Parallel Programming with the Galois System

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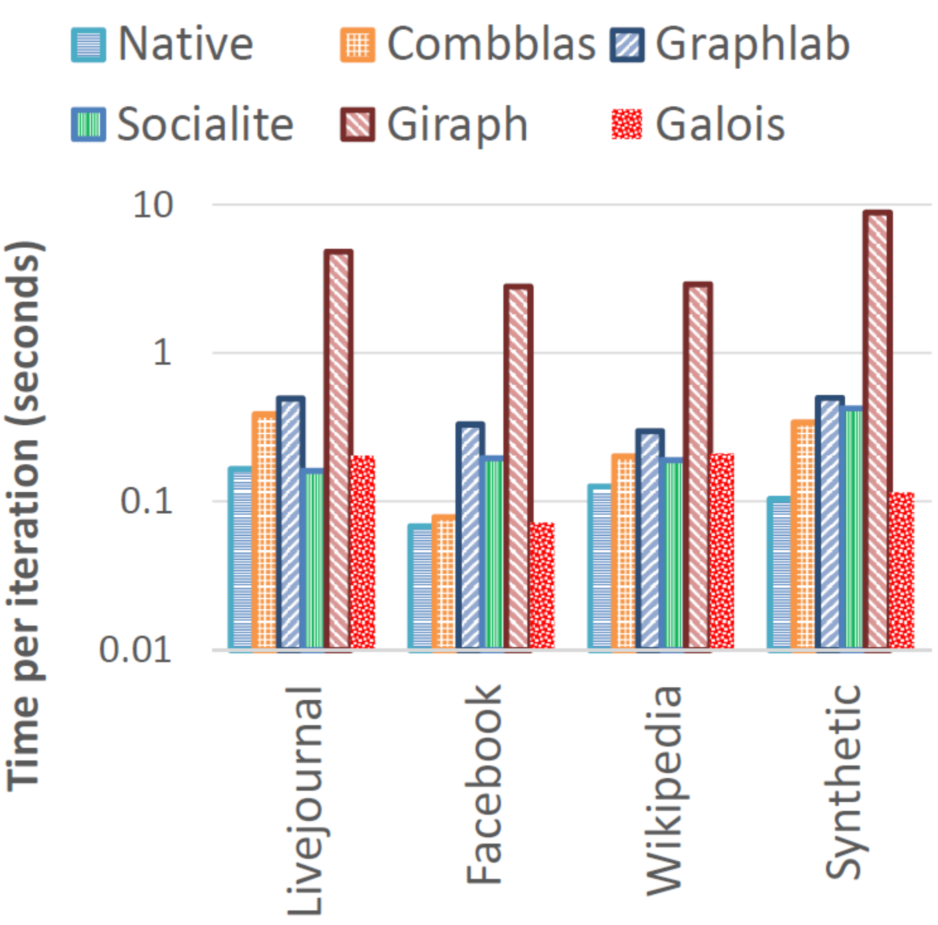
- Thinking about algorithms using the amorphous parallelism framework.
- Implementing them using the Galois runtime.
- Presented with a focus on graph analytics and big data.

