Courier Assignment in Social Networks

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Abstract

Integration is important in politics, business, and technology. In all these fields, the definition of integration is vague. We build a formal measure of integration based on the latency of communication, and show how it can be used to optimize a courier assignment problem. Through simulation, we show how networks grow as couriers are added. Our measure captures the tradeoff between locality and expansion, as well as providing a model for triangle closure. Finally, we form conjectures about political integration which can be tested through empirical research.

1. Introduction

Couriers are still used in an age of electronic communication. By couriers we mean anyone who physically carries a message between two people: a bicycle messenger, a subpoena-server, an ambassador. We need couriers because some communication is best done in a personal manner.

Also, couriers are often used as a communication method by those who wish to avoid their messages being monitored. Gangsters, terrorists, and spies are all in this category.

Consequently, there are two reasons to understand more about the optimal allocation of such resources. First, we may want to allocate resources ourselves. Second, we may want to anticipate how another party will allocate resources.

We have built on our past research designing sensor networks. In that work, we imagined sets of sensors falling into isolated clusters after being dropped from an airplane. Such sensors can be linked by robotic couriers. In order to allocate these robotic couriers, we proposed a way of measuring integration [1, 2].

Can we create a formal model for social integration? Does this model produce allocations that seem socially plausible? The answers to these questions will be steps toward answering a broader question: does such a model not only provide a prescription for action, but also describe the way people and institutions allocate their resources? In this paper, we will focus on the first two questions, addressing them by using simulation as our research method.

The major contribution of this paper lies in connecting two disparate streams of research: political integration and algorithmic graph theory. By doing so, we formalize the concept of political integration. This formalization may lead to new hypotheses on how institutional networks evolve, as well as normative methods for allocating diplomatic resources.

The work proceeds as follows. First, related work is reviewed. Then, the problem is posed formally, and simulation results are reported. Finally, conjectures are formed and the implications of the work are discussed.

2. Related work

Communication, politics, and integration are connected. In particular, the way coalitions form and dissolve are an observable form of political behavior amenable to modeling [3]. Some have highlighted the battle between the forces of integration and fragmentation [4], while others have discussed integration as one among many political forces [4]. Much of the work on political integration focuses on tradeoffs: there are efficiencies to consolidating states, but the public good of the merged state may marginalize some groups which held power previously. For example, the evolution of the European union has become an intricate case study for economic and political integration [5].

On a smaller scale, integration has been measured and studied within companies, using direct analogies to the processes of diplomacy [6]. Social network researchers have linked the formal properties of graphs

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and organizational characteristics such as resiliency [7]. There is evidence that human interaction attenuates according to distance: researchers talk much more to those in offices close to them [8].

Some researchers have used statistical methods to study political integration. Cobb and Elder [9] summarize the background of such work, including the *field theory* of Lewin [10] and the *communication theory* of Deutsch [11]: trade, communication, and human movement all serve to tie countries together. Countries can bridge distance by transforming information and goods. Distance can be physical, a result of geography, or conceptual, the result of differences in culture or wealth. The different ways of communicating are correlated. Also, physical distance does have an effect on integration, and even correlates with the extent of electronic communication.

Galtung [12] used the number of flights per day between cities as a measure of integration. Recently, a study has shown a high correlation between airline and Internet traffic between major cities [13].

Thus, integration may be a function of interaction, and interaction may, even in an electronic age, involve the slow movement of goods and information which depend on physical travel. Distance may still be a factor.

There is another stream of research relevant to this problem: algorithmic graph theory. Forming optimal graphs is an important and difficult problem in computer science and operations research: most problems are intractable (NP-Complete) [14]. However, many researchers have proposed and tested approximation algorithms based on genetic algorithms (e.g. [15-17]).

These graph problems often assume that, starting with a graph, a tree spanning all nodes will constitute the solution. This may be a fair assumption when designing a telephone network, but not when designing a social network. For example, people and nations can remain isolated from each other for decades, as a result of physical distance or conflicting ideologies.

