Soulmate or Acquaintance? Visualizing Tie Strength for Trust Inference

Tiffany Hyun-Jin Kim[1], Virgil Gligor[1], Jorge Guajardo[2]
Jason Hong[1], and Adrian Perrig[1]

[1] Carnegie Mellon University
{hyunjin,gligor,jasonh,perrig}@cmu.edu
[2] Bosch Research and Technology Center
jorge.guajardomerchan@us.bosch.com

Abstract. Prior social science research has shown that tie strength is a useful indicator of context-dependent trust in many real-world relationships. Yet, it is often challenging to gauge trust in online environments. Given a multitude of variables that represent social relationships, we explore how to visualize interpersonal tie strength to empower people to make informed, context-dependent online trust decisions. Our goal is to develop visualizations that are meaningful, expressive, and comprehensible. In this paper, we describe the design of four visualizations. We also report on the results of two user studies, where users commented that our visualizations are highly comprehensive, meaningful, and easy to understand.

1 Introduction

Social interactions are increasingly moving into the online world. For example, traditional physical-world interactions, such as finding a babysitter, a partner, or a renter, used to work through word-of-mouth; however, people find it convenient to perform the same interactions online nowadays. Unfortunately, the online realm suffers from a lack of cues that can help people make informed trust decisions. As Steiner's famous cartoon depicts, "[o]n the Internet, nobody knows you're a dog," referring to the difficulty of verifying one's identity on the Internet [26].

For example, many people receive friend invitations in online social networks (OSNs) from casual acquaintances, friends of a friend, and even total strangers. A major problem here is that little information exists to help differentiate between people one has actually met, and scammers who impersonate an individual; indeed, prior studies have shown that such attackers fooled many OSN users, including security-conscious individuals [1, 4, 17, 24].

One potential approach for trust establishment is to automate trust decisions such that computers make trust decisions for people. However, two major drawbacks render such automation infeasible: context-dependent nature of trust and differences in individuals.

Context-Dependent Nature of Trust. Trust varies depending on different contexts; different types of trust are needed for identifying an appropriate person for a babysitter for your child, for carpooling, or for new renters for your home. An automated system, however, is not clairvoyant and cannot make accurate decisions about which social

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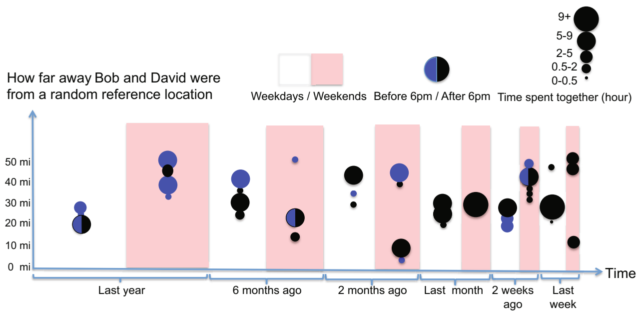


Fig. 1. An example visualization of tie strength between Bob and David. This diagram visualizes how far away from a random reference point two people have been interacting over a period of a year, how much time they have been spending at each location, whether the interactions were before or after 6:00 PM, and whether the interactions were on weekdays or weekends. These data can be feasibly acquired by smartphones (e.g., collocation can be acquired using GPS or Wi-Fi geo-location and duration/time of day/day of the week can be recorded on smartphones).

context the trust decision needs to be made in. For example, OSNs today cannot automatically distinguish between a social friend, a co-worker, an acquaintance of a friend, or a stranger whom you have never met.

Differences in Individuals. Every individual has distinct characteristics which are hard for automated techniques to capture; some people may choose to trust everyone while others may not. For example, extroverts have been found to be more willing to trust other people than introverts [12]. Given such differences in individuals, making trust decisions are difficult to account for in an automated manner.

Our goal in this paper is to understand what kind of information and how to offer it to people so that they can make informed trust decisions. We leverage prior research results which have shown that interpersonal tie strength is a good indicator of large classes of trust relations [16, 19], and social science researchers have established a plethora of parameters that correlate with tie strength [11, 14, 16, 19, 21, 25, 27].

Using parameters that we believe could be feasibly acquired by smartphones or online interactions, we explore the design space of visualizing tie strength to empower users to make informed, context-dependent trust decisions. Past work has shown how collocation data using smartphones and laptops [2], activity data on Facebook [14] and Twitter [13], and sensors and smartphone data [7] can be used to infer a range of characteristics about social relationships between people. Given the past work, one might ask why visualizations are needed, rather than just having, for example, a simple number that summarizes tie strength as, for example, 4 out of 5. A single number, however, is inadequate for at least two reasons: 1) numerical representation of tie strength may not be able to capture the details that are crucial for making informed trust decisions, and 2) deliberate attackers may be able to maliciously enhance numerical tie-strength values. Instead, we suggest visualizing tie strength with a rich set of features, which can be provided to users solely or as a supplement to numerical values. For example, one of the tie-strength visualizations that we propose is Figure 1, which depicts a summary of proximity information over a period of a year such that users can infer tie strength between Bob and David.

Contributions. This paper makes the following research contributions:

1. We explore the design space of interpersonal tie-strength visualizations that empower users to make informed, context-dependent trust decisions.
2. We present the design of four different visualizations illustrating aspects of tie strength (selected from a first-round user study).
3. We analyze usability in terms of meaningfulness, intuitiveness, and applicability to various use cases based on a second round of user study results.

