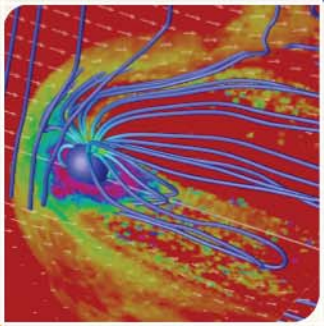
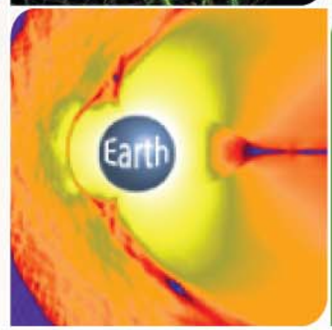
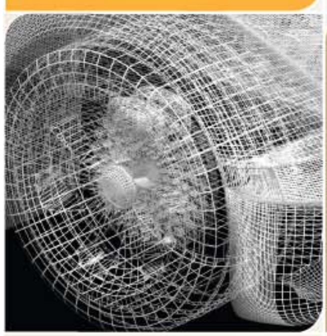




Applications and challenges in large-scale graph analysis

David A. Bader, Jason Riedy, Henning Meyerhenke

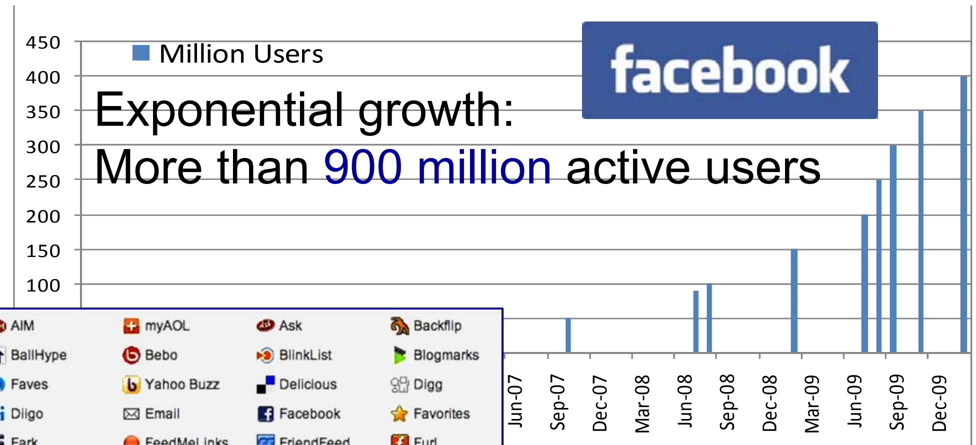


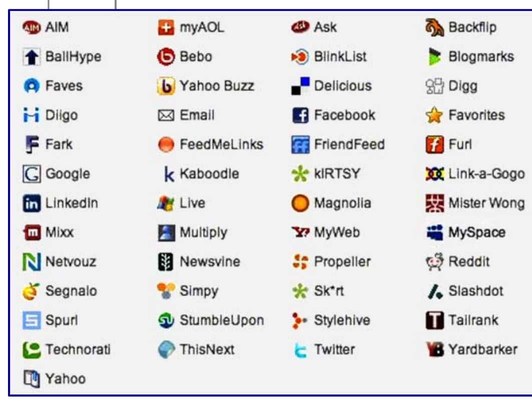
Georgia Tech College of Computing
Computational Science and Engineering

Exascale Streaming Data Analytics: Real-world challenges

All involve analyzing massive streaming complex networks:

- Health care → disease spread, detection and prevention of epidemics/pandemics (e.g. SARS, Avian flu, H1N1 “swine” flu)
- Massive social networks → understanding communities, intentions, population dynamics, pandemic spread, transportation and evacuation
- Intelligence → business analytics, anomaly detection, security, knowledge discovery from massive data sets
- Systems Biology → understanding complex life systems, drug design, microbial research, unravel the mysteries of the HIV virus; understand life, disease,
- Electric Power Grid → communication, transportation, energy, water, food supply
- Modeling and Simulation → Perform full-scale economic-social-political simulations





Ex: discovered minimal changes in O(billions)-size complex network that could hide or reveal top influencers in the community

Sample queries:

Allegiance switching: identify entities that switch communities.

Community structure: identify the genesis and dissipation of communities

Phase change: identify significant change in the network structure

REQUIRES PREDICTING / INFLUENCE CHANGE IN REAL-TIME AT SCALE

Current Example Data Rates

- Financial:
  - NYSE processes 1.5TB daily, maintains 8PB
- Social:
  - Facebook adds >100k users, 55M “status” updates, 80M photos daily; ~1B active users with an average of 130 “friend” connections each.
  - Foursquare reports 1.2M location check-ins per week
- Scientific:
  - MEDLINE adds from 1 to 140 publications a day

Shared features: All data is rich, irregularly connected to other data. All is a mix of “good” and “bad” data… And much real data may be missing or inconsistent.

