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Elements for a Theory of Teams*

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THE PROBLEM OF ORGANIZATIONS. Organizations have been often compared with machines: armies and navies have been called "fighting machines." A machine is built to fulfill a task. So is a military organization, a government, a business firm.

Living organisms have also been compared with machines, each having presumably the task of achieving a high probability of survival and of reproduction. The organic forms which are by and large best fit for a given environment have been selected in the course of millions of years. Man-made organizations are much younger, and changes in their environment have been rapid. It is hard to believe that these machines, the human organizations as they exist today, could not be fitted better to their environment. To construct and improve machines, is the subject of technology: a normative and not merely descriptive science.

Just as the technology of ordinary machines (and, for that matter, the technology of organisms: e.g. medicine) is helped by the use of well-defined scientific concepts, so might be the technology of human organizations. The modern naval vessel as a highly efficient inanimate machine would not exist if Newton had not,

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250 years ago, laid down his clear definitions of mass and force, to supersede the vague and confused concepts of so-called common sense. But what about the "animated" part of the ship, the group of men that decide what to do with those bits of metal and rubber? Is it possible to analyze the ship's organization (and also the organization in charge of its logistic support, and, in principle, any other organization) by hitting upon a system of concepts that is truly essential and, ultimately, useful? No one trained in science or engineering can get much satisfaction from the analysis of complicated organization problems as they are presented in an administration manual or a business school textbook even when the author is a practical genius of organization. Practical intuition is not teachable: genius cannot be transmitted. But science can be taught and transmitted.

Just as pre-Newtonian physicists talked of "force" in terms of confused common sense, so do we today talk of "line vs. staff," "communication vs. command," "authority and responsibility" — concepts that are ambiguous just because everyone thinks he understands them, and everyone understands them differently. Chemistry would not have advanced if it had used the language of cookbooks. Of the social sciences, economics owes its progress and usefulness to the (comparative!) clarity of its concepts.

Recent attempts to analyze organization problems in a scientific manner were stimulated by the classical economic theory of the firm (Walras, Marshall) and by the newer theories of statistical decision functions (Neymann, Wald), the theory of games (von Neumann and Morgenstern), and the theory of communications (Wiener, Shannon). The Office of Naval Research, and especially its Logistics Branch, has encouraged this development.* The task is big and can be carried out only step by

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* The author is aware, in particular, of the pioneering ideas of C. B. Tompkins and J. Kruskal, formerly at the Logistics Research Project of ONR, George Washington University, in collaboration, at that time, with A. Newell of RAND. The present paper is mainly based on the work of the author carried out, in collaboration with R. Radner and others, within the ONR Project on Decision-Making under Uncertainty at the Cowles Commission for Research in Economics, University of Chicago.

step. The first step has been to study a particularly simple form of organization which we call a team.

TEAMS. We define a team as a group of persons each of whom takes decisions about something different but who receive a common reward as the joint result of all those decisions.

In a business firm, for example, one of the executives is in charge of production, another is in charge of sales, or of personnel, of financing and so on. Their separate decisions in these various fields result jointly in the firm's profit. In a fleet or a civilian government agency, the joint result of the decisions of the several officers is the larger or smaller success score in accomplishing a task.

In discussing teams, we abstract from special interests of its members. We thus eliminate, at this stage of our inquiry, the difficult problems of bargaining and of incentives, problems raised but not solved by the young theory of games between two or more persons. [In fact, in terms of that theory, our "team" (for example, a pair of partners in the game of bridge) is a single person!]

Clearly, the team's success score depends not only on the members' decisions but also on the external situation not under their control. A table that describes how the score is determined by all decisions and all external conditions is called "gross score table" (or gross score function, a function of as many variables as there are decision makers plus the number of situation variables). It is exemplified in Table A, below.