Our user study results show that our visualizations are highly understandable; over 90% of study participants correctly interpreted the tie strength information on our visualizations. Also, study participants reported that our visualizations are intuitive while accurately portraying tie strength, and they provided diverse applications where they can use the visualizations to make informed, context-dependent trust decisions.

2 Background: Interpersonal Tie Strength

Pioneering research by Granovetter explored the strength of ties that exist between individuals [16]. Following his work, researchers studied the theoretical parameters for tie strength: amount of time [16,19], intimacy [16], affection [19], emotional intensity [16], reciprocal interaction [16, 19], structural factors [6], emotional support [27], and social distance [21]. Among multiple dimensions, Gilbert and Karahalios argue that relatively simple proxies can be substituted for determining tie strength in practice [14]: communication reciprocity [11, 16, 19], existence of at least one mutual friend [25], recency of communication [20], and interaction frequency [15, 16]. In our work, we embrace many of these insights. In particular, we designed many of our visualizations to convey communication reciprocity, recency, and frequency.

An extensive amount of literature has demonstrated that the frequency of interaction among people increases their likelihood of forming a friendship or romantic relationship [5]. Some studies have used physical proximity as a proxy for the amount of social interaction between pairs [10,23], for example, showing that communication frequency drops exponentially with the distance between a pair [3, 28]. Cranshaw et al. provide a model for predicting friendship based on the contextual features of users' location trails [2], using collocation and where collocations happened as a primary feature. This past work suggests that physical proximity may be a useful proxy for tie strength, an observation that we rely on in many of our visualizations.

Overall, our work builds on a great deal of past work in social science investigating relationships and strength of ties. Our primary contributions here are in the design and evaluation of new visualizations for conveying aspects of tie strength.

3 Problem Definition

Our interest is to explore visualizations that are based on data that have been shown to be feasibly acquired by smartphones or online interactions. Hence, based on these proxies for the variables in Section 2, we specifically consider the following 11 parameters:

1. **Collocation.** As suggested by prior work [2, 9], this parameter represents the placement when multiple users are physically present at the same location.
2. **Number of collocations.** This parameter represents the number of distinct locations where users physically interact [2, 9].
3. **Duration of interaction.** This parameter represents the time duration when users interact [2].
4. **Time of day.** This parameter represents when the interaction takes place [2, 9].
5. **Day of the week.** This parameter represents whether the interaction occurs during weekdays or weekends [2, 9].
6. **Length of relationships.** This parameter represents how long two users have known each other [15, 16].
7. **Interaction frequency.** This parameter represents how frequently users communicate through online (e.g., emails, chatting) and offline (e.g., face-to-face meeting, phone conversation) interactions [15, 16].
8. **Friendship level.** We propose friendship level to represent the social proximity between two users. For example, Alice may be one of Bob's top 10 best friends based on the quality and the quantity of their interactions.
9. **Interaction reciprocity.** This parameter represents whether the interaction was one-way (e.g., Alice attempts to call Bob who never responds) or reciprocal (e.g., When Bob misses Alice's call, he calls her back) [11, 16, 19].
10. **Recency of interaction.** This parameter represents how recent the previous interaction is [20].
11. **Number of mutual friends.** This parameter represents how many common friends two users share [25].

3.1 Assumptions

In this paper, we explore parameters whose values could be feasibly collected using smartphones or online interactions, and we assume that data acquired by smartphones or online interactions is correct. We also assume that visualizing the combination of parameters can be performed on a smartphone, and that a public-key cryptosystem is used for signing the visualization as follows: Bob, who creates a tie-strength visualization with David, has a private key to digitally sign the visualization, and Alice can validate Bob's signature with Bob's public key. Hence, digital signatures enable verification of the diagram and prevent forgeries.

For privacy, we assume that Bob can, at his discretion, decide to whom or whether at all to release information about his relation with David by signing (or not signing) the visualization. Analogously, David can release visualizations at his discretion.

3.2 Design Goals

Our goal is to accurately capture and visualize tie strength such that users can make informed, context-dependent trust decisions. Our desired properties are as follows:

- **Meaningful.** Visual diagrams should be designed using relevant parameters to convey semantically meaningful and useful tie-strength information to users. That is, presented diagrams should not mislead viewers to draw inaccurate conclusions.

– **Intuitive.** Visual diagrams should be intuitive such that users can interpret and understand the diagrams without difficulty. Ordinary users should understand the diagrams without rigorous training or explanations.

Note that the design goals are in tension with each other. For example, satisfying meaningfulness requires accurately portraying parameters of tie strength, and satisfying intuitiveness is in direct conflict with meaningfulness as accurate information can easily be incomprehensible.

3.3 Mapping Visualization Parameters

A multitude of design options exist to visualize tie strength parameters, including for example position on x- and y-axis, shape, size, color, and connection between objects [22]. Based on various mappings for the visual parameters to tie-strength indication values, we designed 12 different diagrams conveying tie strength as a formative exercise to help us explore the design space and solicit early feedback from participants. In particular, we explore visualizing the combination of multiple, relevant parameters in the same plot to accurately convey tie strength. Due to space limitations, however, we only focus on the top four visualizations that were found to be most useful and meaningful by our participants, as shown in Figures 2–5. Low-ranked visualizations are shown in Figure 1 and Figures 10–16 in Appendix.

We evaluated these diagrams through two rounds of user studies. The goal of the first study was to help us qualitatively understand the pros and cons of each of these visualizations, and filter out less useful visualizations. The goal of the second study was to measure the meaningfulness, intuitiveness, and applicability of these visualizations to a range of use cases. Towards this end, we took the top four visualizations from the first study and conducted a series of tests using Mechanical Turk.

