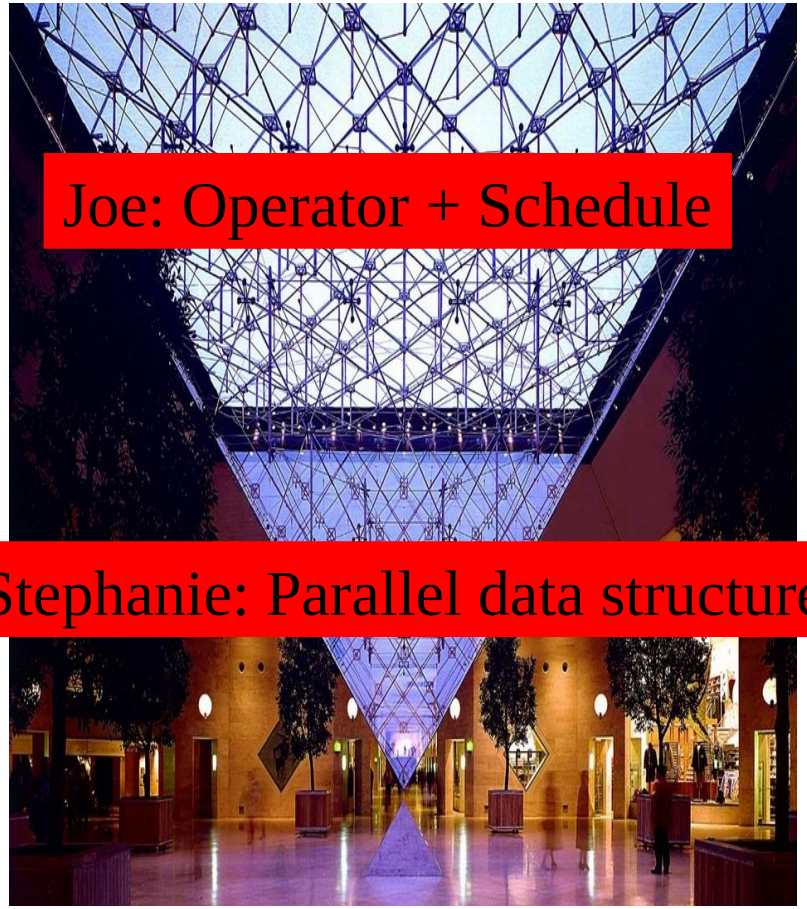
The Galois system for parallel graph analytics

Keshav Pingali
The University of Texas at Austin

Galois system

Parallel program = Operator + Schedule + Parallel data structures

- "Scalable" parallel programming:
  - small number of expert programmers (Stephanies) must support large number of application programmers (Joes)
  - cf. SQL
- Galois system:
  - Stephanie: library of concurrent data structures and runtime system
  - Joe: application code in sequential C++
    - Galois set iterator for highlighting opportunities for exploiting parallelism