We have considered a different problem: optimizing the overall integration of a network, without requiring that all nodes be used, or even that the allocation forms a tree.

The measure for integration came from our previous work on latency and movement in communication. The time it takes to move toward a communication device like a telephone, or toward a person in the case of face-to-face communication, is part of a broader concept of latency: we should count the time it takes to get in contact as well as the time to transmit the actual message [18]. We then suggested that integration is really about minimizing this latency [2]. We showed that a literal interpretation of Metcalfe's law might guide us. Metcalfe claimed the power of a network grows in proportion to the number of edges in the network [19]. He was referring to electronic networks.

We argued that the value of links in networks with longer latencies could be determined using a discount function. The discount function should be distributive: $d(x) + d(y) = d(x + y)$. In other words, the information should have the same value at the end of a journey broken into two legs as it would from the journey taken without any breaks. Consequently, the discount function is exponential. Exponential decay functions are commonly used to model transportation behavior [20], and to model information value over time [21]. Specifically we will use this discount function:

$$d(x) = \frac{1}{2^{ax}} \tag{1}$$

where x is the latency and a is a scaling parameter.

Figure 1 shows the decay of integration over time using the discount function of Equation (1).

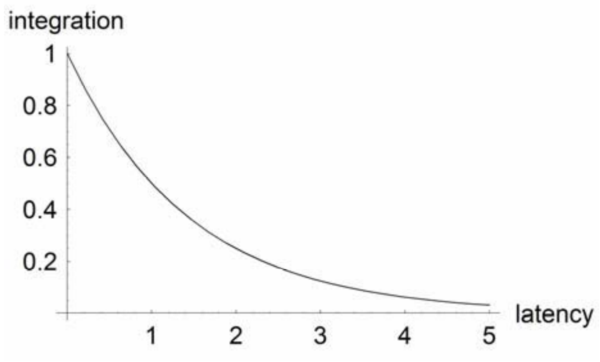

Figure 1. Integration versus latency

The integration of the network is the sum of the discounted edges, which, at the limit, approaches Metcalfe's measure.

In social scenarios there are often clusters of people who within the cluster can communicate with each other instantaneously, as in a family or a village. These clusters, in turn, need to communicate to other clusters, through a slower form of communication. In modeling such situations, we can show clusters as nodes. But links between large clusters have more integrative power than links between small clusters, and therefore we can weight the level of integration along an edge by the size of the clusters represented by each node:

$$f(e) = d(x_e)\,|c_{e_{n1}}|\,|c_{e_{n2}}|\,b = \frac{b\,|c_{e_{n1}}|\,|c_{e_{n2}}|}{2^{ax_e}} \tag{2}$$

The function operates on the edges: $c_{e_{n1}}$ and c_{e2} represent the nodes on either side of the edge. x_e is the latency of the link between the clusters, a is a scaling constant controlling the degree of time discounting, and *b* is a scaling constant controlling the importance of the size of the clusters.

Couriers can be used to manage communication between two nodes (we do not consider multiple stop diplomacy here, only bilateral trips). Adding more couriers decreases the expected latency, but only approaching a limit: the best we can hope for is that an event occurs just as a courier is scheduled to leave, and so the information will be delayed at least the amount of time it takes a single courier to traverse a link

As couriers are added to a link, the expected time to integrate an edge with *m* couriers (m_e) is:

$$\langle \ell \rangle = \frac{d}{t}\left(1+\frac{1}{m_e}\right) \qquad (3)$$

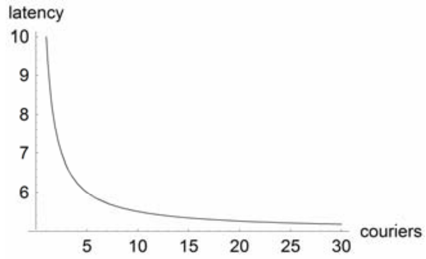

Figure 2. Latency versus couriers

Figure 2 shows that, starting with a link that is five time units away, one courier produces an expected latency of ten time units. Additional couriers will not reduce the latency less than the time it takes to travel between the nodes.