4 Study 1: Formative Study

The objective of this first study was to choose a subset of the 12 diagrams that people find intuitive and helpful in evaluating social tie strength. Note that our goal was not to directly compare the diagrams against each other, but rather to understand what kind of information was useful and desirable to users.

In this study, we recruited 19 volunteers (9 females and 10 males) from diverse locations, including universities, a professional/office building, and a coffee shop. Participants were in the age range of 21 – 54, with various educational backgrounds (from high school graduates to doctoral degrees), and the interview took 20 minutes. In terms of the technical background, all participants were computer-savvy, using computers for at least 10 hours per week.

Procedure. We invited each participant to a room and described 12 diagrams in randomized order. After describing each diagram, we asked the participant to provide feedback on the diagram. Throughout the study, we asked the participant to speak out loud. After seeing all 12 diagrams, we asked the participant to group them in 3 categories: like, dislike, and unsure. We asked reasons behind the decision and asked the participant to pick the best 3 diagrams that (s)he would use to infer tie strength.

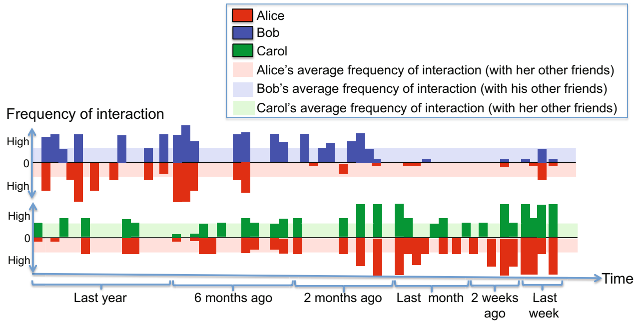


Fig. 2. Diagram A. This diagram presents frequency and recency of interaction, length of relationship, reciprocity, and the number of mutual friends using colored bars. 10 participants selected this diagram as one of their top 3 choices.

Results. In general, participants selected diagrams that they identified as simple, intuitive, and/or fun to examine. Figures 2–5 had the highest rankings overall from the formative study. Below, we describe the design rationale behind each of these 4 diagrams and the feedback that the study participants provided.

4.1 Diagram A: Bar Graph Visualization of Interaction Frequency

Diagram A focuses on displaying how frequently a user has interacted with his friend(s) using bars over the length of their relationships (Fig. 2). In particular, Diagram A illustrates the following parameters:

- *Length of relationships* is displayed on the x-axis in logarithmic scale. We chose this design to let people easily see older information about interactions, as well as more recent interactions.
- *Interaction frequency* is displayed on the y-axis using colored bars. For example, users see that the interaction frequency between Bob and Carol has been decreasing as the sizes of the bars on both Bob's and Carol's sides are decreasing; on the other hand, the interaction frequency between Bob and David has been increasing.
- *Interaction reciprocity* is shown based on the proportion of the bar sizes. For example, equal-sized bars on a graph implies that two users interact reciprocally; however, if one side's bar is significantly longer/shorter than the other side's bar, the interaction has been one-way.
- *Recency of interaction* is portrayed based on the existence of the most recent bars on the graph. In Fig. 2, Bob and Carol's most recent interaction was last week.
- *Number of mutual friends* is represented by the number of distinct graphs on a single plot. In Fig. 2, the viewer and Bob have two mutual friends: Carol and David.

We plot average interaction frequencies with colored background for those who are on a diagram. From Fig. 2, pink background represents the average interaction frequency that Alice has with all her other friends. Hence, this diagram enables users to approximate "friendship level" in comparison to average friend: users can compare if Alice interacts more or less frequently with the given mutual friend, and perceive better tie strengths between Alice and the mutual friend.

Analysis of Diagram A. Diagram A emphasizes the interaction frequency over time. Objectively presenting the actual interaction frequency may be challenging; for

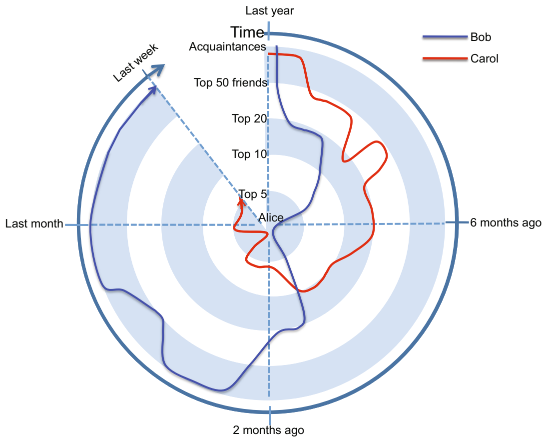


Fig. 3. Diagram B. This diagram presents friendship level, length of relationships, recency of interaction, and number of mutual friends on a Polar coordinate system. 8 participants selected Diagram B as one of their top 3 choices.

example, an introvert user may have low frequency values compared to an extrovert user. On the other hand, by providing an average value on all diagrams and by normalizing the average value to be consistent, Diagram A enables users to remove such biases and evaluate the *relative* frequency values in an intuitive manner.

Extra information regarding the interaction frequency can be encapsulated in Diagram A. For example, users can place the mouse pointer over a bar to get the percentage of online versus offline communications.

A potential limitation of Diagram A may be the scale issue when multiple graphs are shown on a single plot. Fig. 2 displays two graphs, and people may feel overloaded when multiple graphs, with distinct colors, are displayed.

Feedback on Diagram A
Pros. 10 out of 19 participants picked Diagram A as one of their top 3 choices. In particular, participants expressed their preference of this diagram in terms of their familiarity with the bar graphs and the simplicity for understanding its implication. One participant expressed enthusiasm since this diagram can preserve privacy with ambiguity: "[h]aving reciprocal interaction means good relationships, but having no interaction does not necessarily mean negative relationships."
Cons. Although 10 participants picked Diagram A as one of their top 3 choices, they were cautions of sharing their own Diagram A with others. Two participants mentioned that this diagram seemed to reveal information in detail, and 3 people raised the possibility of misinterpretation: given 2 interaction frequency diagrams – one with the participant's significant other and the other with the participant's close friend – on a single plot, the significant other may get upset that the friend is a stronger tie to the participant.

4.2 Diagram B: Polar Coordinate Visualization of Friendship Level

While Diagram A portrays the variations of interaction frequencies over time on the Cartesian coordinate system, Diagram B emphasizes the changes in friendship level on the Polar coordinate system using line graphs (Fig. 3). By placing a user (Alice) on the center, a curve (of Bob) approaching the center can be intuitively interpreted as they are

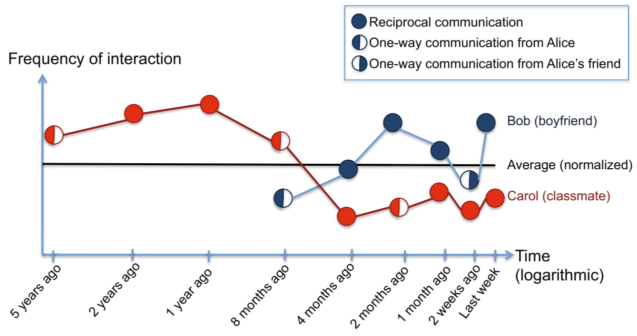


Fig. 4. Diagram C. This diagram maps the frequency and recency of interaction over the length of relationships. 7 participants selected Diagram C as one of their top 3 choices.

getting closer to each other in terms of friendship; on the other hand, a curve moving away from the center may indicate that their friend relationships are not as good as before. Diagram B illustrates the following parameters:

- *Length of relationship* is displayed over the angle in logarithmic scale.
- *Friendship levels* are displayed at uniformly distributed distances away from the origin with the scales of top 5, 10, 20, 50 best friends, and acquaintances.
- *Number of mutual friends* is represented by the number of distinct graphs on a single plot. In Fig. 3, the viewer and Bob have two mutual friends: Carol and David.

Analysis of Diagram B. *Friendship level* is another way of indicating tie strength, and Diagram B illustrates friendship levels using the Polar coordinate system. We assume that a system can automatically deduce friendship ranking among all friends. We conjecture that placing a targeted user on the center of the diagram and showing the changes in friendship level with lines over time is one of the natural ways of visualizing tie strength. Hence, people may find Diagram B attractive and intuitive.

Feedback on Diagram B

Pros. Most people provided positive feedback on Diagram B. For instance, one participant commented that "the information is composed organically." Three people admitted the the circular shape made this graph harder to understand, but they were still attracted to this design. Eight participants selected Diagram B as one of top 3 choices because the information was displayed in a clear manner and they could easily infer relationship changes by examining the flow of the lines.

Cons. Those participants who put Diagram B into the "dislike" category indicated that the circular orientation made this diagram hard to read. One participant also mentioned that this diagram took time to understand how the tie strength was portrayed. Another participant commented that Diagram B did not display too much information.

4.3 Diagram C: Line Graph Visualization of Interaction Frequency

Line graphs are useful in displaying increases and decreases in values over time. We apply line graphs in Diagram C where they depict the variation in interaction frequency over the length of relationships (Fig. 4). Diagram C illustrates the following parameters:

– *Length of relationships* is displayed on the x-axis in logarithmic scale.
– *Interaction frequency* is displayed on the y-axis without a detailed scale.
– *Interaction reciprocity* is shown using the amount of shade on each plotted dot. For example, a fully-colored dot implies that the interaction is reciprocal, and a half-colored dot implies that the interaction is one-way where the originator is based on the side of the color as shown in Fig. 4.
– *Recency of interaction* is conveyed based on the most recent point on the graph. In Fig. 4, Bob and Carol's most recent communication was last week.
– *Number of mutual friends* is represented by the number of distinct graphs on a single plot. In Fig. 4, the viewer and Bob have two mutual friends: Carol and David.

Similar to Diagram A, we introduce an average interaction frequency line on Diagram C, which represents the average interaction frequency that Alice has with all her other friends. This average line enables users to infer approximate "friendship level" relative to average friends. With this average, users can compare if Alice interacts more or less frequently with the given mutual friend, and can perceive better tie strengths between Alice and the mutual friend.

Analysis of Diagram C. Diagram C maps the same set of parameters as Diagram A. However, the reduced reciprocity information on Diagram C enables overlaying the lines which results in a more compact representation as well as the ability to more easily compare the different friendship levels. Instead of a bar graph, Diagram C is a connected line graph. Along with the average line, users may find Diagram C simple to read and easy to interpret. Furthermore, Diagram C can encapsulate extra information (e.g., percentage of online and offline communication and the reciprocity ratio) by placing a mouse pointer over each dot.

Feedback on Diagram C
Pros. Participants enjoyed the representation of reciprocity on this diagram. Seven participants who picked Diagram C as one of their top 3 indicated that this diagram was easy to read and understand. They also mentioned that comparing multiple graphs was straightforward.
Cons. Two participants mentioned that the symbols to represent reciprocity versus one-wayness were confusing. Instead of using the same color within a circle to represent reciprocity as shown in Fig. 4, they suggested using different colors or textures to represent reciprocity on each graph.