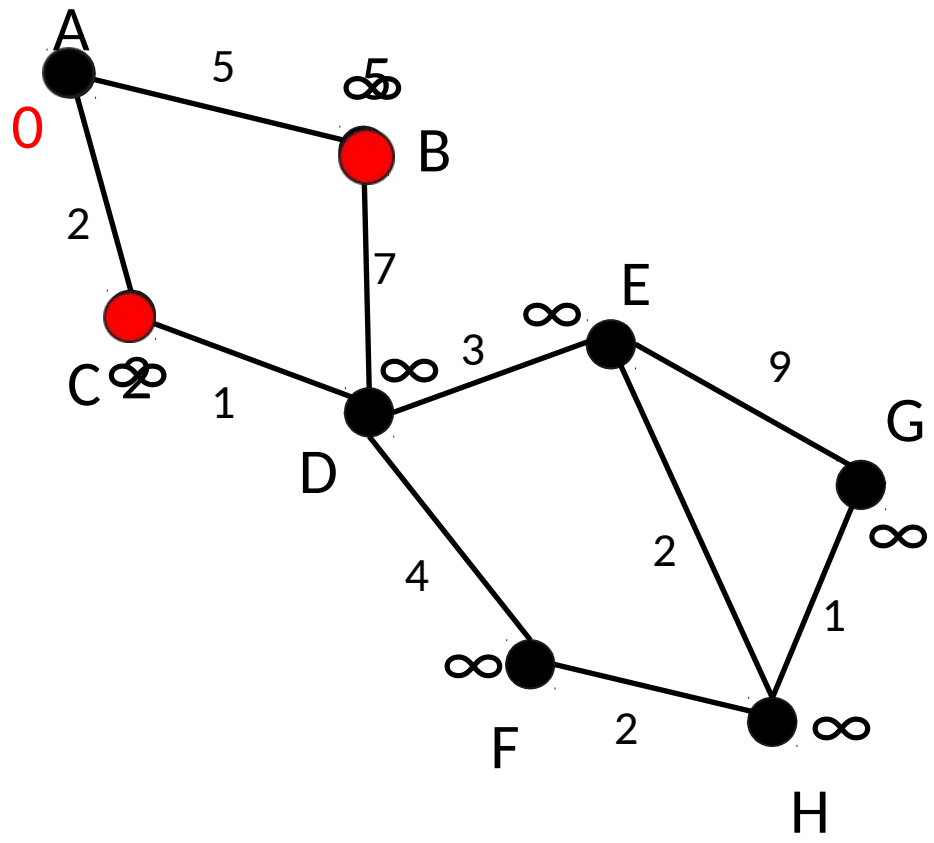
Example: Graph analytics

- Single-source shortest-path
- Many algorithms
  - Dijkstra (1959)
  - Bellman-Ford (1957)
  - Chaotic relaxation (1969)
  - Delta-stepping (1998)
- Common structure:
  - Each node has distance label d
  - Operator:

    relax-edge(u,v):

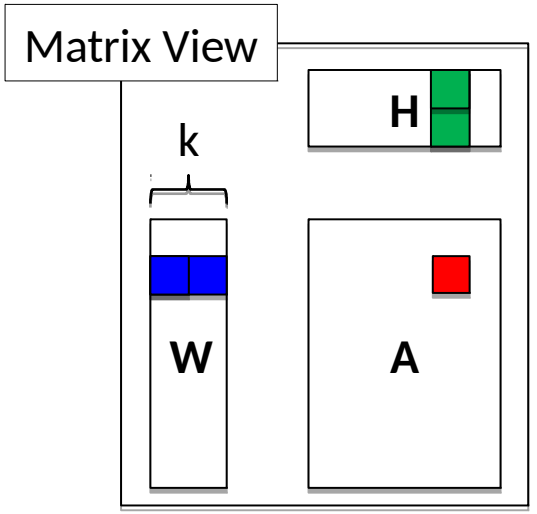
    if d[v] > d[u]+length(u,v)

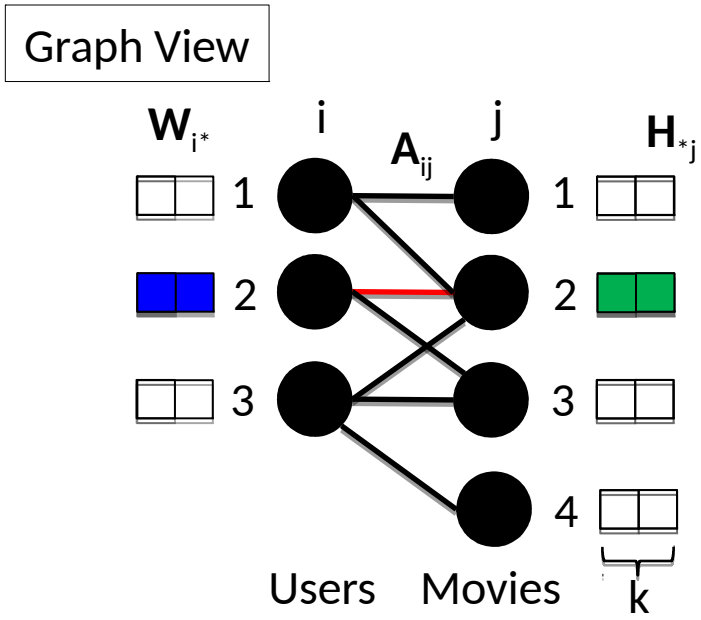
    then d[v] ← d[u]+length(u,v)
  - Active node: unprocessed node whose distance field has been lowered
  - Different algorithms use different schedules
  - Schedules differ in parallelism, locality, work efficiency