Ubiquitous High Performance Computing (UHPC)

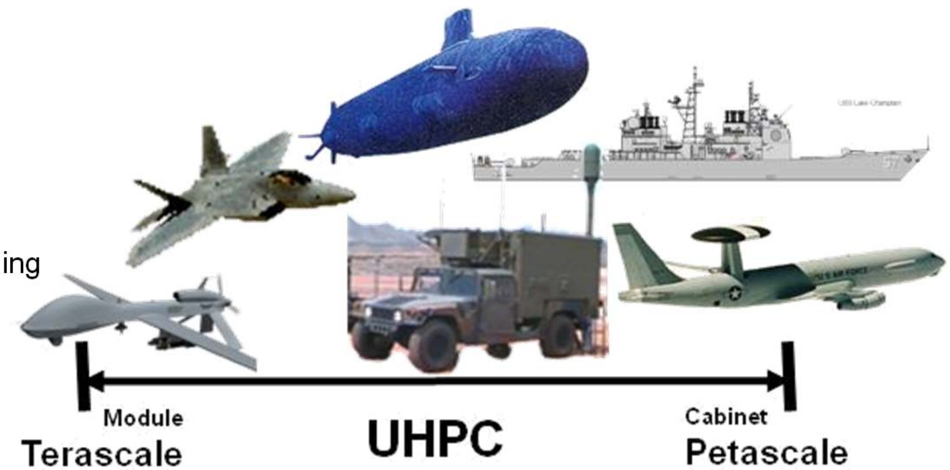
Goal: develop highly parallel, security enabled, power efficient processing systems, supporting ease of programming, with resilient execution through all failure modes and intrusion attacks

Architectural Drivers:

- Energy Efficient
- Security and Dependability
- Programmability

Program Objectives:

- One PFLOPS, single cabinet including self-contained cooling
- 50 GFLOPS/W (equivalent to 20 pJ/FLOP)
- Total cabinet power budget 57KW, includes processing resources, storage and cooling
- Security embedded at all system levels
- Parallel, efficient execution models
- Highly programmable parallel systems
- Scalable systems – from terascale to petascale



David A. Bader (CSE)
Echelon Leadership Team

NVIDIA

CRAY
THE SUPERCOMPUTER COMPANY

GEORGIA TECH

"NVIDIA-Led Team Receives $25 Million Contract From DARPA to Develop High-Performance GPU Computing Systems" -MarketWatch

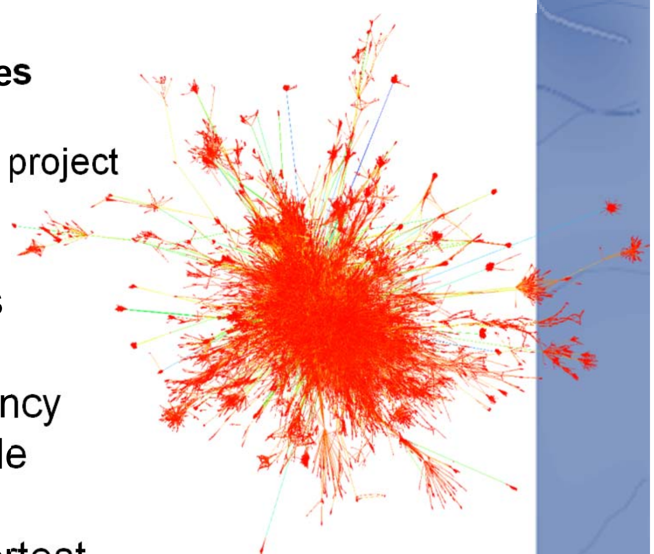
Echelon: Extreme-scale Compute Hierarchies with Efficient Locality-Optimized Nodes

Georgia Institute of Technology

GRATEFUL: Graph Analysis Tackling power Efficiency, Uncertainty, and Locality

Objective: Research and develop new algorithms and software for crucial graph analysis problems in cybersecurity, intelligence integration, and network analysis.

- In-the-field, embedded processing systems have limited computational capabilities due to severe power constraints. **DARPA's Power Efficiency Revolution For Embedded Computing Technologies (PERFECT) program** will address this need by increasing the computational power efficiency of these embedded systems. The project seeks a power efficiency of 75 GFLOPS/watt.

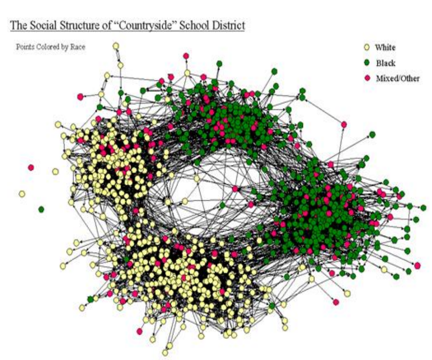


- **GRATEFUL** will extend high-performance graph analysis algorithms to reduce power usage and provide resilience against imperfect data. We will build a model of concurrency requirements for graph algorithms. The project will provide energy-conscious and data error-resilient algorithms on streaming data, including computing and maintaining shortest path trees and graph decompositions into communities.
- *PIs: David A. Bader and Jason Riedy*

Sponsored under the DARPA PERFECT program, Contract HR0011-13-2-0001

Center for Adaptive Supercomputing Software for MultiThreaded Architectures (CASS-MT)

- Launched July 2008
- Pacific-Northwest Lab
  - Georgia Tech, Sandia, WA State, Delaware
- The newest breed of supercomputers have hardware set up not just for speed, but also to better tackle large networks of seemingly random data. And now, a multi-institutional group of researchers has been awarded over $14 million to develop software for these supercomputers. Applications include anywhere complex webs of information can be found: from internet security and power grid stability to complex biological networks.



Example: Mining Twitter for Social Good

ICPP 2010

Massive Social Network Analysis: Mining Twitter for Social Good

David Ediger Karl Jiang
Jason Riedy David A. Bader
Georgia Institute of Technology
Atlanta, GA, USA

Courtney Corley Rob Farber
Pacific Northwest National Lab.
Richland, WA, USA

William N. Reynolds
Least Squares Software, In
Albuquerque, NM, USA

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

involves over 400 million active users with an ave
120 'friendship' connections each and sharing 5
references to items each month [11].
One analysis approach treats the interactions as
and applies tools from graph theory, social r
analysis, and scale-free networks [29]. Howe
volume of data that must be processed to appl
techniques overwhelms current computational cap
Even well-understood analytic methodologies
advances in both hardware and software to proc
growing corpus of social media.
Social media provides staggering amounts

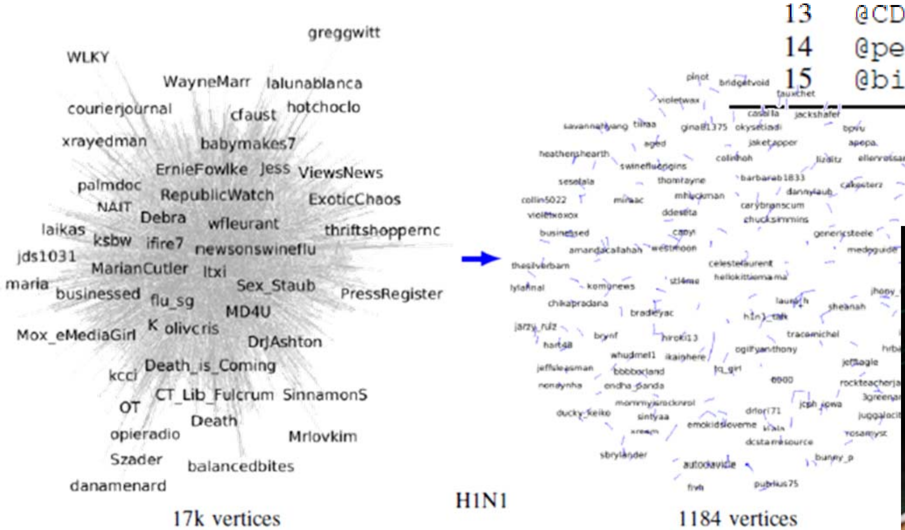
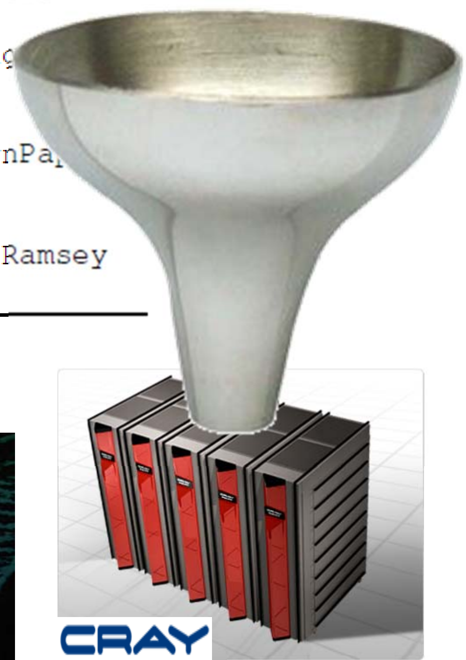


Fig. 3. Subcommunity filtering on Twitter data sets

TOP 15 USERS BY BETWEENNESS CENTRALITY

Rank	Data Set: H1N1	Data Set: atlflood
1	@CDCFlu	@ajc
2	@addthis	@driveafaste
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	@ATLINtownPa
12	@CDCemergency	@TJsDJs
13	@CDC_eHealth	@ATLien
14	@perezhilton	@MarshallRamsey
15	@billmaher	@Kanye

public tweets



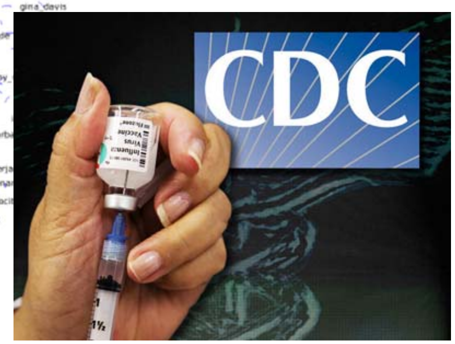
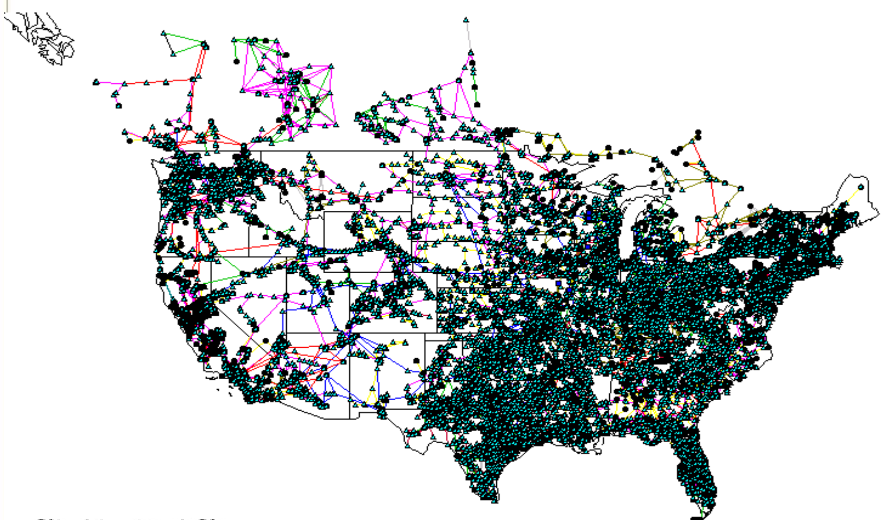
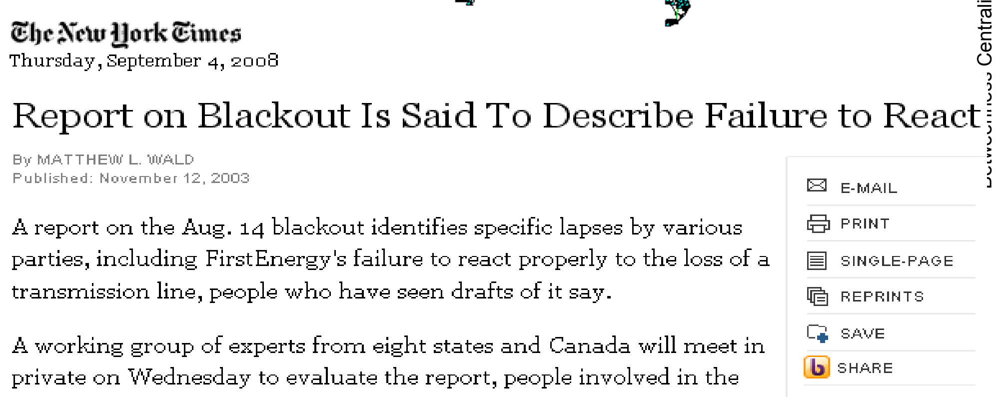


