

On Coalition Formation in Simple Games: A Mathematical Analysis of Caplow's and Gamson's Theories¹

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In this paper, we propose a theory of coalition formation in simple games. The process of coalition formation is modeled as an abstract game. Two solutions of abstract games, the core and the dynamic solution, are used as the predictions of our model. Two classical theories of coalitions in sociology due to Caplow and Gamson are reformulated in a more general and mathematical setting. These theories are then analyzed using the techniques of our theory.

1. INTRODUCTION

This paper deals with the question of coalition formation in simple games. Coalition formation has been the subject of many empirical and theoretical studies in the social sciences. There are a number of simple theories which essentially consist of a hypothesis concerning the player's goals or motives, a premise concerning their payoffs and an inference which singles out the coalitions most likely to form. Some of these theories are reviewed in Shenoy (1977a).

Regarding simple games, the main thrust of the research in game theory has been in determining an index which measures the power of each player and very little has been done regarding coalition formation. Here, assuming we have a "power index," i.e., a rule governing the distribution of power to each player in each coalition structure, we model the process of coalition formation as an abstract game. The core and the dynamic solution of the abstract game are then used as the predictions of our model. Thus, the proposed theory only accounts for coalition structures and this is achieved by assuming that a payoff allocation rule is given.

Two classical theories of coalition formation due to Caplow and Gamson are reformulated in a slightly more general and mathematical setting. These theories are then analyzed using the techniques of our theory.

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In Section 2, we review the core and the dynamic solution of abstract games. Simple games are introduced in Section 3. Our model of coalition formation is presented in Section 4. Section 5 contains a representation of our model by means of directed graphs. The predictions of our model are then described in graph theoretic terminology. The mathematical analysis of Caplow's and Gamson's theories are presented in Section 6 and 7, respectively. Finally, Section 8 contains some concluding remarks.

2. THE CORE AND THE DYNAMIC SOLUTION OF ABSTRACT GAMES

An *abstract game* is a pair (X, dom) where X is an arbitrary set whose members are called *outcomes* of the game, and dom is an arbitrary binary relation defined on X and is called *domination*. An outcome $x \in X$ is said to be *accessible* from an outcome $y \in X$, denoted by $x \leftarrow y$ (or $y \rightarrow x$), if there exists outcomes $z_0 = x, z_1, z_2, \dots, z_{m-1}, z_m = y$, where m is a positive integer such that

$$x = z_0 \text{ dom } z_1 \text{ dom } z_2 \text{ dom } \cdots \text{ dom } z_{m-1} \text{ dom } z_m = y.$$

Also assume $x \leftarrow x$, i.e., an outcome is accessible from itself. Clearly the binary relation accessible is transitive.

An interpretation of the relation accessible is as follows: If the players are considering an outcome y at some stage, then an outcome they will consider next will be a $z \in X$ such that $z \text{ dom } y$. If $x \leftarrow y$ and if the players are considering outcome y at some time, then it is possible that they will consider outcome x at some future time, i.e., one may interpret the relation as a possible succession of transitions from one outcome to another.

Two outcomes x and y which are accessible to each other are said to *communicate* and we write this as $x \leftrightarrow y$. Since the relation accessible is transitive and reflexive it follows that communication is an equivalence relation. We can now partition the set X into *equivalence classes*. Two outcomes are in the same equivalence class if they communicate with each other.

The *core* C (due to Gillies (1959) and Shapley) of an abstract game is defined to be the set of undominated outcomes. We can rewrite the definition of the core in terms of the relation accessible as follows.

$$C = \{x \in X : \text{For all } y \in X, y \neq x, \text{ we have } y \nleftarrow x\}.$$

In the terminology of Markov chains, the core is the set of all *absorbing* outcomes. Note that each outcome in the core (if nonempty) is an equivalence class by itself.

We define an *elementary dynamic solution* (elem. d -solution) of an abstract game (X, dom) as a set $S \subset X$ such that

$$\text{if } x \in S, \quad y \in X - S, \quad \text{then } y \nleftarrow x \text{ and} \quad (1)$$

$$\text{if } x, y \in S, \quad \text{then } x \leftrightarrow y. \quad (2)$$

Condition (1) requires S to be 'externally stable' in a dynamic sense, i.e., if the players are considering $x \in S$ at some time, then they will never consider any outcome that is not in S in the future. We can think of Condition (2) as 'internal stability' in a dynamic sense, i.e., if the players make a transition (in the consideration of outcomes) from x to y , then it is possible that the players will again reconsider the outcome x in the future.

Note that an elem. d -solution is an equivalence class. The converse, however, is not always true, i.e., an equivalence class need not be an elem. d -solution. Condition (1) requires S to be (in the terminology of Markov chains) a *nontransient* equivalence class. Also note that each outcome in the core is an elem. d -solution.

The *dynamic solution* (d -solution) P of an abstract game is the union of all distinct elementary dynamic solutions, i.e.,

$$P = \bigcup \{S \subset X : S \text{ is an elem. } d\text{-solution}\}.$$

The following are easy consequence of the definition.

PROPOSITION 2.1. *Let $\Gamma = (X, \text{dom})$ be any abstract game. Then $C \subset P$.*

THEOREM 2.2. *If X is a finite set, then the dynamic solution of the abstract game (X, dom) is always nonempty and is a unique set.*

Proof. See Shenoy (1977b).

The dynamic solution has also been defined independently by Kalai, Pazner, and Schmeidler (1976).

In Section 5, abstract games are represented in terms of directed graphs. The core and the dynamic solution are then described in terms of certain properties of directed graphs. This may help illustrate some of the concepts presented in this section.

3. SIMPLE GAMES

Simple games form a certain class of n -person cooperative games in which each coalition that might form is either all powerful or completely ineffectual. Let $N = \{1, \dots, n\}$ denote the set of all *players* indexed by the first n natural numbers. Nonempty subsets of N are called *coalitions*. A *simple game* can be represented by a pair $(N, \mathcal{W})$, where $\mathcal{W}$ is the set of all *winning* coalitions. All coalitions that are not in the set $\mathcal{W}$ are called *losing* coalitions. A simple game is said to be *monotonic* if any coalition that contains a winning coalition is winning; and *proper* if the complement of every winning coalition is losing. A winning coalition R is called *minimal winning* if every proper subset of R is losing. A monotonic simple game can also be represented by the pair $(N, \mathcal{W}^m)$, where $\mathcal{W}^m$ is the set of all minimal winning coalitions. Note that the set $\mathcal{W}$ is the set of all supersets of the elements of $\mathcal{W}^m$.