Our previous work describes much of the above, but we did not explore the implications of the measure for political integration. Nor did we look at the patterns of communication that the optimization of this measure would produce.

3. The problem

Given the above definition of integration, how might one allocate couriers to optimize a network?

We can formalize the problem in steps. First, we assume we are presented with a graph *G = (V, E, W),* with the weights in *W* representing distances - the potential latencies if couriers are assigned. Then we define an assignment generation function:

$$h(G,m) = \{\{e_1, |c|_1,\}, \{e_2, |c|_2,\} \ldots\}$$

where $\sum_i |c|_i = m$, $e \in E$ In other words, zero, one, or many couriers are assigned to each edge of the graph, with the constraint that the total number of couriers equals *m*. The couriers can move at a certain rate, so the distance (*w)* and the number of couriers ($|c|$) assigned to an edge can be used to calculate an expected time to communicate (the latency $\langle \ell \rangle$)

$$k(w, |c|) \to \langle \ell \rangle$$

Equation (3) gives the calculation used in our simulations.

Then we can transform the graph: $p(G,h,k) \to G' = (V,E,L)$, producing a new graph where the latencies *L* between vertices have been defined according to the assignment of couriers *h* and the courier function *k.*

We need the metric closure of the graph, because messages can be passed in relays of couriers. The metric closure is a complete graph in which each edge represents the shortest path through the graph: that path consists of edges from the assignment *h*. The calculation of the metric closure can be expressed as follows: $t(G') \to G''$.

We want to associate utility with different degrees of latency: our assumption is that instant communication creates no information loss, which is good, but that broken communication produces total information loss, which is bad. In between these extremes, information decays in relationship to latency. Thus, a courier assignment can have a value ranging from 0 to 1, with 0 representing instant communication (no information loss) and 1 representing no communication (total information loss). We can produce this number by first calculating the discount function as in Equation (1): this function, consistent with economic convention [22], will yield 1 for instant communication and 0 for unconnected nodes. We reverse this range by subtracting from 1:

$$il(\ell) = 1 - d(\langle \ell \rangle) \to s$$

The graph is transformed using this information loss function: $q(G'', il) \to G'''(V,E,S)$.

Then the problem can be stated: find the courier assignment that produces minimum information loss:

$$\min_h \sum_i s_i$$

Alternatively, we can regard integration as the absence of information loss. Then the problem can be stated: find the assignment that will produce maximum integration:

$$\max_h \sum_i d(\langle \ell \rangle_i)$$

We call this the *courier assignment* problem.

If one accepts the definition of integration, then the above set of steps provide a normative solution. In addition, it is possible that the algorithm may also be descriptive.

Our method, then, is to look at the results of the optimization on a set of random graphs, and gather what we can from the results, with the goal of forming testable conjectures.