INFORMATION. Further, it is clear that people should be able to take better (or at least not worse) decisions, if they know much about the external situation than if they know little. But to keep each member of the team in precise knowledge about everything that is relevant to the team as a whole, the team would have to incur heavy costs of information. For it would have to maintain and operate a vast network of observation posts and communication links (besides running the risks of garbling and interception of messages, and of congestion of data on the desk or in the head of the decision maker; these we shall not discuss here, or shall consider included in the "cost").

Accordingly, when each executive of a business firm makes his decision he bases it not only on those facts known to them all, such as, for example, the data on the general financial prospects of the firm, as circularized from a center or pieced together at a conference. He bases his decision also on his special or local information. Moreover, some data he needs to know precisely; others, only approximately. I presume (as a layman) the same is true of a fleet. It is not necessary for every officer to be informed about everything.

This is precisely the problem that faces the organizer of a team: How to balance the advantages of fuller information against its cost. The more information at the disposal of each member the higher is the gross success score of the team. From this, the cost of information is to be deducted. A team is efficient if the net score is maximized.

Further: The information at the basis of each decision may be the knowledge of some constants — e.g., of the laws of physics or of naval tactics, learned by the engineer or admiral, in school and through experience. But, in addition, one needs information about the ever varying situation: for example, about tomorrow's weather and market prices, in the business of farming; about local requirements for gasoline, in the logistic problem of multi-branch storage; about the weather and the enemy dispositions in various parts of the sea, in the business of naval fighting.*

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* I submit that, by and large, "staff" officers know the constants, while "line" officers have information on the values actually taken by random variables.

In this article, we shall concentrate on information in the sense of those day-to-day random variations. We shall assume that the organizer of the team knows all the relevant physical (or military) constants. This implies that he knows with what probabilities the weather or prices of local gas requirements, or enemy's dispositions, etc. will be such-and-such rather than so-and-so — as exemplified in Table B, below. He also knows the gross score table (such as Table A, already mentioned). Therefore he can compute the expected gross score. This is the gross score that would be obtained in the long-run average, if each team member would be given a certain specified part of the information and would respond to it according to some specified decision rule ("do this if you learn that"). He also knows the cost of conveying those specified parts of information (a cost that, too, may depend on the external situation). Thus, the expected net score can be computed for any given system of communication and any given set of decision rules.

Hence the team problem: find the best communication system and the best decision rules, given the gross score table, the probabilities of situations, and the cost of communication.

SCORING. We have assumed that the success of the team can be scored on the scale that has the following property: a higher expected net score is to be preferred to a lower one. Such a scale is called "utility scale" by economists; while, I believe, soldiers and sailors speak of "military worth." In the simplest case the scale may have just two points: "1" for success (however small), "0" for failure (however disastrous). In this case the expected score is identical with the probability of success (because it is equal to 1 times this probability, plus 0 times the probability of failure). But more detailed scales are in use by decision-makers and organizers of teams, albeit often only semi-consciously. They are mostly guided by some numerical facts, taken singly or in combination: dollars;

casualties; weapons or territory taken or lost; finally the estimated gain or loss in the "posture" — i.e., in the probability of success of some super-team such as the nation itself, — for example in the probability of national victory.

In this short paper the author will permit himself to skip the difficult problem of actual scoring, and of how to train responsible people to think in scores. He states the hope that tables expressing the score as a function of decisions and situations will become a recognized tool.

SIMPLE MODELS. In the meantime, let us construct such tables hypothetically, and study their implications, step by step. Admittedly, such simple models are highly unrealistic. Bodies falling in a vacuum or deprived of dimensions were simple models too. To calculate the capacity of a bridge represented by a web of geometric lines seems also unrealistic. Yet, such abstractions have created useful clarity where there was confusion. This is encouraging.

A TWO-MEMBER TEAM. Let a team consist of just two members (call them I and II), each having to decide whether "to act" in some unique way, or "not to act": for example, whether or not to attack the enemy. We thus have two two-valued decision-variables. Further, let x_1 and x_2 be two situation variables: for example, the strength of enemy forces near the first and near the second team member, respectively. Finally, suppose that each situation variable can take three values: "unfavorable to us" (denoted by $-$), "favorable to us" (denoted by $+$), and "medium" (denoted by 0); thus, $-$, $+$, and 0 may correspond to the enemy in a given locality being strong, weak, or of medium strength. A particularly simple gross score function is represented on Table A.

TABLE A*

Gross Scores (Without Interaction)

	x_1= \ x_2=	II doesn't act -	II doesn't act 0	II doesn't act +	II acts -	II acts 0	II acts +
I doesn't	-	0	0	0	-20	-10	0
	0	0	0	0	-10	0	10
	+	0	0	0	0	10	20
I acts	-	-20	-10	0	-40	-20	0
	0	-10	0	10	-20	0	20
	+	0	10	20	0	20	40

* The algebraically inclined reader will have noticed that we have assumed the gross score to be equal to $(d_1+d_2)(x_1+x_2)$, where the d's stand for decision variables and can take values 0 and 1, and the x's stand for situation variables and can take values -10, 0 and +10. I chose this very special function (and generalize it only slightly in Table F by adding an "interaction" term), to make the exposition easy. Much insight into the general nature of the team problem has been obtained by Radner who studied the implications of a score function quadratic in the "decision vector" $(d_1, \ldots, d_m)$, with coefficients depending on a random "situation vector" $(x_1, \ldots, x_n)$.

Since we shall have to compute expected scores, we need to know the probability with which each of the 3 x 3=9 situations can occur. On Table B a probability distribution is assumed that will make our computations and our reasoning simple and without tears.

TABLE B

Probability Distribution of Situations

x_1= \ x_2=	-	0	+
-	.1	.1	.1
0	.1	.2	.1
+	.1	.1	.1

Clearly, if each member were informed about the enemy forces in both locations, the team's expected score would be highest if negative scores were avoided altogether, each member obeying the following decision rule: "act only if the situation is (+,+) or (+,0) or (0,+)," the first sign in each pair referring to the first, and the second sign to the second situation variable (in words: "act if at least one of the variables is favorable"). We call this a good decision rule because it earns the highest expected gross score, viz., (multiplying scores in Table A with probabilities in Table B):

(40)(0.1)+(20)(0.1)+(20)(0.1)+(0)(0.7) = 8. No decision rule is better though some are as good, e.g. the rule "don't act if the situation is (-,-), (-,0) or (0,-)."

This was easy. So is the opposite extreme case, when, instead of both commanders being all-knowing, they are both fully ignorant of the situation. Then the following rules are both good: "always act," and "never act." Both earn the same expected gross score, zero.

These were special cases. Generally each team member has information different from the other's. Each can be informed on: 1) x_1 and x_2; 2) x_1 only; 3) x_2 only; 4) nothing. There are thus 4x4=16 "information structures," each defined by "who knows what." For each information structure, a good decision rule for each member has to be found, and thus the maximum expected gross score computed for the team.

This is simple when the score table is like Table A, where the team's score can be regarded as the sum of partial scores contributed by the members independently of each other (the scores earned by both members' acting are simply the double of those earned by a single member's acting). In such a case we say that there is no interaction between decisions. Table C states, accordingly, a good decision rule and the maximum expected partial score for any of the two members taken separately:

TABLE C

When the member knows:	then a good decision rule is:	and his partial expected gross score is:
nothing,	never act	0
x_1,	act if x_1 = +;	(10)(0.1)+(20)(0.1)=3
x_2,	act if x_2 = +;	(10)(0.1)+(20)(0.1)=3
x_1 and x_2;	act if x_1 or x_2 = +;	(10)(0.1)+(20)(0.1)+(10)(0.1)=4

We can use these results to obtain, in Table D, the total gross expected score for the team, in the case of each of the 16 possible information structures.

TABLE D

Team's Gross Expected Score for Each of the 16 Information Structures
(each entry shows the two contributions and their sum).

If I knows	and if II knows			
	nothing;	x_1;	x_2;	x_1 and x_2.
nothing;	0+0=0	0+3=3	0+3=3	0+4=4
x_1;	3+0=3	3+3=6	3+3=6	3+4=7
x_2;	3+0=3	3+3=6	3+3=6	3+4=7
x_1 and x_2;	4+0=4	4+3=7	4+3=7	4+4=8

We have now to allow for the cost of information. In our simplest model, we shall identify the communication system with a network consisting of two (or one, or none) observation posts, each attached to one of the team members, and of a communication link (one-way, or two-way or none) between the team members. As information cost we consider, at the present stage, simply the expense of maintaining the necessary personnel and equipment, regardless of how often it is used. In particular take the case where it is prohibitively costly, or impossible, for member I to observe x_2 and for member II to observe x_1; while the observation cost of x_1 by I, and of x_2 by II, is the same. In that case, only six out of the 16 information structures of Table D need to be considered; the other 10 being either the mirror-images of the six (our assumptions on score function, probabilities, and costs being symmetrical) or being prohibitively expensive. These six are generated by networks listed in Table E, where an arrow ⟶ indicates the direction of one-way communication (mail), and ⟷ indicates two-way communication (telephone); "□" means "no observation" and "x" means "observation," the left of each pair of symbols corresponding to member I and variable x_1, and the right to II and x_2. Thus "x □" means "I observes x_1, II observes nothing"; and "x→□" means "I observes x_1 and tells II; II observes nothing." The resulting information structure is given in the second and third column of Table E.

TABLE E

Six Simple Networks

	Network	Information Structure		Gross Expected Score (from Table D)
		I knows	II knows	
(a)	□ □	nothing	nothing	0
(b)	x □	x_1	nothing	3
(c)	x x	x_1	x_2	6
(d)	x ⟶ □	x_1	x_1	6
(e)	x ⟶ x	x_1	x_1 and x_2	7
(f)	x ⟷ x	x_1 and x_2	x_1 and x_2	8

Thus, in our model (as also summarized in the last column of Table H, below), to add one observation post, i.e. to replace (a) by (b) or (b) by (c), will pay only if it costs less than 3 score units. To set up a one-way communication line from a team member who has an observation post to another who has none, i.e. to replace (b) by (d), will only pay if a one-way communication line costs less than 3 units. But if both have observation posts, the advantage of setting up a one-way communication between them, replacing (c) by (e), is only 1 unit; and the advantage of replacing one-way (e) by two-way (f) communication is also 1 unit.

INTERACTION BETWEEN DECISIONS. A more general and realistic model will take account of the usual advantage of coordination between members, the disadvantage of their being out of step with each. More precisely: the effect of one man's decision on the team's score depends on what the other man has decided to do. We call this dependence, interaction. The Score Table F is constructed from Table A by adding 4 units to the team's score when both members act (e.g., attack) or both don't; otherwise, the team pays a penalty of 4 units.

TABLE F*

Gross Scores (With Interaction)

	x_2 / x_1	II doesn't act			II acts		
		-	0	+	-	0	+
I doesn't act	-	4	4	4	-24	-14	-4
	0	4	4	4	-14	-4	6
	+	4	4	4	-4	6	16
I acts	-	-24	-14	-4	-36	-16	4
	0	-14	-4	6	-16	4	24
	+	-4	6	16	4	24	44

* We can now generalize the formula for the score function given in the footnote to Table A. In both Tables, A and F, the gross score = $(x_1+x_2)(d_1+d_2)+C.(d_1-\frac{1}{2})(d_2-\frac{1}{2})$, with C=0 in Table A, and C=16 in Table F. Thus interaction has shown itself through the presence of a product of the decision variables in the score function; and the coefficient C expresses the strength of interaction.

How will the presence of interaction affect the choice of the most efficient network? To answer this, we have again to find the good decision rules. They are given in Table G, where the expected gross score for the team is shown, assuming as before the probabilities from Table B (the reader will be able to check),, and is compared with the corresponding score in the absence of interaction.

TABLE G

Effect of Interaction

		When coordination premium = ± 4 (as in Table C)			When coordination premium =0 (as in Table A)
	Network	Good decision rule: Member I shall act	Member II shall act	Gross expected score	Gross expected score (from Table E)
(a)	□ □	never	never	4.0	0.0
(b)	x □	only if x_1=+	never	4.6	3.0
(c)	x⟶x	only if x_1=+	only if x_2=+	6.8	6.0
(d)	x⟶□	only if x_1=+	only if x_1=+	10.0	6.0
(e)	x⟶x	only if x_1=+	only if x_1=+ or x_1=0, x_2=+	10.2	7.0
(f)	x⟵⟶x	only if x_1=+ or x_2=+ or both =0	only if x_1=+ or x_2=+ or both =0	12.0	8.0

The interesting thing is to see (on Table H) how the presence of interaction affects the importance of certain changes in the network. The role of communication is increased, that of direct observations diminished:

TABLE H

Advantage of setting up:	Explanation	Case of interaction	Case of no interaction
first observation post	(b) - (a)	.6	3
second " "	(c) - (b)	2.2	3
one-way communication line	(d) - (b)	5.4	3
" " "	(e) - (c)	3.4	1
second-way " "	(f) - (e)	1.8	1

DEPENDENCE BETWEEN SITUATION VARIABLES. The need for communication would be also enhanced through another kind of change in the conditions of the problem. If the dependence between the situation variables was decreased (so that it would be more difficult to predict x_2 on the basis of information on x_1, than in our model so far), then communications would become more worthwhile. In fact, on Table B, the variables were not independent: if $x_1=0$, the chance that x_2 also $=0$ is $\frac{1}{2}$; but if x_1 is not $=0$, the chance that $x_2=0$ is only $\frac{1}{3}$. We leave to the reader to show that communication becomes more profitable if Table B is replaced by Table I (where the variables are completely independent) and less profitable if it is replaced by, for example, Table J (where there is a stronger dependence between variables than in B). This, of course, is what common sense would expect.

Three Probability Distributions

$x_1 \backslash x_2$	TABLE I -	0	+	TABLE B (repeated) -	0	+	TABLE J -	0	+
-	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$	.1	.1	.1	.2	.1	0
0	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$	.1	.2	.1	.1	.2	.1
+	-	-	-	.1	.1	.1	0	.1	.2

DEGREE OF UNCERTAINTY ABOUT A VARIABLE. Another common sense hunch would also be easy to confirm numerically: if a variable fluctuates only little, it is not worthwhile to pay for observing it. The reader may check this if he interprets Table A as follows (see footnote to that table): each man's action contributes to the team's score the amount x_1+x_2, where x_1 and x_2 can each take the values: -10, 0, 10. Suppose now that x_1 can still take the same values, but the values of x_2 have doubled and are: -20, 0, 20. The spread of x_2, the average error in predicting it, has increased. Then the worth of knowing x_2 becomes larger than that of knowing x_1; whereas on Table C (and D) they were equal.*

GOOD NETWORK vs. GOOD CODE. So far our team problem was: given the gross score table, the probabilities of situation, and the cost of various networks, find simultaneously a good network and a good set of decision rules appropriate to it: see, for example, Table G. In this problem, the team economizes on some information costs by keeping its members informed possibly of some but (in general) not all situation variables: see the 16 different "information structures" of Table D. However, the concept of information structure can be enlarged, to mean that the team members' knowledge is, in general, not only not complete (i.e., does not embrace all situation variables relevant to the team) but also not precise. For example: "the wind is in NW direction," rather than "so and so many degrees, minutes and seconds." We may call such communication a "coded" one: a code replaces a whole set of values (in our case, all the directions contained in a 45° angle) by a single symbol. Coding may mean economy. Our problem becomes: to find simultaneously a good network, a good code and a good decision rule.