4.4 Diagram D: Dot Graph Visualization of Distinct Collocation

People tend to spend a lot of time together with their strong ties. However, the amount of time spent together by itself may not be a robust parameter to infer tie strength due to high false positive rate. For example, co-workers spend a lot of time together while they may not necessarily be close friends. On the other hand, people do not tend to visit many distinct places with casual acquaintances; people only interact with casual co-workers at their work place. Based on this observation, we conjecture that strong ties

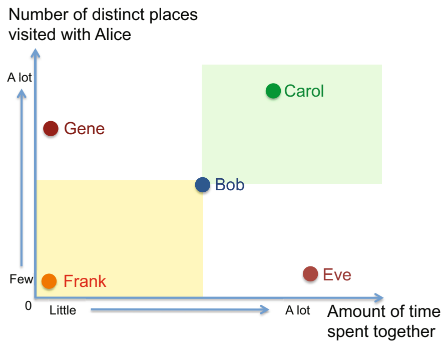


Fig. 5. Diagram D. This diagram displays the magnitude of the number of distinct places Alice visited together with her other friends and how much time Alice has spent interacting with them. 8 participants selected Diagram D as one of their top 3 choices.

can be distinguishable based on the number of collocation and duration of interaction. Diagram D (Fig. 5) maps the following parameters:

– *Number of distinct collocations* is mapped on the y-axis, ranging from a few to a lot of locations.
– *Duration of interaction* is mapped on the x-axis, ranging from little interaction to a lot of interactions, expressed in terms of time. In this diagram, the time duration includes not only physical but also other offline and online interactions.
– *Number of mutual friends* is displayed using dots over the plot.
– *Reciprocal interaction* is implied in this diagram since physical interactions can only occur when two people are near each other's vicinity.

For example, Fig. 5 shows that Alice and Carol have been spending a lot of time together while visiting many distinct places, possibly implying their strong-tie friend relationship. On the other hand, Alice and Eve have been spending a lot of time together but in few places, possibly implying a weak-tie co-worker or classmate relationship.

Analysis of Diagram D. Diagram D incorporates fewer parameters than others. We presumed that such simplicity would be better in preserving users' privacy, and that people would find this simpler diagram easy to understand and suitable for a number of use cases.

Feedback on Diagram D
Pros. All participants emphasized that Diagram D was straightforward and simple to understand. They also enjoyed to see a large number of mutual friends on the same plot.
Cons. Although participants enjoyed the simplicity, three of them raised the issue that it might be hard to determine the relationship since they might not get as much information from this diagram versus the other diagrams. Also, two participants were confused by the yellow and green quadrant representations and suggested better use of colors.

4.5 Summary of Study 1

The formative study enabled us to pick the top 4 diagrams that people expressed suitability and usefulness in inferring tie strength.

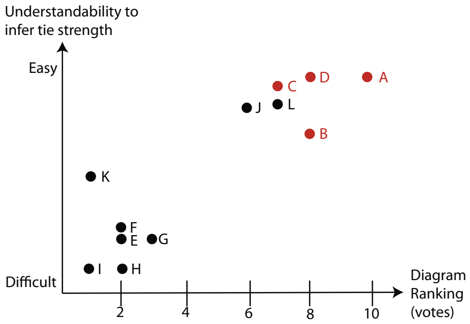


Fig. 6. Scatterplot showing diagram popularity vs. understandability in inferring tie strength. This diagram shows that the popular diagrams (e.g., Diagrams A–D, L) were easier to understand and infer tie strength compared to those low-ranked diagrams (Diagrams E–K). Note that we selected Diagram C over Diagram L as one of the top 4 diagrams because participants indicated that Diagram C carries more information and is easier to infer tie strength than Diagram L.

Fig. 6 summarizes the relationship between the participants' understandability in inferring tie strength and the popularity of 12 diagrams (Diagrams F – L are in Appendix). In summary, the participants favored diagrams that are easy to understand and infer tie strength. Note that Diagram C and Diagram L both received 7 votes. However, we selected Diagram C as one of the top 4 choices based on two reasons: 1) the participants indicated that Diagram C carries more information that would be useful to infer tie strength compared to Diagram L, and 2) Diagram L visualizes the same parameters as Diagram B for which a lot of participants expressed their fondness.

5 Study 2: Evaluation of Visualizations

Using the top 4 diagrams from Study 1 (as rated by participants), we conducted an online user study to analyze if the top 4 diagrams convey semantically meaningful and useful tie-strength information to users, and if these diagrams are easy to interpret and understand. we also studied the applicability of these diagrams to other use cases.

5.1 User Study Background

We conducted an online survey using Amazon Mechanical Turk (MTurk). We followed common methodologies for running MTurk studies [8, 18]. We wanted to focus on U.S. participants first; hence, we set the location restriction flag on MTurk to invite only users located within the U.S.

Our online survey had two rounds: the first round was to analyze meaningfulness and intuitiveness of Diagrams A–D, and to solicit other use cases for the diagrams. Based on the use cases that participants provided, we designed a follow-up survey to evaluate the applicability of Diagrams A–D to various use cases.

From 201 total participants, we analyzed the responses from 96 participants who completed both rounds after eliminating careless users as follows: 1) we eliminated anyone who provided contradicting answers to simple questions that we purposefully asked multiple times with different wording, and 2) we eliminated anyone who provided the same answers (both multiple-choice and fill-in answers) for at least 3 diagrams. The demographics of the 96 participants are as follows: 73% female and 27% male within the age range of 16 – 41 (μ = 36.4, σ = 9.4), all living in the U.S. All participants, even those we eliminated, were paid at least $1.00. Participants who provided accurate

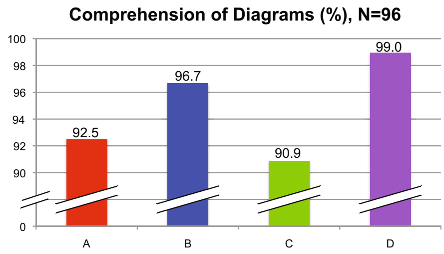


Fig. 7. Comprehension of Diagrams A–D. This bar graph presents the percentage of correctly answered questions on each diagram. Note that the y-axis is skipped over to 90%.

answers in the comprehension section of our study were paid $2.00. Finally, participants who returned for our follow-up survey on use cases were paid an additional $0.30. Thus, the 96 participants whose data we report on were paid $2.30 each.

5.2 Study Scenario

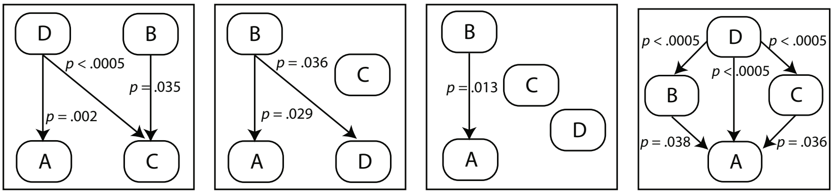
We used a within-subjects design and asked study participants to play a role as follows: "You are coordinating a surprise party for your best friend Alex. You would like to invite Alex's best friends whom you don't know, but you don't want to ask Alex directly. You found an application which analyzes how close people are to Alex. This application can show you 4 different diagrams, each of which draws different features to represent how close of a friend a person is to Alex. You are now ready to explore all 4 options and find out whom to invite to Alex's surprise party. Please explore each diagram carefully and answer the questions."

To minimize biases, we randomized the order of Diagrams A–D, and for each diagram, we described in detail what parameters the diagram visualizes and how users can interpret them along with some examples. We then asked questions on each diagram to test comprehension, meaningfulness, and intuitiveness. At the end of the study, we asked the participants to provide other use cases for each diagram in their own words.

5.3 Study Results

For all analyses reported in this section, we conducted repeated measures ANOVA tests using Greenhouse-Geisser correction (if the sphericity assumption was violated) and post-hoc pairwise comparison tests using the Bonferroni adjustment.

Comprehension. To measure how well participants comprehended Diagrams A–D, we asked 5 questions about each diagram; we asked 3 questions pertaining to the individual parameters that each diagram illustrates (e.g., when was the most recent interaction that Alex and Bailey had?, how many distinct places did Alex and Casey visit?), 1 question for interpreting the graphs in general (e.g., how did the interaction frequency change between Alex and Bailey over the last year?), and 1 question for comparing two different graphs/points on each diagram (e.g., between Casey and Drew, who did Alex interact more frequently with last week?). Note that not all diagrams carry the same parameters and the same information; hence, we modified some questions on the diagrams while maintaining the same relative level of difficulty.



(a) (b) (c) (d)

Fig. 8. Partial order graph from the Bonferroni post-hoc pairwise test based on (a) comprehension, (b) accuracy, (c) appropriateness, and (d) intuitiveness of Diagrams A–D. An arrow from X to Y means that Diagram X is statistically significant than Diagram Y in each property with 95% confidence rate. A *p-value* is shown next to the corresponding arrow.

Figure 7 shows the percentage of correctly answered questions on each diagram. As Figure 7 shows, all diagrams achieved high comprehension rate (over 90%). In particular, some diagrams resulted in significantly better comprehension than others according to the ANOVA test (see Table 1). Post-hoc pairwise comparison tests reported that Diagram D resulted in significantly higher comprehension rate compared to Diagrams A and C, and so did Diagram B compared to Diagram C. Figure 8(a) is the partial order graph based on this pairwise comparison test results.

Meaningfulness. To evaluate meaningfulness, we asked participants to evaluate how accurately each diagram portrays tie strength and how appropriate each diagram is for surprise party invitation, both using the 7-point Likert scales (1: not meaningful at all – 7: very meaningful). We used subjective measures to capture people's perceptions of how accurately each diagram portrays tie strength and how appropriate each diagram is for the use case of surprise party invitation.

An ANOVA test ($\chi^2 = 11.84$, $p = 0.037$) reported that the mean accuracy ratings of 4 diagrams were statistically significant as shown in Table 1. The partial order graph based on the pairwise test results is shown in Figure 8(b). Based on the results, we can conclude that Diagram B, depicting the level of friendship over length of relationship, is the visualization that participants rated as portraying tie strength most accurately.

In terms of how appropriate each diagram is for the use case of surprise party invitation, an ANOVA with the sphericity assumption satisfaction ($\chi^2 = 16.83$, $p = 0.005$) reported that mean appropriateness differed with statistical significance among 4 diagrams (see Table 1). The partial order graph based on the pairwise test results is shown

Table 1. Means and repeated measure ANOVA results for design goals (*N* = 96). The highest means that are statistically significant from others are highlighted in bold.

	Comprehension min:0 max:5	Accuracy min:1 max:7	Appropriateness min:1 max:7	Intuitiveness min:1 max:7
A	$4.623 \pm .079$	$5.146 \pm .147$	$5.104 \pm .183$	$4.521 \pm .200$
B	$\mathbf{4.823 \pm .071}$	$\mathbf{5.667 \pm .152}$	$\mathbf{5.708 \pm .159}$	$5.198 \pm .168$
C	$4.544 \pm .072$	$5.229 \pm .139$	$5.188 \pm .160$	$5.167 \pm .146$
D	$\mathbf{4.948 \pm .027}$	$5.031 \pm .154$	$5.115 \pm .175$	$\mathbf{6.135 \pm .100}$
ANOVA	$F(2.365, 285) = 8.30$ $p < 0.0005$	$F(2.748, 285) = 4.29$ $p = .007$	$F(3, 285) = 4.06$ $p = .008$	$F(2.657, 285) = 20.00$ $p < 0.0005$

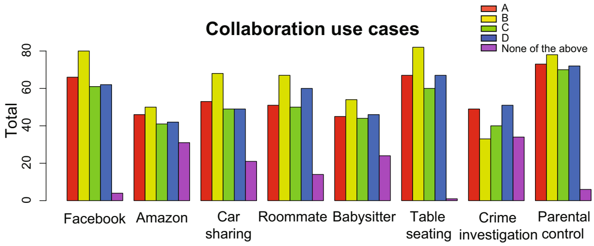


Fig. 9. Applicability of Diagrams A–D to various use cases ($N = 96$)

in Figure 8(c). Based on these results, we can conclude that Diagram B is the most appropriate visualization to infer tie strength for the use case of surprise party invitation.

Intuitiveness. We asked participants to rate how intuitive each diagram was to understand given a Likert scale from 1 (not intuitive at all) to 7 (very intuitive). An ANOVA test ($\chi^2 = 21.17, p = 0.001$) reported that mean intuitiveness differed statistically significantly among 4 diagrams as shown in Table 1. Figure 8(d) is the partial order graph based on the pairwise-test results. Hence, participants found Diagram D as the most intuitive visualization.

Use Cases. We wanted to understand what participants thought about using 4 diagrams for other use cases. To evaluate use cases, we asked participants to provide their own (if possible). Based on participants' feedback, we created a follow-up survey and invited them back to select the diagram(s) they deemed suitable for each use case.

Figure 9 is the bar graph summarizing the result for the use cases. We provided 4 examples based on our conjectures: 1) validating Facebook friend inviter, 2) validating product recommenders on Amazon, 3) verifying the renter of the participants' vehicles, and 4) finding a roommate. Among many examples that the participants provided, we show the following on Figure 9: 1) finding a babysitter, 2) finding close people for determining table seatings, 3) analyzing crime investigation, and 4) learning whom the participants' children hang out with.

Overall, Diagram B had the highest scores on all use cases except crime investigation; for this case, the participants reported that Diagram A, depicting interaction frequency, and Diagram D, depicting collocation, are suitable.

6 Discussion

Table 2 summarizes how Diagrams A–D satisfy the design goals based on the participants' feedback. Based on the study results, we can conclude that Diagram B, depicting the changes in the friendship level over the length of time period using simple lines, is the best tie-strength visualization among 4 designs since it was ranked to be the most meaningful diagram and had a high comprehension rate. For implementation, further study may be needed to study how to represent such concrete friendship levels using online and offline communications.

One major complaint about Diagram B was that the Polar coordinate system was challenging to read (although it graphically depicts distance from the center point); indeed, Diagram C plots the interaction frequency over length of time using simple

Property \ Diagram	A	B	C	D
Comprehension		•		•
Meaningfulness		•		
Intuitiveness				•

Table 2. Summary of design goal satisfactions for Diagrams A–D. A dot is placed on the diagram with the highest mean value that was statistically significant from other diagrams for each property.

lines on the Cartesian coordinate system. However, a recurring downside of Diagram C was the representation of the reciprocity: users expressed the difficulty of understanding the definition of reciprocity. Hence, we leave it as a future study to verify the criticality of reciprocity for inferring tie strength for context-dependent trust decisions.

Privacy. In this paper, our main focus was to study the utility of the visualizations. Although these diagrams show sensitive information, it is also abstracted to minimize specific details, such as when calls are made or what the content of the communications are. Furthermore, privacy-sensitive data is aggregated and normalized, without revealing exact values, and release of tie strength visualization information is entirely voluntary. Thus, a user can suppress releasing information that s/he does not feel comfortable about. For example, one participant in Study 1 mentioned, "I like [Diagram A] since it doesn't look trivial to figure out the exact interaction frequency. To me, this diagram greatly preserves privacy." Another participant also mentioned, "although [Diagram D] shows less information than other diagrams that I've seen so far, I think this diagram can still be useful. But I'm not quite sure how helpful this diagram would be to check how close people are." We plan to study privacy aspects in our future work once the utility is recognized.

7 Conclusion

We explored the design space of visualizing interpersonal tie strength to empower users to make their own informed, context-dependent trust decisions for various collaborative activities. We designed 12 different diagrams for visualizing tie strength, based on data that have been shown to be feasibly gathered from smartphones and online interactions. In our first user study, we solicited qualitative feedback from our participants regarding our designs, and based on this feedback, we narrowed our visualizations down to four. In a second user study, we were able to analyze how comprehensive, meaningful, and easy to understand our visualizations were. Although we found that participants appreciated the applicability of our visualization to a wide range of collaboration use cases, future research still needs to determine the extent of its suitability.

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A Low-Ranked Diagrams

The following diagrams, along with Diagram E in Figure 1 are the ones that were not selected as top 4 diagrams from Study 1.

Fig. 10. Diagram F. This diagram shows how far away from a random reference location two people have been interacting over a period of a year, how much time they have been spending at each location, and whether the interactions happened on weekdays or weekends.