Image credit: bioethicsinstitute.org

Massive Data Analytics: Protecting our Nation

US High Voltage Transmission Grid (>150,000 miles of line)





The New York Times
Thursday, September 4, 2008

Report on Blackout Is Said To Describe Failure to React

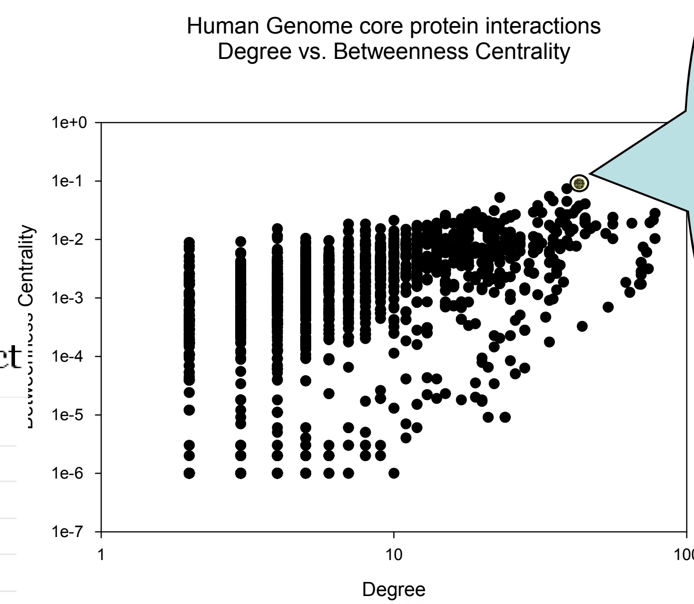
By MATTHEW L. WALD
Published: November 12, 2003

A report on the Aug. 14 blackout identifies specific lapses by various parties, including FirstEnergy's failure to react properly to the loss of a transmission line, people who have seen drafts of it say.

A working group of experts from eight states and Canada will meet in private on Wednesday to evaluate the report, people involved in the

Public Health

- CDC / Nation-scale surveillance of public health
- Cancer genomics and drug design
  - computed Betweenness Centrality of Human Proteome



ENSG0000145332.2 Kelch-like protein implicated in breast cancer

Network Analysis for Intelligence and Surveillance

- [Krebs '04] Post 9/11 Terrorist Network Analysis from public domain information
- Plot masterminds correctly identified from interaction patterns: centrality

- A global view of entities is often more insightful
- Detect anomalous activities by exact/approximate graph matching

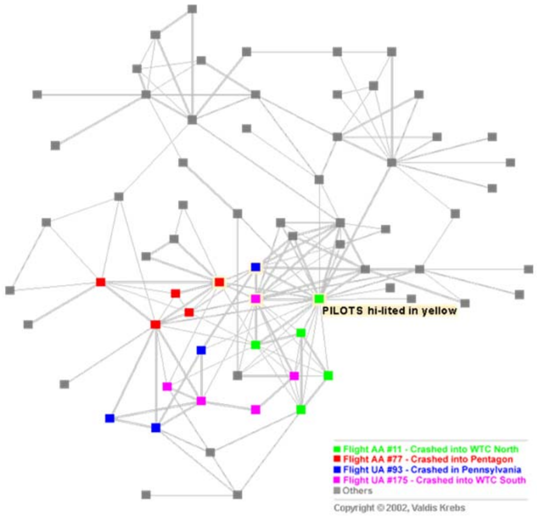


Image Source: http://www.orgnet.com/hijackers.html

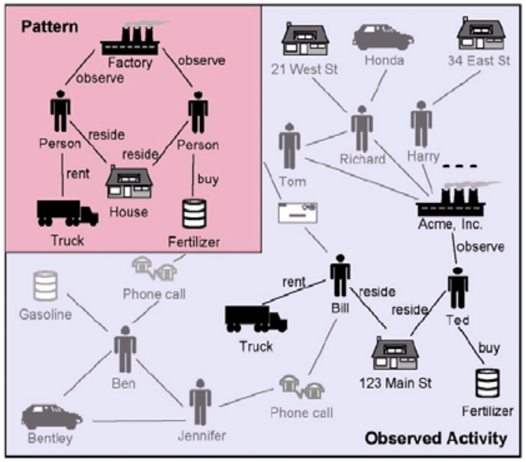


Image Source: T. Coffman, S. Greenblatt, S. Marcus, Graph-based technologies for intelligence analysis, CACM, 47 (3, March 2004): pp 45-47

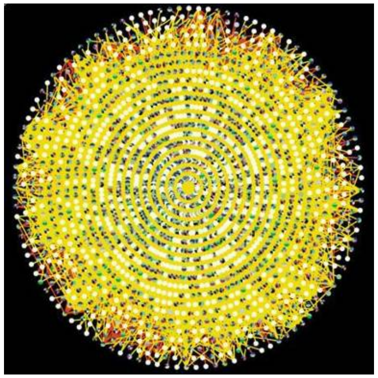
Graphs are pervasive in large-scale data analysis

- Sources of massive data: petascale simulations, experimental devices, the Internet, scientific applications.
- New challenges for analysis: data sizes, heterogeneity, uncertainty, data quality.