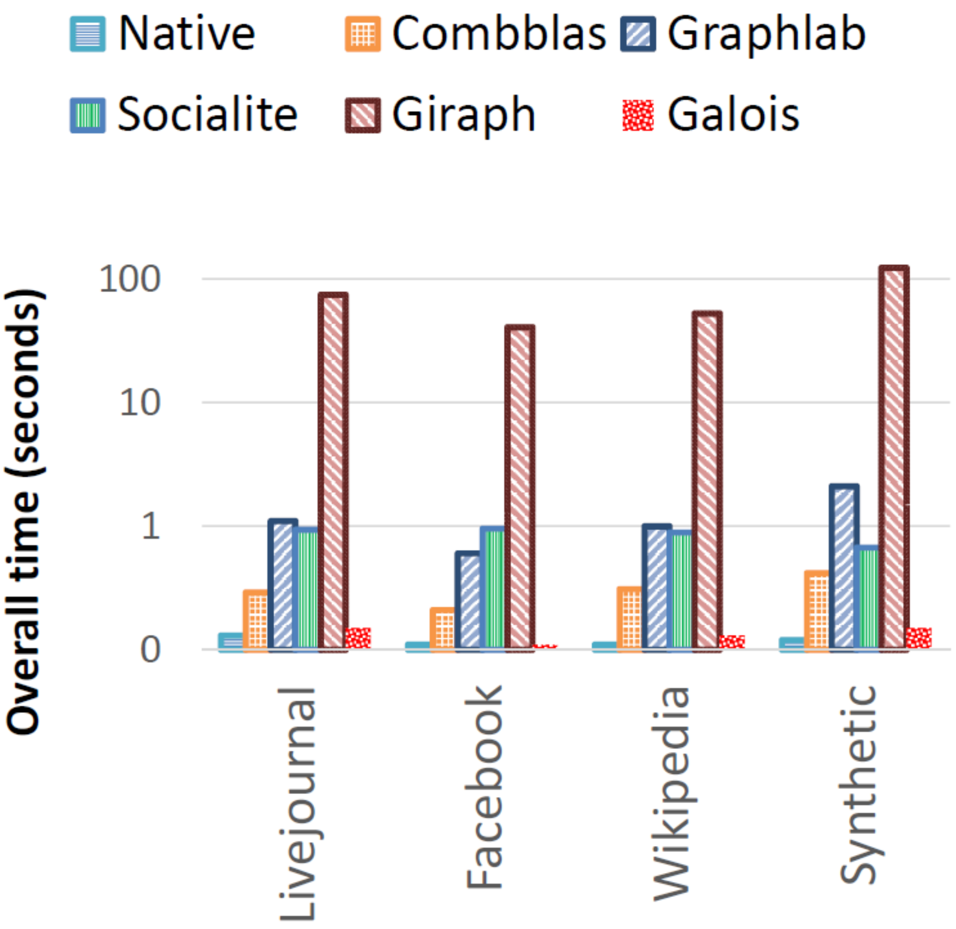
Outline

- Current State of Parallel programming
- Amorphous data parallelism / Operator formulation
- High Level Galois
- Current state of the system
- Implementing Graph Analytic DSLs on Galois
- Practical Galois
- Extended Example: SSSP
- Scheduling
- Active research

Intel Study: Galois vs. Graph Frameworks



(a) PageRank



(b) Breadth-First Search

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

FROM:
COMPUTATION CENTRIC
TO:
DATA CENTRIC

PROGRAMMING MODELS

Parallelism is everywhere

Texas Advanced Computing Center

Laptops

Cell-phones

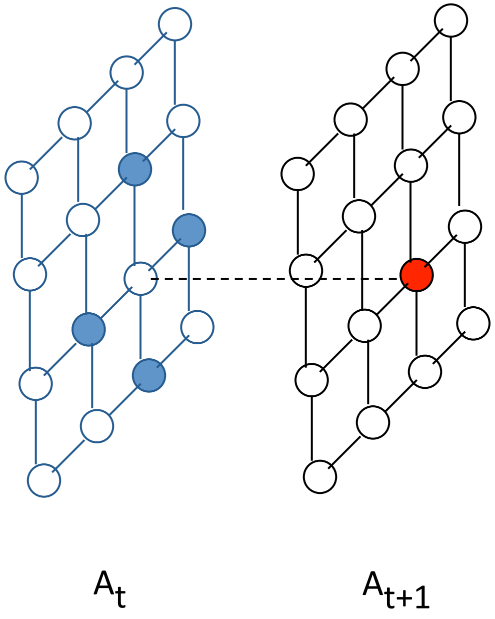
Parallel programming?

- 40-50 years of work on parallel programming in HPC domain
- Focused mostly on "regular" dense matrix/vector algorithms
  - Stencil computations, FFT, etc.
  - Mature theory and tools
- Not useful for "irregular" algorithms that use graphs, sets, and other complex data structures
  - Most algorithms are irregular ☹
- Galois project:
  - New data-centric abstractions for parallelism and locality
  - Galois system for multicores and GPUs

"The Alchemist"
Cornelius Bega (1663)

HPC example

- Finite-difference computation
- Algorithm
  - Operator: five-point stencil
  - Different schedules have different locality
- Regular application
  - Application can be parallelized at compile-time