If $k \notin \bigcup \mathcal{W}^m$, then player k is said to be a *dummy*. If $\mathcal{W}^m = \{\{i\}\}$, then player i is called a *dictator* and all other players are of course dummies. If $j \in \bigcap \mathcal{W}^m \neq \phi$, then player j is said to be a *veto player*.

A *weighted majority game* is a monotonic simple game that can be represented by the symbol

$$[q; a_1, \dots, a_n], \quad (3)$$

where $q \geq 0$ is called the *quota*, $a_i \geq 0$ is the *weight* associated with the i th player and $R \in \mathcal{W} \Leftrightarrow \sum_{i \in R} a_i \geq q$. Note that the weighted majority game represented by (3) is proper if $q > (a_1 + \dots + a_n)/2$.

See Shapley (1962) for a detailed description of simple games. Also Lucas (1976) presents several real-life examples of organizations, committees, and legislatures modeled as simple games.

4. A MODEL OF COALITION FORMATION

Let Γ be a n -person simple game. Let 2^N denote the set of all nonempty subsets (*coalitions*) of N and Π denote the set of all partitions (*coalition structures*) of N . Let $\varphi: \Pi \rightarrow E^n$ be a *power index* (p.i.), where E^n denotes the n -dimensional Euclidean space. Intuitively, given that players in N align themselves into coalitions in the coalition structure (c.s.) $\mathcal{P} \in \Pi$, we interpret $\mathcal{S}(\mathcal{P})$ as a vector in E^n whose i th component $\mathcal{S}(\mathcal{P})(i)$ is a numerical measure of player i 's power, e.g., $\mathcal{S}$ may denote the Shapley–Shubik power index, the Banzhaf–Coleman power index, the nucleolus, etc.

We can regard Π as the set of outcomes of an abstract game. We define a binary relation on Π as follows.

Let $\mathcal{P}_1, \mathcal{P}_2 \in \Pi$, and $\mathcal{S}$ be a p.i. Then $\mathcal{P}_1$ *dominates* $\mathcal{P}_2$ *with respect to p.i. $\mathcal{S}$* , denoted by $\mathcal{P}_1 \text{ dom}(\mathcal{S}) \mathcal{P}_2$, iff

$$\exists \text{ a nonempty } R \in \mathcal{P}_1 \text{ such that } \mathcal{S}(\mathcal{P}_1)(i) > \mathcal{S}(\mathcal{P}_2)(i) \forall i \in R.$$

Intuitively, if $\mathcal{P}_1 \text{ dom}(\mathcal{S}) \mathcal{P}_2$, then the players in some coalition R in c.s. $\mathcal{P}_1$ prefer $\mathcal{P}_1$ to $\mathcal{P}_2$. We require the players in subset R to be together in a coalition in c.s. $\mathcal{P}_1$ so that there is no conflict of interest between these players' preference for $\mathcal{P}_1$ and their allegiance to the other players in their coalition.

The dominance relation as defined above may be neither asymmetric nor transitive. We now have an abstract game $(\Pi, \text{dom}(\mathcal{S}))$, where Π is the set of outcomes and $\text{dom}(\mathcal{S})$ is a binary relation on Π . Let $K_0(\mathcal{S})$ and $K_1(\mathcal{S})$ denote the core and the dynamic solution respectively of this abstract game. By Proposition 2.1, we have $K_0(\mathcal{S}) \subset K_1(\mathcal{S})$. It is conceivable that $K_0(\mathcal{S})$ may sometimes be empty. However, since N is a finite set, Π is a finite set and hence by Theorem 2.2 we have $K_1(\mathcal{S}) \neq \emptyset$. $K_0(\mathcal{S})$ and $K_1(\mathcal{S})$ can be considered as the predictions of our model.

In Section 6, several examples of abstract games $(\Pi, \text{dom}(\mathcal{S}))$ are exhibited where $\mathcal{S}$ is replaced by κ , the Caplow power index defined in that section. These examples help illustrate the model presented in this section.

5. REPRESENTATION BY DIGRAPHS

Since the number of coalition structures is finite, we can represent the abstract game $(\Pi, \text{dom}(\mathcal{S}))$ by means of a directed graph (or digraph). Let D be a digraph whose vertex set $V(D) = \Pi$ and whose arc set $A(D)$ is given by

$$A(D) = \{(\mathcal{P}_1, \mathcal{P}_2) \in \Pi \times \Pi : \mathcal{P}_2 \text{ dom}(\mathcal{S}) \mathcal{P}_1\}.$$

We call such a digraph D the *transition digraph* of the abstract game $(\Pi, \text{dom}(\mathcal{S}))$.

Let $(\mathcal{P}_1, \mathcal{P}_2) \in A(D)$. Then we say $\mathcal{P}_1$ is *adjacent to* $\mathcal{P}_2$ and $\mathcal{P}_2$ is *adjacent from* $\mathcal{P}_1$. The *outdegree*, $\text{od}(\mathcal{P})$, for $\mathcal{P} \in \Pi$ is the number of c.s.'s adjacent from it and the *indegree*, $\text{id}(\mathcal{P})$, for $\mathcal{P} \in \Pi$ is the number adjacent to it. Then in terms of this terminology, the core of the abstract game $(\Pi, \text{dom}(\mathcal{S}))$ is given by

$$K_0(\mathcal{S}) = \{\mathcal{P} \in \Pi : \text{od}(\mathcal{P}) = 0\}.$$

To define the dynamic solution in terms of the transition digraph, we need a few more basic definitions from graph theory (cf. Harary (1969)). A (*directed*) *walk* in a digraph is an alternating sequence of vertices and arcs $\mathcal{P}_0, e_1, \mathcal{P}_1, \dots, e_n, \mathcal{P}_n$ in which each arc e_i is $(\mathcal{P}_{i-1}, \mathcal{P}_i)$. A *closed walk* has the same first and last vertex. A *path* is a walk in which all vertices are distinct; a *cycle* is a nontrivial closed walk with all vertices distinct (except the first and the last). If there is a path from $\mathcal{P}_1$ to $\mathcal{P}_2$, then $\mathcal{P}_2$ is said to be *accessible from* $\mathcal{P}_1$. A digraph is *strongly connected* or *strong* if any two vertices are mutually accessible. A *strong component* of a digraph is a maximal strong subgraph. Let $T_1, T_2, \dots, T_m$ be the strong components of D . The *condensation* D^* of D has the strong components of D as its vertices, with an arc from T_i to T_j whenever there is at least one arc in D from a vertex of T_i to a vertex of T_j (see Fig. 1). It follows from the maximality of strong components that the condensation D^* of any graph has no cycles. The dynamic solution of the abstract game $(\Pi, \text{dom}(\mathcal{S}))$ is given by

$$K_1(\mathcal{S}) = \bigcup \{T_i : \text{od}(T_i) = 0 \text{ in the condensation } D^*\}.$$

