposition 3, except that we replace the sequence S_- with a single particle at a position x_{-n} , we fix a particle at $x_0 = 0$ which does not have to be in equilibrium, and we introduce particles $\{x_{-1}^n, \dots, x_{-(n-1)}^n\}$ in equilibrium for each $n \in \mathbb{N}$. We need to show that, by choosing x_{-n}, x_n appropriately, we can bring the particles x_{-1}^n, x_1^n to the desired positions for each n . We can then take a limit of such configurations as $n \rightarrow \infty$ as in Proposition 3.

Define a *0-centered configuration* to be a sequence $\{x_{-n}, \dots, x_{-1}, x_0 = 0, x_1, \dots, x_n\}$ in which all particles except possibly x_{-n}, x_0, x_n are in equilibrium (when forces between particles are given by F). Thus it remains to prove that for every $a < 0, b > 0, n \in \mathbb{N}_*$, there is a 0-centered configuration $\{x_{-n}, \dots, x_{-1}, x_0, x_1, \dots, x_n\}$ with $x_{-1} = a$ and $x_1 = b$.

To prove this, let

$$d := \sup\{x - x' \mid \text{there is a 0-centered configuration with } x_{-n} = x', x_n = x, x_{-1} \geq a, \text{ and } x_1 \leq b\}.$$

Let us prove that $d < \infty$. Let $\{x_{-n}, \dots, x_{-1}, x_0, x_1, \dots, x_n\}$ be a candidate configuration. Since $x_1 \leq b$, the force to the right exerted on x_1 from particle 0 is at least $F(b)$, and has to be balanced by the particles x_2, \dots, x_n . This gives an upper bound b' on x_2 , as the force on x_1 to the left is less than $(n-1)F(x_2 - x_1)$ by the monotonicity of F . Similarly, the force to the right exerted on x_2 from particle 0 is lower bounded by $F(b')$, and this imposes an upper bound on x_3 , and so on up to x_n . Applying the same argument to the negative particles we also see that x_{-n} is bounded, hence $x_n - x_{-n}$ is bounded.

Since F is continuous, this supremum is attained by some 0-centered configuration $Y = \{y_{-n}, \dots, y_{-1}, y_0, y_1, \dots, y_n\}$. We claim that $y_1 = a$ and $y_1 = b$ in C , which would complete our proof.

Suppose to the contrary that $y_{-1} = a + \epsilon$ for some $\epsilon > 0$ (and possibly $y_1 < b$). We will produce a 0-centered configuration $Y' = \{y'_{-n}, \dots, y'_{-1}, y_0 = 0, y'_1, \dots, y'_n\}$ where $y'_{-n} = y_{-n} - \epsilon$ and $y'_i \in [y_i - \epsilon, y_i]$ for every i , and in fact $y'_0 = y_0 = 0$ and $y'_n = y_n$. This contradicts the choice of Y as Y' increases d by ϵ , and satisfies all other requirements.

We will obtain Y' as a limit of sequences $Y^j = \{y^j_{-n}, \dots, y^j_{-1}, y_0 = 0, y^j_1, \dots, y^j_n\}, j = 0, 1, \dots$

To begin with, we define Y^0 by letting $y^0_{-n} = y_{-n} - \epsilon$, and letting $y^0_i = y_i$ for every other i . In fact, we will never change the position of the particle $-n$ again, that is, we fix $y^j_{-n} = y_{-n} - \epsilon$ for every j . We will also never change the positions of particles 0 and n ; we call the particles $-n, 0, n$ the *fixed particles*.

Note that no non-fixed particle is in equilibrium in Y^0 : for all non-fixed particles, we have reduced the force from the left in comparison to Y , and kept the force from the right fixed. By the continuity and monotonicity of F , there is a position $y \in (y^0_{-n}, y^0_{-n+1})$ such that if we move the particle $-n+1$ from y^0_{-n+1} to y , then that particle will be in equilibrium. We now define Y^1 by letting $y^1_{-n+1} = y$ and $y^1_i = y^0_i$ for every other i .

We proceed similarly with the next particle $-n + 2$. Since we moved the previous two particles to the left, it is still true that the net force on that particle from the left has been reduced, and we move it to the left to a position y_{-n+2}^2 to bring it to equilibrium and define Y^2 (we are aware that the particle $-n + 1$ is not any more in equilibrium in Y^2).

We proceed inductively to define the sequences $Y^3, Y^4, \dots, Y^{2(n-1)}$, each of which only moves the position of the non-fixed particle $-n + 3, \dots, -1, 1, \dots, n - 1$ respectively to the left. Note that after these changes, all non-fixed particles but $n - 1$ are again out of equilibrium, and the net force they experience is to the left. We repeat another round of similar changes, obtaining sequences $Y^{2(n-1)+1}, \dots, Y^{4(n-1)}$ in which particle $-n + 1, \dots, -1, 1, \dots, n - 1$ respectively are moved to the left to reach a temporary equilibrium. After we are done we perform another such round, and so on ad infinitum.

Since each y_i^j is monotone decreasing in j , and bounded below by y_{-n}^0 , it converges to some value y_i' , and we use these values to define the limit configuration Y' .

Next, we claim that for every j , and every particle i , we have $y_i^j \in [y_i - \epsilon, y_i]$. For if not, then consider the first step j when a counterexample y_i^j arises. Then particle i has to be in equilibrium in Y^j because it must have just been moved. Let us compare the forces exerted on this particle in Y^j to those exerted on it in Y . All particles have been moved to the left if at all, and particle i has experienced the largest displacement as all other particles have moved by at most ϵ . But this means that all particles to the left of i are closer to i in Y^j than they were in Y , and all particles to the right of i are further from i in Y^j than they were in Y . By the strict monotonicity of F , this contradicts the fact that i was in equilibrium in both Y and Y^j .

This proves our claim, which implies that $y_i' \in [y_i - \epsilon, y_i]$ for every i . In particular, $y'_{-1} \geq y_{-1} - \epsilon$, and so $y'_{-1} \geq a$ (and clearly $y'_1 \leq b$). Thus Y' is a candidate for the definition of d if it is 0-centered. And indeed it is: since the positions of all particles converge in the sequence (Y^j) , the net force on each particle i converges as $j \rightarrow \infty$ by the continuity of F , and as it assumes the value 0 infinitely often—namely, at steps at which we bring i to equilibrium—it has to converge to 0.

Thus Y' contradicts the choice of Y as claimed, which proves that $y_{-1} = a$. By the same arguments, we obtain a contradiction if $y_1 < b$ by moving all particles to the right a bit. \square

5. QUESTIONS

Theorem 4 says that if a 1-way infinite sequence of particles S_+ (at bounded distances) can be brought to equilibrium by another 1-way infinite sequence S_- , then S_+ uniquely determines S_- . We can ask if the converse can be proved: if S_- can be used to bring some S_+ to equilibrium, is S_+ uniquely determined by S_- ?

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