* In terms of the footnote to Table A, one can also say that the score function $(d_1+d_2)(x_1+x_2)$ is replaced by $(d_1+d_2)(x_1+2x_2)$, while x_1 and x_2 take the same values as before, viz., -10, 0, 10. That is, the "importance" of the situation variable x_2 has doubled. Again, it is commonsense to expect that this will increase the worth of knowing x_2.

For example, assume again the score function of Table A, and suppose two observation posts and a two-way communication line (telephone) exist already (and therefore cost nothing) but it costs the commanders' valuable time to use the line. Each of them upon having observed "his" situation variable can either act on his own, or not act, or call up the other member; in the latter case, the two decide either to act or not to act. Note the "coding": if member I does not call up, this very fact conveys some information to II, at no cost to the team. The question is: <u>when</u> shall each partner call up, or not call up (and, in the latter case, shall he act or not)?

What would your common sense tell you: shall he phone to warn (when the situation on his front is bad)? Or to encourage (when it is good)? Or to inquire (when it is intermediate)? Try it on your friends: you will receive widely different answers. Common sense does not seem to help here. The author addressed himself to C. B. Tompkins who, with the help of the SWAC computer of the Institute for Numerical Analysis (then with the National Bureau of Standards), has found the following good rules of decision and communication (Table K, with "mirror-images" eliminated).

TABLE K*

Good rules as to when a member shall "act," do nothing (="not") or phone (="ph").

If the communication

	costs 4 or more						costs 4 or less					
	I shall, whenever x_1=			II shall, whenever x_2=			I shall, whenever x_1=			II shall, whenever x_2=		
	-	0	+	-	0	+	-	0	+	-	0	+
Rule 1	not	not	act	not	not	act	not	not	ph	not	not	act
Rule 2	not	not	act	not	act	act	not	act	ph	ph	not	act
Rule 3							not	ph	act	not	ph	act
Rule 4							ph	ph	act	act	act	act
Rule 5							ph	act	act	ph	act	act

* The assumed probability distribution was that of Table I (i.e., x_1 and x_2 are assumed independent). A solution, though not a quite complete one, of the analogous case, when x_1 and x_2 are continuous and thus can take <u>any</u> values (with equal probability) within a given interval, was obtained by J. Kiefer and S. Orey, Cowles Commission Discussion Paper, Economics 2068 (mimeographed).

TOWARDS GREATER REALISM. Of the necessary extensions of the problem, the extension to an arbitrary number of team members and of situation variables, and to general score functions and probability distributions is mathematically feasible.* More serious is the lack of a theory of determination of costs of networks and codes.**

A realistic theory of teams would be dynamic: it takes time to process and pass messages along a chain of team members; and messages must include not only information on external variables but also information on what has been done by other members of the team. Problems of feedback (with "checking-up" or "inspection" as an important variety) thus arise. Further, probability distributions, score functions, and costs are seldom known at the time when the team is set up; rather, knowledge about them is acquired gradually, while the team already proceeds with decisions.

These facts make the dynamic team problem similar to those in cybernetics and in sequential statistical analysis. Earlier in this paper we have also mentioned the game-theoretical nature of the problems that would arise if we had not deliberately abstracted from the diversity of interests of the individual members of an organization: another gap to be filled by a realistic theory.

Theory apart, much empirical work is needed to get an insight into the constants of the problem, such as the score functions, the probability distributions, the communication costs that do occur in real organizations. In addition,

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* See footnote to Table A.

** The ONR project on task-oriented groups carried out at M.I.T. by A. Bavelas, D. Luce and others, has, however, contributed much to the understanding of the communication cost inasmuch as it depends on the number of transmissions necessary to spread information among the team-members.

those organizations that can be presumed to have already developed into approximately efficient ones, through the experience, clear thinking, and intuition of their leaders, may provide not only the constants but also the (approximate) solutions of their team problems. Thus theory can be checked against facts. Most likely the leaders of efficient organizations are not averse to an articulate and unambiguous language of the serious research worker and would cooperate in the task of putting empirical flesh on the bones of abstraction.