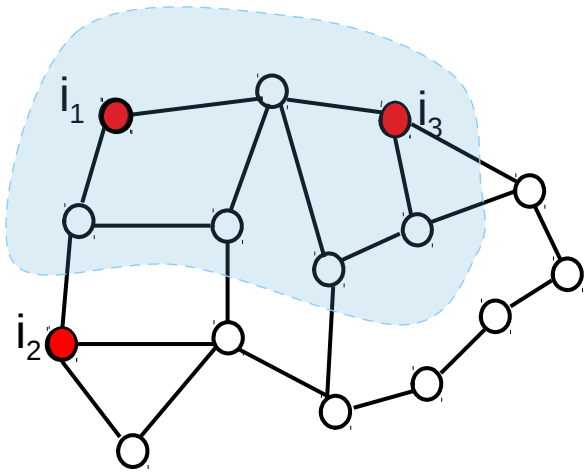
Matrix Completion using SGD

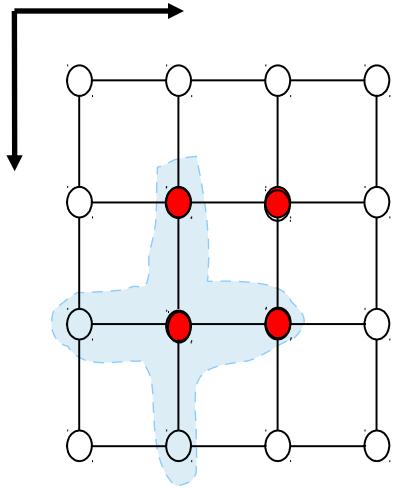
- Matrix completion problem
  - Given incomplete database A of (user,movie) ratings, predict missing ratings
- An optimization problem
  - Find m×k matrix **W** and k×n matrix **H** (k << min(m,n)) such that **A** ≈ **WH**
  - Low-rank approximation
- SGD algorithm
  - Round-based execution
  - In each round, iterate over edges and heuristically update node labels