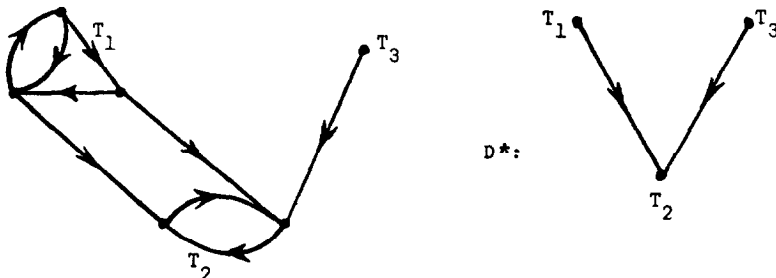


FIG. 1. A digraph and its condensation.

6. A MATHEMATICAL ANALYSIS OF CAPLOW'S THEORY OF COALITIONS IN THE TRIAD

Much of the recent research on coalition formation in sociology and psychology was generated by a paper by Caplow (1956). Caplow proposes that the formation of coalitions

depends upon the initial distribution of power, and other things being equal, may be predicted under certain assumptions when the initial distribution of power is known. (Caplow (1956))

Caplow's four assumptions are:

A.1. Members of a triad may differ in strength. A stronger member can control a weaker member and will seek to do so.

A.2. Each member of the triad seeks control over the others. Control over two others is preferred to control over one other. Control over one other is preferred to control over none.

A.3. Strength is additive. The strength of a coalition is equal to the sum of the strengths of its two members.

A.4. The formation of coalitions takes place in an existing triadic situation, so that there is a precoalition condition in every triad. Any attempt by a stronger member to coerce a weaker member into joining a nonadvantageous coalition will provoke the formation of an advantageous coalition to oppose the coercion.

Caplow enumerates six different triadic power structures and, based on his assumptions, makes predictions as to which coalitions will form in each type of triad. In a subsequent paper, Caplow (1959) lists two more types of triads that were overlooked in the original presentation along with his predictions. The predictions are listed in Table 1. Before we compare our theories with Caplow's theory, we will restate Caplow's theory in a mathematical setting.²

Let Γ be an n -person weighted majority game

$$[q; a_1, \dots, a_n], \quad \text{where } q > (a_1 + \dots + a_n)/2,$$

and let $\mathcal{W}$ denote the set of all winning coalitions in Γ . Let i and j be two distinct players. We say that *player i controls player j in coalition structure $\mathcal{P}$* iff either

$$a_i > a_j, \quad \text{and} \quad i, j \in R \in \mathcal{W}, R \in \mathcal{P}, \quad \text{or} \quad i \in R \in \mathcal{W}, j \notin R, R \in \mathcal{P}.$$

Let $\beta(\mathcal{P})(i)$ denote the number of players player i controls in c.s. $\mathcal{P}$. The *Caplow Power Index*, denoted by κ , is defined as follows:

$$\begin{aligned} \kappa(\mathcal{P})(i) &= \beta(\mathcal{P})(i) / \sum_{j \in N} \beta(\mathcal{P})(j) & \text{if } \sum_{j \in N} \beta(\mathcal{P})(j) \neq 0 \\ &= 0 & \text{otherwise} \end{aligned}$$

² The author assumes full responsibility for the ensuing formulation, which, though never formally stated, is implicit in Caplow (1956).

TABLE 1
A Comparison of Caplow's Predictions with $K_0(\kappa)$

Triad type	Distribution of resources	Equivalent weighted majority representation	Predictions	
			Caplow	$K_0(\kappa)$
1	$A = B = C$	[2; 1, 1, 1]	$(AB)(C), (AC)(B), (A)(BC)$	$(AB)(C), (AC)(B), (A)(BC)$
2	$A > B, B = C, A < (B + C)$	[4; 3, 2, 2]	$(A)(BC)$	$(A)(BC)$
3	$A < B, B = C$	[3; 1, 2, 2]	$(AB)(C), (AC)(B)$	$(AB)(C), (AC)(B)$
4	$A > (B + C), B = C$	[3; 3, 1, 1]	$(A)(B)(C)$	$(A)(B)(C), (A)(BC), (ABC)$
5	$A > B > C, A < (B + C)$	[5; 4, 3, 2]	$(AC)(B), (A)(BC)$	$(AC)(B), (A)(BC)$
6	$A > B > C, A > (B + C)$	[4; 4, 2, 1]	$(A)(B)(C)$	$(A)(B)(C), (A)(BC)$
7	$A > B > C, A = (B + C)$	[4; 3, 2, 1]	$(AB)(C), (AC)(B)$	$(AB)(C), (AC)(B), (ABC)$
8	$A = (B + C), B = C$	[3; 2, 1, 1]	$(AB)(C), (AC)(B)$	$(AB)(C), (AC)(B), (ABC)$

for all $i \in N$ and all $\mathcal{P} \in \Pi$. Intuitively, $\kappa(\mathcal{P})(i)$ denotes the relative power of player i when the players are aligned as in c.s. $\mathcal{P}$.³

We are now in a position to compare Caplow's predictions with the predictions of our theory. Examples 1–8 deal with the eight different types of triads analyzed by Caplow. At the end of each example, we quote Caplow's analysis of the triad, partly to justify our definition of the Caplow power index.

EXAMPLE 1. Consider the Type 1 triad $[2; \frac{1}{2}, \frac{1}{2}, \frac{1}{2}]$. Then the Caplow power index, κ , is given by

$$\begin{aligned}\kappa(\mathcal{P}) &= (0, 0, 0) && \text{if } \mathcal{P} = (A)(B)(C) \\ &= (\frac{1}{2}, \frac{1}{2}, 0) && \text{if } \mathcal{P} = (AB)(C) \\ &= (\frac{1}{2}, 0, \frac{1}{2}) && \text{if } \mathcal{P} = (AC)(B) \\ &= (0, \frac{1}{2}, \frac{1}{2}) && \text{if } \mathcal{P} = (A)(BC) \\ &= (0, 0, 0) && \text{if } \mathcal{P} = (ABC).\end{aligned}$$

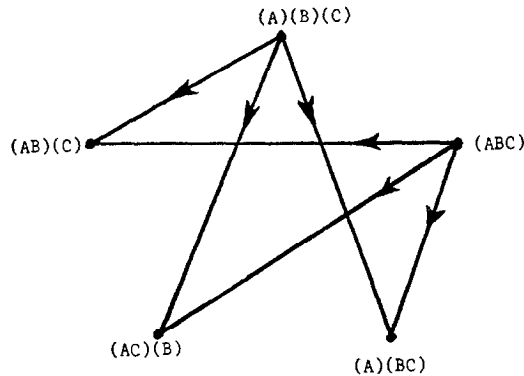


FIG. 2. The transition digraph of Type 1 triad.