Astrophysics
Problem: Outlier detection.
Challenges: massive datasets, temporal variations.
Graph problems: clustering, matching.

Bioinformatics
Problem: Identifying drug target proteins.
Challenges: Data heterogeneity, quality.
Graph problems: centrality, clustering.

Social Informatics
Problem: Discover emergent communities, model spread of information.
Challenges: new analytics routines, uncertainty in data.
Graph problems: clustering, shortest paths, flows.



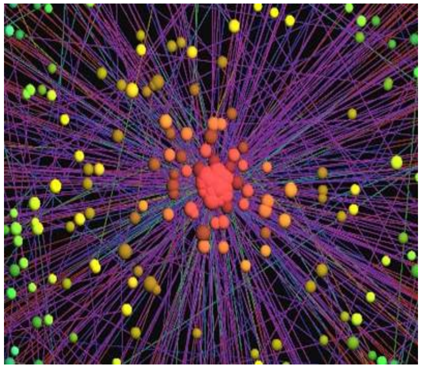


Image sources: (1) http://physics.nmt.edu/images/astro/hst_starfield.jpg
(2,3) www.visualComplexity.com

Graph Analytics for Social Networks

- Are there new graph techniques? Do they parallelize? Can the computational systems (algorithms, machines) handle massive networks with millions to billions of individuals? Can the techniques tolerate noisy data, massive data, streaming data, etc. …
- Communities may overlap, exhibit different properties and sizes, and be driven by different models
  - Detect communities (static or emerging)
  - Identify important individuals
  - Detect anomalous behavior
  - Given a community, find a representative member of the community
  - Given a set of individuals, find the best community that includes them

Suddenly, the flock became suspicious:
How come the newcomer wasn't shorn?

Graph500 Benchmark, www.graph500.org

Defining a new set of benchmarks to guide the design of hardware architectures and software systems intended to support such applications and to help procurements. Graph algorithms are a core part of many analytics workloads.

Executive Committee: D.A. Bader, R. Murphy, M. Snir, A. Lumsdaine

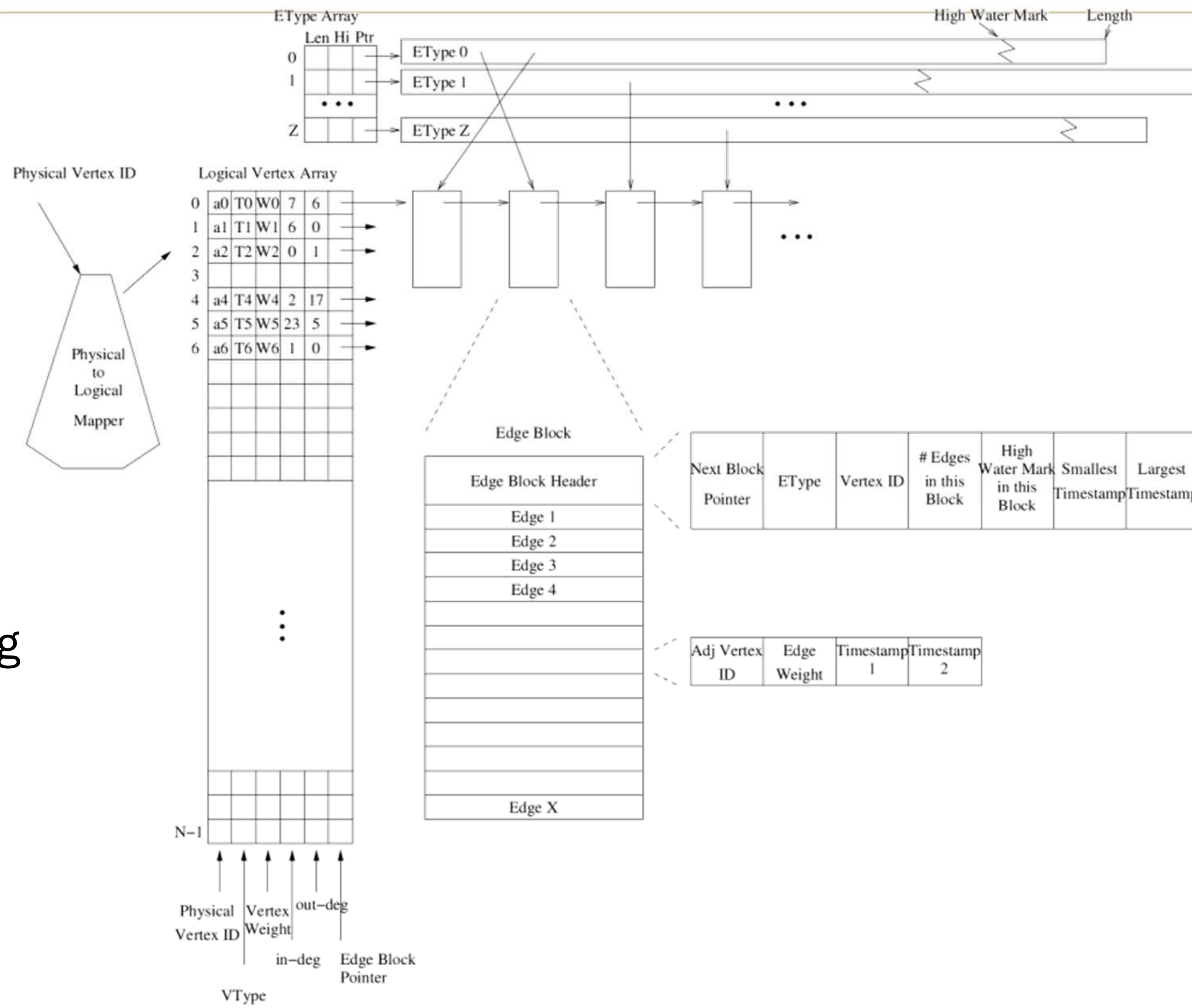
- Five Business Area Data Sets:
  - Cybersecurity
    - 15 Billion Log Entires/Day (for large enterprises)
    - Full Data Scan with End-to-End Join Required
  - Medical Informatics
    - 50M patient records, 20-200 records/patient, billions of individuals
    - Entity Resolution Important
  - Social Networks
    - Example, Facebook, Twitter
    - Nearly Unbounded Dataset Size
  - Data Enrichment
    - Easily PB of data
    - Example: Maritime Domain Awareness
      - Hundreds of Millions of Transponders
      - Tens of Thousands of Cargo Ships
      - Tens of Millions of Pieces of Bulk Cargo
      - May involve additional data (images, etc.)
  - Symbolic Networks
    - Example, the Human Brain
    - 25B Neurons
    - 7,000+ Connections/Neuron

