1.0 Introduction

In classical Social Network Analysis (SNA), what counted as a "tie" was fixed by available methods of data collection (e.g., self-reported and limited observational data). However, the emergence of large-scale unobtrusive data collection techniques has sparked renewed interest in the very idea of what counts as a "tie" or, more prosaically, the procedures that justify putting a "one" instead of a "zero" in an adjacency matrix (Borgatti et al., 2009; Butts, 2009, p. 415; Kitts, 2014; Kitts & Quintane, 2020; Wuchty, 2009). Notably, there has been an acknowledgment that the core issues raised by these developments are primarily *conceptual*, not purely methodological in the narrow sense (Borgatti & Halgin, 2011). As a result, there is renewed interest in developing a scientifically grounded characterization (and derivatively, possible taxonomies) of what is arguably the most central concept in social network analysis: the notion of a social *tie* (Borgatti et al., 2009; Kitts, 2014). This paper aims to contribute to this conceptual effort. I focus my attention on the core concept of a *social tie*, introducing a helpful approach to representing the structure and linkages between core attributes of the scientific concept (or at least the attributes that feature most centrally in the most successful network theories). I rely on a technique for representing concepts in general and scientific concepts in particular, namely, *Barsalou-frames* (Löbner, 2015; Petersen, 2015). There are two advantages of performing a conceptual analysis of the core notion of network analysis using the representational strategy of Barsalou-frames.

First, while not very well-known or used in SNA or social science more generally, frame-based representations have proven fruitful in fields such as the philosophy and history of science (Andersen et al., 1996; Andersen & Nersessian, 2000; Chen, 2003; Chen et al., 1998; Chen & Barker, 2000; Kornmesser, 2016, 2018; Votsis & Schurz, 2012), the cognitive psychology of concepts (Barsalou, 1992; Barsalou & Hale, 1993), philosophy (Hommen, 2018), and cognitive linguistics (Löbner, 2014, 2021). In the first case, the frame approach has already been put to productive use to analyze, disambiguate, specify, and clarify the structure of core scientific concepts, both historical and contemporary, in biology, physics, astronomy, and other fields (Kornmesser, 2016). As noted by the philosophers Votsis and Schurz, "[o]ne of frame theory's strengths is its ability to lay bare the inner structure of scientific concepts" (2012, p. 108).

Specifically, the frame approach has proven particularly valuable for comparing the structure of concepts standing on different sides of episodes of a scientific revolution and related shifts in "paradigms" (Chen, 2003; Chen & Barker, 2000). Used in this way, the frame approach has helped philosophers and historians of science settle issues related to how much "incommensurability" and comparability across conceptual eras exist. Contrary to expectations of radical "incommensurability" across episodes of conceptual change in science (e.g., from the caloric to the kinetic theory of heat; from Aristotelian to Copernican celestial mechanics). The frame-based perspective reveals more underlying structural continuity in core notions across theoretical systems than expected, given predictions from theories positing radical incommensurability across paradigms once the relevant concepts are represented using frames (Andersen & Nersessian, 2000; Schurz & Votsis, 2014). In more general respects, "frame-theoretic reconstructions offer an intuitively simple way to illustrate similarities and differences between scientific theories, their concepts and their ontology" (Votsis & Schurz, 2012, p. 105). As such, the frame approach, with a firm grounding in cognitive psychology, is tailor-made for examining, analyzing, and scrutiny of notoriously ambiguous, polysemous, and vague social science concepts (Goertz & Mahoney, 2012; Lizardo, 2013; Sartori, 1984), perhaps revealing the unifying conceptual threads that link seemingly disparate theoretical proposals.

Second, Barsalou-frames have a feature familiar to social network analysts; they can be represented as *graphs* (Löbner, 2021; Petersen, 2015). This representational strategy can reveal many *implicit* aspects of scientific concepts, such as "social ties" in network theory. As such, they can be of help in the process of formalization and clarification of key concepts. Frames for concepts represented as graphs bring out the full complexity of even a single unitary notion by making explicit the structured organization of its key attributes and the main attributes of its key attributes recursively. The claims and predictions made by core network theories can then be specified as *constraints* in the values of those attributes—e.g., necessary linkages or empirical correlations. Additionally, typologies, classifications, and the like emerge organically from the frame representation rather than being imposed exogenously (and in *ad hoc* ways) by theorists when constructing proprietary classifications. In this respect, frame representation and analysis of scientific concepts can help separate the work of "definition"—establishing critical attributes of a concept—and "classification"—delimiting subtypes of a superordinate concept. Traditional approaches, such as developing "typologies" of social ties

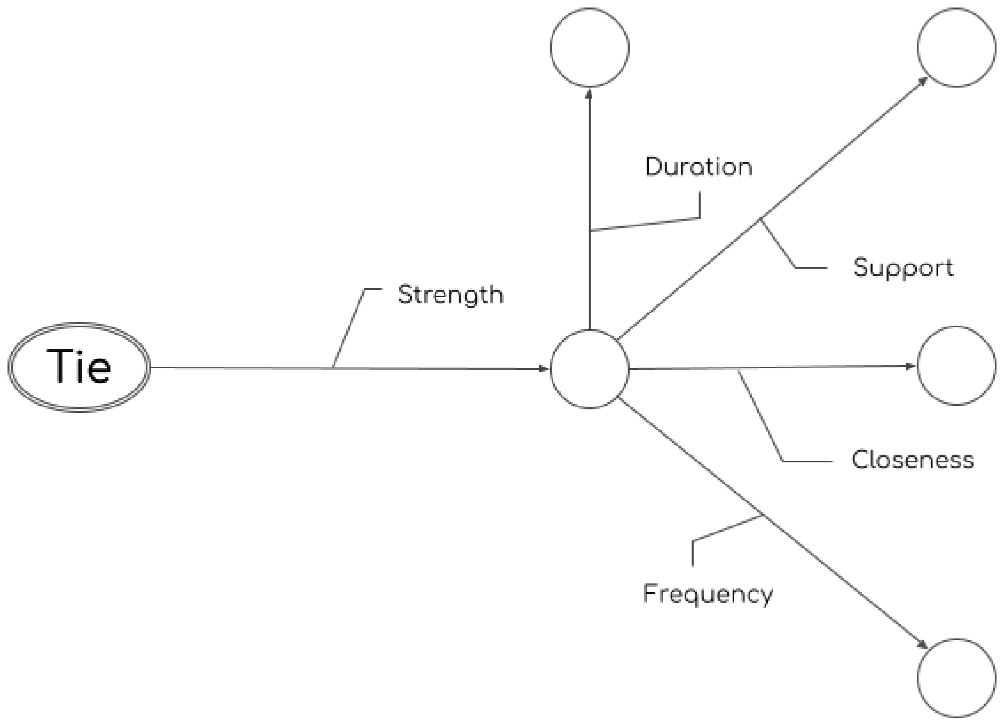

Figure 1. Partial tie frame showing a recursive frame for tie strength.

represented as dimensional tables or inductively deriving such types by looking at distributions of cases across dimensions, conflate empirical, definitional, and typological work.

1.2 Roadmap

The rest of the paper is organized as follows. In the next section, I introduce the basic idea of Barsalou-frames (and their graph representations), showing how we can use them to represent relatively simple attributes of social ties in SNA (e.g., strength). Then, I consider other uses of frame representations of the attributes of social ties, allowing us to clarify the sort of claims various network theories make (e.g., imposing restrictions on possible values to derive typologies), helping establish *intra-theoretical* conceptual relations. Next, I show how *inter-theoretic* relations can be clarified by showing how the claims of particular network theories can be codified as proposed restrictions across the values *between* distinctly conceptualized attributes of the tie concept. In the final section, I consider the more significant implications of the analysis, paying particular attention to clarifying the relationship across theories, helping the work of specification and theory testing, identifying surprising gaps in network theory, and helping avoid the pervasive issue of construct confounding in empirical work. I close by outlining the payoff of the approach and considering some possible objections.