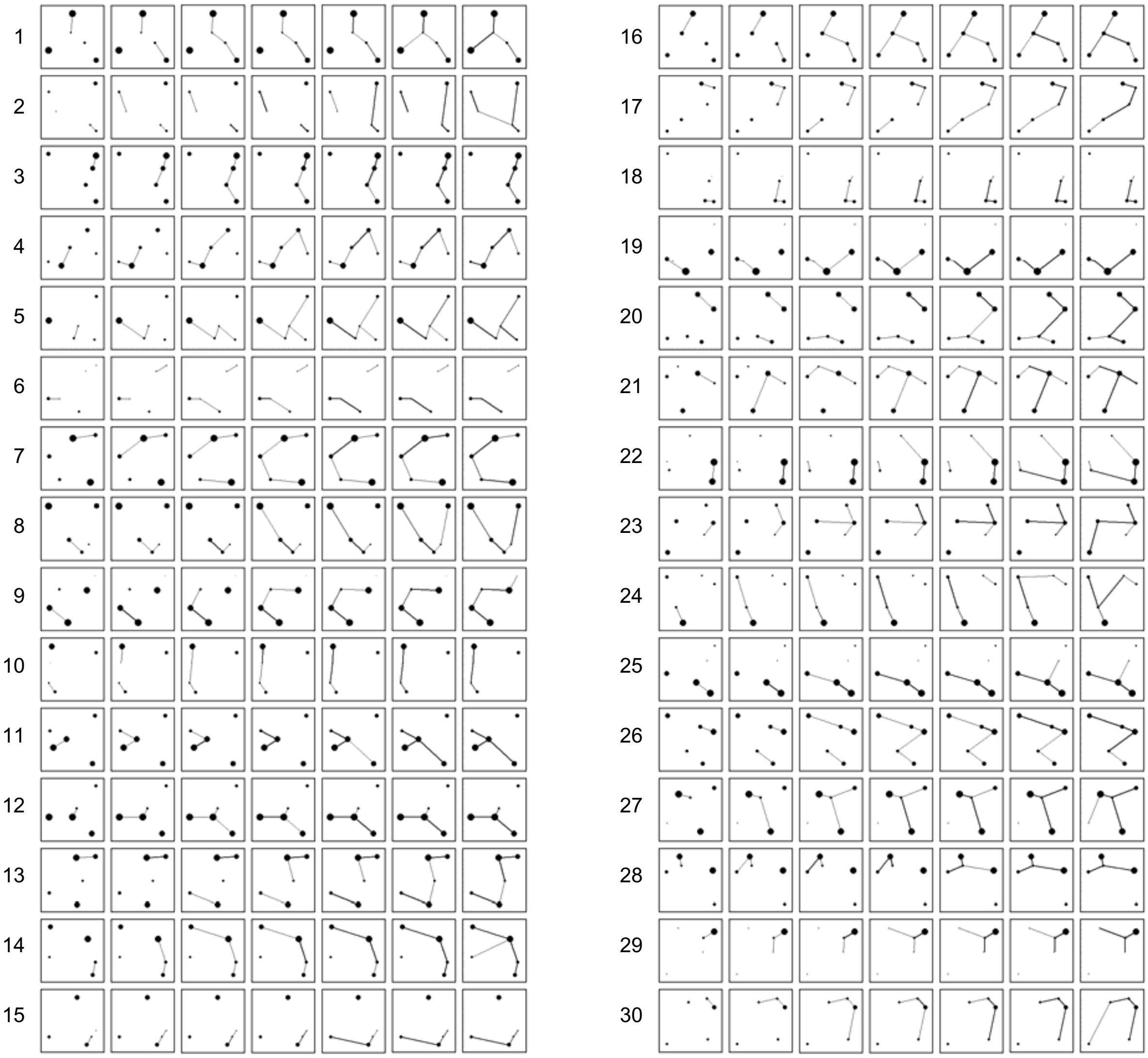

Figure 3. Each of the 30 rows is a random graph with random weighted nodes: each column shows the assignment of one to seven couriers. The assignments of all couriers are reconsidered as each new courier is added. The parameter *a* from Equation (1) was set to 0.375.

4. Simulation results

4.1 Simulations on 30 random graphs

In order to see what patterns were created by optimizing courier assignment, we formed random graphs of nodes, each node possessing a weight which we show with differing diameters in Figure 3. The placement of nodes was random, but graphs with overlapping nodes were eliminated from the starting set. The diameter of the nodes was random up to a limit: 10% of the field width.