Operator formulation





: active node

: neighborhood

Algorithm

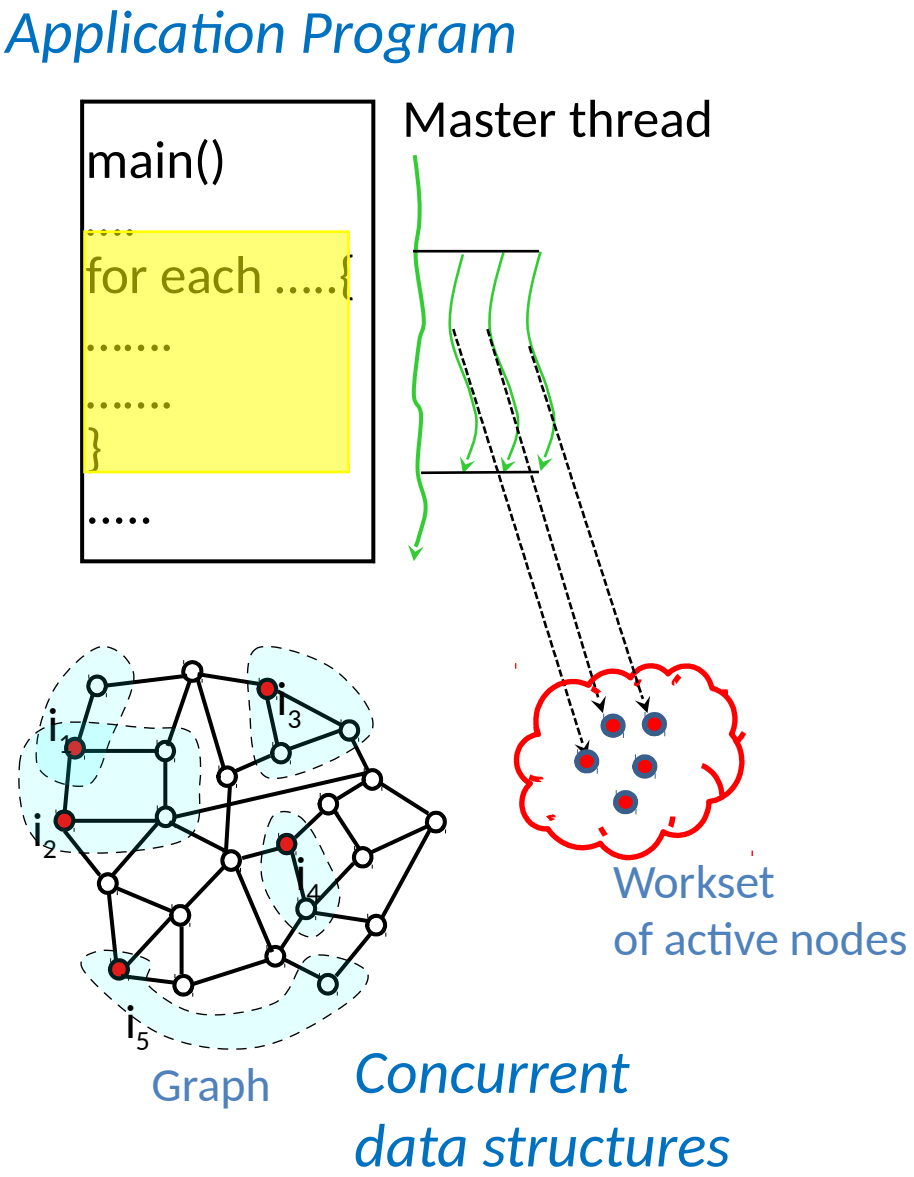
- State update: (local view)
- Schedule (global view)
  - Location (where?)
    - Topology-driven
    - Data-driven
  - Ordering (when?)
    - Unordered
    - Ordered

Operator

Parallel program = Operator + Schedule + Parallel data structure

Galois programs: parallel execution

- Joe program
  - Sequential C++
  - Galois set iterator: for each
    - New elements can be added to set during iteration
    - Body is operator; data structure accesses through API
    - Optional scheduling specification (cf. OpenMP)
    - Highlights opportunities in program for exploiting amorphous data-parallelism
- Runtime system
  - Ensures serializability of iterations
  - Execution strategies
    - Optimistic
    - Interference graphs



Scheduling in Galois

- Users write high-level scheduling policies
  - DSL for specifying policies
- Separation of concerns
  - Users understand their operator but have vague understanding of scheduling
  - Schedulers are difficult to implement efficiently
- Galois system synthesizes scheduler by composing elements from a scheduler library

Nguyen and Pingali. Synthesizing concurrent schedulers for irregular algorithms. ASPLOS 2011.

Hello graph Galois Program

```
#include "Galois/Galois.h"
#include "Galois/Graphs/LCGraph.h"

struct Data { int value; float f; };

typedef Galois::Graph::LC_CSR_Graph<Data,void> Graph;
typedef Galois::Graph::GraphNode Node;

Graph graph;

struct P {
  void operator()(Node n, Galois::UserContext<Node>& ctx){
    graph.getData(n).value += 1;
  }
};

int main(int argc, char** argv){
  graph.structureFromGraph(argv[1]);
  Galois::for_each(graph.begin(), graph.end(), P());
  return 0;
}
```