2 A Partial Frame for Tie Strength

Barsalou-frames are recursive attribute-value structures (Barsalou, 1992) representing a superordinate category—in our case, the notion of "tie" in social networks—and thus the concept to which it corresponds. Accordingly, the essential components of the frame are the *attributes* corresponding to the concept and the *values* attributes can take. As noted by Petersen (2015), frames for sortal (kind) concepts can be represented as directed acyclic graphs with a root node—representing the concept to be specified—sending but never being the recipient of directed (antisymmetric) links. The directed links emanating from the root node represent the focal concept's attributes, while the destination nodes represent the *values* the attributes can take. There are as many outgoing links from the root node as theoretically relevant attributes of the concept. The recursive nature of frames can be represented by edge attributes originating in the root concept, pointing to nodes representing possible values that are also frames, meaning destination nodes can have outgoing attribute links, pointing to possible values, and so on. In this respect, the network corresponding to a frame is a Directed Acyclic Graph (a tree graph).

2.1 Representing Tie Strength

An example of a recursive partial frame for the concept of a social tie with a single attribute (tie strength) that is also a subframe with a separate set of attributes is shown in Figure 1. Following Petersen's diagrammatic conventions (2015), the root node in the partial frame shown in Figure 1 is represented using a double-lined oval, and source nodes are represented using circles. Note that what counts as the root node in a frame depends on the concept we aim to depict. Thus, the fact that "tie" is a root node in Figure 1 does *not* mean that it is a primitive concept (e.g., a "child" with no "parent" in a larger tree-like conceptual structure). Like every other folk or scientific concept, the notion of a social tie is itself embedded within a larger nested frame composed of super-ordinate concepts. In this case, the more general notion of "dyad" is the relevant super-ordinate concept. A "tie" is a dyad with the value of the attribute "connectivity" set to one by *default* (Schurz & Votsis, 2014, p.

95).

Thus, when comparing ties and "non-ties" (e.g., null dyads) in networks, it is clear that there are some attributes that only ties have that cannot be had by non-ties. For instance, null dyads cannot (by default) have a "tie strength" (although conventionally, it could be set to zero). However, it is also possible for ties and non-ties to share attributes, just in the same way that non-overlapping categories in nested taxonomies can share attributes (e.g., mammals and reptiles can both have a value for the attribute "skeleton type"). For instance, null and connected dyads can have values for the attribute of *similarity* or *embeddedness*. Most theories of "tie formation" in social network analysis point to systematic constraints on the range these attributes can take for both non-ties and realized ties, such that after they go beyond a certain threshold, the probability of a "non-tie" turning into a "tie" increases (Rivera et al., 2010). This is also the principle underlying much work on the so-called "link prediction" problem in machine learning applications to SNA (Liben-Nowell & Kleinberg, 2003). In what follows, my discussion and illustrations focus on the more restricted notion of "tie" in social network analysis, not the less constrained notion of "dyad." However, all the general points I make about representing the notion of "social tie" using Barsalou frames apply to the less constrained case.

The "tie" frame in Figure 1 is *partial* since it only represents one of the many possible attributes that could characterize a social tie. Of course, this frame could be further augmented with other properties or show even further levels of recursiveness (as we will see later), so the use of "augmented" here is only relative. Frames for a natural kind and other notions, like human concepts more generally, are technically open-ended (Barsalou, 1993; Rosch, 1999) and would include all the properties relevant for characterizing the entity they are about. Technically, especially for the case of scientific concepts, frames are made partial by the fact that only properties that enter into generative theoretical propositions are worth listing and that, at some point, recursiveness "bottoms out" at some fundamental level or at a level of description that falls outside the scientific discipline in question (Andersen & Nersessian, 2000; Chen & Barker, 2000). Since frames for all scientific concepts are partial, scientific knowledge is always open to revision and discovery of new attributes (which accounts for what has been referred to as "conceptual revolutions" in the history of science) or the demotion or even deletion of attributes initially thought of as critical. The ability to represent partial knowledge (or even conflicting frame representations of the same scientific concept) is a feature of

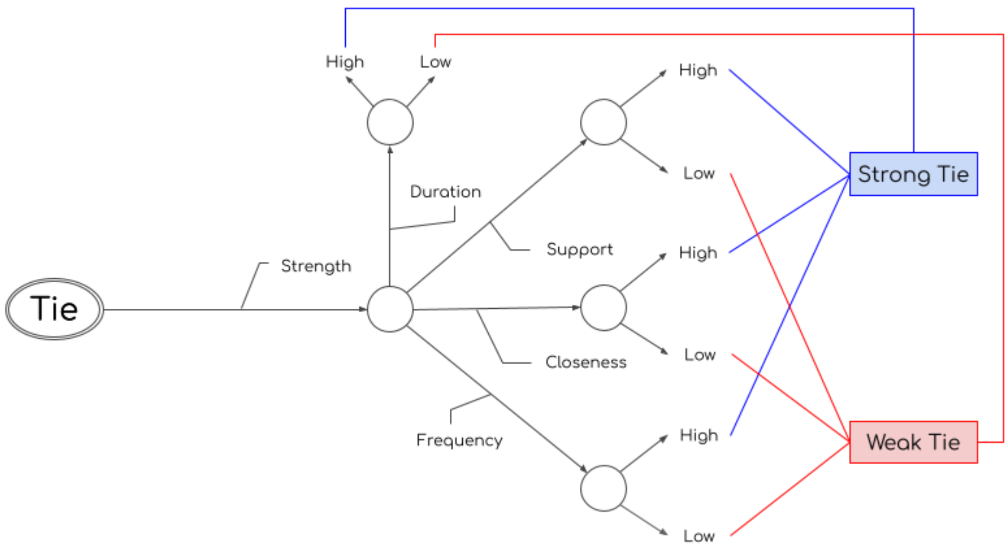

Figure 2. Partial tie frame showing a recursive frame for tie strength (subordinate concepts represented).

the frame approach, not a bug.[1] In this respect, given that "[i]n science we often do not have the complete story regarding a classification system…the ability to represent incomplete information in terms of partial frames is one of frame theory's strengths" (Schurz & Votsis, 2014, p. 95). As we will see below, many other attributes of social ties have been proposed, uncovered, and conceptualized in network theory beyond strength. However, we start with tie strength, given this attribute's central role in some of the most influential and well-established theories (Borgatti & Halgin, 2011; Granovetter, 1973). The frame is also recursive because the attribute "strength" points to a value that is itself a frame with its corresponding sub-attributes.

In Figure 1, the sub-attribute set selected for the main attribute of strength comes from the classic paper by Marsden and Campbell (1984). In the paper, Marsden and Campbell differentiate between *predictors* of tie strength (other tie properties such as role-relation labels and similarities), which may lead to ties becoming stronger, and *indicators* of tie strength which are attributes of social constitutive of the concept of strength (for more recent work in this vein, see Gilbert & Karahalios, 2009; Mathews et al., 1998; Petróczi et al., 2007). I choose Granovetter's (1973) and Marsden and Campbell's (1984) four indicators as the main attributes of the strength subframe, as these have

[1] For instance, an anonymous reviewer proposed a different frame representation of the concept of social tie in which "strength" does not feature as an attribute.

become canonical in subsequent work (Gilbert & Karahalios, 2009; Krackhardt, 1992, 1998). These are (1) support and social exchanges, (2) subjective closeness and positive sentiments, (3) relationship duration, and (4) frequency of interaction. Ties with higher values on these attributes are strong. In this way, frame recursiveness captures an essential aspect of the structure of scientific concepts (such as social ties), namely, not all features of a concept are located at the same "level" of importance, as is sometimes implied when concepts are defined by unstructured *lists* of features (Barsalou & Hale, 1993). Instead, frames have a hierarchical *structure* with some attributes (e.g., "frequency of interaction") embedded within others ("tie strength") (Chen, 2003, p. 964). For instance, in Figure 1, it is possible to go further and characterize the sub-attribute "support" as a frame composed of many sub-sub-attributes, such as emotional, financial, confiding, companionship, and so on (Wellman & Wortley, 1990).

2.2 Strong and Weak Ties as Subordinate Concepts

One crucial feature of Barsalou-frames is that typologies are *implied* in the frame structure itself, given the structure of the attributes and the values they can take (we will return to this point later). A frame-based typology implies the existence of subordinate members of the larger category having specified values in the terminal nodes of the frame; in this respect, "every frame is a classification system with an associated ontology" (Votsis & Schurz, 2012, p. 107). Frames can thus establish *intra-conceptual* relations between the super-ordinate (root node) concept attributes and *inter-conceptual* relations between notions at different levels of a nested classificatory hierarchy. In this respect, we can consider scientific taxonomies as ultimately based on frame representations of the underlying concept (Chen et al., 1998; Chen & Barker, 2000), even if this is not always made explicit by people who develop such taxonomies.