The transition digraph is as in Fig. 2. $K_0(\kappa) = \{(AB)(C), (AC)(B), (A)(BC)\}$. Caplow argues:

... each member strives to enter a coalition within which he is equal to his ally and stronger (by virtue of the coalition) than the isolate. (Caplow, 1956.)

EXAMPLE 2. Consider the Type 2 triad $[4; \frac{3}{2}, \frac{2}{2}, \frac{2}{2}]$. Then the Caplow power index, κ , is given by

$$\begin{aligned}\kappa(\mathcal{P}) &= (0, 0, 0) && \text{if } \mathcal{P} = (A)(B)(C) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) && \text{if } \mathcal{P} = (AB)(C) \\ &= (\frac{2}{3}, 0, \frac{1}{3}) && \text{if } \mathcal{P} = (AC)(B) \\ &= (0, \frac{1}{2}, \frac{1}{2}) && \text{if } \mathcal{P} = (A)(BC) \\ &= (1, 0, 0) && \text{if } \mathcal{P} = (ABC).\end{aligned}$$

³ Note that, although Caplow stated his theory only for the restricted case of triads, our formulation of Caplow's theory holds for the more general case of n -person proper weighted majority games.

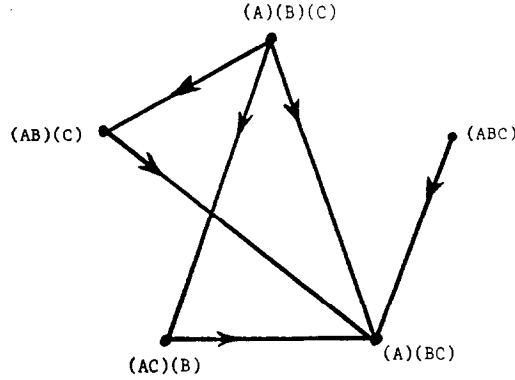


FIG. 3. The transition digraph of Type 2 triad.

The transition digraph is shown in Fig. 3. $K_0(\kappa) = \{(A)(BC)\}$. Caplow argues:

... Consider the position of B . If he forms a coalition with A , he will (by virtue of the coalition) be stronger than C , but within the coalition he will be weaker than A . If, on the other hand, he forms a coalition with C , he will be equal to C within the coalition and stronger than A by virtue of the coalition. The position of C is identical with that of B . (Caplow, 1956.)

EXAMPLE 3. Consider the Type 3 triad $[3; \begin{smallmatrix} 1,2,2 \\ ABC \end{smallmatrix}]$. Then the Caplow power index, κ , is given by

$$\begin{aligned} \kappa(\mathcal{P}) &= (0, 0, 0) & \text{if } \mathcal{P} &= (A)(B)(C) \\ &= (\tfrac{1}{3}, \tfrac{2}{3}, 0) & \text{if } \mathcal{P} &= (AB)(C) \\ &= (\tfrac{1}{3}, 0, \tfrac{2}{3}) & \text{if } \mathcal{P} &= (AC)(B) \\ &= (0, \tfrac{1}{2}, \tfrac{1}{2}) & \text{if } \mathcal{P} &= (A)(BC) \\ &= (0, \tfrac{1}{2}, \tfrac{1}{2}) & \text{if } \mathcal{P} &= (ABC). \end{aligned}$$

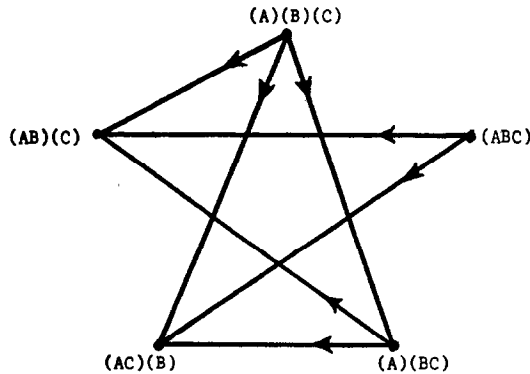


FIG. 4. The transition digraph of Type 3 triad.

The transition digraph is shown in Fig. 4. $K_0(\kappa) = \{(AB)(C), (AC)(B)\}$. Caplow argues:

... A may strengthen his position by forming a coalition with either B or C, and will be welcomed as an ally by either B or C. On the other hand, if B joins C, he does not improve his pre-coalition position of equality with C and superiority to A. His only motive to enter a coalition with C is to block AC. However, C's position is identical with B and he, too, will prefer A to B as an ally. (Caplow, 1956.)

EXAMPLE 4. Consider the Type 4 triad $[3; \frac{3}{ABC}]$. Then the Caplow power index, κ , is given by

$$\begin{aligned}\kappa(\mathcal{P}) &= (1, 0, 0) && \text{if } \mathcal{P} = (A)(B)(C) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) && \text{if } \mathcal{P} = (AB)(C) \\ &= (\frac{2}{3}, 0, \frac{1}{3}) && \text{if } \mathcal{P} = (AC)(B) \\ &= (1, 0, 0) && \text{if } \mathcal{P} = (A)(BC) \\ &= (1, 0, 0) && \text{if } \mathcal{P} = (ABC).\end{aligned}$$

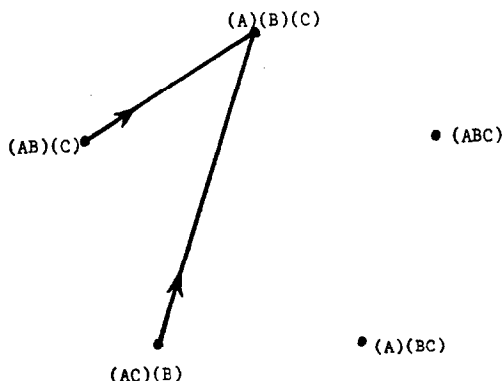


FIG. 5. The transition digraph of Type 4 triad.

The transition digraph is shown in Fig. 5. $K_0(\kappa) = \{(A)(B)(C), (A)(BC), (ABC)\}$. Caplow argues:

... B and C have no motive to enter a coalition with each other. Once formed, the coalition would still be weaker than A and they would still be equal within it. A on the other hand, has no motive to form a coalition with B or C, since he is stronger than each of them and is not threatened by their coalition. No coalition will be formed, unless B or C can find some extraneous means of inducing A to join them. (Caplow, 1956.)

EXAMPLE 5. Consider the Type 5 triad $[5; \frac{4,3,2}{ABC}]$. Then the Caplow power index, κ , is given by

$$\begin{aligned}\kappa(\mathcal{P}) &= (0, 0, 0) && \text{if } \mathcal{P} = (A)(B)(C) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) && \text{if } \mathcal{P} = (AB)(C) \\ &= (\frac{2}{3}, 0, \frac{1}{3}) && \text{if } \mathcal{P} = (AC)(B) \\ &= (0, \frac{2}{3}, \frac{1}{3}) && \text{if } \mathcal{P} = (A)(BC) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) && \text{if } \mathcal{P} = (ABC).\end{aligned}$$

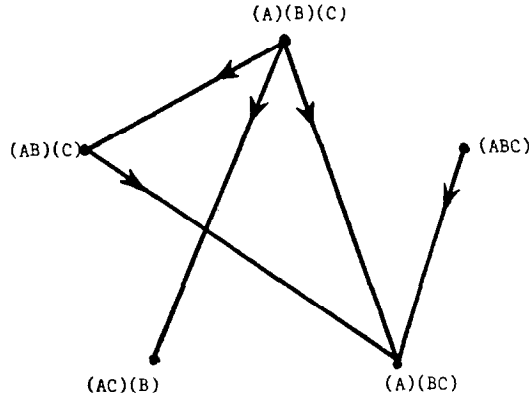


FIG. 6. The transition digraph of Type 5 triad.

The transition digraph is shown in Fig. 6. $K_0(\kappa) = \{(AC)(B), (A)(BC)\}$. Caplow argues:

... A seeks to join both B and C and C seeks to join both A and B but B has no incentive to enter a coalition with A and has a very strong incentive to enter a coalition with C . Whether the differential strength of A and B will make them differentially attractive to C lies outside the scope of our present assumptions. (Caplow, 1956.)

EXAMPLE 6. Consider the Type 6 triad $[4; \frac{4}{3}, \frac{2}{3}, 1]$. Then the Caplow power index, κ , is given by

$$\begin{aligned} \kappa(\mathcal{P}) &= (1, 0, 0) & \text{if } \mathcal{P} &= (A)(B)(C) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) & \text{if } \mathcal{P} &= (AB)(C) \\ &= (\frac{2}{3}, 0, \frac{1}{3}) & \text{if } \mathcal{P} &= (AC)(B) \\ &= (1, 0, 0) & \text{if } \mathcal{P} &= (A)(BC) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) & \text{if } \mathcal{P} &= (ABC). \end{aligned}$$

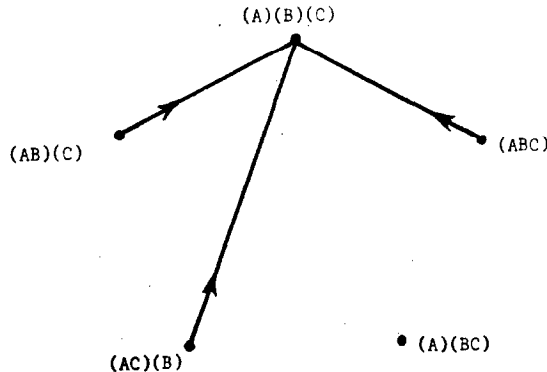


FIG. 7. The transition digraph of Type 6 triad.

The transition digraph is as in Fig. 7. $K_0(\kappa) = \{(A)(B)(C), (A)(BC)\}$. Caplow argues:

... A is stronger than B and C combined and has no motive to form a coalition. As in Type 4, true coalition is impossible. However, while in Type 4 both of the weaker members seek to join the stronger member, only C can improve his position by finding some extraneous means of inducing A to join him. (Caplow, 1956.)

By claiming that only C can improve his position by joining A , Caplow seems to imply that B controls C in the c.s. $(A)(B)(C)$. Such an assumption seems unreasonable to us and we resolve this small discrepancy by suggesting that Caplow has erred in making such a claim. Note that a similar discrepancy arises in Caplow's analysis of the Type 3 triad where he claims that B is superior to A in c.s. $(A)(B)(C)$.

EXAMPLE 7. Consider the Type 7 triad $[4; \frac{3,2,1}{ABC}]$. Then the Caplow power index, κ , is given by

$$\begin{aligned} \kappa(\mathcal{P}) &= (0, 0, 0) & \text{if } \mathcal{P} &= (A)(B)(C) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) & \text{if } \mathcal{P} &= (AB)(C) \\ &= (\frac{2}{3}, 0, \frac{1}{3}) & \text{if } \mathcal{P} &= (AC)(B) \\ &= (0, 0, 0) & \text{if } \mathcal{P} &= (A)(BC) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) & \text{if } \mathcal{P} &= (ABC). \end{aligned}$$

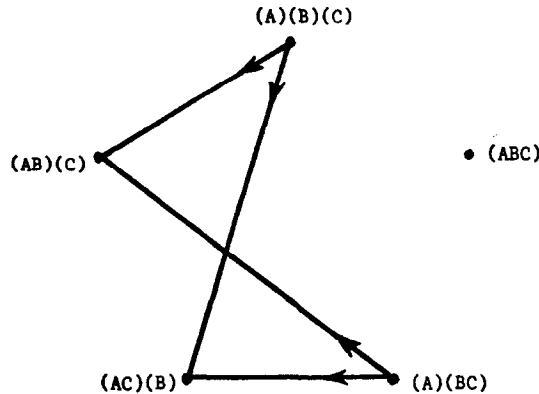


FIG. 8. The transition digraph of Types 7 and 8 triads.

The transition digraph is shown in Fig. 8. Hence, $K_0(\kappa) = \{(AB)(C), (AC)(B), (ABC)\}$.