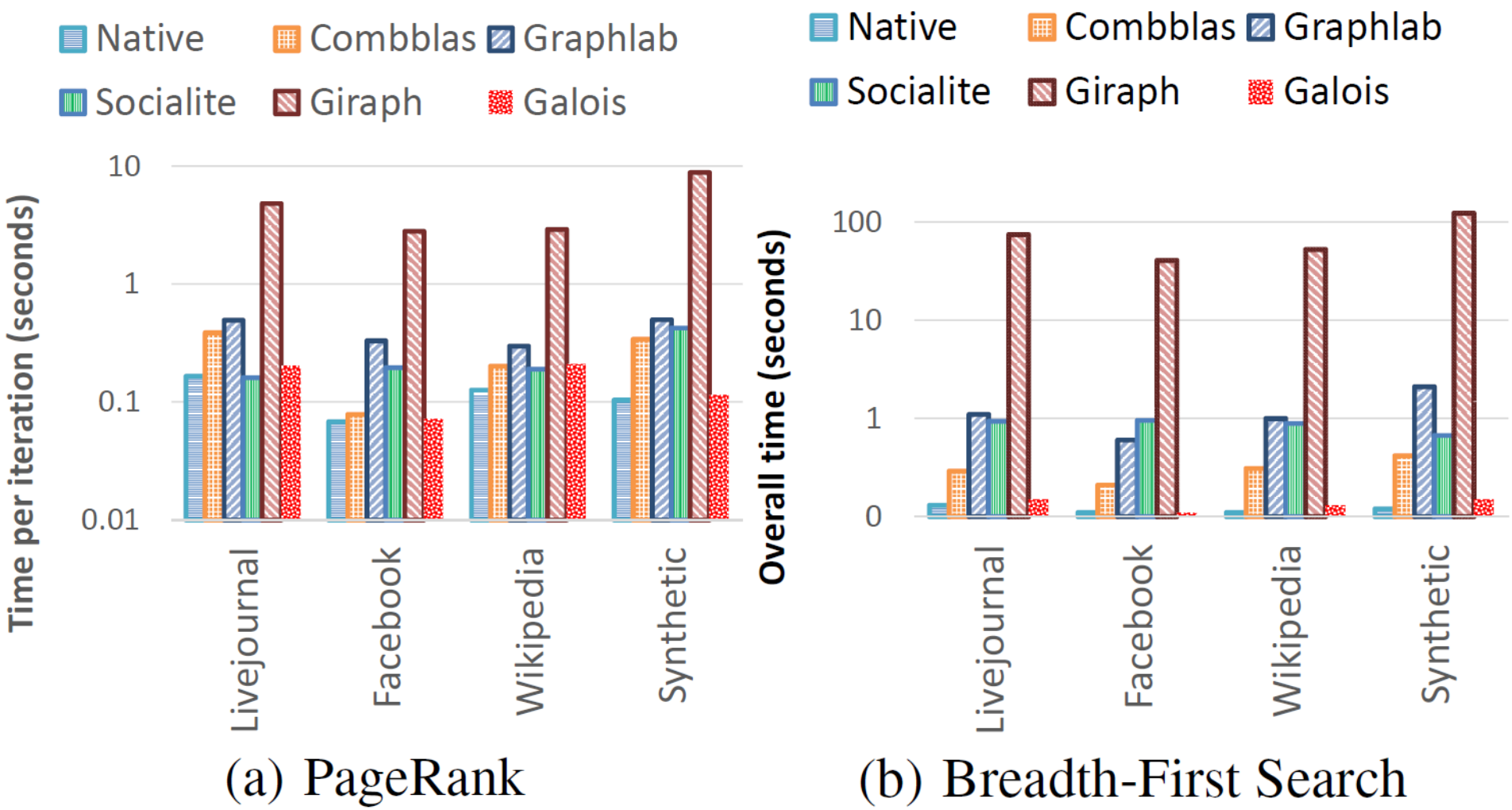
Data structure Declarations

Operator

Galois Iterator

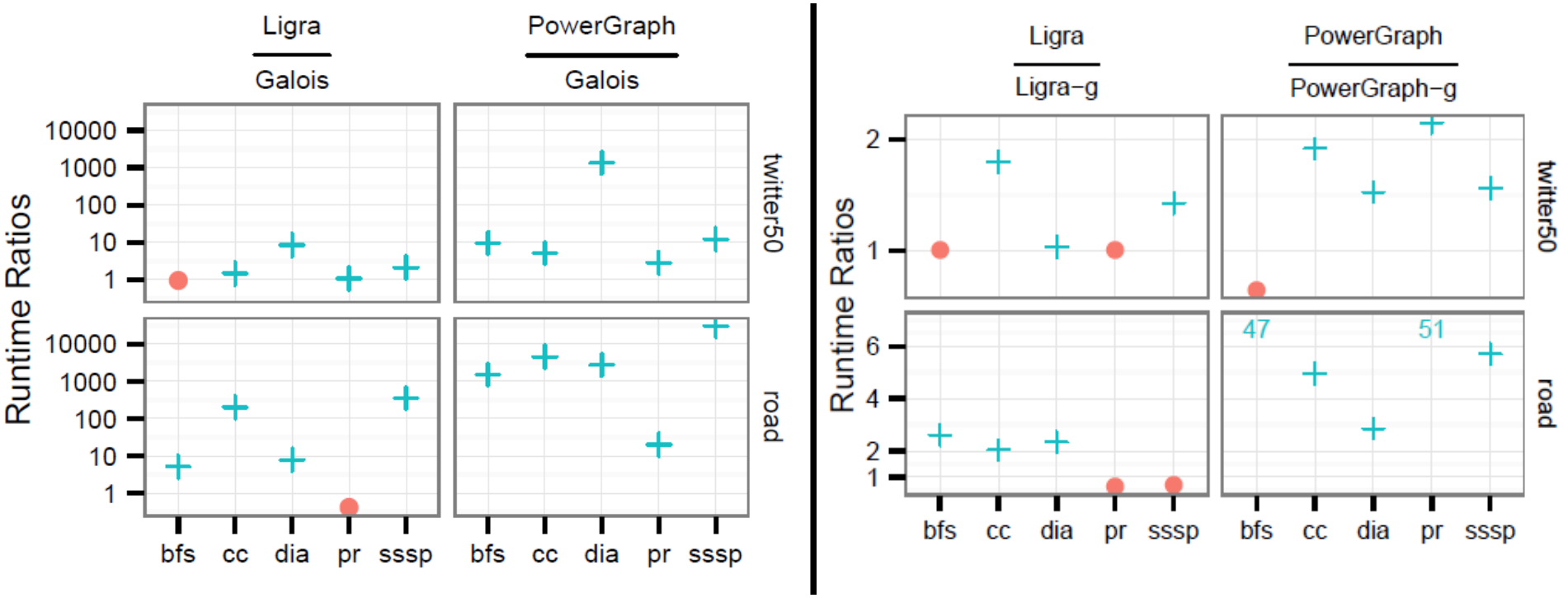
Performance studies

Intel Study: Galois vs. Graph Frameworks



"Navigating the maze of graph analytics frameworks" Nadathur et al SIGMOD 2014

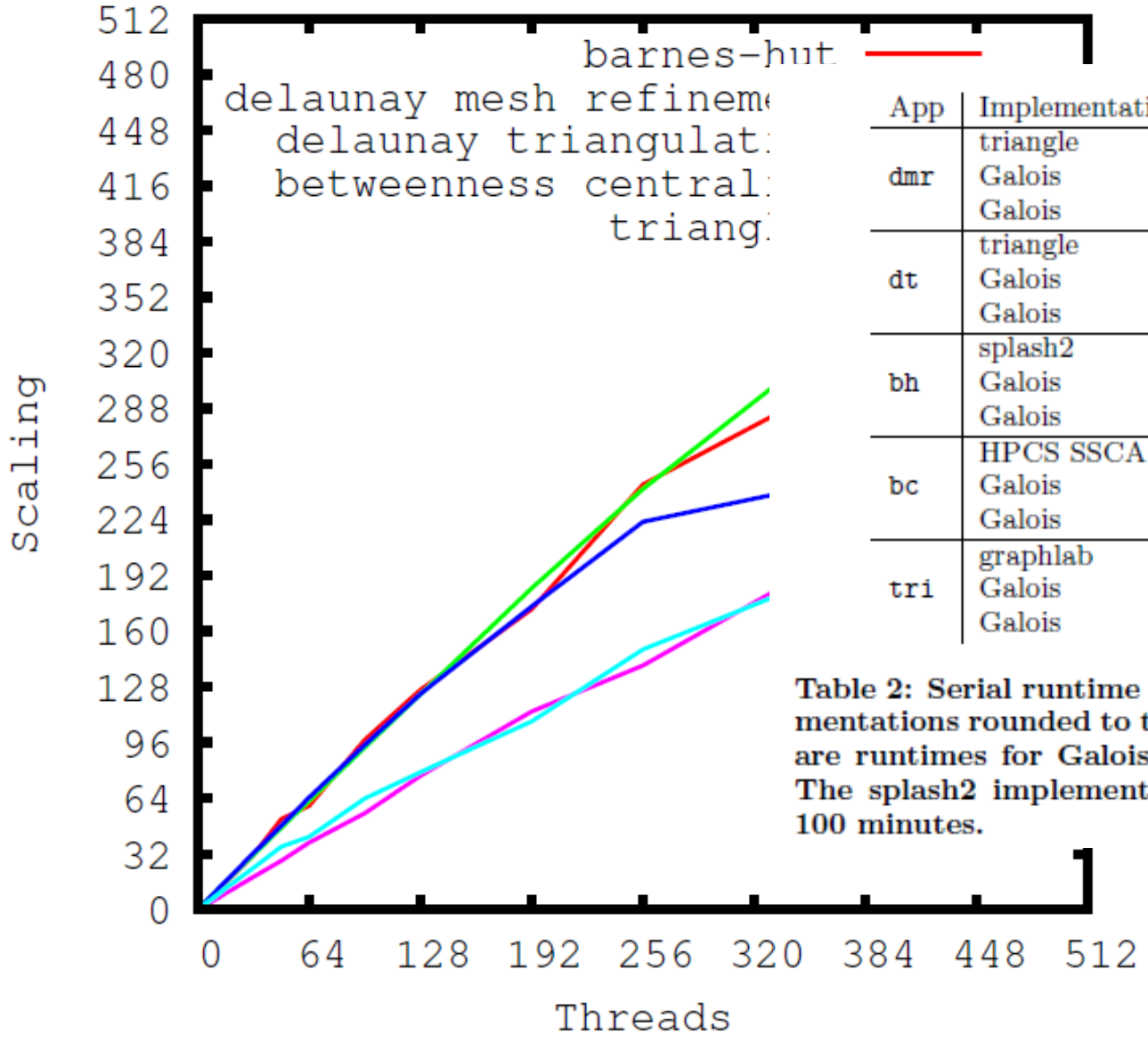
Galois: Graph analytics



- Galois lets you code more effective algorithms for graph analytics than DSLs like PowerGraph (left figure)
- Easy to implement APIs for graph DSLs on top on Galois and exploit better infrastructure (few hundred lines of code for PowerGraph and Ligra) (right figure)