Figure 2 illustrates this point regarding the classic distinction between "strong ties" and "weak ties" in network theory (Granovetter, 1973; Marsden & Campbell, 1984; Mathews et al., 1998; see also Petróczi et al., 2007). Figure 1 is a modification of Figure 2 in which previously terminal value nodes (represented as circles) now point to possible values. While values of an attribute in a frame can be of any type (nominal, ordinal, continuous) here, they are represented as a high/low binary for simplicity's sake. Restrictions imposed on the values across attributes in a frame yield a *subordinate concept*—in this case, weak and strong ties, with this last being a subtype of the entity represented by the root node. Barsalou-frames can thus recover hierarchically organized categories organized around a "ladder of abstraction," a typical feature of scientific taxonomies and classifications (Sartori, 1984). In the figure, subordinate concept nodes (represented as rectangles) link to their typical values via non-directed links called *determination links* (Kornmesser, 2018, p. 207).

Following this approach, the frame for a superordinate concept can generate a scientific taxonomy, distinguishing between "pure" types of weak and strong ties by establishing exclusion relations between subordinate concepts. In this case, this is the idea that there exist (at least) two ideal-typical and mutually exclusive types of ties defined by strength. High levels of subjective closeness, social exchange, support, high-frequency interaction, and long duration prototypically characterize strong ties. Weak ties, by contrast, are characterized by low values of the same attributes. Note that partial frames, like those in Figure 2, can be used as guidelines for the measurement and operationalization of subordinate tie concepts (like weak and strong ties); as such, they have also been referred to as *operationalizing frames* (Kornmesser, 2017, p. 218).

An advantage of using a frame representation is the expressive capacity to represent a multiplicity of subordinate concepts beyond these pure types. Even though the frame in the figure is restricted to binary values at the terminal nodes, it can represent 2^4 distinct tie types based on the strength attribute. Many of the cells in this typological space will, naturally, be empirically empty (Elman, 2005). Others, however, point to existing social tie subtypes characterized by mixtures of strength attributes, some of which have already been noted in the literature. For instance, Burt (1990) and Wellman (1996) point to social ties characterized by high interaction frequency, such as co-worker or neighbor ties, otherwise weak regarding the rest of the strength-related attributes. Small (2017), conversely, points to the importance of social ties characterized by high values of the support attribute—e.g., in the form of confiding and advice—but otherwise weak in subjective closeness, frequency of interaction, and duration. Other non-typical combinations of strength attribute values, yet to be recognized in the literature, may define coherent subtypes of social ties based on explicit combinations of strength sub-attributes. Importantly, we do not need to use *all* properties in a partial frame to define subordinate concepts. For instance, Krackhardt (1992, p. 219ff) defined an analytically distinct type of strong tie referred to as a *philos tie*, characterized by high levels of affection and subjective closeness, long duration, and high frequency of interaction. Philos ties thus emerge straightforwardly in the frame representation by specifying links to the "high" levels of the duration, frequency, and closeness sub-attributes only.

Finally, note that, in a frame, not all attributes need to have the same weight. On the contrary, in most scientific taxonomies, some attributes will be more critical in defining concept subtypes than others. Conceptual change in scientific taxonomies can happen when weights are redistributed across attributes within a frame, with some becoming more salient and others receding in importance. For instance, Granovetter's (1973: 1361) classic definition of tie strength as "…a (probably linear) combination of the amount of time, the emotional intensity, the intimacy (mutual confiding) and the reciprocal services which characterize the tie" was initially taken to imply an equal weight constraint across the tie-strength attributes listed in the definition. A key observation of Marsden and Campbell's (1984) classic paper on measuring tie strength is that one sub-attribute of strength, namely, subjective emotional closeness, was the most empirically reliable cue indicating the presence of a strong tie—(see also Roberts & Dunbar, 2011)—and that others, such as frequency or amount of time spent interacting were less reliable attributes of strong ties (Burt 1990). Recent work building on Marsden and Campbell's approach finds that items associated with mutual confiding and social support are the most reliable indicators of the strength concept, suggesting this attribute should receive greater weight in the subframe (Mathews et al., 1998; Wellman & Wortley, 1990). Diagrammatically, differential emphasis on different attributes as characterizing a concept could be represented as attribute *edge-weights* in the frame. More important attributes would be conventionally displayed using thicker outgoing arrows emanating from the root concept.

2.3 Within-Frame Constraints

A useful feature of the frame representation of scientific concepts is the incorporation of frame constraints (Chen, 2003; Votsis & Schurz, 2012). Constraints are (more or less) "fixed" relations *between* attributes and values of the focal concept represented in the frame. The idea of "fixed relations" could be used in a weak or a strong sense. In the weak sense, these include well-known empirical *correlations* between values of attributes. In a strong sense, these include forced mutual exclusion or inclusion as given by theory, logical entailments, or the nature of the world. Constraints add structure to the frame, which cannot be captured by other representational formats, such as feature lists or dictionary-style definitions (Barsalou, 1992). Regarding theoretical concepts in social

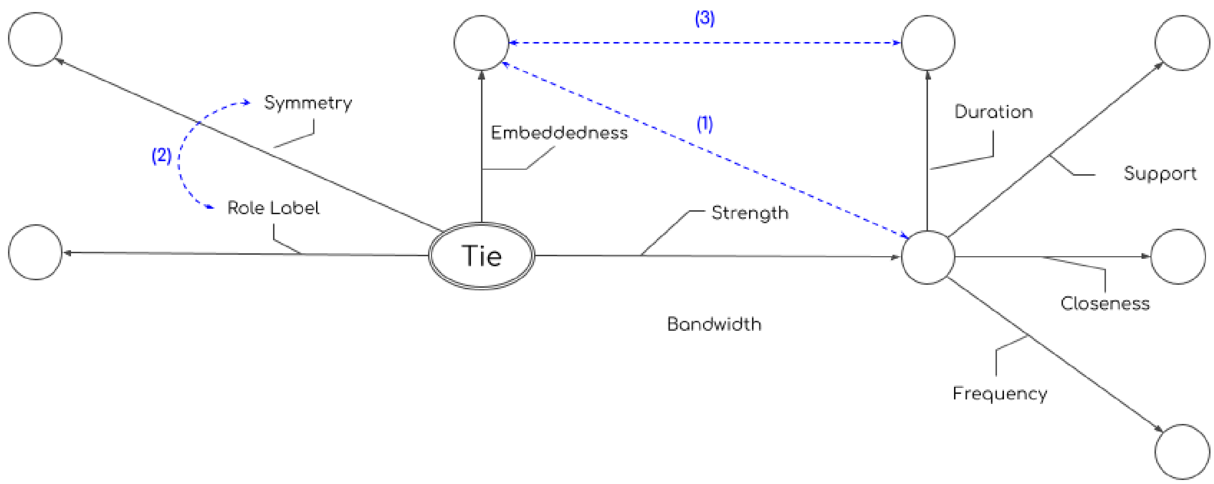

Figure 3. Partial tie frame showing a recursive frame showing value-value and attribute-attribute frame constraints.

science, such as social ties in network theory—constraints are usually dictated by psychological, behavioral, or structural theories of how people and social networks "work." Conversely, constraints may also be logical, as when values of the presence of a given attribute systematically exclude values of other attributes by definition. Thus, in contrast to most natural science, where frame constraints are either structural or dictated by natural laws, frame constraints in concepts in social network theory come from what our best behavioral, sociological, and psychological theories tell us (and are fixed by persistent social and psychological mechanisms), or from how specific attributes are defined— either technically or informally—in the larger culture (e.g., as with role labels). Notably, and this is the approach I will pursue here, the core postulates of the most influential and generative social network theories can be characterized as within-frame constraints on social tie attributes.