EXAMPLE 8. Consider the Type 8 triad $[3; \frac{2,1,1}{ABC}]$. Then the Caplow power index, κ , is given by

$$\begin{aligned} \kappa(\mathcal{P}) &= (0, 0, 0) & \text{if } \mathcal{P} &= (A)(B)(C) \\ &= (\frac{2}{3}, \frac{1}{3}, 0) & \text{if } \mathcal{P} &= (AB)(C) \\ &= (\frac{2}{3}, 0, \frac{1}{3}) & \text{if } \mathcal{P} &= (AC)(B) \\ &= (0, 0, 0) & \text{if } \mathcal{P} &= (A)(BC) \\ &= (1, 0, 0) & \text{if } \mathcal{P} &= (ABC). \end{aligned}$$

The transition digraph is as in Fig. 8. Hence, $K_0(\kappa) = \{(AB)(C), (AC)(B), (ABC)\}$. For the Type 7 and 8 triads, Caplow argues:

... the combined strength of *B* and *C* is exactly equal to *A*, so that no effective coalition of *B* and *C* is strategically possible. In other words, although a coalition of *B* and *C* can block the dominance of *A*, it is not sufficient to control the situation, and, therefore, the probable coalitions under the standard assumptions are *AB* or *AC*. (Caplow, 1959.)

This completes our analysis of the eight different triads. The results are summarized in Table 1. A comparison reveals almost total agreement. All the c.s.'s predicted by Caplow are predicted by our theory. The only disagreements are in Types 4, 6, 7, 8, where our theory predicts more c.s.'s than predicted by Caplow. However, this can easily be explained. Caplow implicitly assumes that in every triad, bargaining for coalitions start from the c.s. $(A)(B)(C)$. A quick look at Figs. 2–8, will reveal that with this additional assumption, our theory gives exactly the same predictions as Caplow's.

Vinacke and Arkoff conducted experiments to test Caplow's theory.⁴ Their results, shown in Table 2, tend to support Caplow's theory in general with a few disagreements

TABLE 2

Coalition Structures Formed in the Six Types of Triads in the Vinacke–Arkoff Experiments

Coalition structures	Type and equivalent weighted majority representation					
	1 [2; 1, 1, 1]	2 [4; 3, 2, 2]	3 [3; 1, 2, 2]	4 [3; 3, 1, 1]	5 [5; 4, 3, 2]	6 [4; 4, 2, 1]
$(A)(B)(C)$	8	1	11	62	2	60
$(AB)(C)$	33	13	24	11	9	9
$(AC)(B)$	17	12	40	10	20	13
$(A)(BC)$	30	64	15	7	59	8
(ABC)	2	0	0	0	0	0
Total	90	90	90	90	90	90

⁴ See Vinacke and Arkoff (1957) for a detailed description of their experiments. We briefly sketch their method here. The subjects of the experiment played a game on a modified pachisi board in which only the external lanes of the board were used. The object of the game was to reach "home" first and the winner was awarded a prize of 100 points. In the event a coalition formed, the prize was shared between the allies in a manner agreed upon by all the allies. A single die, cast by the experimenter was used. Each player was entitled to move forward the number of spaces equal to his weight times the number shown by the die. All the players started from the home base and moved simultaneously. At anytime during the game, any player, in return for a promise of a specified portion of the prize, could form an alliance with any other player. In this case, the allies immediately pooled their strengths and proceeded to a position equal to their combined acquired spaces; in future throws they moved forward according to their combined weights (times the die). Once an alliance was formed it was considered permanent for that game. (We have quoted Vinacke and Arkoff (1957) almost verbatim here.)

especially in the case of Type 3 and Type 5 triads. In the Type 3 triad, Caplow predicts coalition structures $(AB)(C)$ and $(AC)(B)$ without any reference to their relative frequency of occurrence. However Vinacke and Arkoff note that in the Type 3 triad, c.s. $(AC)(B)$ occurs more frequently than c.s. $(AB)(C)$. In the Type 5 triad, Caplow predicts coalition structures $(AC)(B)$ and $(A)(BC)$ with the reservation that

... whether the differential strength of A and B will make them differentially attractive to C lies outside the scope of our present assumptions. (Caplow, 1956.)

The results of the Vinacke-Arkoff experiments indicate that in the Type 5 triad, c.s. $(A)(BC)$ occurs more often than c.s. $(AC)(B)$.

Chertkoff (1967) makes an additional assumption which leads to the conclusion that in the Type 5 triad, c.s. $(A)(BC)$ occurs twice as frequently as $(AC)(B)$ and that c.s. $(AB)(C)$ does not occur at all. Also, the same assumption when applied to the case of Type 3 triad leads to the conclusion that c.s.'s $(AB)(C)$ and $(AC)(B)$ are equally likely and c.s. $(A)(BC)$ does not occur at all.

Let us assume that all transitions from each coalition structure are equally likely. Then given an initial probability distribution on the set of all coalition structures, we can compute the probability of formation of each coalition structure in $K_1(\mathcal{S})$, e.g., in the Type 5 triad, given that players start (with probability 1) from c.s. $(A)(B)(C)$, we observe that (Fig. 9) c.s. $(AB)(C)$ forms with probability $\frac{1}{3}$, c.s. $(AC)(B)$ forms with probability $\frac{1}{3}$ and c.s. $(A)(BC)$ forms with probability $\frac{1}{3}$. However, once c.s. $(AB)(C)$ is formed, c.s. $(A)(BC)$ occurs with probability 1. The net result is that c.s. $(A)(BC)$ occurs with probability $\frac{2}{3}$ and c.s. $(AC)(B)$ occurs with probability $\frac{1}{3}$. Coalition structure $(AB)(C)$ also forms with probability $\frac{1}{3}$ but only as an intermediate c.s., i.e., only temporarily.

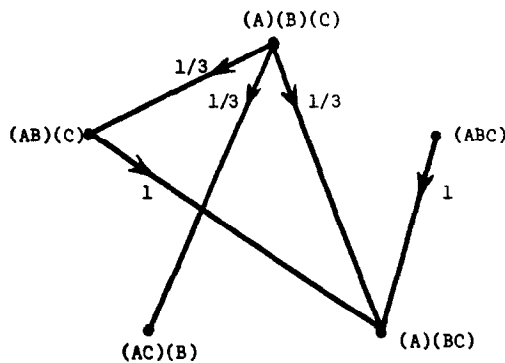


FIG. 9. The transition digraph of Type 5 triad with the probabilities of transitions under the assumption of equiprobable transitions.

A similar analysis of the Type 3 triad (Fig. 10) indicates that, starting from c.s. $(A)(B)(C)$ (with probability 1), c.s. $(AB)(C)$ occurs with probability $\frac{1}{2}$ and c.s. $(AC)(B)$ occurs with probability $\frac{1}{2}$. Coalition structure $(A)(BC)$ occurs only as an intermediate

coalition structure with probability $\frac{1}{3}$. A summary of the predictions of our theories under the assumption of equiprobable transitions is shown in Table 3. Note that these predictions agree quite well with the Vinacke-Arkoff experimental results.

