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# A PCANS Model of Structure in Organizations

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**Abstract**

We present a network based approach to characterize $C^2$ architectures in terms of three domain elements - individuals, tasks, and resources. Characterizing the possible relations among these elements results in five relational primitives - Precedence, Commitment of resources, Assignment of individuals to tasks, Networks (of relations among personnel) and Skills linking individuals to resources. We demonstrate the utility of this model for recharacterizing classical organizational theory and for generating a series of testable hypotheses about $C^2$ performance.

## 1. Introduction

This paper proposes that organizations, and in particular their $C^2$ architecture, can be better understood, analyzed and even managed by understanding the complex structure of interdependencies that exist within its boundaries. This is not a new claim. Galbraith [1977], Thompson [1967], Perrow [1970], and Pfeffer and Salancik [1978] have all suggested ways in which such technological and human interdependencies can be predicted and used to further our theoretical understanding of organizational phenomena. While these models have been useful, they are abstract and nonspecific on how the interdependencies can be assessed. We propose that these earlier models can be enhanced with formalisms incorporating the inherent complexities of these interdependencies.

Specifically, we propose a set of three domains in organizations that are universal: 1) Organizations are composed of individuals (I)[1] ; 2) These individuals are assigned tasks (T) to accomplish as part of their membership in the organization; and 3) there is a specification of resources (R)[2] that are required to accomplish certain tasks. All three domains exist within any $C^2$ architecture.

In order to characterize and understand the C2 architecture of a unit, to understand the structure of an organization's set of

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[1] Although we have used the term individual, the model we define is equally valid when these "individuals" are more generally described as DMUs (decision making units). DMUs can be either individuals, groups, combination of humans and intelligent agents, etc. The point is that this unit acts from a task based perspective as a single decision making unit.

[2] At the level of detail appropriate to this approach resources can be alternatively characterized as the individual's specific skills, their access to particular equipment, or some combination of the two.

interdependencies, it is necessary to understand how various elements of these domains map onto one another. For example, certain personnel are assigned certain tasks; different personnel have access to different resources required for those tasks; certain personnel have access to (are connected to) each other; different tasks must be accomplished before other tasks can begin; etc. It is the specification of these mappings of particular objects in each domain onto one another that we take as the primitives in our formalisms, that we use to understand the $C^2$ architecture of the unit in a more complete way than has been possible heretofore.

## 2. The PCANS Model

To be specific, we propose that all organizations are structured along these three domains, Individuals, Tasks and Resources. The C2 architecture of the unit can be characterized as a mapping of the elements of these three domains onto one another in meaningful ways. We begin by proposing a set of five primitive relations among these three domains of elements.

Precedence (P): There is a temporal ordering of tasks in organizations. That is, some tasks are completed before other tasks begin. For example, marine based units must take the beach before they can move inland. PERT charts are one type of mechanism that provides a visual map of these temporal dependencies. Thompson [1967] used temporal ordering of tasks as a key to defining types of interdependencies -- for example, pooled interdependence, with no temporal ordering; and sequential interdependence, where task A had to precede task B. We refer to this temporal ordering as a Precedence mapping, a set of ordered pairs of tasks (T1, T2) which designate that Task 1 precedes Task 2. This precedence relation is defined by the matrix P where $P_{ij} = 1$ iff task i must precede task j; else $P_{ij} = 0$. P then is of order TxT.

Commitment of resources (C): Certain tasks require certain resources. For example, analysis of a particularly complex research problem may require time on a super computer; a stock trade may require a seat on the NYSE; maintaining an Air Force F-15 may require access to a spare parts depot, shooting down a ballistic missile requires an ABM. That is, the organization must commit certain resources to a task in order for it to be accomplished. The mapping of these resources (R) onto these tasks (T) describes these dependencies. Specifically, we define these commitments by a matrix C where $C_{ij} = 1$ iff resource j has been committed to task i; else $C_{ij} = 0$. C then is of order TxR.