Jacobi iteration, 5-point stencil

```
//Jacobi iteration with 5-point stencil
//initialize array A
for time = 1, nsteps
   for <i,j> in [2,n-1]x[2,n-1]
       temp(i,j)=0.25*(A(i-1,j)+A(i+1,j)+A(i,j-1)+A(i,j+1))
   for <i,j> in [2,n-1]x[2,n-1]:
       A(i,j) = temp(i,j)
```

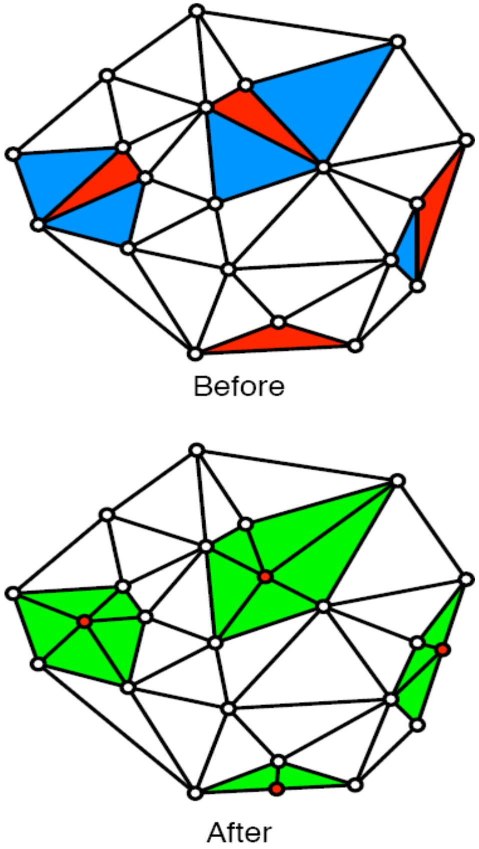
Irregular example

```
Mesh m = /* read in mesh */
WorkList wl;
wl.add(m.badTriangles());
while (true) {
   if (wl.empty()) break;
   Element e = wl.get();
   if (e no longer in mesh)
      continue;
   Cavity c = new
      Cavity();
   c.expand();
   c.retriangulate();
   m.update(c);//update mesh
   wl.add(c.badTriangles());
}
```

- Where is parallelism in program?
  - Loop: do static analysis to find dependence graph
- Static analysis fails to find parallelism.
  - May be there is no parallelism in program?

Computation-centric view of parallelism

Data-centric view of algorithm



Before

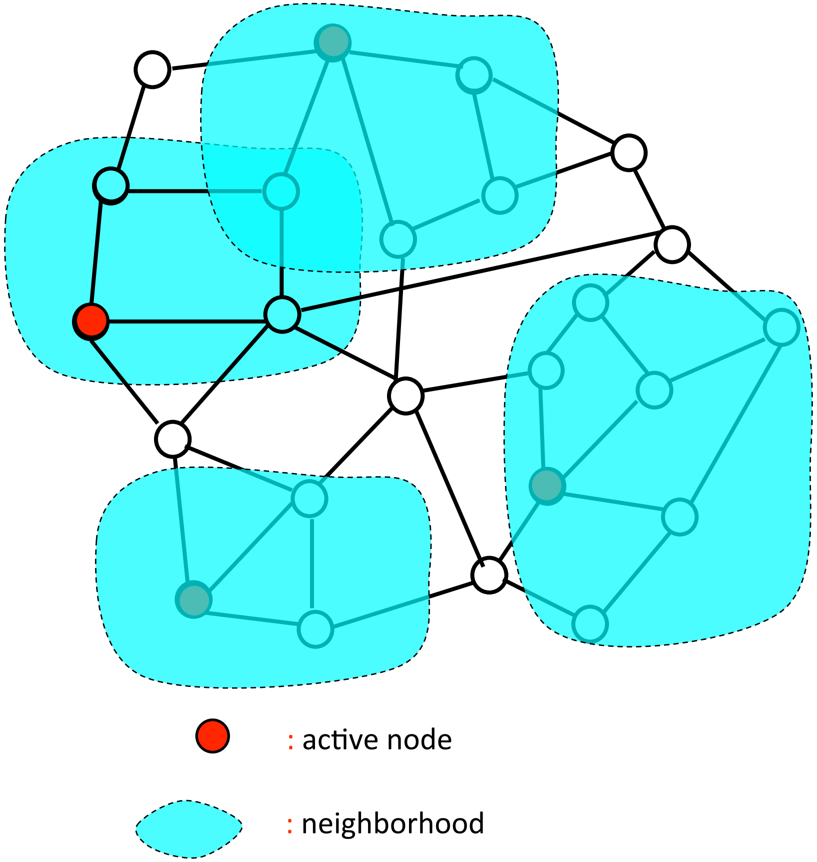
After

Delaunay mesh refinement (DMR)
Red Triangle: badly shaped triangle
Blue triangles: cavity of bad triangle