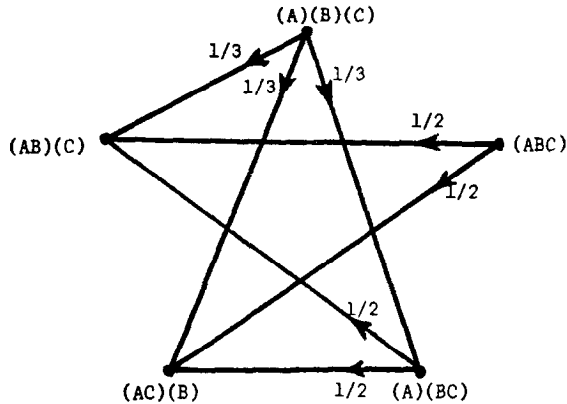


FIG. 10. The transition digraph of Type 3 triad with the probabilities of transitions under the assumption of equiprobable transitions.

TABLE 3

A Summary of the Predictions of the Coalition Structure Model under the Assumption of Equiprobable Transitions

Triad type	Equivalent weighted majority representation	Starting coalition structure (assumed)	Probability	Intermediate coalition structures	Probability	Final coalition structures $K_1(\kappa)$	Probability
1	[2; 1, 1, 1]	(A)(B)(C)	1			(AB)(C) (AC)(B) (A)(BC)	$\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$
2	[4; 3, 2, 2]	(A)(B)(C)	1	(AB)(C) (AC)(B)	$\frac{1}{3}$ $\frac{1}{3}$	(A)(BC)	1
3	[3; 1, 2, 2]	(A)(B)(C)	1	(A)(BC)	$\frac{1}{3}$	(AB)(C) (AC)(B)	$\frac{1}{2}$ $\frac{1}{2}$
4	[3; 3, 1, 1]	(A)(B)(C)	1			(A)(B)(C)	1
5	[5; 4, 3, 2]	(A)(B)(C)	1	(AB)(C)	$\frac{1}{3}$	(AC)(B) (A)(BC)	$\frac{1}{3}$ $\frac{2}{3}$
6	[4; 4, 2, 1]	(A)(B)(C)	1			(A)(B)(C)	1
7	[4; 3, 2, 1]	(A)(B)(C)	1			(AB)(C) (AC)(B)	$\frac{1}{2}$ $\frac{1}{2}$
8	[3; 2, 1, 1]	(A)(B)(C)	1			(AB)(C) (AC)(B)	$\frac{1}{2}$ $\frac{1}{2}$

7. A MATHEMATICAL ANALYSIS OF GAMSON'S THEORY OF COALITION FORMATION

Following Caplow, Gamson formulated a slightly more general theory of coalition formation in proper weighted majority games without dictators or veto players. Before we present Gamson's theory, we need a definition. Let Γ be a weighted majority game. A *cheapest winning coalition* is a winning coalition whose total weight is a minimum among all winning coalitions. Gamson's main hypothesis is as follows:

Any participant will expect others to demand from a coalition a share of the payoff proportional to the amount of resources which they contribute to a coalition. (Gamson, 1961.)

Here, a *participant* refers to a player, and his *resources* refers to his weight in the weighted majority game. Based on his main hypothesis, Gamson makes the following predictions about coalition formation.

- (i) A player will favor a cheapest winning coalition.
- (ii) A coalition of two distinct players $\{i, j\}$ will form if and only if there are reciprocal strategy choices between the two players, i.e., both player i and player j prefer coalition $\{i, j\}$.
- (iii) The process of coalition formation is a step-by-step process where two players merge together into a coalition at a time.
- (iv) Once a two-person coalition forms, the situation becomes a new one—the two players in the coalition are replaced by one player whose weight equals the sum of the weights of the two players in the coalition.

Implicit in Gamson's main hypothesis is a definition of a power index. Let $\Gamma = [q; a_1, \dots, a_n]$ be a proper weighted majority game without a dictator or veto players. Then the *Gamson power index*, denoted by γ , is given by

$$\begin{aligned} \gamma(\mathcal{P})(i) &= a_i / \sum_{i \in R} a_i && \text{if } \sum_{i \in R} a_i \neq 0 \text{ and } R \in \mathcal{W} \\ &= 0 && \text{if } \sum_{i \in R} a_i = 0 \text{ or } R \notin \mathcal{W}, \end{aligned} \quad (7.1)$$

where $R \in \mathcal{P}$ is such that $i \in R$, for all $\mathcal{P} \in \Pi$ and all $i \in N$. Let

$$g = \min_{R \in \mathcal{W}} \sum_{i \in R} a_i$$

and

$$\Pi_g = \{\mathcal{P} \in \Pi : \mathcal{P} \text{ contains a cheapest winning coalition}\}.$$

Then Theorem 7.1 tells us what our model predicts.

THEOREM 7.1. *Let Γ be a proper weighted majority game. Then $K_0(\gamma) = \Pi_g$.*

Proof. Let $\mathcal{P}_1 \in \Pi_g$. Suppose $\mathcal{P}_2 \in \Pi$ such that $\mathcal{P}_2 \text{ dom}_R(\gamma)\mathcal{P}_1$ for some $R \in \mathcal{P}_2$ with $R \in \mathcal{W}$. Then $\gamma(\mathcal{P}_2)(i) > \gamma(\mathcal{P}_1)(i)$ for all $i \in R$. Let $T \in \mathcal{P}_1$ such that $T \in \mathcal{W}$ and $\sum_{i \in T} a_i = g$. Since Γ is proper, $R \cap T \neq \emptyset$. Let $j \in R \cap T$. Then $\gamma(\mathcal{P}_1)(j) = a_j/g$. Since $j \in R$, $\gamma(\mathcal{P}_2)(j) = a_j/(\sum_{i \in R} a_i) > a_j/g$; i.e., $\sum_{i \in R} a_i < g$ and a contradiction (from the definition of g) results. Hence $K_0(\gamma) \supset \Pi_g$.

Let $\mathcal{P}_1 \in \Pi_g$ and $\mathcal{P}_2 \in \Pi$ such that $\mathcal{P}_2 \notin \Pi_g$. Then $\mathcal{P}_1 \text{ dom}_T(\gamma)\mathcal{P}_2$, where $T \in \mathcal{P}_1$ such that $T \in \mathcal{W}$ and $\sum_{i \in T} a_i = g$, because $\gamma(\mathcal{P}_1)(i) = a_i/g$ for all $i \in T$ and $\gamma(\mathcal{P}_2)(i) < a_i/g$ for all $i \in T$. Hence $K_0(\gamma) \subset \Pi_g$. ■

It can be easily shown that Gamson's predictions (i)–(iv) about coalition formation lead to c.s.'s in Π_g . However Gamson assumes that players begin forming coalitions starting from one player coalitions. So if we choose only those c.s.'s in Π_g that are accessible from the c.s. consisting of only one-player coalitions, our model reaches the same conclusions as Gamson's predictions.