Assignment of personnel to tasks (A): Personnel are assigned to accomplish certain tasks. Sometimes these assignments are distinct (for example, in a joint task force one commander may be in command of all amphibious based assaults and another in command of all air based assaults); sometimes these assignments are diffuse (several battalions are assigned to the same task). These assignments have the effect of giving particular personnel (or DMUs) responsibility for completing these tasks. We define these assignments by a matrix A where $A_{ij} = 1$ iff individual i is assigned to task j; else $A_{ij} = 0$. A then is of order IxT.

Network (N): Personnel have differential access to each other. This access is sometimes determined by formal arrangements (such as the chain of command or the formal org chart), but often it is the informal relationships that prove to be critical in how the organization functions as a whole [Krackhardt and Hanson, 1993]. Of all the primitives, the Network is the one most familiar to organizational theorists. The Network itself is often considered the true structure in an organization [Burt, 1982; 1992]. In keeping with the tradition of network analysis in organizations, we define these relations among personnel by a matrix N where $N_{ij}$ = 1 iff individual i has a relationship directly with individual j; else $N_{ij}$ = 0. N then is of order IxI.

Skill (S): Personnel bring to their work different abilities and resources. Some of these they develop individually through education or training; some are provided to them by the organization, such as access to special equipment or financial resources. By "skill", we mean to include all such resources that an individual may hold or have access to. We define skill, then, by a matrix S where $S_{ij}$ = 1 iff individual i has direct access to or control over resource j; else $S_{ij}$ = 0. S then is of order IxR.

This completes the set of five primitives: Precedence, Commitment, Assignment, Network and Skill -- or PCANS for short. These primitives are summarized in Table 1.

Table 1. PCANS Primitives

| | | |
|---|---|---|
| Assign | A | IxT |
| | i->t = person i is Assigned task t | |
| Skill | S | IxR |
| | i->r = person i has Skill defined by r | |
| Commit | C | TxR |
| | t->r = resource r is Committed to task r | |
| Network | N | IxI |
| | i1->i2 = person i1 is connected to person i2 | |
| Precedence | P | TxT |
| | t1->t2 = task t1 must be done before t2 | |

There is a considerable amount of information contained in these primitives by themselves. But, as we shall see shortly, these five relations are just the tip of the iceberg. For example, each relation has a transpose, designated with '. In addition we can differentiate and idea or desired state (marked with a *) from an actual or observed state. Thus, we have the following 20 primitive relations:

P C A N S
P' C' A' N' S'
P* C* A* N* S*
P*' C*' A*' N*' S*'

## 3. Compound Words

One of the traditions in network analysis is to combine primitives mathematically into compound relations, deriving new relations that may hold new insight into the structure of the system as a whole [Wasserman and Faust, 1994; Lorraine and White, 1971; White, Boorman and Breiger, 1976]. For example, suppose we were to start with a simple relation K, "is a child of," such that Kij = 1 iff person i is a child of person j. If we perform a simple matrix multiplication of K on itself, then the result (=KK) would be a matrix that could be interpreted as "is a child of a child of", or "is a grandchild of". That is, if $KK_{ij}$=1, then i is a grandchild of j.

Another useful mathematical function for such relations is the transpose, where the (i,j) values of a matrix are switched with the (j,i) values. The transpose of matrix K is designated K' and may be interpreted as "is a parent of." That is, $K'_{ij}$ = 1 iff i is the parent of j; else $K'_{ij}$ = 0. K'K' is the matrix that identifies grandparents. If we combine the transpose with the original matrix, we can identify other important relations. For example, KK' can be thought of as "is a child of a parent of", or, in other words "is a sibling of". K'K, on the other hand, defines "is a parent of a child of", or, in other words "is a spouse of." By tradition, when these primitive relations, such as K, are multiplied together in this way, the results are called "words" [Lorraine and White, 1971].

These same mathematical manipulations can be applied with equal ease and utility to the PCANS primitives. For example, if we multiply a friendship matrix N by itself, we get a matrix NN whereby $NN_{ij}$ tells us whether j is a "friend of friends" of i. If we multiply A by A', we get a AA', where $AA'_{ij}$ equals the number of tasks that individuals i and j are assigned to in common. There are restrictions on what words are legal (the rules of mathematics prohibit, for example, multiplying P by N because they are not conformable, that is the number of columns in P does not match the number of rows in N). But we are presented here with a vast array of possibilities with which we may describe, analyze, and even control organizations.

For example, the P relation by itself describes sequential interdependence among tasks. By pre-multiplying P by A (the assignment of individuals to those tasks), we find which tasks those people are dependent on having done before they can do their own tasks. By post-multiplying this word by A' (=APA'), we find the particular personnel they are dependent on to complete tasks before they can complete their own tasks.

We can find deeper levels of dependencies by multiplying P by itself an arbitrary number of times. For example, PP tells us which tasks are required to complete before the immediately preceding tasks are completed. APPA' would identify who is dependent on whom to complete these tasks from two sequential links earlier; APPPA' would identify dependencies among personnel who must complete their tasks from three sequential links earlier; and so on. Pursuing these links could reveal subtler and more powerful trails of dependencies that are likely to be missed by the participants themselves. By identifying these long links of dependencies, the commander would have a firmer grasp of the coordination problems he or she is facing.

## 4. Application to Thompson's Theory of Interdependence

One of the insights this kind of analysis can bring is to extend the typology of interdependencies that Thompson theorized about. For example, he suggested that his three types of interdependencies (pooled, sequential and reciprocated) could be used to characterize whole organizations or subunits within an organization. For example, banks branch systems represent the classic pooled technology wherein each bank branch independently contributes to the profitability of the central bank as a whole. But more precise measures and analyses of the interdependencies can reveal how organizational systems are much more complex than that. That is, it is likely that within the bank branches, there are some elements of sequential interdependence (a teller must seek approval from his superior before cashing a check for over $1000) and some elements of reciprocated interdependence (loan officers confer with each other before deciding whether a particularly risky client can receive a loan).

The PCANS model can be used to uncover these patterns that are often glossed over by researchers or commanders, constrained as they are by the limits of time and information they have available to them. P is a direct measure of Thompson's sequential interdependence among tasks. APA' is a direct measure of sequential interdependence among personnel responsible for those tasks. We can use other compound words, though, to assess the extent of other kinds of interdependence in his model. For example, suppose that one person (Agent 1) has as a task the responsibility of deciding whether to launch a missile from a cruise ship. Suppose that that decision depends in large part on information coming from three other quarters (Agents 2, 3, and 4) about the nature of the hostile environment and whether the target of the missile is truly an enemy. APA' would describe how Agent 1 is sequentially dependent on Agents 2, 3 and 4 for their information before he/she could make a decision. But PP' would describe how two tasks, i and j, are pooled, in that they are not directly interdependent on each other but their completion is jointly required before the subsequent task downstream is completed. APP'A' would identify the personnel who are co-responsible for performing these pooled interdependent tasks. Thus, whereas APA' would describe how Agent 1 is sequentially dependent on Agents 2, 3 and 4, APP'A' would identify Agents 2, 3 and 4 as sharing a pooled interdependence.

Thompson's reciprocated interdependence is particularly interesting. He envisioned it as a direct interdependence, whereby Agent 1 was dependent on Agent 2 and vice versa. He argued that such an interdependence required "mutual adjustment" between the interdependent parties as a coordination mechanism. Such reciprocated interdependence can happen through a sequence of sequential tasks: Task 1 is required before Task 2, Task 2 before Task 3; but Agent 1 is responsible for both Task 1 and 3 while Agent 2 is responsible for Task 2. This creates a reciprocated interdependence between Agents 1 and 2.

We can identify this reciprocated interdependence by taking the intersection of two separate words, each capturing the sequential dependence in each direction:

D = Int [APA', (APA')']

But perhaps more interestingly, we can extend Thompson's theory to include chains of interdependence that result in cycles rather than dyadic reciprocation. That is, assume the following task precedence:

T1->T2->T3->T4

Assume Agents 1, 2 and 3 cover Tasks 1, 2 and 3 respectively, and that Agent 1 is responsible for Task 4. Then there is not a direct reciprocation between Agent 1 and Agent 2 -- only an indirect one as Agent 1 depends on Agent 3 who in turn depends on Agent 2. Nonetheless, coordination is required here as well as in any direct reciprocation. Indeed, this indirect dependence may require more "mutual adjustment" (Thompson, 1967) than direct interdependence.