"A lightweight infrastructure for graph analytics" Nguyen, Lenharth, Pingali (SOSP 2013)

Galois: Performance on SGI Ultraviolet



App	Implementation	Threads	Time (s)
dmr	triangle	1	96
	Galois	1	155.7
	Galois	512	0.37
dt	triangle	1	1185
	Galois	1	56.6
	Galois	512	0.18
bh	splash2	1	>6000
	Galois	1	1386
	Galois	512	3.55
bc	HPCS SSCA	1	6720
	Galois	1	5394
	Galois	512	21.6
tri	graphlab	2	531
	Galois	1	7.03
	Galois	512	0.028

Table 2: Serial runtime comparisons to other implementations rounded to the nearest second. Included are runtimes for Galois algorithms at 512 threads. The splash2 implementation of bh timed out after 100 minutes.

Summary

- Operator formulation of algorithms:
  - Data-centric description of algorithms
  - Algorithm = Operator + Schedule
- Parallel program = Operator + Schedule + Parallel data structures
- Complexity of parallel programming arises mainly from parallel data structures
- Galois approach to scalable parallel programming:
  - Stephanie:
    - library of parallel data structures and schedulers
    - runtime system that provides services like load-balancing
  - Joe: specifies operator and schedule

More information

- Website
  - http://iss.ices.utexas.edu
- Download
  - Galois system for multicores
  - Lonestar benchmarks
  - All our papers
- Coming soon
  - Distributed-memory
  - CUDA and OpenCL backends