- Algorithm
  - composition of unitary actions on data structures
- Actions: operator
  - DMR: {find cavity, retriangulate, update mesh}
- Composition of actions:
  - specified by a schedule
- Parallelism
  - disjoint actions can be performed in parallel
- Parallel data structures
  - graph
  - worklist of bad triangles

Operator formulation of algorithms

- Active element
  - Site where computation is needed
- Operator
  - Computation at active element
  - Activity: application of operator to active element
- Neighborhood
  - Set of nodes/edges read/written by activity
  - Distinct usually from neighbors in graph
- Ordering : scheduling constraints on execution order of activities
  - Unordered algorithms: no semantic constraints but performance may depend on schedule
  - Ordered algorithms: problem-dependent order
- Amorphous data-parallelism
  - Multiple active nodes can be processed in parallel subject to neighborhood and ordering constraints



Parallel program = Operator + Schedule + Parallel data structure

Parallelization strategies: Binding Time

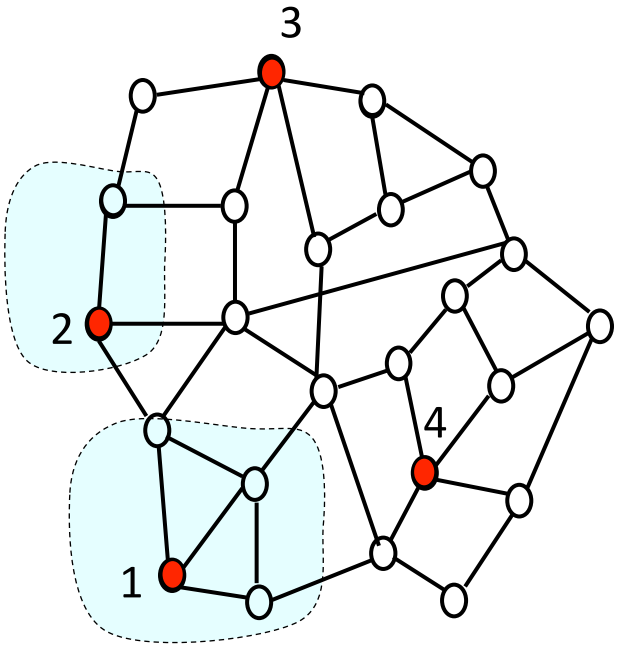
When do you know the active nodes and neighborhoods?

Compile-time — **Static parallelization (stencil codes, FFT, dense linear algebra)**

After input is given — **Inspector-executor (Bellman-Ford)**

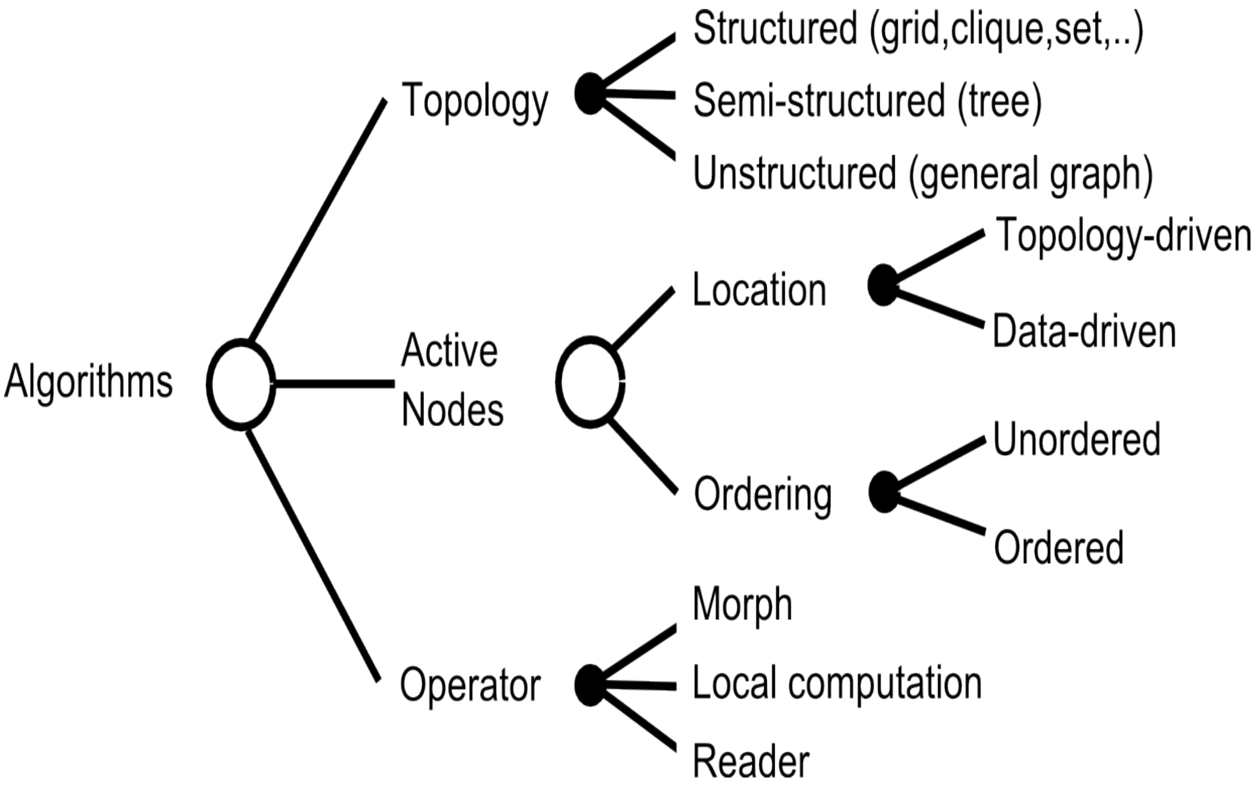
During program execution — **Interference graph (DMR, chaotic SSSP)**

After program is finished — **Optimistic Parallelization (Time-warp)**



“The TAO of parallelism in algorithms” Pingali et al, PLDI 2011

TAO analysis: Structure in algorithms (PLDI 2011)

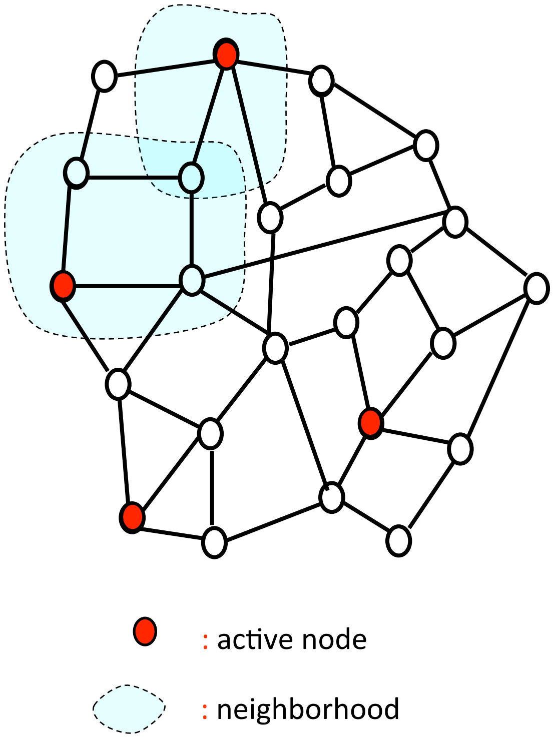


Algorithms

Topology
- Structured (grid,clique,set,..)
- Semi-structured (tree)
- Unstructured (general graph)

Active Nodes
- Location
  - Topology-driven
  - Data-driven
- Ordering
  - Unordered
  - Ordered

Operator
- Morph
- Local computation
- Reader



● : active node

▨ : neighborhood

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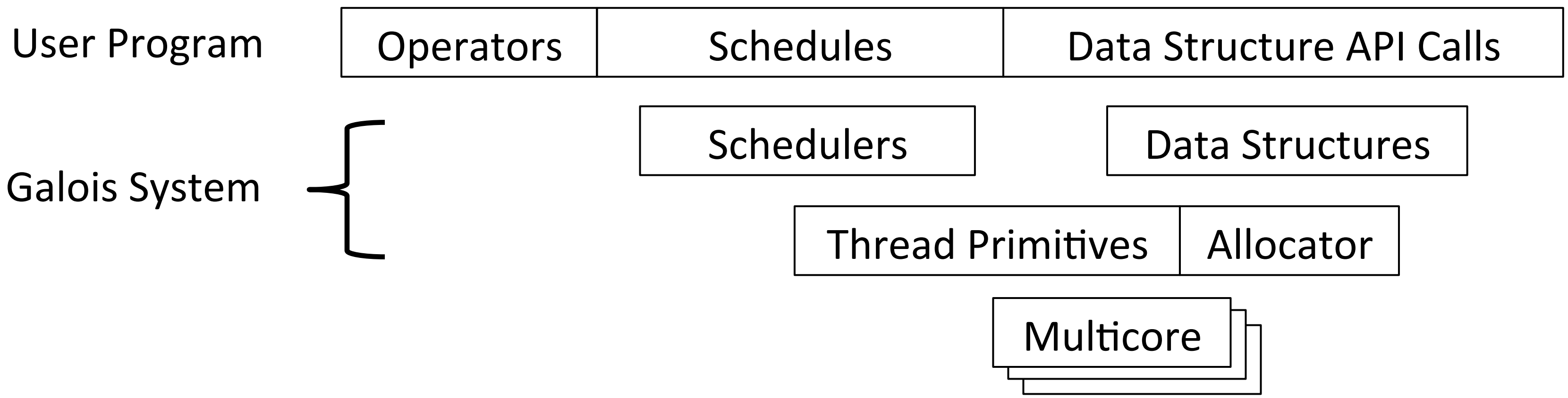
Galois System

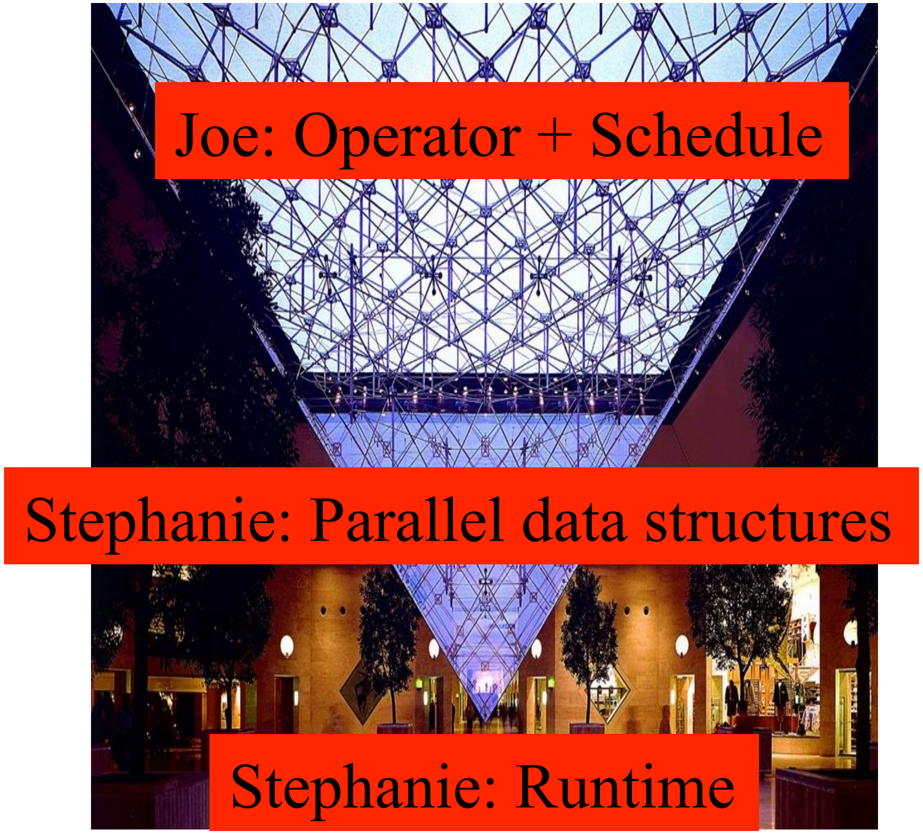
Parallel Program = Operator + Schedule + Parallel Data Structure



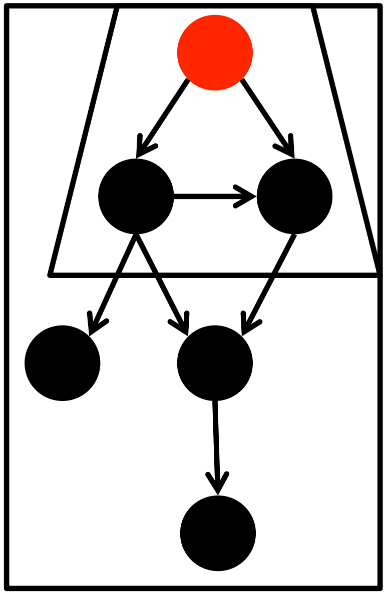
Multi-level Programming Model

Parallel program = Operator + Schedule + Parallel data structures

- Ubiquitous parallelism:
  - 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
    - Provides serializable, atomic execution of activities
  - Joe: application code in sequential C++
    - Galois set iterator for highlighting opportunities for exploiting ADP

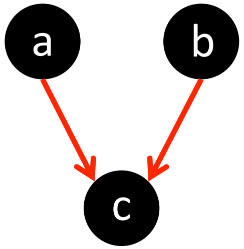


$$\text{Parallel Program} = \underbrace{\text{Operator} + \text{Schedule}}_{\text{Algorithm}} + \text{Parallel Data Structure}$$



- What is the operator?
  - Other graph analytics frameworks: only vertex programs
  - Galois: Unrestricted, may even morph graph by adding/removing nodes and edges

- Where/When does it execute?
  - Autonomous scheduling: activities execute asynchronously and transactionally
  - Coordinated scheduling: activities execute in rounds
    - Read values refer to previous rounds
    - Multiple updates to the same location are resolved with reduction, etc.



Galois Parallel Execution Model

Parallel execution model:

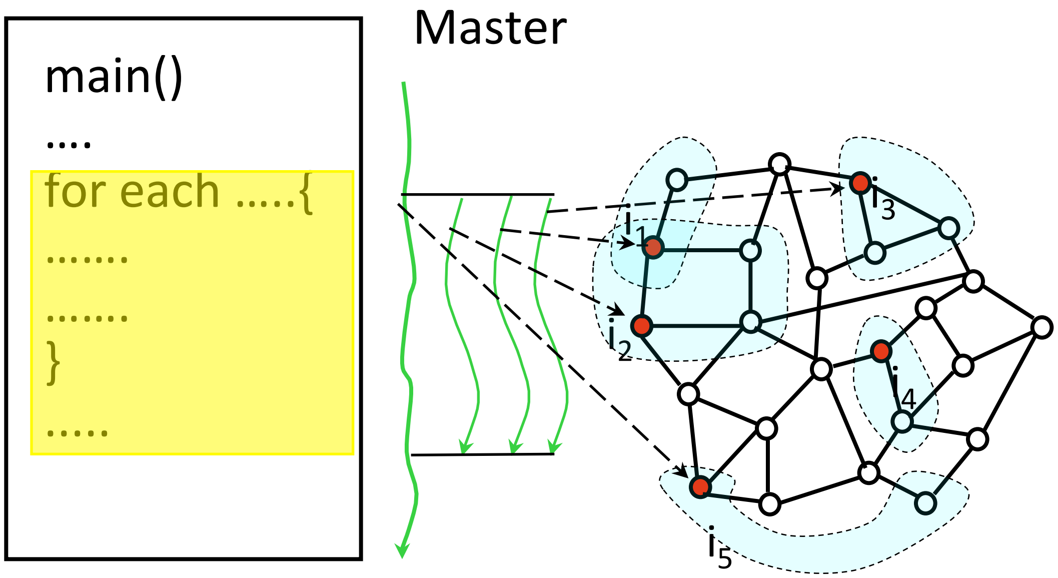
- Shared-memory
- