

Massive Social Network Analysis: Mining Twitter for Social Good

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Abstract—Social networks produce an enormous quantity of data. Facebook consists of over 400 million active users sharing over 5 billion pieces of information each month. Analyzing this vast quantity of unstructured data presents challenges for software and hardware. We present GraphCT, a *Graph Characterization Toolkit* for massive graphs representing social network data. On a 128-processor Cray XMT, GraphCT estimates the betweenness centrality of an artificially generated (R-MAT) 537 million vertex, 8.6 billion edge graph in 55 minutes and a real-world graph (Kwak, *et al.*) with 61.6 million vertices and 1.47 billion edges in 105 minutes. We use GraphCT to analyze public data from Twitter, a microblogging network. Twitter's message connections appear primarily tree-structured as a news dissemination system. Within the public data, however, are clusters of conversations. Using GraphCT, we can rank actors within these conversations and help analysts focus attention on a much smaller data subset.

I. INTRODUCTION

Since the explosion of the Internet in the 1990s, numerous researchers have focused on identifying unifying characteristics of online communities. Efforts such as identifying political factionalism [1] or recommendation networks [24] have provided unique, simplifying insights into the behavior of human social groups linked by electronic networks. Such insights are of intellectual and practical interest. Underlying this interest is the hypothesis that relationships and behaviors in virtual communities reflect similar phenomena in the real world, such as commercial proclivities, political leanings, and propensity for violence.

Social media provide tremendous challenges for researchers and analysts trying to gain insight into human and group dynamics. A central problem is the sheer amount of data available in social media. For example, the social media aggregation site Spinn3r [34] advertises that they provide information on over 20 million blogs, feeds that stream over 100 thousand posts and an 8 month archive consisting of 21 TB of data. Facebook currently

involves over 400 million active users with an average of 120 friendship connections each and sharing 5 billion references to items each month [11].

One analysis approach treats the interactions as graphs and applies tools from graph theory, social network analysis, and scale-free networks [29]. However, the volume of data that must be processed to apply these techniques overwhelms current computational capabilities. Even well-understood analytic methodologies require advances in both hardware and software to process the growing corpus of social media.

Social media provides staggering amounts of data. Extracting knowledge from these volumes requires automation. Computing quickly over this data is a challenge for both algorithms and architectures.

We present GraphCT, a *Graph Characterization Toolkit* capable of applying complex analysis tools to massive graphs. We analyze graphs representing Twitter's public data stream using GraphCT and demonstrate that the packaged metrics reveal interesting characteristics of Twitter users' interactions. The graph is rich with broadcast trees that repeat the same news stories or other information. We want to identify influential sources and not those who only rebroadcast information. Removing tree-like broadcast networks identifies conversations, and ranking users focuses on conversations with important or influential users. An analyst can focus on a handful of conversations rather than tens of thousands of interactions.

These graphs are huge with respect to traditional social network analysis tools but do not present GraphCT's full capabilities. We also apply GraphCT to massive artificial networks similar in size to the Facebook friend network. On a 128-processor Cray XMT, approximating a complex metric, betweenness centrality, on an artificial graph with 537 million vertices and 8.54 billion edges takes 55 minutes. An estimate on a real-world graph [22], [23] with 61.6 million vertices and 1.47 billion edges takes 105 minutes. We are unaware of any other package or

system that applies complex measurements to graphs of this size. These graphs are 3-4 orders of magnitude larger than graphs analyzed by packages with similar features. The Cray XMT is an architecture designed for analysis of large data sets. The cost even of approximating a metric on massive graphs is worth noting. Approximations on Section III's real data demonstrate large variability and significant errors; more work on approximation quality is needed.

The remainder of this introduction provides further background on graph representations for social networks. Section II briefly summarizes the algorithms we apply to the Twitter network. The analysis results are discussed in Section III. Details of GraphCT, our tool for massive social network analysis, appear in Section IV. Section V summarizes GraphCT's application to the Twitter data and presents future directions for massive social network analysis.

A. Graph Analysis for Social Networks

We treat social network interactions as a graph and use graph metrics to ascribe importance within the network. There are two common representation approaches. One is to represent the actors by vertices and connect two actors whenever they share an interaction. Another forms a bipartite graph considering both actors and interactions as vertices and connecting actors with interactions. We use the former representation connecting actors to actors in the remainder of this paper.

For social media sites like Twitter, user names (@foo) are vertices, and we add an edge from @foo to @bar whenever @foo posts a message mentioning @bar. For most metrics, we treat the graph as undirected, so an edge from @foo to @bar also connects @bar back to @foo. This representation aggregates interactions and focuses on the relationships between actors. A directed model connecting only @foo to @bar could model directed flow and is of future interest.

Various measures of the vertices and connectivity within a graph identify critical portions. A simple measure like the degree distribution reflects the relative volume of messages related to individual actors. Another measure, betweenness centrality [14], can identify critical vertices in a network. High centrality scores indicate that a vertex lies on a considerable fraction of shortest paths connecting pairs of vertices and may play an important role in the network. Betweenness centrality has been applied extensively to the study of various networks including biological networks [19], sexual networks and the transmission of the AIDS virus [25], identifying key actors in terrorist networks [8], organizational behavior,

and transportation networks [16].

Betweenness centrality measures the fraction of shortest paths passing through a vertex. Considering *short* paths within a length k of the shortest paths produces k -betweenness centrality [20], a measure intended to be more robust against changes within the graph. Section II-A summarizes the k -betweenness centrality algorithm.

B. Social Network Graph Characteristics

The graphs representing social networks often share common characteristics [28] useful for tuning software. The degree distribution tends towards a heavy tail; a few vertices have high degree while most have very low degrees. Natural clusters form, but the clusters do not partition the graph. The clusters overlap where communities share members, and some actors may not join any larger communities. Characteristics change over time. This paper considers only a snapshot, but ongoing work examines the data's temporal aspects.

II. ALGORITHMS FOR MASSIVE SOCIAL NETWORK ANALYSIS

GraphCT supplies multithreaded implementations of known algorithms for the Cray XMT. We review the algorithms and their implications for multithreaded implementation.

A. Algorithm Summary

The analysis in Section III considers degree distributions, connected components, and betweenness centrality along with a few graph manipulations. GraphCT provides routines for the former but assumes all manipulations occur before being given the data or can be expressed as colorings. GraphCT collects highly parallel algorithms for betweenness centrality [26], [20], connected components (similar to [5]), and others. We briefly describe these algorithms.

Computing degree distributions and histograms is straight-forward. Our static, undirected graph data structure uses the compressed sparse row format and contains the degrees implicitly. The degree statistics are summarized by their mean and variance. A histogram produces a general characterization of the graph; a few high degree vertices with many low degree vertices indicates a similarity to scale-free social networks.

GraphCT extracts connected components from the graph through a technique similar to Kahan's algorithm [5]. In the first phase searches breadth-first simultaneously from every vertex of the graph to greedily color neighbors with integers. These parallel searches track which colors

collide. The next phase repeatedly absorbs higher labeled colors into lower labeled neighbors. Relabeling the colors downward occurs as another parallel breadth-first search. This effectively combines the second and third steps in Kahan's method. Once there are no more collisions, the remaining colors determine the components.

Betweenness centrality is a more complex metric for ranking vertices. Betweenness centrality counts along how many shortest paths a particular vertex lies. More precisely,

$$BC(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}},$$

where V is the set of vertices, $\sigma_{st}(v)$ is the number of shortest paths from s to t passing through v , and σ_{st} is the total number of shortest paths from s to t . Approximating this metric by randomly sampling a small number of source vertices s improves the running times and allows computation of approximate betweenness centrality on massive graphs. Sampling does not degrade the score quality significantly on artificial networks [3]. Section III investigates the sampling trade-off on real data.

Betweenness centrality is not robust against noise. Adding or removing a single edge may drastically alter many vertices' betweenness centrality scores. Considering not only the shortest paths but also all paths within length k of the shortest paths introduces robustness against small changes and produces k -betweenness centrality [26]. k -Betweenness centrality considers alternate paths that may become important should the shortest path change. When $k = 0$, this produces the traditional betweenness centrality.

The algorithm GraphCT uses to compute k -betweenness centrality runs across every source vertex s . The contributions by each source vertex can be computed independently and in parallel, given sufficient memory ($O(S(m+n))$, where S is the number of parallel source vertices). A parallel breadth-first search finds the shortest paths from s to all other vertices. The breadth-first search also follows links within the same level, one level back, and so on up to $k - 1$ levels back to accumulate paths of length at most k longer than the shortest.

A recurrence generalizing Brandes's betweenness centrality recurrence [6] computes the k -betweenness centrality path counts. The value for a vertex v depends on its predecessors' values. Another parallel sweep following the breadth-first search levels evaluates the recurrence.

B. Software and Hardware Needs for Massive SNA

Path-based metrics like betweenness centrality contain opportunities for fine-grained parallelism beyond running

multiple searches simultaneously. Unlike that coarse level of parallelism, the fine-grained parallelism within each search does not require $O(m+n)$ data storage per task. Exposing the fine-grained parallelism permits pipelining of memory accesses for latency tolerance, but exploiting the parallelism requires a few programming environment and hardware features. The irregular memory access patterns also dictate a globally addressable memory space.

Such common programming environments as OpenMP [31] and Cray [32] compilers expose the fine-grained parallelism through looping constructs and compiler directives. The only synchronization operation required by Section II-A's analysis algorithms is an atomic fetch-and-add operation. This operation is available through standard environments like OpenMP and platform-specific compilers like Cray's.

Taking advantage of the fine-grained parallelism requires light-weight thread management. The loops are not strict vector loops but irregular combinations of reads, conditionals, operations, and writes. Some current hardware platforms such as current GPGPUs vectorize conditional-laden loops through predicated instructions [36]. All threads read all instructions for all possible conditional outcomes, but each thread executes fully only those instructions that match a particular conditional path. For our algorithms, the irregular activities within the loops restrict the active execution to only a few threads at any time, wasting computational resources.

In contrast, the Cray XMT [21] provides significant hardware assistance for massive graph analysis. The architecture tolerates high memory latencies by maintaining many active thread contexts in hardware. These threads are fully general and do not rely on pseudo-vectorization. Synchronization costs are amortized over the same memory latencies, leading to high processor efficiency even with many data dependencies. Scaling the number of available thread contexts directly with memory size permits.

Each Threadstorm processor within a Cray XMT contains 128 thread contexts in *hardware streams*. Streams may be blocked temporarily waiting for memory and are remapped to new threads when synchronizing memory accesses retry too often. The processor dispatches one instruction per cycle, selecting an instruction from each ready stream in turn. There is no cache in the processors; all latency is handled by threading. Each processor is accompanied by 8 GiB of DDR RAM, and processors are connected through Cray's SeaStar network.

The Cray XMT features a large, globally addressable memory with hashed addresses breaking locality and alleviating hot spots. Synchronization takes place at

TABLE I
COMMON MICROBLOGGING SYMBOLS USED ON TWITTER.

Symbol	Interpretation
@	User foo is addressed as @foo within notices.
#	A “hashtag” is a user-provided word denoting a topic.

the level of 64-bit words. The Cray XMT supports atomic fetch-and-add operations along with more exotic synchronization primitives like full/empty bits. The cost of synchronization is amortized over the cost of memory access, and fine-grained synchronization latency is tolerated through same the massively multithreaded architecture.

The Cray XMT used for these experiments is located at Pacific Northwest National Lab and contains 128 Threadstorm processors running at 500 MHz. These 128 processors support over 12 thousand user thread contexts. The globally addressable shared memory totals 1 TiB and can hold graph data structures containing more than 4 billion vertices and 34 billion edges.

III. APPLYING MASSIVE SNA TO REAL DATA

A. Micro-Blogging: Twitter

As an example of the power and utility of GraphCT for projecting complex network data into analytically tractable information, we consider networks derived from real-world social media, Twitter. Twitter is a social network in which short 140-character messages, known as “tweets”, are transmitted via cell phones and personal computers onto a central server where they can be viewed by the entire community. Analyses reported here are evaluated on Twitter updates aggregated by Spinn3r [34], a web and social media indexing service which conducts real-time indexing of all blogs. From the Spinn3r corpus several representative Twitter data sets are extracted motivated by two crises occurring in September 2009.

1) *In uenza H1N1 Tweets in September 2009*: While the impact of the 2009 global in uenza H1N1/A pandemic was milder than expected, concern persists due to the severity of previous pandemics. In particular the 1918 Spanish Flu infected 500 million individuals and caused 50 million deaths worldwide between March 1918 and June 1920 [27]. The correlation between open communications and public health information is clear in the abrupt explosion of social media articles published in the 17th week of April 2009. Table II reports the number of English non-spam social media articles (not including micro-blogs), with keywords `h1n1` or `swine flu`, posted during the first eight weeks of the pandemic

TABLE II
NOVEL INFLUENZA H1N1/A ENGLISH, NON-SPAM ARTICLES (NOT INCLUDING MICRO-BLOGS) POSTED PER WEEK IN 2009

Week in 2009	# Articles
17th	5 591
18th	108 038
19th	61 341
20th	26 256
21th	19 224
22th	37 938
23th	14 393
24th	27 502

in 2009 [9]. Informed by the previous statement, a harvest of all public tweets published during an arbitrary time-frame, September 2009, containing the keywords `flu`, `h1n1`, `influenza` and `swine flu` is aggregated into one data set. An example H1N1 topic Twitter stream is provided in Fig. 1.

2) *Atlanta Flood Tweets in September 2009*
#atlfflood: A second crisis motivating a Twitter data set is the dramatic flooding of Atlanta, Georgia in late September 2009. The following is a quote from the federal agency that tracks flooding in the United States:

the U.S. Geological Survey cannot accurately characterize the probability due to its extreme rarity [...] Nationwide, given that our oldest streamgauging records span about 100 years, the USGS does not cite probabilities for floods that are beyond a 0.2 percent (500-year) flood [35].

Twitter users flocked to this medium to share photographs, news updates, weather conditions and the location of

- **jaketapper**: every yr 36,000 Ams (on avg) die from regular u. this COULD be higher. + the big diff is the reg u kills older Ams, H1N1 kills the young
- **jaketapper**: @EdMorrissey Asserting that all thats being done to prevent the spread of H1N1 is offering that hand-washing advice is just not true.
- **jaketapper**: @dancharles as someone with a pregnant wife i will clearly take issue with that craziness. they are more vulnerable to H1N1,as are toddlers
- **dancharles**: RT @jaketapper @Slate: Sanjay Gupta has swine u http://bit.ly/B9IFe <= Glad I listened to his “stay u free ” tips

Fig. 1. Example of a Twitter conversation between Jake Tapper and Dan Charles in the H1N1 data set.

current flood points throughout the metroplex by concatenating the hashtag #atlfflood to their tweets. We created a data set of all public tweets during a five day window between the 20th and 25th of September 2009 containing the hashtag #atlfflood.

3) *All public tweets September 1st, 2009*: A third data set is compiled from all public tweets posted on September 1st, 2009. We leverage the larger size of this data to evaluate performance (runtime and accuracy) of GraphCT's algorithms.

B. Tweet Graphs

User interaction graphs are created by adding an edge into the graph for every mention (denoted by the prefix @) of a user by the tweet author. Duplicate user interactions are thrown out so that only unique user-interactions are represented in the graph. Selected tweet graph characteristics are listed in Table III of both the full graph and of the largest weakly connected component (LWCC).

TABLE III
TWITTER USER-TO-USER GRAPH CHARACTERISTICS

Tweet Graph Data	Users	Unique user interactions	Tweets with responses
Sep 2009 H1N1 (LWCC)	46,457 13,200	36,886 16,541	3,444 1,772
20-25 Sep 2009 #atlfflood (LWCC)	2,283 1,488	2,774 2,267	279 247
1 Sep 2009 all (LWCC)	735,465 512,010	1,020,671 879,621	171,512 148,708

C. Degree (Power Law) Distribution of Data

A criterion in many complex systems is that properties are often distributed as power laws, also known as 80/20 rules or Pareto rules where 80% of the effects come from 20% of the causes. The numbers 80 and 20 are not special, one observes power laws with different breakdowns. The key fact is the disproportionate influence of relatively few elements. For our purposes, power laws are important since they imply that by characterizing the influential elements in a community, we can characterize the community as a whole. In network theory, a key distribution of interest is the degree distribution. So called scale-free¹

¹The term "scale-free" is a technical characterization of power law distributions. They are so named because changing the scale of measurement (e.g. going from imperial to metric units) leaves the mathematical structure of the distribution unchanged; there is no preferred scale in the distribution. In contrast, the normal distribution, can be transformed to a simpler mathematical form by choosing a length scale equal to the standard deviation.

TABLE IV
TOP 15 USERS BY BETWEENNESS CENTRALITY

Rank	H1N1	Data Set atl flood
1	@CDCFlu	@ajc
2	@addthis	@driveafastercar
3	@Official_PAX	@ATLCheap
4	@FluGov	@TWCi
5	@nytimes	@HelloNorthGA
6	@tweetmeme	@11AliveNews
7	@mercola	@WSB_TV
8	@CNN	@shaunking
9	@backstreetboys	@Carl
10	@EllieSmith_x	@SpaceyG
11	@TIME	@ATLIntownPaper
12	@CDCemergency	@TJsDJs
13	@CDC_eHealth	@ATLien
14	@perezhilton	@MarshallRamsey
15	@billmaher	@Kanye

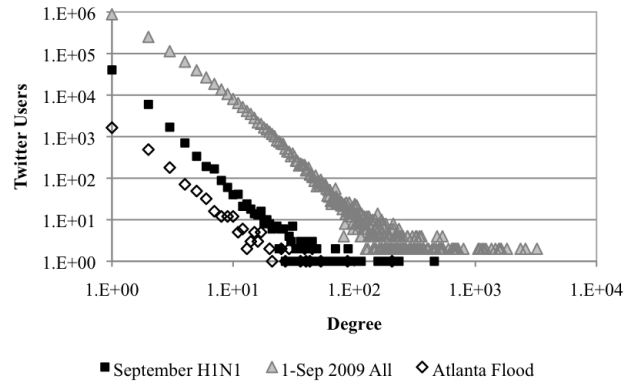


Fig. 2. Degree distribution of the Twitter user-user graph.

networks exhibit power-law distributions in their degree distributions—most connections are concentrated in a small fraction of the vertices (e.g. 80 of the connections involve 20% of the vertices or 90/10 or 99/1) [30]. Power laws have been observed in broad variety of social networks [30], [13], [25]. Scale-free tweet mention graphs would imply that a few Twitter users and “mentioners” are responsible for a disproportionately high fraction of a community’s discourse.

An observation in all three datasets is that there are relatively few high-degree vertices (see Fig. 2). Twitter users tend to refer to relatively few “broadcast” vertices. Empirically examining some of the top vertices (Table. IV) in the twitter datasets reveals that these high-degree vertices are dominated by major media outlets

and government organizations².

One interpretation of Twitter's user network structure is in news dissemination. Users track topics of interest from major sources and occasionally re-broadcast (*retweet*) that information. Information flows one way, from the broadcast hub out to the users. In incidental communication, the user will refer to the broadcast source. This leads to the question about the nature of these "second order" communications. Is Twitter used simply as a one-to-many broadcast medium, or are there many-to-many communication patterns hidden in the data?

To examine this question, we looked for subgraphs in the data that exhibited many-to-many attributes. We used a straight-forward approach to identify subgraphs. We retained only pairs of vertices that referred to one-another through `@` tags (see Table III). This led to dramatic reductions in the size of the networks. We present the results graphically in Fig. 3 for each of the data sets and an example Twitter stream with conversation from ABC news correspondent Jake Tapper in Fig. 1.

Our analyses of sub-communities in Twitter data informed the following conclusions. Sub-communities are relatively small fractions of the overall data. Qualitative measurements assist identification of scaling behavior. We observed reduction factors, due to filtering non-conversation interactions, as high as two orders of magnitude (see Table III). Inspection of the high ranking users derived from the GraphCT betweenness centrality scores on the smaller datasets show the content is on-topic (i.e. relevant to keyword search) and uncluttered with noise (e.g. spam, off-topic conversations). We also observe some groups within the subcommunities using Twitter as a text messaging service, engaging in *direct* conversations regarding the topic of interest. An interesting artifact in the tweet graphs show numerous "self-referring" vertices, Tweeters whose updates reference themselves, informing evidence that Twitter mimics an echo chamber in addition to a broadcast messaging service.

D. Runtime Characteristics

In social media analysis, many times we are interested in only the most information rich sources, or those actors that have the greatest ability to broker information between parties. The betweenness centrality metric is used to assign varying scores related to the latter of the previous statement. To evaluate the effectiveness of

GraphCT on real-world data we compare performance, both in accuracy and runtime, on the task of identifying top ranked actors, across evaluation settings. Exact betweenness centrality is compared against approximate centrality. The value in this comparison is the identification of trade-offs between run-time performance and accuracy. Even on medium sized graphs, on the order of 10^7 vertices and edges, exact centrality measurements become intractable (bounded by memory capacity and processor speeds) on commodity machines. Because of this the GraphCT betweenness algorithm allows for varying levels of approximation (see Section II-A). In addition to understanding the trade-offs through varying levels of approximation, an analyst or user may require a task to identify a set of the top $N\%$ actors in a given social network. Moreover, to compare accuracy of approximate BC vs. exact we use normalized set Hamming distance as a metric to compare the top $N\%$ ranked actors across evaluations [17], [12].

E. Analysis and Conclusions

Let us first consider the runtime performance of GraphCT executed on real-world graphs. Due to the many-component property of the Twitter data, we allocate several evaluation settings by varying the percentage of randomly sampled nodes (see Section II-A). Specifically we randomly sample 10%, 25% and 50% of the nodes in each tweet graph, achieving 90% confidence with the runtime averaged over 10 realizations for each evaluation setting and data set. Exact centrality, 100% node sampling, is the control for these calculations. The runtime characteristics are graphed on a log-linear scale in Fig. 4; the x-axis is the percentage of all vertices randomly sampled in the approximate betweenness centrality calculations and the y-axis measures the runtime in seconds. Inspecting the figure, there is a clear and dramatic runtime performance difference of 10% sampling compared to exact calculations, 30 seconds compared to nearly 49 minutes respectively.

Analysts incorporating GraphCT algorithms into their work flows may have explicit requirements on the accuracy of results, acknowledging the trade-off between runtime speed and accuracy of the approximate betweenness centrality. In analyzing social networks, the analyst is most interested in the actors with the highest score. To inform these decisions we evaluate accuracy of simple betweenness centrality when 10%, 25% and 50% of the nodes in each real-world tweet graph are sampled. The chosen metric, described in the previous section, is the normalized top k set Hamming distance. The top 1%,

²For the H1N1 data, the authors were able to identify the high-referenced vertices as media and government outlets. For the Atlanta Flood data, the authors from the Atlanta area examined the data and identified most of the top vertices as Atlanta based newspapers, TV and radio personalities.

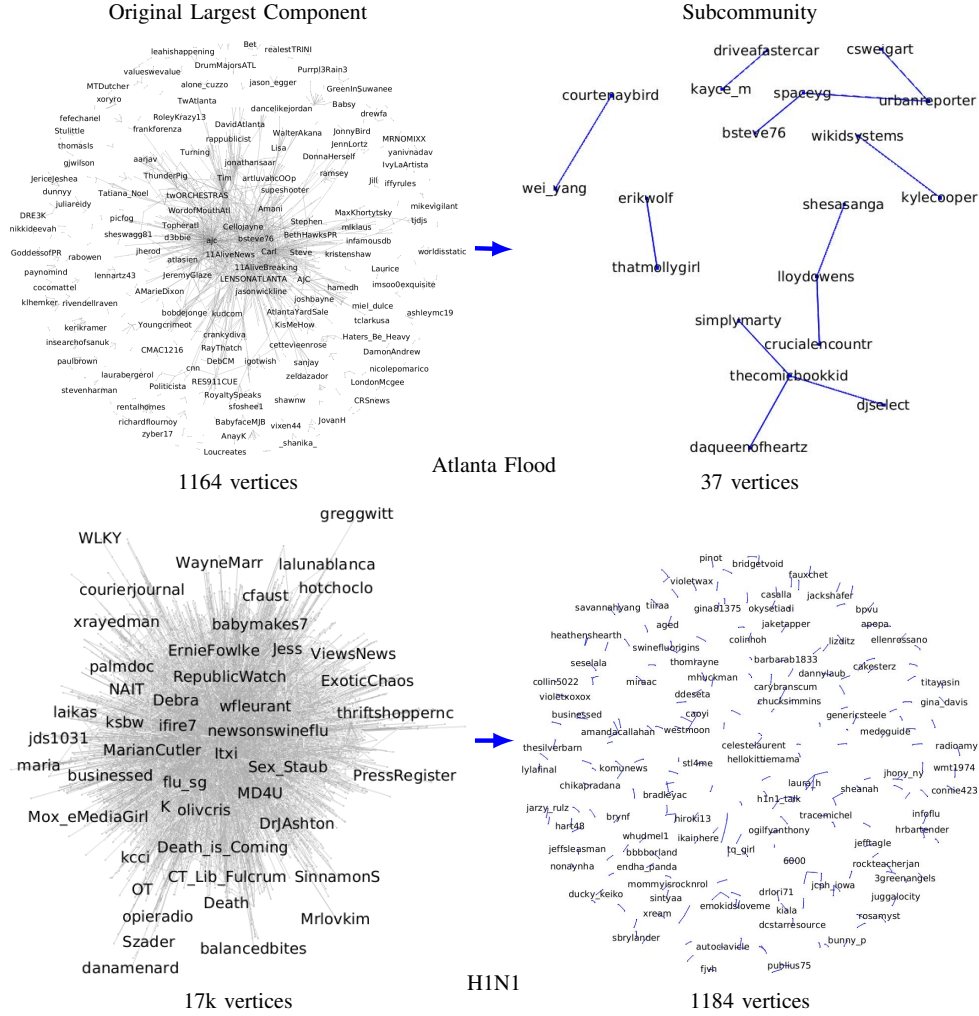


Fig. 3. Subcommunity filtering on Twitter data sets

5%, 10% and 20% users by approximate betweenness centrality score are compared to the top $N\%$ exact centrality ranked users, achieving 90% confidence with the accuracies averaged over 10 realizations for each evaluation setting and data set. The accuracy trade-off results are plotted in Fig. 5; the y-axis is labeled with the percent of top k actors present in both exact and approximate BC rankings and the x-axis labels the percentage of all vertices randomly sampled in the approximate betweenness centrality calculations. The accuracy remains above 80% comparing the top 1% and 5% users when sampling 10% of the real-world tweet graphs. The accuracy climbs to over 90% comparing the top 1% and 5% ranked users and sampling 25% and 50% of the vertices.

IV. GRAPHCT: SNA ALGORITHMS FOR MASSIVE GRAPHS

The literature contains a number of different social network analysis software packages developed for sequential workstations and high performance, parallel machines [33], [4], [15]. Workstation implementations are limited in the size of graphs they analyze by the size of main memory and the inability of the cache hierarchy to accelerate irregular memory accesses. A representative software package is typically limited to several hundred thousand or several million vertices.

GraphCT is a multithreaded Graph Characterization Toolkit implemented on the massively multithreaded Cray XMT. It is designed from the ground up to expose fine-grained parallelism and profitably use tens of thousands of hardware threads. Loading massive datasets into

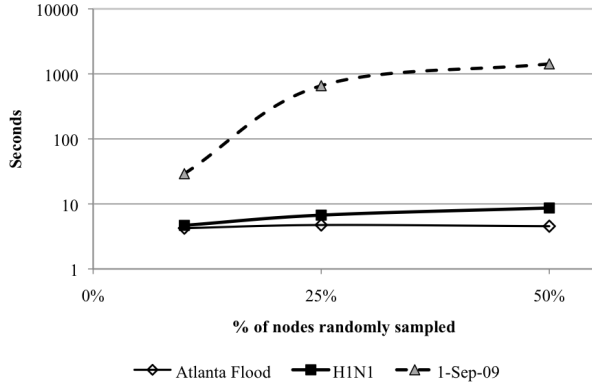


Fig. 4. Runtime performance of GraphCT Simple Betweenness Centrality. *x axis*: The percentage of the total vertices that were randomly sampled in the simple betweenness centrality calculations. *y-axis*: Kernel runtime performance, in seconds (log scale), on the 128 node Cray XMT

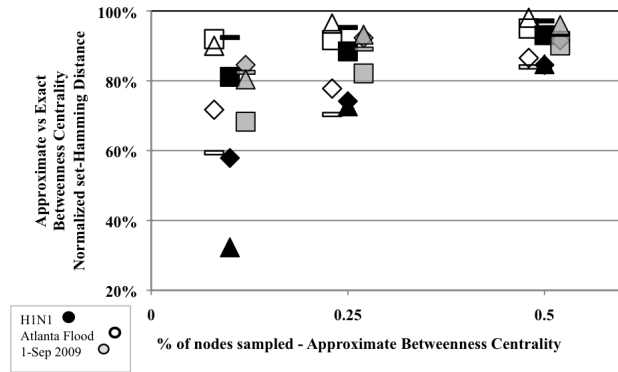


Fig. 5. Accuracy trade-off between exact and approximate BC. *x axis*: The percentage of the total vertices that were randomly sampled in the approximate BC calculations. *y-axis*: The percent of top k actors present in both exact and approximate BC rankings. Legend: $k = 1(\triangle)$, $5(\diamond)$, $10(\square)$, $20(\circ)$

memory and unloading results often occupies a majority of computation time. GraphCT contains a small scripting interface to amortize I/O time over multiple analysis passes within a dataset. GraphCT also runs sequentially on POSIX-like platforms.

A. Kernels

Running multiple analytic kernels over one in-memory graph requires each kernel to use a common graph data structure. Some social network analysis software packages require the user to choose a data representation according to the structure of the graph and the analysis to be performed. GraphCT makes no assumptions about the type or structure being analyzed. The graph is stored in compressed-sparse row (CSR) format, a common representation for sparse matrices. The number of vertices

and edges is known when ingesting the data, so the size of the allocated graph is fixed.

Implemented top-level kernels include marking connected components, calculating statistical distributions of out-degree and component sizes, extracting k -cores, marking a breadth-first search from a given vertex of a given length, finding the per-vertex clustering coefficients, and ranking vertices according to their k -betweenness centrality. Provided utility functions convert a directed graph to an undirected graph or extract a subgraph induced by a coloring function. Implementing additional graph kernels is straightforward due to the common data structure and interface.

After loading the graph into memory and before running any kernel, the diameter of the graph is estimated by performing a breadth-first search from 256 randomly selected source vertices. The diameter is estimated by four times the longest path distance found in those searches. The diameter estimate is stored globally for use in determining the length of queues to allocate in traversal-based kernels. Users do not need to supply topology information but may specify an alternate multiplier or number of samples. Overestimates waste some memory, while underestimates cause later routines to run out of space and fail. This determines the lengths of queues and does not affect accuracy of the kernels.

Graph kernels accumulate results in structures accessible by later kernel functions. Finding all connected components, extracting components according to their size, and analyzing those components is a common sequence. The connected components function returns the number of components and the coloring, and utility functions produce the relevant subgraphs to analyze.

B. Scripting Interface

Not every analyst is a C language application developer. To make GraphCT usable by domain scientists interested in studying their graphs, GraphCT contains a prototype scripting interface to the various analytics.

The script is executed sequentially with the first line reading in a graph data file from disk and the following lines calling one kernel function each. Kernels that produce per-vertex data can write the outputs to files as specified in the command. All other kernels will print their results to the screen.

The language employs a stack-based “memory” function, similar to that of a basic calculator. At any time, the graph that is currently being operated on can be pushed onto the stack. Another graph, or a subgraph of the original, can then be analyzed. When ready to discard

this graph and return to the previous, the graph can be recalled.

An example script follows:

```
read dimacs patents.txt
print diameter 10
save graph
extract component 1 => compl.bin
print degrees
kcentrality 1 256 => k1scores.txt
kcentrality 2 256 => k2scores.txt
restore graph
extract component 2
print degrees
```

The script reads a DIMACS-formatted file called `patents.txt` into memory. The diameter of the graph is explicitly estimated using breadth first searches originating from a random selection of 10 percent of the vertices. The full graph is stored, and then the largest component is extracted. At the same time, this component is stored to disk in a binary format called `compl.bin`. The degree distribution statistics from this component are printed to the screen. k -Betweenness centrality is estimated for $k = 1$ on this component using 256 random source vertices and the resulting scores are written to disk in a per-vertex manner as `k1scores.txt`. This is repeated for $k = 2$. The full graph is restored in memory and the second largest component is then extracted. The degree distribution statistics are produced for this component.

The current implementation contains no loop constructs or feedback mechanisms. GraphCT reads the script line-by-line; an external process can monitor the results and control execution. Simple loop structures are a topic for future consideration.