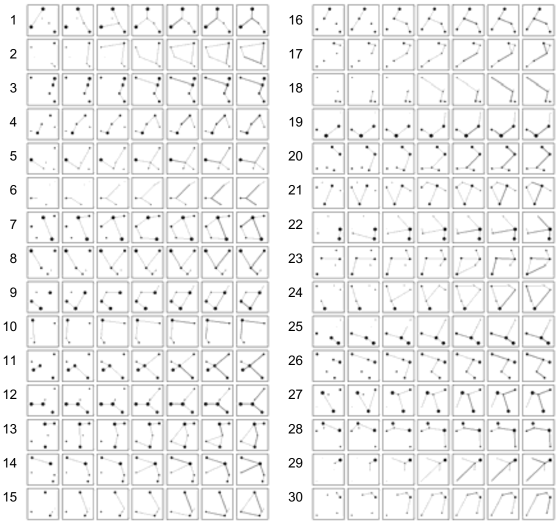

Figure 4. As with Figure 3, except the parameter *a* from Equation (1) was set to 0.1.

We then optimized our measure of integration by considering all possible allocations of couriers, and then computing the measure of the metric closure of the graph created by the assignment, as described in the previous section.

For each of 30 random graphs, we assigned first one courier, then two, up to seven couriers. At each step we re-optimized the assignment of couriers. In other words, we considered reallocating earlier assigned couriers to new edges.

Figure 5.

Figures 3 and 4 show the results for different values of the parameter *a* in Equation (1): in Figure 3, $a = .375$, and in Figure 4 $a = .1$. The edges are thin if only one courier is assigned, and are thick if multiple couriers are assigned. Each row represents a new random graph, showing the allocation of one to seven couriers. Figure 5 shows a typical row (the first row in figure 3).

With one courier, shown in the left hand frame, the largest node connects to the central node. With two couriers, a separate cluster is formed between two other nodes. With three couriers, the clusters connect. Couriers four and five are used to reinforce the existing links, and only with six couriers is a spanning tree formed. The seventh courier reinforces the link to the newcomer.

In Figure 3, all the final assignments are trees, but full spanning trees often do not form: see rows 3, 6, 10, 11, 12, 15, 18, 19, 25, 28, and 29. By reducing the rate of decay by setting $a = .1$, we see in Figure 4 that all nodes are spanned. But the assignments are not all trees: several configurations form graphs: see rows 2, 7, 9, 13, 15, 17, 21, 23, and 24. We will discuss this in more detail in the next section.

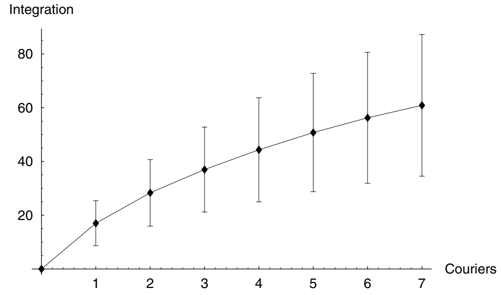

Figure 6. Integration increases as couriers are added. Means are shown for the 30 different configurations simulated in Figure 3. Error bars show the standard deviation.

Now we examine the overall integration trend. Figure 6 shows, as expected, that adding couriers increases integration.

There is a lot of variance. But for a given random configuration, the graphs are shaped much like the mean line of Figure 6. We see this in Figure 7, which plots the integration of row 1 of Figure 3.

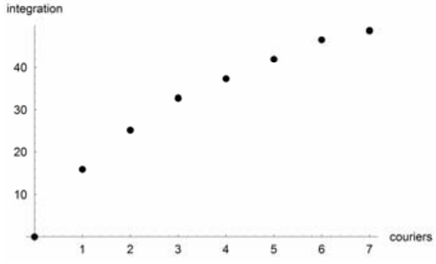

Figure 7. The integration of row 1.

Notice that both curves head toward a limit. If couriers could travel at the speed of light, then the latency between all parties would approach zero with the addition of new couriers, and perfect integration could be achieved. When couriers travel at normal speeds, the latency of each edge approaches the time it takes to traverse that edge with a single courier, regardless of the number of couriers that are added. Every edge can have a latency only as low as the distance between the nodes allow. As more couriers are added, the integration of the graph will approach that number as a limit. The limit is a function of the initial spatial distribution of the nodes, which explains the variance of Figure 6.

4. 2 Expansion and isolation

While most models of transportation networks presume spanning tree structures, our simulations show that a single parameter, *a* in Equation (1), can change the degree of inclusion.

Figure 8. From tree to graph (*a* = .1)

Figure 9. Spanning tree (*a* = .25)

Figure 10. Disconnected components (*a* = .5)

Figures 8-10 show the same starting configuration (row 13) with different values of *a*. In Figure 8, a spanning tree quickly forms. Then new direct links are chosen between already indirectly connected nodes. This forms a graph instead of a tree. We can say that in Figure 8 distance matters, but not very much. There is a tendency to form new links, and only later to deepen them.

In Figure 9, two separate components are formed. As more couriers become available, a spanning tree is formed. The social analogy is as follows: when we have established relationships, we can choose to deepen those relationships or to create new ones. Sometimes deepening current ones makes more sense than adding new ones.

Triangle closure happens in social settings when we introduce two of our acquaintances to each other so that they can directly interact [23, 24]. This is the principle behind social networking Internet sites. But sometimes people don’t form triangles. It may be wiser to use one's limited resources to deepen current relationships - or to include a previously unknown party - rather than create a new triangle. In Figure 9, there is no triangle closure: the tree never becomes a graph. Instead additional resources reinforce existing links.

With few resources, separate clusters maybe optimal. With more resources, clusters can and should be bridged. So, for example, countries of one continent might tend to integrate first; and when more resources are available, countries will integrate with countries in other continents.

In Figure 10, where exponential decay is strongest, a spanning tree has not formed even with seven couriers. Instead, close ties are strengthened and the two main clusters remain separated. This happens because in the model the value of information decays so rapidly that it may become nearly worthless on a journey: therefore it makes sense to reinforce the links between nearby neighbors.

It is possible that the tuning of the discount function through parameters reflects an underlying multi-attribute decision problem (e. g. [25]). In other words, all the end graphs of the above figures can be considered optimal, depending on the weighting of the criteria applied. Decision makers may be interested in such alternative graphs, which can be seen as Pareto optimal along the dimensions of cohesiveness (strengthen local relationships) and expansiveness (build new relationships).

Our graph-based model may enjoy an advantage over spanning-tree-based optimization: such spanning tree models always bias toward inclusion, but in the social arena, exclusion is a possibility. We can model isolation because courier assignment does not necessarily include all parties. In addition, triangle closure can be modeled.

5. Conjectures and Implications

5.1 Conjectures

The optimization of a measure of integration produces diagrams that look analogous to forms of social behavior. While it is obviously not the case that all political actors agree on integration as a goal, it is still possible that their aggregate behavior does perform a kind of optimization, in the same way investors with disparate goals end up maximizing market efficiency [26, 27], or in the same way biological structures evolve into optimal forms [28]. But there is also the possibility that integration is just one of many forces which are important in determining political behavior.

We could test the general hypothesis that the forces of integration drive political behavior: *Networks over time will tend to self-optimize with respect to integration*. However, more information may be gleaned by testing more specific issues which arose in our simulation study.

Conjecture 1: Decision makers regard local versus expanded allocation of courier resources as a multi-attribute tradeoff.

This is suggested by the alternative deployment of resources shown in Figures 8-10. The issue is important. If tradeoffs truly exist, then the battle between the forces of integration and fragmentation may be more profitably described as a tradeoff that will change with the allocation of additional resources.

A similar issue has been studied in economics: companies tend to specialize at first, and then later attempt to expand [29]. However, such economic studies tend to focus on product diversification, rather than the informational effects of geographic expansion.

Conjecture 1 can be tested in the same ways multi-attribute decision problems are often studied, through the use of conjoint analysis in human subject experiments [25]. Such a study might show that a leader's choice between these options is characteristic of a personality type, in the same way risk tolerance is sometimes seen as an aspect of investor personality. Alternatively, the study might show that situations are a stronger determiner of these decisions than personality.

Conjecture 2: Triangle closure will tend to happen only after spanning trees have been formed.