STING Extensible Representation (STINGER)

- Enhanced representation developed for dynamic graphs developed in consultation with David A. Bader, Jon Berry, Adam Amos-Binks, Daniel Chavarría-Miranda, Charles Hastings, Kamesh Madduri, and Steven C. Poulos.
- Design goals:
  - Be useful for the entire “large graph” community
  - Portable semantics and high-level optimizations across multiple platforms & frameworks (XMT C, MTGL, etc.)
  - Permit good performance: No single structure is optimal for all.
  - Assume globally addressable memory access
  - Support multiple, parallel readers and a single writer
- Operations:
  - Insert/update & delete both vertices & edges
  - Aging-off: Remove old edges (by timestamp)
  - Serialization to support checkpointing, etc.

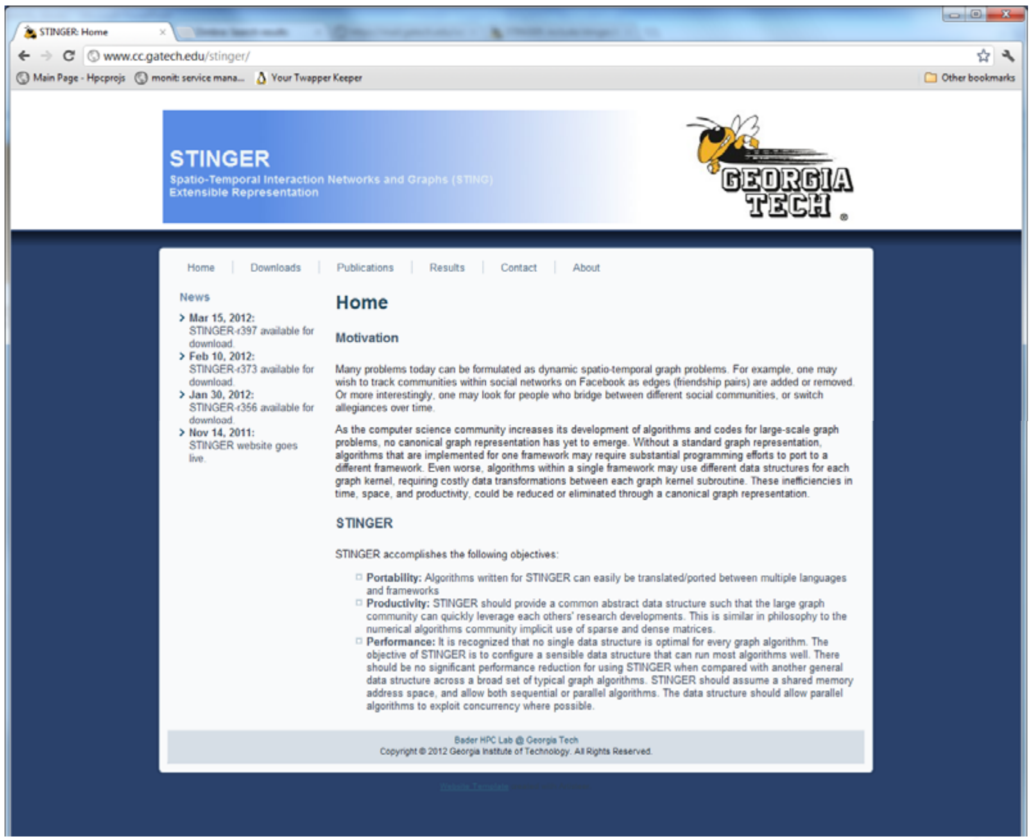
STING Extensible Representation

- Semi-dense edge list blocks with free space
- Compactly stores timestamps, types, weights
- Maps from application IDs to storage IDs
- Deletion by negating IDs, separate compaction



STINGER Software Dissemination

- http://www.cc.gatech.edu/stinger



Bader, Related Recent Publications (2005-2008)