C. Performance and Scalability Characteristics

The software implementation of GraphCT was designed from the ground up to take advantage of the massively multithreaded Cray XMT architecture and leverage the fine-grained multithreading and low-cost synchronization primitives in order to achieve high performance on a variety of sparse graphs. Previously published experiments establish GraphCT's scalability on the Cray XMT for social networks [26], [20], [10]. Fig. 6 shows performance of betweenness centrality estimation on our data sets (Table III) and the much larger follower graph from Kwak, *et al.* [22], [23]. The follower graph from Kwak, *et al.* contains 61.6 million and 1.47 *billion* edges. GraphCT required 105 minutes on 128 processor Cray XMT to estimate betweenness centrality using 256 source vertices. Estimation on an artificial, scale-29 R-

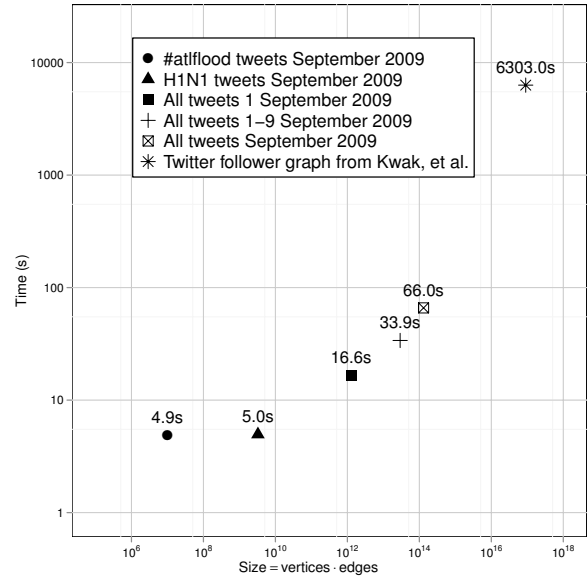


Fig. 6. Time in seconds for GraphCT to estimate betweenness centrality using 256 source vertices on a 128-processor Cray XMT. Table III gives sizes for the first three data sets. The user interaction graph of tweets from 1-9 Sept. 2009 consists of 4.1 million vertices, 7.1 million edges; the graph for all of Sept. 2009 consist of 7.2 million vertices and 18.2 million edges. The follower graph from [22], [23] contains 61.6 million and 1.47 *billion* edges.

MAT [7] graph of 537 million vertices and 8.6 billion edges³ requires 55 minutes, emphasizing a difference between real-world and artificial data.

A large number of graph datasets consist of plain text files. One simple example is a DIMACS formatted graph [2], which is made up of an edge list and an integer weight for each edge. A single file with millions of lines of edge list could overwhelm the main memory on a service node, so GraphCT parses large text files on the Cray XMT. We copy the file from disk to the main memory of the Cray XMT and parse the file in parallel into the internal binary compressed sparse row format. A 1 TiB main memory enables efficient loading and parsing of much larger text input than does relying on the service node and out-of-core algorithms.

V. CONCLUSIONS

Analyzing the social interaction graph induced by public Twitter messages exposes Twitter's use in news dissemination. Many relationships fall into tree-like broadcast patterns. A few users are repeated by many.

³R-MAT parameters: $A = 0.55$, $B = C = 0.1$, $D = 0.25$, scale 29, edge factor 16

Considering direction, bidirectional links are good indicators of conversations even ignoring the time of each message.

The moderate quality of approximations in Section III show that more work on sampling is needed. We currently conjecture that the unguided random sampling in GraphCT may miss components when the graph is not connected. Another interesting problem is in quantifying significance and confidence of approximations over noisy graph data.

The September 2009 Twitter data also is relatively small compared to GraphCT's capabilities. The data from September 2009 has 735 thousand vertices and 1 million edges, requiring only around 30 MiB of memory in our naïve storage format. The Facebook friend network consists of over 400 million users. A scale-29 R-MAT [7] graph of 537 million vertices and 8.6 billion edges emulates such a network and requires at least 7 GiB for the basic graph connectivity data without weights or other generally useful information. Approximating the centrality on this graph using the 1 TiB Cray XMT requires 55 minutes using 256 samples. Approximating centrality similarly on the real-world Kwak, *et al.* Twitter data set [22], [23] of 61.6 million vertices and 1.47 billion edges requires 105 minutes. We are unaware of other tools for evaluating complex metrics on such large graphs.

The combination of GraphCT and the Cray XMT's massive multithreading permits exploration of graph data sets previously considered too massive. GraphCT is freely available as open source software from our web site and runs both on the Cray XMT and on POSIX platforms.

During the publishing of this paper, we discovered (via a re-send of a Twitter message) independent research also analyzing public Twitter streams [22], [23]. We have applied GraphCT on the Cray XMT to their data set to gather performance data and still are analyzing the graph metric results. Java, *et al.* [18] in 2007 present an early work analyzing Twitter that applies relatively simple analysis to a smaller data set and hypothesizes more varied use than appears in our research.

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