Cycles were absent in the graphs of Figure 3, but were present in Figure 4. Triangle closure in Figure 4 only occurred after a spanning tree had already been formed.

This conjecture may be wrong. Diplomats like to establish informal, back channels, which often form association triangles. It is unclear when such channels get built. There may be a tradeoff between efficiency, in which case triangle closure comes late or not at all, and effectiveness, in which case back channels might be built early in order to provide a forum for unofficial diplomatic discussions.

The literature on social networks treats the problem statistically: the more common associates there are of person i and person j, the more likely they will be connected [23, 24]. Such a model can be parametized and can be tuned to match empirical research. But this does not explain why some portions of a graph exhibit more or less closure.

In the political world, back channels are often hidden and might be underestimated if counted through observation. Therefore this conjecture could be more easily tested by using human subject experiments utilizing political games.

If the conjecture is refuted, the result will still be interesting: there may be another valued attribute of social networks: the *alternate path*. Assigning resources to alternate paths may be a wise tactic, because it allows for flexibility, and it is robust in the sense alternate paths may compensate for failures along primary paths [7]. But there is a tradeoff: such a tactic is inefficient.

Conjecture 3: Transportation networks over time will move toward configurations predicted by courier assignment.

While there are many other factors at work in the planning of transport networks, it can be argued that these networks are ultimately the result of integration forces.

Others have provided alternative explanations. Such networks are seen to grow because of economics: people travel a road, and pay tolls, which are invested in widening the road [30]. Food webs, in which predators gain energy through eating prey, form spanning tree structures that have been compared to transportation networks [31]. Studies of biological structures have claimed that there is a natural optimization occurring through evolution [28].

Transportation models sometimes incorporate decay functions based on distance [20]. However, the decay is seen as related to an individual's antipathy to travel, not as related to the need to optimize integration resources.

Since alternative models exist, an integration model can be checked not only against empirical data, but also against the predictions of the other models.

This can be studied using airplane flight data [12, 13]. The conjecture implies that the strongest links will correlate to both the size of connecting cities and the distance between them. Airplane network topology, however, is influenced by constraints: hubs cannot grow at an unlimited rate [32]. Our model could be modified to limit the allowed number of links to particular nodes, which would in turn change the structure of the networks produced.

5.2. Implications

There are theoretical and pragmatic implications to this work. From the theoretical perspective, we could use this theory to look closer at communication latency from a historical perspective. At the points where communication and transportation technology changed the latency between geographic areas, the degree of integration should have drastically increased. For example, airline traffic should have increased integration.

On a large scale, examining the history of isolationist and expansionist states in the context of their surrounding states might provide empirical data on how extreme strategies are responded to – and whether or not a network of states optimizes over time.

Electronic integration would seem to annihilate space, but this may not be true. The correlations between Internet and airline traffic [13] suggest that space might still be important. For example, time zone distances continue to introduce latency, even in electronic communication. This is because people don't communicate when they sleep: the greater the time zone difference, the greater the average latency of communication. Thus, the measure of integration we describe could also be used to analyze electronic communication.

This work has implications for the design of mobile ad hoc networks: such networks are difficult to scale if random connections are assumed [33], and are more tractable if people tend to communicate with those close to them. In ad hoc communication situations, people can often move toward or away from each other as they choose. They can also pick the time to make the communication. It could be that small encouragements would make ad hoc communication tractable. In other words, an incentive could drive personal behavior to be consistent with the optimization of a global criterion such as integration.

Could global optimization occur out of the efforts of individual actors? It is possible, if we think of actors as possessing some subset of allocatable attention, which they make rational decisions about. Over time, their local optimization in response to the local optimization of others might lead to global optimization.

However, it is also possible that people make decisions that are short-sighted, fixating on a particular strategy. For example, actors may become insular, and never branch out. Or they may overextend, ignoring opportunities to deepen existing relationships. Such ideas can be explored at a small scale through longitudinal studies of social networks.