8. CONCLUSION

Under the same assumptions, our theory of coalition formation makes the same predictions as Caplow's and Gamson's theories. This, however, should not be misinterpreted as an endorsement of these two theories. Both Caplow's and Gamson's theories are descriptive and depend heavily on their (implicit) definition of a power index. From a normative point of view these power indices have many shortcomings. Several power indices have been defined for simple games. Two of these, the Shapley–Shubik index (Shapley & Shubik, 1954) and the Banzhaf–Coleman index (Banzhaf, 1965, 1966, 1968a, 1968; Coleman, 1971) have been extensively used and studied. Hence it is most appropriate to study the predictions of our model with respect to these power indices. A detailed analysis of the predictions of our theory with respect to the Shapley–Shubik power index is presented by Shenoy (1977c).

REFERENCES

- AUMANN, R. J., & DREZE, J. H. Cooperative games with coalition structures. *International Journal of Game Theory*, 1974, **3**, 217–237.
- BANZHAF, J. F. Weighted voting doesn't work: A mathematical analysis. *Rutgers Law Review*, 1965, **19**, 317–343.
- BANZHAF, J. F. Multi-member electoral districts—Do they violate the “one man, one vote” principle. *Yale Law Journal*, 1966, **75**, 1309–1338.
- BANZHAF, J. F. One man, 3,312 votes: A mathematical analysis of the electoral college. *Villanova Law Review*, 1968a, **13**, 303–346.
- BANZHAF, J. F. One man, ? votes: Mathematical analysis of political consequences and judicial choices. *The George Washington Law Review*, 1968b, **36**, 808–823.
- BRAMS, S. J. *Paradoxes in Politics*. New York: Free Press, 1976.
- CAPLOW, T. A theory of coalitions in the triad. *American Sociological Review*, 1956, **21**, 489–493.
- CAPLOW, T. Further development of a theory of coalitions in the triad. *American Journal of Sociology*, 1959, **64**, 488–493.

- CAPLOW, T. *Two Against One: Coalitions in Triads*. Englewood Cliffs, N.J.: Prentice-Hall, 1968.
- CHERTKOFF, J. M. A revision of Caplow's coalition theory. *Journal of Experimental Social Psychology*, 1967, 3, 172-177.
- COLEMAN, J. S. Control of collectivities and the power of a collectivity to act. In B. Lieberman (Ed.), *Social Choice*. New York: Gordon & Breach, 1971. Pp. 269-300.
- DUBEY, P. Some results on values of finite and infinite games. *Technical Report*, Center for Applied Mathematics, Cornell University, New York, 1975.
- GAMSON, W. A. A theory of coalition formation. *American Sociological Review*, 1961, 21, 373-382.
- GILLIES, D. B. Solutions to general non-zero-sum games. In A. W. Tucker & R. D. Luce (Eds.), *Contributions to the Theory of Games*, Vol. IV, *Annals of Mathematics Studies* No. 40, Princeton: Princeton University Press, 1959. Pp. 47-85.
- GROENING, S., KELLEY, E. W., & LEISERSON, M. (Eds.), *The Study of Coalition Behavior*. New York: Holt, Rinehart & Winston, 1970.
- HARARY, F. *Graph Theory*. Reading, Mass.: Addison-Wesley, 1969.
- KALAI, E., PAZNER, E. A., & SCHMEIDLER, D. Collective choice correspondences as admissible outcomes of social bargaining processes. *Econometrica*, 1976, 44, 223-240.
- KALAI, E., & SCHMEIDLER, D. An admissible set occurring in various bargaining situations. *Discussion Paper* No. 191, The Center for Mathematical Studies in Economics and Management Science, Northwestern University, Illinois, 1975.
- LUCAS, W. F. Measuring power in weighted voting systems. In M. D. Thompson (Ed.), *Case Studies in Applied Mathematics*, Washington, D.C.: The Mathematical Association of America, 1976. Pp. 42-106.
- LUCAS, W. F., & MACELI, J. C. Discrete partition function games. *Technical Report* No. 344, School of Operations Research and Industrial Engineering, Cornell University, New York, 1977.
- VON NEUMANN, J., & MORGENTHAU, O. *Theory of Games and Economic Behavior*. Princeton: Princeton University Press, 1953.
- RIKER, W. H. A new proof of the size principle. In J. L. Bernd (Ed.), *Mathematical Applications in Political Science*, II. Dallas: Southern Methodist University Press, 1966. Pp. 167-174.
- SHAPLEY, L. S. A value for n -person games. In H. W. Huhn and A. W. Tucker (Eds.), *Contributions to the Theory of Games* Vol. II, *Annals of Mathematics Studies* No. 28. Princeton: Princeton University Press, 1953. Pp. 307-317.
- SHAPLEY, L. S. Simple games: An outline of the descriptive theory. *Behavioral Science*, 1962, 7, 59-66.
- SHAPLEY, L. S. A comparison of power indices and a nonsymmetric generalization. *Rand Paper* P-5872, The Rand Corporation, California, 1977.
- SHAPLEY, L. S., & SHUBIK, M. A method for evaluating the distribution of power in a committee system. *American Political Science Review*, 1954, 48, 787-792.
- SHENOY, P. P. On game theory and coalition formation. *Technical Report* No. 342, School of Operations Research and Industrial Engineering, Cornell University, New York, 1977a.
- SHENOY, P. P. A dynamic solution concept for abstract games. *Mathematics Research Center Technical Summary Report* No. 1804, University of Wisconsin-Madison, 1977b.
- SHENOY, P. P. On coalition formation: A game theoretical approach. *Mathematics Research Center Technical Summary Report* No. 1805, University of Wisconsin-Madison, 1977c.
- STRAFFIN, P. D. Power indices in politics. In *Modules in Applied Mathematics*, School of Operations Research and Industrial Engineering, Cornell University, New York, 1976.
- STRAFFIN, P. D. Homogeneity, independence and power indices. *Public Choice*, 1977, 30, 107-118.
- VINACKE, W. E., & ARKOFF, A. An experimental study of coalitions in the triad. *American Sociological Review*, 1957, 22, 406-414.

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