the model then becomes identical to a well-ordered system, the zero temperature finite size ferromagnetic Ising model.[6]

In contrast, most AB comments and conclusions are based on the existence of frustration in the countries' or firms' interactions. Such local frustration would produce a degeneracy of the energy landscape which in turn would yield instabilities in the global system. However, there is no frustration in the model they derived from their data.

In fact, they are confusing two models associated with disordered magnetic systems: one without frustration, the Mattis spin-glass model, and one with frustration, the Edwards–Anderson spin-glass model.[7] The AB model turns out to be of the Mattis spin-glass type, while all their comments are drawn from the physics associated with an Edwards–Anderson spin-glass model. Most of Axelrod and Bennett's conclusions cannot be drawn from their model.

To demonstrate our statement requires the use of some mathematical technicalities which are lengthy and not appropriate to the present journal. Therefore, our demonstration has been published in a physics journal, where, first, the AB model is analysed within the field of statistical physics[8] and then the conclusions mentioned above are demonstrated. Furthermore, we are able to build up a new coalition model to describe alignment and competition among a group of actors. Our model does embody the main properties claimed in the AB model. Moreover, it also predicts new behaviour related to the dynamics of biomodal coalitions. In particular, the stability of the Cold War period and the East European fragmentation process induced by the collapse of the Warsaw Pact are given an explanation.

[6] R. K. Pathria, *Statistical Mechanics* (Oxford: Pergamon Press, 1977), p. 45.
[7] Axelrod and Bennett, 'A Landscape Theory of Aggregation'.
[8] Pathria, *Statistical Mechanics.*

Response to Galam's Comment

ROBERT AXELROD AND D. SCOTT BENNETT*

Landscape theory[1] proposed a model of the alignment of actors (such as nations) based upon the importance of individual actors and their pairwise relationships. The model was implemented in simulation software and its predictions compared favourably with empirical reality given several input situations. The model successfully predicted the alignment of seventeen European nations in the Second World War alliance patterns since the Cold War.

Galam criticizes our work by summarizing his arguments from another paper.[2] In short, he asserts that the landscape model actually does not include three of its claimed

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[1] Robert Axelrod and D. Scott Bennett, 'A Landscape Theory of Aggregation', *British Journal of Political Science*, 23 (1993), 211–33.
[2] Serge Galam 'Fragmentation versus Stability in Bimodal Coalitions', *Physica A*, 230 (1996), 174–88.

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results. In fact, Galam's criticisms of our work are based upon several misunderstandings.

Briefly, the landscape model is centred around the key concepts of 'frustration' and 'energy'. Frustration was defined in our first equation for a state i as:

$$F_i(X) = \Sigma s_j p_{ij} d_{ij}(X) \quad (1)$$

where s_j is the size of actor j, p_{ij} is the propensity of i to be close to j, the summation is over all $i \neq j$, and $d_{ij}(X)$ is the distance from i to j in a configuration, X, of the actors into distinct alliances. Distance between two actors is 0 when they are on the same side, and 1 when they are on different sides. Energy is defined for a system of actors as the sum of frustration over the states i, weighted by their size. Any configuration of actors in distinct coalitions has an associated energy. The theory predicts that actors will change sides one at a time whenever such a move would reduce an actor's frustration, which necessarily reduces system energy. The system will settle into a stable alignment when no actor can further reduce its frustration.

Galam criticizes three points made in our article. His first two criticisms are based on misunderstandings of what we did, and his third point is based on a misunderstanding of the relationship between the input and output of any model.

Galam's first misunderstanding concerns our observation that the source of conflict with a small country is not as important for determining alignment as an equivalent source of conflict with a large country. To clarify this matter, consider a state, i, that is aligned with two other states j and k. Since the source of conflict is assumed to be equivalent, assume that $p_{ij} = p_{ik}$. Galam interprets our claim as saying that the effect on total energy depends on whether it is i or j that chooses to change its alignment. Actually what we claim is that the effect on i's frustration depends on whether j or k changes its alignment with i. If j is smaller than k ($s_j < s_k$) and $p_{ij} = p_{jk}$, then our definition of frustration guarantees that j's changing sides will have a smaller effect on i's frustration, and in turn on system energy, than will k's changing sides.

Galam's second misunderstanding comes in the use of the term 'frustration'. We use the term frustration specifically as we define it in Equation (1), as noted earlier. We also pointed out that particular alignments may leave some states frustrated 'in the sense that some "friends" will be in the opposite grouping and/or some "enemies" will be in the same grouping.'[3] Galam's criticism of our statement relies on his using the conception of frustration from spin glass physics where frustration means 'the existence of several ground states with exactly the same energy'.[4] Using our definition, our statement is true: even in a globally optimum configuration, some actors may not be able to completely satisfy their propensity to be with or apart from some others. An example would be three mutually antagonistic countries forced to choose one of two sides. Perhaps we should have been clearer that our definition of frustration is more in keeping with the social conception of frustration than with the physics term, but Galam himself notes on p. 176 that our quantity 'frustration' is not to be confused with spin glass frustration before he proceeds to criticize us for using the spin glass frustration concept.

Finally, Galam questions our ability to predict alignments using the model, trivializing the model by stating that 'the output reduces to the input' and that 'to get the right alignment is not a result of the model, but instead … of propensity'.[5] While it

[3] Axelrod and Bennett, 'A Landscape Theory of Aggregation', p. 217.
[4] Galam, 'Fragmentation versus Stability', p. 178
[5] Galam, 'Fragmentation versus Stability, p. 179.

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is trivially true that the output of any deterministic model is determined by its input, that does not imply that the intervening model is unimportant. There are many ways (models or methods) in which pairwise propensities could be used to make predictions. Landscape theory presents a theoretically motivated way to do so, namely by summing pairwise propensities weighted by size, and assuming limited rationality to justify incremental changes in alignment. This method yielded predictions that fit empirical reality quite well. This fit is necessarily a result of input data, which must be based on a sensible operationalization of sizes and propensities. But there is no guarantee that a different model would combine these elements in a way that fit predicts observed alignments so successfully.

Galam proposes a new coalition model. We leave it to others to assess its value. In any case, he offers no operationalization of his model, let alone any statistical tests of its accuracy.

Since our original article was published, landscape theory has been successfully applied in an entirely new domain and made accurate predictions of the alignment of nine computer firms seeking to establish standards for the UNIX operating system.[6] Complete documentation, source codes, input information, and numerical results of both applications are now available as part of the supplementary material for a book by Axelrod.[7] This material is on the Internet at http://pscs.physics.lsa.umich.edu/Software/ComplexCoop.html.

[6] Robert Axelrod, Will Mitchell, Robert E. Thomas, D. Scott Bennett and Erhard Bruderer, 'Coalition Formation in Standard-Setting Alliances', *Management Science*, 41 (1995), 1493–508.

[7] Robert Axelrod, *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration* (Princeton, NJ: Princeton University Press, 1997).

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