From a pragmatic standpoint, this work suggests that transportation resources can be applied to maximize the overall integration of a network. Such an integrated network will probably not be a minimum spanning tree, and may not even span all nodes. It might consist of multiple disconnected components, and any component may be a graph rather than a tree.

How, then, can decisions be made as to the allocation of limited resources? We showed that the problem can be simulated and then optimized. In the absence of a computation model, there are several heuristic decisions that managers can make. First, high-value and close-together components should be linked immediately. Then, as resources become available, a choice needs to be made: deepen an existing link by adding more couriers or broaden the network by adding more distant and less important nodes. A third choice is also possible: form triangles by directly linking indirectly connected nodes.

The thresholds for these decisions will depend on the value given to fast communication versus the value of including all participants in the network. As new resources become available, the network should be reoptimized: with additional resource, a link to a node once considered too unimportant to include may now produce a greater benefit than any other possible assignment of a courier.

This is what should happen. What actually happens may be different. By looking for and understanding the way such decisions are made, a manager might gain insights into the weaknesses of existing networks of communication. In the case of state actors, this knowledge might be used in two ways: to fix an ineffective network, or to exploit it. Also, if we really understood courier networks, we might be able to infer the shape of another party's network from the latencies we measure in our communications with those inside that network.

We have analyzed couriers, but our analysis may apply in a more general way. Decision makers need to allocate their attention. There are certain kinds of tasks where attention cannot be multiplexed, and in which the duration of involvement is fixed: for example, meetings. The allocation of attention by each member of group may look very much like a courier network. Thus, the decisions about how to direct the attention resources of a group might be represented as a variation of the courier assignment problem.

6. Future Research

Our next step is to predict network topologies from data on node locations, and then compare them to real-world topologies.

Exhaustive searches of possible network topologies for a given set of nodes cannot be done on anything but the smallest of node sets, and therefore methods for generating solutions for larger graphs are important. Others have used meta-heuristics to solve similar graph optimization problems [16]. Our preliminary attempts using such techniques have been successful, and so we believe it is practical to generate near-optimally-integrated graphs for many realistic problems.

With this infrastructure, researchers might extend the work presented here by studying the structure and evolution of transportation networks. Air travel is a logical domain to study, but any network in which goods or information changes hands might yield interesting results. The questions to be asked are: How optimal are such networks with respect to information integration? How do they form? And can incentives nudge such networks into globally optimal forms?

Research on political integration has stressed the importance of multiple channels. Therefore our work might be extended to consider such networks. For example, one might consider the assignment of couriers of different types: official ambassadors, and unofficial contacts, with the later group more flexibly assigned to handle situations of high urgency, or to establish back channels which can be invoked during a crisis period. Such research might begin through the design of structured games [34] in which all communication can be monitored and traced.

Political behavior is most likely the conjunction of many forces, not just the force of integration. Consequently, this work might be extended to consider how integration and other forces together influence social behavior. This might be researched using game-theoretic human subject experiments first, and later through field study.

7. Conclusions

Distance has always been an important aspect of social analysis, whether the distance is seen as physical or conceptual. We built a formal measure of integration based on latency in communication. This measure can be optimized. Such an optimization results in the creation of networks that are logical: at least on first glance they look like networks that exist in the social world. The model is plausible, if still unproven.

Networks can assume many shapes; we showed how parameters can influence the optimization process toward a local deepening of existing links, or, in contrast, toward global inclusiveness.

We formulated a set of conjectures and described how they might be tested. What distinguishes our model is its focus on the information: we claim that one reason people move is because they want to communicate. We also claim that electronic communication has changed the nature of communication but not eliminated the role of distance. With many modes of communication and transportation possible between so many people, the allocation of our attention becomes a central decision we make, and this decision may be guided by factors which include the distance between our potential contacts.

In business and politics, there is an interest in optimizing the design and use of communication networks. Our work suggests that there are globally optimal ways of allocating resources with respect to information integration. We leave open the question of whether locally made decisions lead over time to optimally integrated networks.

Acknowledgements

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