For example, Figure 3 shows value-value frame constraints between two well-studied attributes of social ties in network theory, namely, embeddedness and strength. The figure also shows attribute-attribute constraints between two properties of ties, namely, symmetric and role-label. While Figure 3 focuses on these attributes only, other attributes of social ties, like valence, sentiments, and so forth (and the associated frame constraints), could also be represented. What attributes go into the frame representation of a core social science concept and which ones do not make it—and what level of the frame hierarchy a given attribute should be represented—should itself be a point of contention and further discussion. For instance, one might question the inclusion of properties involving actors beyond the dyad, such as *embeddedness* into the sortal frame for the tie concept. From this perspective, a practical guideline to restrict membership in the set of listed properties would be to include only those defined exclusively by the two actors involved, excluding all others. This is not an unreasonable proposal. However, especially in the case of the tie-embeddedness property, it runs into the issue that embeddedness is arguably (apart from strength) *the* central property featured in most empirical studies and involving the concept of a social tie, with the core proposition being the proposal of a built-in correlation or constraint between embeddedness and other tie properties, thus making it an ideal case to illustrate how constraints work within the context of Barsalou frames. Moreover, some theories—like Krackhardt's Simmelian Tie Theory—explicitly conceptualize embeddedness as a property of the tie (connected dyad). For these reasons, I retain embeddedness as a tie-level attribute in the current presentation.

Three types of constraints can exist in a frame: *value-value* constraints, *attribute-attribute* constraints, and *attribute-value* constraints (Schurz & Votsis, 2014, p. 95ff). An attribute-attribute constraint speaks to either conceptual (e.g., definitional) or well-verified empirical linkages between attributes of a concept that are given by theory or the nature of the world. In the case of social network theory, such considerations would involve the nature of people, their interactions, and related behavioral and psychological tendencies (Kilduff & Tsai, 2003). In the type of frame representation shown in Figure 3, attribute-attribute constraints would be represented as double-sided dashed arrows linking the labels of antisymmetric attribute *edges*. Value-value constraints encode strong empirical regularities or fixed trade-offs we know should exist given the way people go about forming and maintaining social ties as well as using them for purposes of interaction, communication, information flow, social exchange, and the like (Borgatti et al., 2009; Borgatti & Halgin, 2011). In Figure 3, value-value constraints are represented as double-sided dashed arrows linking *terminal nodes* in the frame graph (circles), representing attribute values. Finally, attribute-value constraints arise when the existence of a given attribute necessarily entails particular values in another attribute. This usually happens for attributes whose values are themselves represented as nested frames. Thus, in Figure 3, for instance, knowing that a given tie has "strength" as an attribute necessarily gives rise to values along the frequency of interaction or subjective closeness sub-attributes. The core claims of most substantive network theories in which the concept of social ties is a central notion can be represented as constraints on a proposed tie frame.

2.3.1 Value-Value Constraints

Take, for instance, value-value constraint (1) in Figure 3; this tells us that the values taken by the property of *embeddedness* (e.g., whether a tie is standalone or part of a triad) are systematically linked to the possible values the property of *strength* can take; this means the range of values these two attributes can take are not independent, but systematically correlated. This should be recognizable as the fundamental postulate of both Granovetter's (1973) *Strength of Weak Ties* (SWT) theory and Krackhardt's (1998) *Simmelian Tie Theory* (STT), which are both stated as theoretical argument and well-attested empirical generalization. This theoretical postulate is represented in the frame as a constraint link defined on the values (end-nodes) of these two tie attributes. Importantly, while the two theories postulate the same frame constraint, they do so in distinct ways. In Granovetter's SWT, value-value constraint (1) is realized by a causal process going *from* the strength *to* the embeddedness attribute. According to the postulate of *Granovetter-transitivity*, a triad composed of two strong ties should also contain a third link that is at *least* a weak tie (it could also be a strong tie). The basic idea is that dyadic tie strength reliably generates the triadic embeddedness property, such that strong tie dyads also have a high probability of being embedded. In the same way, if we know there is a triad in which two of the links are weak, then the transitivity process is not mandatory. There is a chance that we can observe a "forbidden triad" with two nodes sharing a common neighbor but not being connected. Because open triads are likely to link people to contacts belonging to different segments of the social world, they have an information advantage over strong ties (Burt, 1995). Thus, a key premise of "classic weak tie theory" (Aral, 2016) can be represented as a substantive frame constraint across the values of two core tie attributes.

Even though Krackhardt's STT posits the same attribute-attribute frame constraint as Granovetter's SWT, it does so by postulating the reverse causal process, one going *from* embeddedness *to* strength. While in Granovetter's SWT, ties are embedded because they are strong, in Krackhardt's STT, the interactional, monitoring, and social-psychological processes set off by embeddedness make “Simmelian ties” strong.[2] To show this, Krackhardt and Handcock (2007) re-specify the embeddedness-strength constraint shown as (1) in Figure 3 as a more specific value-value constraint linking the values of embeddedness (yes/no) to possible values of a sub-attribute of strength (tie duration), shown as (2) in Figure 3. they theorize—taking the classical idea of cognitive balance as a foil—that Simmelian ties will last longer than non-Simmelian ties, and that via a process of differential survival (rather than pressures toward cognitive balance), Simmelian ties will be stronger at the end of multiple observation periods. Using Newcomb’s classic dataset, they find evidence for that hypothesis. In the frame, this more specific claim made by Simmelian tie theory can thus be represented as a symmetrical link between values of embeddedness and the duration attribute of the recursive strength frame, as in (2). The systematic link between embeddedness and duration has also been verified in other types of naturalistic data (e.g., Burt, 2000, 2002; Martin & Yeung, 2006), suggesting that this is a reasonable frame constraint.

Variations of the same theory may impose different sets of restrictions on the values taken by different attributes in a frame. Following the theoretical reasoning proposed by Simmel (1902), STT conceptualizes embeddedness as a *binary* state. Either a tie is contained within a triad, or it is not. Whether a tie contained in multiple triads is irrelevant, as the theory presumes this makes no difference for the attribute-attribute constraints postulated. We can think of this as a—theory-based—constraint on the *range* of values a given attribute can take. We may refer to this as “value constraints” within a frame (and could be represented as loops on the terminal end-node). Some value constraints are obvious (e.g., the strength of an observed tie cannot be zero). However, others, like restricting embeddedness to binary (yes/no) values, are not so obvious and require theoretical justification. Krackhardt (1998, p. 25ff) provides such an argument for the value-constraint on embeddedness proposed by STT.

However, just as constraints can be imposed, they can also be relaxed. Accordingly, more recent work in large-scale networks, done independently of STT, relaxes the binary restriction on the possible values the attribute of embeddedness can take. This work conceptualizes embeddedness as an ordinal attribute instead, typically given by the *number of common neighbors* shared by two

[2] Feld’s (1997) theory of structural embeddedness is indistinguishable from STT in this respect. As Feld notes, “[f]or understanding stability and change in social networks…structural embeddedness has two important properties. (1) It is less under the control of the individuals than other properties of the relationship, and (2) it tends to be more stable than other properties of relationships” (92).

individuals linked by a tie (e.g., Aral & Walker, 2014; Feld, 1997; Louch, 2000). Here values of the attribute of embeddedness can take any value on the whole number line. Alternatively, embeddedness can be continuously characterized as the *structural overlap* given by Jaccard's coefficient between ego neighborhoods (e.g., Navarro et al., 2017, eq. 2; Weng et al., 2018, eq 1). As the value of structural overlap gets closer to one, the stronger we expect the tie to be. Here, values of the attribute of embeddedness are constrained to take any value on the rational number line bounded between zero and one. Empirical work using this less constrained set of values on this attribute also confirms the linkage between embeddedness and tie strength—indexed by the sub-attribute of interaction frequency—in large-scale social networks (Navarro et al., 2017; Onnela et al., 2007). The basic idea is that the larger the number of common contacts (or the structural overlap) of the tie, the more frequently people interact. This is represented as the value-value frame constraint (3) in Figure 3.

2.3.2 Attribute-Attribute Constraints

Next, consider the attribute-attribute constraint (4) in Figure 3. This constraint is a link between the symmetry of the role-label attribute of a tie. As Martin (2009) notes, there are intimate linkages between these two properties that come down to the *definition* of the nature of the ties that come from common cultural understandings and the "heuristics" people follow when forming (or dissolving) a given tie. The symmetry property of a tie can take one of three values. When tie directionality is not recognized, the tie is *symmetric*; when directionality is recognized and reciprocity allowed, the tie is *asymmetric*; finally, when directionality is recognized and reciprocity is not allowed, the tie is *antisymmetric*. Note that all ties *must* have a value on the symmetry attribute. Constraints between the symmetry and cultural role label attributes of a tie come from the fact that often, one can "deduce" the symmetry property of a tie from knowing the role label attached to it, and sometimes, vice versa (Nadel, 1957). Therefore, these two attributes are not independent; one deterministically (or even socio-logically) fixes the other. Thus, the relationship of *siblingship* is necessarily symmetric (lacking meaningful directionality). If I am your sibling, you are also necessarily my sibling; this contrasts with the role-relation "parent of," which is necessarily antisymmetric. If I am your parent, you cannot be my parent (the same goes for the role-complement "son/daughter of").