- D.A. Bader, G. Cong, and J. Feo, “On the Architectural Requirements for Efficient Execution of Graph Algorithms,” *The 34th International Conference on Parallel Processing* (ICPP 2005), pp. 547-556, Georg Sverdrups House, University of Oslo, Norway, June 14-17, 2005.
- D.A. Bader and K. Madduri, “Design and Implementation of the HPCS Graph Analysis Benchmark on Symmetric Multiprocessors,” *The 12th International Conference on High Performance Computing* (HiPC 2005), D.A. Bader *et al.*, (eds.), Springer-Verlag LNCS 3769, 465-476, Goa, India, December 2005.
- D.A. Bader and K. Madduri, “Designing Multithreaded Algorithms for Breadth-First Search and st-connectivity on the Cray MTA-2,” *The 35th International Conference on Parallel Processing* (ICPP 2006), Columbus, OH, August 14-18, 2006.
- D.A. Bader and K. Madduri, “Parallel Algorithms for Evaluating Centrality Indices in Real-world Networks,” *The 35th International Conference on Parallel Processing* (ICPP 2006), Columbus, OH, August 14-18, 2006.
- K. Madduri, D.A. Bader, J.W. Berry, and J.R. Crobak, “Parallel Shortest Path Algorithms for Solving Large-Scale Instances,” *9th DIMACS Implementation Challenge -- The Shortest Path Problem*, DIMACS Center, Rutgers University, Piscataway, NJ, November 13-14, 2006.
- K. Madduri, D.A. Bader, J.W. Berry, and J.R. Crobak, “An Experimental Study of A Parallel Shortest Path Algorithm for Solving Large-Scale Graph Instances,” *Workshop on Algorithm Engineering and Experiments* (ALENEX), New Orleans, LA, January 6, 2007.
- J.R. Crobak, J.W. Berry, K. Madduri, and D.A. Bader, “Advanced Shortest Path Algorithms on a Massively-Multithreaded Architecture,” *First Workshop on Multithreaded Architectures and Applications* (MTAAP), Long Beach, CA, March 30, 2007.
- D.A. Bader and K. Madduri, “High-Performance Combinatorial Techniques for Analyzing Massive Dynamic Interaction Networks,” *DIMACS Workshop on Computational Methods for Dynamic Interaction Networks*, DIMACS Center, Rutgers University, Piscataway, NJ, September 24-25, 2007.
- D.A. Bader, S. Kintali, K. Madduri, and M. Mihail, “Approximating Betewenness Centrality,” The *5th Workshop on Algorithms and Models for the Web-Graph* (WAW2007), San Diego, CA, December 11-12, 2007.
- David A. Bader, Kamesh Madduri, Guojing Cong, and John Feo, “Design of Multithreaded Algorithms for Combinatorial Problems,” in S. Rajasekaran and J. Reif, editors, *Handbook of Parallel Computing: Models, Algorithms, and Applications*, CRC Press, Chapter 31, 2007.
- Kamesh Madduri, David A. Bader, Jonathan W. Berry, Joseph R. Crobak, and Bruce A. Hendrickson, “Multithreaded Algorithms for Processing Massive Graphs,” in D.A. Bader, editor, *Petascale Computing: Algorithms and Applications*, Chapman & Hall / CRC Press, Chapter 12, 2007.
- D.A. Bader and K. Madduri, “SNAP, Small-world Network Analysis and Partitioning: an open-source parallel graph framework for the exploration of large-scale networks,” *22nd IEEE International Parallel and Distributed Processing Symposium* (IPDPS), Miami, FL, April 14-18, 2008.

Bader, Related Recent Publications (2009-2010)

- S. Kang, D.A. Bader, “An Efficient Transactional Memory Algorithm for Computing Minimum Spanning Forest of Sparse Graphs,” 14th ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming (PPoPP), Raleigh, NC, February 2009.
- Karl Jiang, David Ediger, and David A. Bader. “Generalizing k-Betweenness Centrality Using Short Paths and a Parallel Multithreaded Implementation.” The 38th International Conference on Parallel Processing (ICPP), Vienna, Austria, September 2009.
- Kamesh Madduri, David Ediger, Karl Jiang, David A. Bader, Daniel Chavarría-Miranda. “A Faster Parallel Algorithm and Efficient Multithreaded Implementations for Evaluating Betweenness Centrality on Massive Datasets.” 3rd Workshop on Multithreaded Architectures and Applications (MTAAP), Rome, Italy, May 2009.
- David A. Bader, et al. “STINGER: Spatio-Temporal Interaction Networks and Graphs (STING) Extensible Representation.” 2009.
- David Ediger, Karl Jiang, E. Jason Riedy, and David A. Bader. “Massive Streaming Data Analytics: A Case Study with Clustering Coefficients,” Fourth Workshop in Multithreaded Architectures and Applications (MTAAP), Atlanta, GA, April 2010.
- Seunghwa Kang, David A. Bader. “Large Scale Complex Network Analysis using the Hybrid Combination of a MapReduce cluster and a Highly Multithreaded System:,” Fourth Workshop in Multithreaded Architectures and Applications (MTAAP), Atlanta, GA, April 2010.
- David Ediger, Karl Jiang, Jason Riedy, David A. Bader, Courtney Corley, Rob Farber and William N. Reynolds. “Massive Social Network Analysis: Mining Twitter for Social Good,” The 39th International Conference on Parallel Processing (ICPP 2010), San Diego, CA, September 2010.
- Virat Agarwal, Fabrizio Petrini, Davide Pasetto and David A. Bader. “Scalable Graph Exploration on Multicore Processors,” *The 22nd IEEE and ACM Supercomputing Conference* (SC10), New Orleans, LA, November 2010.
- Z. Du, Z. Yin, W. Liu, and D.A. Bader, “On Accelerating Iterative Algorithms with CUDA: A Case Study on Conditional Random Fields Training Algorithm for Biological Sequence Alignment,” IEEE International Conference on Bioinformatics & Biomedicine, Workshop on Data-Mining of Next Generation Sequencing Data (NGS2010), Hong Kong, December 20, 2010.