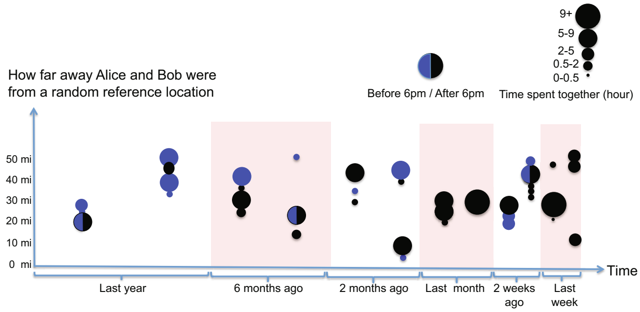

Fig. 11. Diagram G. This diagram shows how far away from a random reference location two people have been interacting over a period of a year, how much time they have been spending at each location, and whether the interactions were before 6:00 PM or after 6:00 PM.

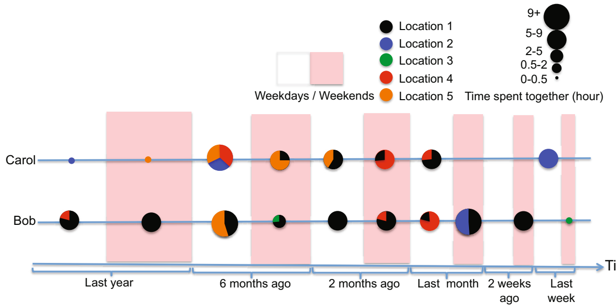

Fig. 12. Diagram H. This diagram shows the number of distinct locations that Alice has physically been collocated with her friends Bob and Carol over a period of a year, and how much time they have been spending at each location, and whether the interactions took place on weekdays or weekends.

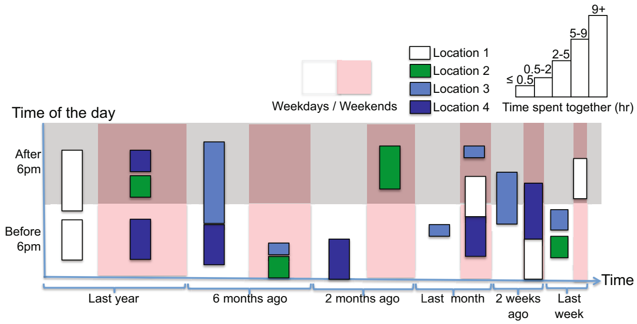

Fig. 13. Diagram I. This diagram is a variation of Diagram H, emphasizing distinct collocations. Unlike Diagram H, this diagram visualizes collocations of two people using blocks. Different colored blocks represent distinct locations and the size of the blocks indicates the amount of time two people have spent together.

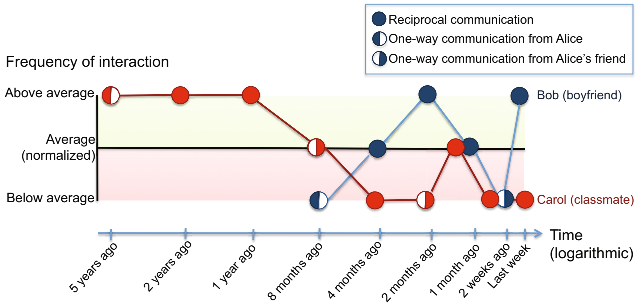

Fig. 14. Diagram J. This diagram displays the same parameters as Diagram C. The distinction is that Diagram J categorizes the interaction frequency into three groups: above average, average, or below average.

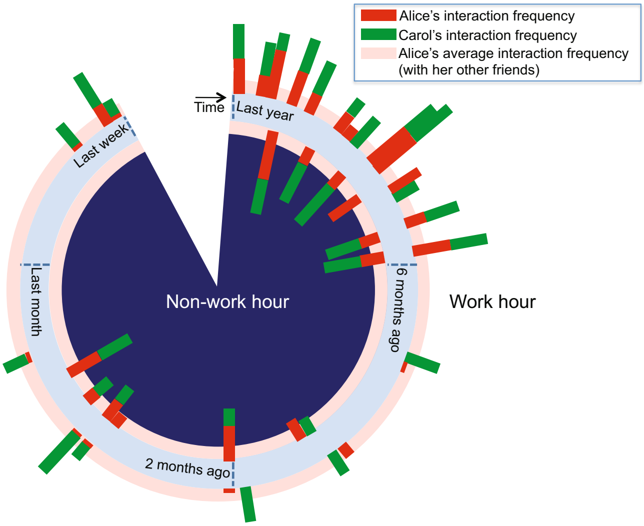

Fig. 15. Diagram K. This diagram plots two user's interaction frequency over time, as in Diagram A. In contrast to Diagram A, Diagram K displays an additional parameter: time of day.

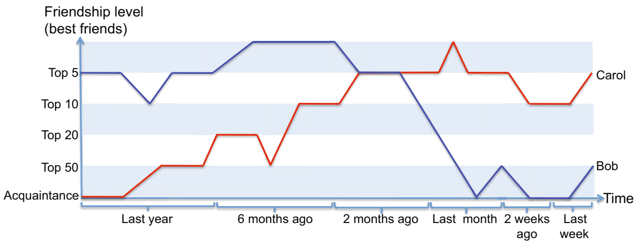

Fig. 16. Diagram L. This diagram is a variation of Diagram B. Instead of using the Polar coordinate system, Diagram L displays changes in friendship levels using the Cartesian coordinate system.