We can use the PCANS model to identify such cycles of reciprocated interdependence. The union of a set of words, each identifying interdependencies of a certain cycle length (called K), will give us the set of pairs of personnel who are sequentially interdependent:

B = Union [APA', APPA', APPPA',...],

up to K cycles, where K is the number of P-relations in the largest word.

Then as before we take the intersection of B with B', which provides us a matrix of the set of pairs of personnel who are dependent on each other either directly or indirectly:

M = Int [B, B'].

## 5. Example Hypotheses

This model not only allows sophisticated analytical descriptions of complex interrelations, it also permits hypotheses to be formalized and tested. For example, one of the key predictions in Thompson is that reciprocated interdependence will lead to coordination through mutual adjustment. Such a coordination requires direct and reciprocated interaction, which we can capture independently in the N primitive by taking the intersection of N with its transpose (H=Int [N, N']). Therefore, this hypothesis can be reduced to:

> Hypothesis 1: The dependence matrix D (defined above) will lead to interaction patterns in H (defined above) such that there is a significant correlation between D and H.

The natural extension of Thompson's model suggests that reciprocated interdependence through K cycles may also lead to mutual adjustment. In this case, we immediately derive the comparable hypothesis:

> Hypothesis 2: The dependence matrix M (defined above) will lead to interaction patterns in H such that there is a significant correlation between M and H.

However, we could argue that dependence that depends on larger and larger cycles (K) will attenuate the strength and need for mutual adjustment, since the interdependence will be less obvious to the employees. Thus, we suggest the following:

> Hypothesis 3: The correlation between M and H will decrease in size as M is defined by larger and larger K.

Thompson was also normative in his predictions. Regarding the current discussion, the failure of the firm to establish mutual adjustment processes in cases of reciprocated interdependence amounts to a coordination failure, which in turn leads to relatively poor organizational performance. This leads us directly to a comparable set of normative hypotheses:

> Hypothesis 4: To the extent that the correlation between D and H is low, the unit's performance will be low.

Again, we would expect the same effect for cycles of interdependence. But the most critical interdependencies are likely to be direct interdependencies; those with longer cycles of interdependencies, while still important, will not be as critical to the organization's overall performance. Thus, we would expect that failures to coordinate interdependencies based on large cycles will not hamper performance as much as failures based on short cycles.

> Hypothesis 5: The effect of a low correspondence (correlation) between M and H on the unit's performance will be attenuated as K increases.

## 6. Summary and Conclusions

This paper proposes that by formalizing dependencies among Individuals, Tasks and Resources provides a rich grammar for theorizing about organizations. We demonstrate the versatility of this approach with an application and extension of Thompson's theory of interdependencies. As a future application we intend to apply this modeling approach to specific $C^2$ architectures and determine whether or not hypotheses, such as those suggested, hold in this context.

The possibilities here, both for descriptive and normative theories, are boundless. Our examples have only scratched the surface. Using the PCANS primitives, one could also develop formalisms and extensions of resource dependency theory, coordination theory, conflict theory, to name just a few of the dimensions of organizational theory that could be addressed. The power of this approach is limited only by the imagination of the researchers and practitioners who apply it.

The approach suggested here is more comprehensive than most network based approaches to measuring and characterizing organizational units. Most other approaches focus exclusively on only one domain (personnel or task) and so only one type of relationship (network or precedence). See for example earlier work on measuring and monitoring hierarchies [Krackhardt, 1989; Lin, 1994]. In contrast, we have defined a grammar that covers multiple domains and multiple relations.

The approach we have suggested is consistent with current simulation models of adaptive $C^2$ architectures [Carley, 1995; Carley and Svoboda, 1996] and various analytic models. In fact, many extant computer simulation models generate as output or expect as input data in forms characterizable by the PCANS model. If field data, data from war games and live simulations, and data from experiments was also collected according to the primitives of PCANS it would be possible to cross compare empirical results, more accurately validate formal models of unit level behavior, and thus increase our understanding of the structural factors in the $C^2$ architecture that affect various unit level behaviors such as those that engender flexibility, high performance, sustainable performance in the place of changing ROEs.

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