Bader, Related Recent Publications (2011-2012)

- D. Ediger, J. Riedy, H. Meyerhenke, and D.A. Bader, "Tracking Structure of Streaming Social Networks," 5th Workshop on Multithreaded Architectures and Applications (MTAAP), Anchorage, AK, May 20, 2011.
- D. Mizell, D.A. Bader, E.L. Goodman, and D.J. Haglin, "Semantic Databases and Supercomputers," 2011 Semantic Technology Conference (SemTech), San Francisco, CA, June 5-9, 2011.
- E.J. Riedy, H. Meyerhenke, D. Ediger, and D.A. Bader, "Parallel Community Detection for Massive Graphs," The 9th International Conference on Parallel Processing and Applied Mathematics (PPAM 2011), Torun, Poland, September 11-14, 2011. Lecture Notes in Computer Science, 7203:286-296, 2012.
- E.J. Riedy, D. Ediger, D.A. Bader, and H. Meyerhenke, "Parallel Community Detection for Massive Graphs," 10th DIMACS Implementation Challenge -- Graph Partitioning and Graph Clustering, Atlanta, GA, February 13-14, 2012.
- E.J. Riedy, H. Meyerhenke, D.A. Bader, D. Ediger, and T. Mattson, "Analysis of Streaming Social Networks and Graphs on Multicore Architectures," The 37th IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Kyoto, Japan, March 25-30, 2012.
- J. Riedy, H. Meyerhenke, and D.A. Bader, "Scalable Multi-threaded Community Detection in Social Networks," 6th Workshop on Multithreaded Architectures and Applications (MTAAP), Shanghai, China, May 25, 2012.
- P. Pande and D.A. Bader, "Computing Betweenness Centrality for Small World Networks on a GPU," *The 15th Annual High Performance Embedded Computing Workshop* (HPEC), Lexington, MA, September 21-22, 2011.
- H. Meyerhenke, E.J. Riedy, and D.A. Bader, "Parallel Community Detection in Streaming Graphs," Minisymposium on Parallel Analysis of Massive Social Networks, *15th SIAM Conference on Parallel Processing for Scientific Computing* (PP12), Savannah, GA, February 15-17, 2012.
- D. Ediger, E.J. Riedy, H. Meyerhenke, and D.A. Bader, "Analyzing Massive Networks with GraphCT," Poster Session, *15th SIAM Conference on Parallel Processing for Scientific Computing* (PP12), Savannah, GA, February 15-17, 2012.
- R.C. McColl, D. Ediger, and D.A. Bader, "Many-Core Memory Hierarchies and Parallel Graph Analysis," Poster Session, *15th SIAM Conference on Parallel Processing for Scientific Computing* (PP12), Savannah, GA, February 15-17, 2012.
- E.J. Riedy, D. Ediger, H. Meyerhenke, and D.A. Bader, "STING: Software for Analysis of Spatio-Temporal Interaction Networks and Graphs," Poster Session, *15th SIAM Conference on Parallel Processing for Scientific Computing* (PP12), Savannah, GA, February 15-17, 2012.
- David A. Bader, Christine Heitsch, and Kamesh Madduri, "Large-Scale Network Analysis," in J. Kepner and J. Gilbert, editor, *Graph Algorithms in the Language of Linear Algebra*, SIAM Press, Chapter 12, pages 253-285, 2011.
- Jeremy Kepner, David A. Bader, Robert Bond, Nadya Bliss, Christos Faloutsos, Bruce Hendrickson, John Gilbert, and Eric Robinson, "Fundamental Questions in the Analysis of Large Graphs," in J. Kepner and J. Gilbert, editor, *Graph Algorithms in the Language of Linear Algebra*, SIAM Press, Chapter 16, pages 353-357, 2011.

Acknowledgment of Support

SIAM CSE13
Frontiers in Large-Scale Graph Analysis

- **2:00-2:25 Applications and challenges in large-scale graph analysis**
- *David A. Bader* and Jason Riedy, Georgia Institute of Technology, USA; Henning Meyerhenke, Karlsruhe Institute of Technology, Germany
- **2:30-2:55 Large scale graph analytics and randomized algorithms for applications in cybersecurity**
- *John Johnson*, Pacific Northwest National Laboratory, USA
- **3:00-3:25 Anomaly Detection in Very Large Graphs: Modeling and Computational Considerations**
- *Benjamin Miller*, Nicholas Arcolano, Edward Rutledge, Matthew Schmidt, and Nadya Bliss, Massachusetts Institute of Technology, USA
- **3:30-3:55 Combinatorial and Numerical Algorithms for Network Analysis**
- *Henning Meyerhenke* and Christian Staudt, Karlsruhe Institute of Technology, Germany

Part II (MS179) Thursday, February 28, 9:30 AM - 11:30 AM

- **9:30-9:55 Are we there yet? When to stop a Markov chain while generating random graphs?**
- *Ali Pinar*, Jaideep Ray, and C. Seshadhri, Sandia National Laboratories, USA
- **10:00-10:25 Analyzing graph structure in streaming data with STINGER**
- *Jason Riedy*, David A. Bader, Robert C. Mccoll, and David Ediger, Georgia Institute of Technology, USA
- **10:30-10:55 High-Performance Filtered Queries in Attributed Semantic Graphs**
- *John R. Gilbert*, University of California, Santa Barbara, USA; Aydin Buluc, Lawrence Berkeley National Laboratory, USA; Armando Fox, University of California, Berkeley, USA; Shoaib Kamil, Massachusetts Institute of Technology, USA; Adam Lugowski, University of California, Santa Barbara, USA; Leonid Oliker and Samuel Williams, Lawrence Berkeley National Laboratory, USA
- **11:00-11:25 Large-Scale Graph-Structured Machine Learning: GraphLab in the Cloud and GraphChi in your PC**
- Joseph Gonzalez and *Carlos Guestrin*, Carnegie Mellon University, USA