The fundamental postulate of Martin's (2009) heuristic concatenation theory (HCT) is that people use the behavioral recipes embedded in culturally defined roles to concatenate different ties to each other. Cultural role labels have direct graph-theoretic ("structural") implications. For instance, patron-client tries are antisymmetric and thus have to form hierarchical trees when concatenated. Therefore, systematic large-scale properties of sets of ties emerge (or fail to) from the micro-heuristic embedded in their role-label definitions. Systematic linkages between role-label behavioral heuristics and large-scale social structures and the subsequent crystallization of those structures via institutionalization processes can thus be expected to be a regular occurrence (Martin, 2009, p. 21ff).

Given the aforementioned, the constraint between cultural role labels and symmetry status differs from the value-value constraints discussed regarding the link between embeddedness and strength. Rather than being an empirical generalization (e.g., "most parent-child ties are antisymmetric"), the constraints are logical, followed by definitional necessity. If we know the value one attribute takes (cultural role label is parent-child), then we can figure out the value the other attribute takes (anti-symmetry). This may not apply the other way around, as not all antisymmetric ties are parent-child; however, if we know a tie is anti-symmetrical, we can rule out a good chunk of possible role labels (e.g., friendship). Overall, the type of constraint under consideration links the two attributes as a whole (or systematic sets of values) and does so in a deterministic (or logical) way rather than in a probabilistic (or empirical) manner.

It is unclear how many explicit—or implicit—attribute-attribute constraints exist in contemporary network theory, although some can be uncovered by examining extant theoretical proposals and definitions. For instance, Granovetter's famous definition of tie strength as involving *reciprocal* services, *mutual* confiding, and amount of time *together* implies that attribute-value constraint should join the symmetry edge-label to support and frequency (respectively) in the tie strength frame.[3] More specifically, for a tie to have any level of strength, it must be either symmetric (if considering undirected relations) or reciprocal (if considering directed links). The implication here is that if we know that a tie is cognitively non-reciprocal (Carley & Krackhardt, 1996)—in the sense that the tie "exists" for one partner but does not from the other—then we can guess *not* that it is a "weak" tie, but simply that the value of strength is not meaningfully defined for that tie. The same reasoning goes for behaviorally non-reciprocal ties (Hammer, 1985). Note, however, that almost no

[3] Thanks to a reviewer for pointing this out.

one respects this implied attribute-attribute constraint in Granovetter's definition of tie strength in actual research applications. For instance, people speak of one-directional (not mutual) confiding and even one-directional (non-reciprocal) services as a feature of social support within "weak ties" (Small, 2017). Moreover, even within ties characterized by high levels of subjective closeness, one can imagine many non-mutualities regarding those attributes of the tie strength sub-frame having an implied direction. As such, it is clear that any *logical* frame constraint limiting strong ties to be reciprocal or non-directional is too strong and unlikely to be respected in practice.

3.0 Specifying the Use of Frames in Social Networks Theory and Research

3.1 Identifying Differences and Commonalities Across Theories

The frame representation of the tie concept allows us to recognize implicit commonalities across seemingly unrelated theoretical proposals. For instance, Burt's theory of *bridge decay* (2002) makes the converse prediction as Krackhardt's STT, proposing a causal link between embeddedness and the strength sub-attribute of duration, with the basic proposition is that disembedded ties do not last long (value-value constraint 3 in Figure 3). On one level, bridge decay theory is indistinguishable from the dynamic version of Krackhardt's STT at the level of the frame constraint it imposes; in fact, Burt's (2000) original work on tie decay functions found that tie embeddedness was the best predictor of a tie surviving the sensitive initial period where there is what the called a "liability of newness" increasing the chances of dissolution (hence achieving high values of the duration attribute). This is the exact prediction made by STT (Krackhardt & Handcock, 2007), and in this sense, the two theories are not conceptually distinguishable on this particular criterion. Thus, perhaps rather than being thought of as two distinct theories, STT, and Bridge Decay Theory can be best thought of as variations on the same theme.

In addition to helping specify implicit commonalities, the frame representation can also help us specify meaningful *differences* between theoretical proposals. For instance, as Mattie et al. (2018) have noted, Elizabeth Bott (1957) proposed her own "structural" theory of tie strength, one that can be profitably compared to the overlapping proposals of SWT and STT. Specifically, Bott proposed a theory of tie *weakness* by linking two tie attributes. According to Bott, one mechanism that weakens social ties (in her original treatment, constrained to having the role label attribute fixed to "spouse") is how *densely* knit the *non-overlapping* segment of each person's ego networks: The more densely connected non-shared contacts are, the weaker the tie. In the full tie frame, this could be indicated as a constraint between a new attribute we can label "disembeddedness." Values on this attribute could be indicated by the sum or the average of the clustering coefficients for each ego in the dyad, counting only non-shared contacts. From the frame perspective, we can reconstruct Bott's model as proposing a value-value constraint between disembeddedness and strength, such that the higher the former, the lower the latter (Mattie et al., 2018).

3.2 Helping Evaluate Social Network Theories

The frame representation also suggests one way in which network theories can be evaluated against empirical data, and that is by checking to see if the value constraints they impose on tie attributes can be observed empirically. For instance, "Tönniesian" conceptions of community posit necessary correlations between distinct type properties, in particular, a propinquity-based property (same neighborhood residence), role-label property ("neighbor"), and a sub-cluster of strength properties (e.g., social exchanges and support, frequency of contact, and subjective closeness). It was the great contribution of Wellman's classic East York studies (1979, 1996; Wellman and Wortley 1990) to show that this correlation was hardly necessary in contemporary settings. Instead, Wellman's Personal Community Thesis argues that most strong ties, especially when the "support" sub-attribute of strength is highlighted, escape the geographic bounds of the local community. People have "personal communities" characterized by ties low in propinquity similarity but high in the sub-dimensions of strength.

Note that in this respect, the values taken by the propinquity do not have to be binary. They can be continuous, as in work where propinquity is measured using physical distance. When this is done, it is possible to determine whether removing a particular constraint from a frame is warranted. Thus, work by Carter Butts and collaborators (e.g., Spiro et al., 2016) argues for *reimposing* a constraint between the propinquity sub-attribute of similarity and some strength sub-attributes. They argue that the "death of distance" proposal is overstated. Tie strength decreases at some (e.g., exponential) function of physical distance. One way to settle this debate is to move down the abstraction ladder, specifying each theory's key terms. We can thus specify Wellman's PCT as implying that no constraint should be imposed linking propinquity and the *support* sub-attribute of strength. At the same time, Butts's "law of distance" argument proposes imposing a constraint between the propinquity attribute (measured in continuous values) and other sub-attributes of strength, perhaps most prototypically *frequency of interaction*, but perhaps including others (but not support). This is an example of how the frame model can help sharpen and clarify the terms of theoretical debate in the field.

3.3 Helping Identify Surprising Gaps in Network Theory

The frame representation is also useful for identifying surprising or unexpected *gaps* in network theory (Borgatti & Halgin, 2011). As noted, core theoretical propositions in network theory are specified in the frame representation mainly as logical or empirical constraints across tie attributes, values of attributes, or attribute-value pairs. For instance, in a recent paper McMillan (2022) makes the surprising observation that the link between two of the most widely researched and theorized ties properties, namely, strength and similarity (homophily), has never been systematically considered in any network theory we know of (see Figure 4). Instead, analysts have simply made the (implicit) simplifying assumption—which can itself be represented as a (logical) attribute-attribute constraint in the frame—that similar (homophilous) ties are (usually) strong, and thus there should be nothing to see there (Feld, 1981; e.g., Granovetter, 1973). As such, the possible linkages between dimensions of the strength concept and tie similarity have not—with some scattered exceptions—been the subject of much research or theorizing in social network analysis.

In frame terms, McMillan proposes we relax this (implicit) attribute-attribute constraint in previous work. That is, rather than assuming a built-in (e.g., logical or presumed empirical) linkage between the attribute "similar" and the attribute "strong," McMillan proposes that we let them vary independently and see whether the "off" cells are empirically empty or not. This is a similar strategy—at the inter-conceptual level—that, as we have seen, some researchers have pursued regarding intra-conceptual attributes in the case of tie strength. Letting them vary independently allows us to discover new types of ties not previously considered (Burt, 1990; Small, 2017). Using this approach, McMillan distinguishes between two types of homophilous ties: Those characterized by *strong tie homophily* and those characterized by *weak tie homophily*. Because similarity splits into various kinds (e.g., cultural, demographic, and so forth), it is possible that in some social settings, there is strong-tie homophily for a given attribute but no weak-tie homophily. However, when considering the link between tie strength and other similarity sub-attributes (e.g., sociodemographic similarity based on gender or age), we may observe homophily independently of strength (both weak and strong ties are more likely to be similar than expected by chance), and even homophily on weak but not strong ties. Thus, if we think of homophily along a given (cultural, demographic) dimension (pictured in the frame in Figure 4 as sub-attributes of similarity) as a tie attribute that can vary independently of (any of the dimensions) of strength, we can define new types of social ties following the same approach illustrated in Figure 2 in which specific subordinate "types of tie" concepts are specified by fixing the values of a distinct combination of attributes. Thus, we may have culturally or socio-demographically similar weak ties, dissimilar strong ties, dissimilar weak ties, and so forth (McMillan, 2022, p. 140, fig. 1).

In a related line of work, Brashears & Quintane (2018) review previous work proposing intra-conceptual value-value constraints between dimensions of tie strength (e.g., frequency), the embeddedness of a given tie in the larger network of contacts (such as Burt's (1995) redundancy), and the capacity of a social tie to serve as conduits for rich and complex information—a tie attribute that Aral & Van Alstyne (2011) have referred to as *bandwidth* in previous work. Brashears & Quintane make the surprising observation that, by and large, the empirical linkage between redundancy, frequency, and capacity has been largely assumed and seldom demonstrated using large-scale data. They argue on theoretical and later empirical grounds that the constraint fixing the values across these attributes to be strongly correlated should be relaxed and that "separable characteristics of ties that in combination yield qualitatively different types of relationships." Thus, it is possible to envision ties sharing a "non-standard" combination of attributes in the three-way table defined by different "high" and "low" combinations of values across these attributes. These may include high-capacity, highly redundant ties activated infrequently or low-capacity, highly redundant ties activated frequently (Brashears & Quintane, 2018, p. 108, fig. 1).

Overall, the above considerations suggest a way a more reflexive use of the frame representation for social ties can be used to develop a two-pronged heuristic strategy for theoretical development and innovation in social network analysis, one that could help avoid researchers falling into theoretical blind spots. On the one hand, we can search a proposed partial frame for any "gaps" or "holes" defined as attributes for which no existing theory proposes a constraint. Using substantive knowledge, simulated computational scenarios, or exploratory empirical research. We can then examine whether postulating a constraint between attributes makes sense. In this way, discovering and postulating novel constraints among tie properties is thus one possible avenue for theoretical elaboration and development. Another approach, closer to Brashears & Quintane's (2018) and McMillan's (2022) work, would use the reverse tack; looking at "closed" triangles in a given tie frame (representing existing constraints proposed by various theories), one can question whether the proposed constraint is empirical or theoretically justified (see Figure 3). Perhaps, as in those cases, it has been taken for granted but never empirically examined. One removes the constraint and considers the typological or broader empirical implications of letting the two attributes freely covary. Note that if the goal is implicitly or explicitly typological, as with McMillan and Brashears & Quintane's work, then the analysis would benefit from the analyst explicitly considering value restrictions, determination links, and the overt proposal of a new *operationalizing frame* (similar to the one shown in figure 2) as a way to explore the possibility space of types of ties.

3.4 Helping Avoid Construct-Confounding in Social Network Analysis

Construct-confounding in social network theory and research is a relatively common but somewhat neglected issue. The frame approach to concept representation introduced here can help us identify, diagnose, and address this problem. For instance, in their classic work on measuring tie strength, Marsden and Campbell (1984) advocated for an approach to dealing with construct-confounding that differentiated empirical elements that are *predictors* of a construct from those that are *constitutive* of it (e.g., "indicators") (Mathews et al., 1998). In frame terms, Marsden and Campbell proposed that we differentiate attributes located within the strength subframe, defining possible strength values along different dimensions (constitutive), from other tie-attributes that are correlated (but are not conceptually connected) to strength (predictive), which would be represented as inter-theoretic constraints across frames (e.g., value-value or attribute-value constraints). Nevertheless, even though the paper on measuring tie strength was influential (Marsden & Campbell, 2012), contemporary analysts continue to engage in construct-confounding when conceptualizing and measuring tie strength (Petróczi et al., 2007), especially regarding other empirically related, related, related, but conceptually distinct tie attributes.

For instance, Aral and Walker (2014: 1358) measure tie strength

….as including (a) the social context of the relationship (how individuals met, know one another, or interact

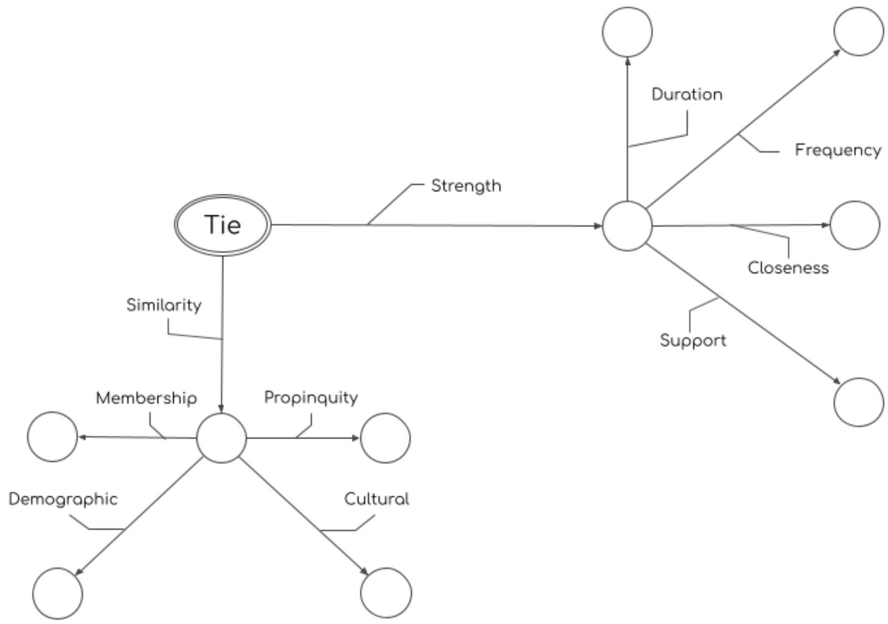

Figure 4. Partial tie frame showing two recursive frames: One for tie strength, the other for similarity (homophily).

with each other, e.g., whether two Facebook friends attended the same college, come from the same hometown, or the number of common institutional affiliations they share), (b) the recency of the relationship (e.g., whether two Facebook friends currently live in the same town), (c) the overlap of common interests (e.g., the number of common Facebook pages they are "fans" of or the number of common Facebook groups they have joined), and (d) frequency of the interaction (e.g., friends' copresence in photos online).

It is clear that here Aral and Walker are confounding the *strength* and *similarity* attributes of a social tie, using measures that pertain to the latter's subframe attributes (e.g., co-memberships, shared interests, propinquity) as if they were attributes of the former's subframe. Figure 4 shows a frame representation differentiating between these two attributes of a social tie, representing similarity (homophily) as a tie attribute, which is also a different recursive frame with attributes composed of the various types of similarities proposed in the literature (Borgatti et al., 2009). There is nothing wrong with using one attribute of a social tie (e.g., similarities) as a predictor of another (e.g., strength) or in terms of the frame representation to suggest value-value or attribute-attribute frame restrictions between attributes associated with the similarity between people and the expected levels of frequency of interaction, closeness, support, and even tie longevity we may observe. We have observed that this is a common trait of some of the most influential theories in social network analysis, and it is precisely what Marsden and Campbell recommended in 1984 regarding role labels and demographic similarities related to strength attributes like subjective closeness, regularity, or duration. However, treating sub-attributes pointing to one tie property (similarities) as attributes of another property (strength) leads to conceptual confusion and invalid inferences in empirical research on social networks. For instance, Aral and Walker present their main results as indicating the effects of "tie strength" on social influence when better understood as evidence that people are likely to be influenced by similar others as found in other work (e.g., Edelmann, 2019). In this case, sticking with a uni-dimensional but construct-valid measurement of strength (e.g., interaction frequency) may be preferable to going the construct-confounding route.

Aral and Walker are not unique in taking analytically distinct tie attributes as if they were sub-attributes of the tie-strength frame; they just represent a particularly overt case. Construct-confounding around tie strength seems to be a resurgent trend in the literature, especially after the rise of "network science" and "computational social science" work that has an increasingly large number of researchers with little background in social science doing work on social networks (Bonacich, 2004). For instance, Shi et al. (2007) purport to study a network of "strong ties," but they use the attribute of *embeddedness* as a measure of strength. This particular instance of construct confounding has become so pervasive that some even *reimagine* Granovetter's notion of tie strength to fit it. For instance, Weng et al. (2018) claim that "Granovetter...defines the *strength* of social ties as proportional to the size of the shared social circles of connected individuals. The more common friends two individuals have, the stronger is the tie between them. We adopt this same definition here." This is a definition of structural embeddedness (Feld, 1997), not Granovetter's famous definition of tie strength. As we have seen, while various theories (most explicitly Krackhardt's (1998) STT) specify an empirical correlation between these two tie attributes, it is essential to keep them distinct. Using one as a measure of the other leads to confusion since whatever correlates are found should be

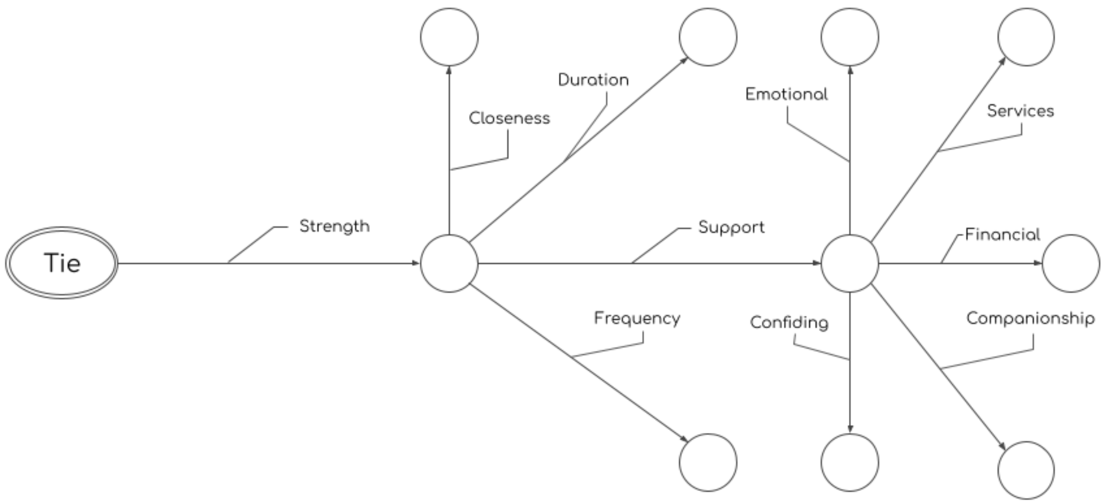

Figure 5. Partial frame for a social tie with a single attribute (strength) and two levels of recursion.

phrased as effects of the attribute measures (e.g., structural embeddedness) and not be directly imputed to "strength."

As noted initially, frames are *hierarchically* and *recursively* organized attribute-value structures; this means that values of attributes can themselves be frames, as are the values of sub-attributes and so on. Frames thus provide a more sophisticated way of appreciating the conceptual organization of a given construct compared to an unstructured list of attributes (Chen & Barker, 2000; Votsis & Schurz, 2012). An example of how frames can guard against this unprincipled approach to construct specification and measurement is provided by a paper by Gilbert & Karahalios (2009). In this paper, the authors tried to "update" Marsden & Campbell's (1984) measuring framework for tie strength to social media (Facebook) networks. In the paper, Gilbert and Karahalios suggest that strength should be measured using *seven* indicators: Intensity, intimacy, duration, reciprocal services, structural, emotional support, and social distance. The frame representation shown in Figure 5 makes it easy to see that this proposal is both unstructured and conceptually inflationary.

First, as noted above, reciprocal services and emotional support are best conceptualized as two sub-attributes of a hypothetical sub-subframe for the strength attribute of "support." Thus, rather than multiplying the various types of social support uncovered and considered in the literature as direct sub-attributes of the tie attribute of strength, it is more efficient to see them as hierarchical components of a "support" subframe. This support subframe is embedded in the overall tie frame at a third level of recursiveness (because support is an attribute of strength, and strength is an attribute of social ties), as in Figure 5. As with strength, it is possible to weigh the different attributes of the concept of support equally or consider some kinds of support to be more crucial for the overall definition of the concept (Small, 2017; Wellman & Wortley, 1990).

Second, mistaking "social distance" for an attribute of the strength concept is a classic case of construct-confounding across distinct tie properties; namely, the typical case of confusing a *similarity* sub-attribute (in this case, demographic similarity) for an attribute of the concept of strength (see Figure 4). As noted, there is nothing wrong with specifying a theory that links these two tie attributes in a cause-effect relation or simply sees similarity as a *predictor* of strength (imputing a necessary correlation between two attributes as in Marsden & Campbell (1984)). These theoretical postulates and empirical generalizations can be represented in a frame representation like that shown in Figure 4 as attribute-attribute constraints (linking similarity and strength). However, it is undesirable to conceptually scramble the overall frame for a tie by moving a subattribute (demographic similarity) of the overall superordinate tie concept (demographic similarity) to play the role of subattribute in a distinct attribute subframe of the same concept (strength).

Third, what Gilbert & Karahalios (2009) call the "structural" indicator of strength is just our old friend structural embeddedness. As already argued, embeddedness is a distinct tie-property whose linkage with strength should be empirical and not conceptual; hence another case of construct-confounding. Beyond this, what Gilbert & Karahalios (2009) call "intensity" maps to Marsden and Campbell's frequency of contact, and what they call "intimacy" maps to the emotional closeness attribute (duration maps to duration). Thus, subsuming the two types of support under a more encompassing support subframe and eliminating the two construct-confounded attributes leads us back to the more parsimonious (see Figure 5) four-attribute proposal initially proposed by Marsden and Campbell.

4.0 Concluding Remarks

4.1 Summary of the Argument and Extensions

In this paper, I introduced a framework for representing and analyzing what is arguably the core concept of social network analysis: The notion of a social tie. The analysis revealed that this is far from a unitary or straightforward concept. Instead, its core attributes are themselves multi-attribute concepts (and so forth, recursively). Network theories (and empirical puzzles) are revealed as *constraints* imposed on the larger frame, fixing relations between attributes or restricting the range of covariation between the values of attributes. This approach helps clarify *intra-conceptual* and *inter-conceptual* relations between the core notions, constructs, and theoretical approaches in SNA. The approach can also help us picture the line of theoretical progress in network theory. In the frame approach, a concept changes via three mechanisms: Attribute addition, attribute deletion, or attribute consolidation.

It is clear from the various frame representations of the notion of a social tie discussed earlier, which could easily be augmented and elaborated even further, that in the past seventy years of network analysis, the overall conceptual framework around the idea of "social tie" has primarily grown via addition so that today it is the very complex concept that we all know and love. Perhaps future theoretical work can concentrate on the consolidation route geared toward revealing commonalities in operationalization and functioning between attributes considered distinct today. This would allow for perhaps a much-needed simplification of the concept. Of course, another (and possibly more likely) route is the continuing addition of other tie properties discovered empirically or postulated by a new theory. As an example of the former, Park et al. (2018) propose the new attribute of "tie range" defined as "the second-shortest path length, i.e., the number of intermediary ties required to reach from an individual node to its neighbor if their direct tie were removed." We have already seen novel theoretical proposals for tie attributes going beyond those classically considered, such as Aral & Van Alstyne's (2011) idea of tie "bandwidth" or "capacity" (Brashears & Quintane, 2018). As tie properties continue to add up, the work would then focus on exploring inter-theoretical relations of convergence, such that theories postulating the same range of restrictions in the frame can be consolidated into more portable, more user-friendly, and unified frameworks.

4.2 Considering Some Objections

4.2.1 A Grand Theory?

One possible objection to the frame representation of social ties presented here is that it is intended as some sort of "grand" network theory aimed at displacing other conceptualizations of the notion of social ties in the field. This is a misconception of what the frame representation is meant to accomplish. The frame construct is just a *tool* to clarify and specify key scientific concepts. It is—and it cannot—replace or play the role of substantive scientific theories. What it can do is represent some of the most important implications and explicit claims of existing theory in a user-friendly and, most importantly, explicit and exploitable way, helping highlight some otherwise non-obvious linkages—and most importantly, tensions and contradictions—between them. Existing network theories (like typologies) are *embedded* in the frame (as attribute-attribute or attribute-value constraints). However, the various frame representations are not intended as a "theory" or a "meta-theory." To the extent that the frame looks like a meta-theory or a substantive proposal about the "nature" of social ties, then it can be said to be *recovering* those deeper assumptions in the field—as the most reasonable ones to make sense of researchers' activities—rather than *imposing* them from the armchair. In this respect, the core aim of proposing the social tie frame comes closer to what older (e.g., pre-Kuhnian) traditions in the philosophy of science referred to as "rational reconstruction" (e.g., Popper, 1959/2005, p. 8). In this case, the rational reconstruction of how a core concept in contemporary social network analysis is used, operationalized, theorized, and conceptualized by network researchers.

4.2.2 Conceptual Misuse or Conceptual Revision?

Nevertheless, it could be argued that when the frame representation is used to make claims about the *misuse* of concepts in previous work—as in the previous discussion of construct confounding—then it is functioning as a chauvinistic or biased imposition on what could be more charitably constructed as *alternative* conceptualizations of the concept of social tie, ones that depart from the traditional legacy of the work of Granovetter, Marsden and Campbell, Krackhardt and others. [4] For instance, there is no reason why, rather than abiding by the nested frame shown in Figures 1 and 5, where tie attributes like duration, emotional closeness, frequency of interaction, support, and the like are conceptualized as *sub*-attributes of an overall property labeled "strength," an analyst might simply *delete* strength as an omnibus property of social ties and simply list these as direct attributes of the concept (e.g., as directed edges directly emanating from the root node). This would imply a *different* conceptualization of the notion of social tie relative to the concept of strength, one that

[4] Thanks to an anonymous reviewer for emphasizing this point.

perhaps an argument could be made for, as superior to the classical Granovetter conceptualization as portrayed in Figure 1.

From the frame perspective, this is a perfectly acceptable move. Scientific concepts are regularly reconceptualized relative to previous theories (Chen & Barker, 2000). In this case, the frame-based representation is actually a help rather than a hindrance because it would make such conceptual revisions explicit rather than being left to an implicit, unguided, slow drift process of incremental but seldom highlighted modifications by various scholars across different publications. Frame-based representations of conceptual knowledge in SNA and social science more generally would thus play a clarifying role analogous to that which directed acyclic graphs representations of empirical causal claims have to play in quantitative social science (Pearl, 1998).

This would also be a way to "reframe"—pun intended— the previous critical discussion of the work of Aral & Walker, Shi et al., Gilbert & Karahalios and others. For instance, a defender of their work might posit that, rather than a case of construct *confounding*, what we have a case of *conceptual revision*. That is, rather than being constrained by the classic Granovetter conceptualization shown in Figure 1, what these analysts are doing is completely reconfiguring the traditional conception of the concept of tie strength by *adding* attributes taken from other attributes sub-frames (such as similarity and even triadic embeddedness) that were not considered sub-attributes of this concept in previous work that followed Granovetter more closely. That is, while in the traditional formulation of SWT theory, something like structural embeddedness is a *correlate* of strength (and thus best represented as a structural constraint between two distinct attributes of ties in a frame), in the new formulation, structural embeddedness is a *sub-attribute* of strength (e.g., its "structural component"). The same argument would apply to the various sub-attributes of the overall concept of similarity (or social distance). Rather than there being inter-conceptual relations (empirical or logical) between strength and similarity, social distance would become intra-conceptual components of the idea of tie strength (as in Aral & Walker).

While the idea of self-conscious and intended radical conceptual revision or change does not quite apply to the work mentioned—since these analysts clearly see themselves as working *within* the Granovetter tradition rather than radically revising it—let us stipulate, for the sake of argument, that this is what these analysts were doing. In this case, the frame-based representation would be doubly useful because it would not only help us specify what these analysts were doing but it would also help us identify a possible case of recent *paradigmatic shift* (or radical theory change) in SNA (Andersen & Nersessian, 2000), one that would be moving beyond the classical (and perhaps outdated or no longer applicable) conception of Granovetter and Marsden & Campbell. Such episodes of radical theory change do happen (although not very often) in the history of science (Chen et al., 1998). Thus, explicitly marking such a radical revision of a classical concept would be helpful for the larger research community. To do so, we could thus "redraw" the frame representation of a social tie to correspond to this new representation. In either case, whether we judge a given example of conceptual use as "misuse" or radical innovation is always *relative* to an implicit or, better yet, explicitly specified frame for the concept in question.

4.2.3 What About Time?

One final objection I will consider is that the frame representation of social ties favors an older, perhaps obsolete idea of a social tie as a static entity or state rather than an inherently temporal, interactive process or event. Indeed, the version of the frame representation used is primarily geared toward representing "kind" and not "event" concepts. However, there are ways (although cumbersome and outside the scope of this paper to consider) to modify the pictorial frame conventions to more faithfully represent event concepts embedded in time (see Chen, 2005). Nevertheless, as represented here, the traditional "state" concept of tie can take *temporal features* as traditional attributes. Accordingly, as you might have guessed, these can be incorporated as specific *temporal attributes* of ties. This approach is premised on distinguishing the presumed existence of social ties from the events, interactions, and exchanges that the existence of the tie affords. For instance, in Burt's theory of tie decay, an interaction taking place is indicative that a tie is still "alive," but this also logically implies that interactions are not the same thing as ties. This distinction has been incorporated in recent work that uses tie decay theory to analyze large-scale interaction in communication networks (Michalski et al., 2021; Miritello, 2013; Raeder et al., 2011). In related work, Ahmad et al. (2021) develop a continuous time model of tie decay in networks, premised on distinguishing ties from interactions. In their model, an interaction involves two entities linked by a tie (face-to-face meetings, text messages, phone calls, zooming). In contrast, the tie is the underlying relationship between actors, which can have attributes such as strength and the like. The "lifespan" of a tie can then be modeled using the decay function approach, and interactions come in as events that affect decay (e.g., by "resetting" the tie or delaying it) (Ahmad et al., 2021; Burt, 2000, 2002; Miritello, 2013).

Nevertheless, how can temporal processes be incorporated into the frame representation of the *concept* of social tie? One approach to represent temporal tie properties would follow recent work by Miritello (2013, p. 91ff; see also Navarro et al., 2017, pp. 5–7). The basic idea is to consider the temporal signature a higher-level tie attribute, which can be represented as a sub-frame endowed with its temporal subattributes. For instance, one aspect (subattribute) of temporal signature is tie *freshness*, a property introduced by Raeder et al. (2011). This is simply the difference between the time of last interaction and the current time of observation (e.g., "the last time I spoke to you"); therefore, it is a property that admits continuous values. Another sub-attribute of the temporal signature of ties is *burstiness* (Karsai, Kaski, Barabási, et al., 2012; Navarro et al., 2017), which is a given by the spread (e.g., second moment of the distribution or the coefficient of variation) of *inter-event* times in a tie during an observation period; for instance, the length of time between phone calls, exchanges, face-to-face interactions, and the like.[5] Ties in which interactions happen regularly (talk every day at the same time) have the lower bound value on burstiness. Ties in which multiple interactions cluster successively in relatively short spurts but do not repeat until much later again have higher values of the burstiness property (e.g., seeing a good friend at Sunbelt every year). Following the previously described approach, we can theorize possible frame constraints between attributes of the temporal signature of ties and other standard tie properties such as role relations, similarity, embeddedness, emotional closeness, and the like. Novel theoretical insights would result from considering these possibilities.

[5] That burstiness is a property of *ties* and not a derivative of node-level propensities is shown by Karsai et al. (2012).

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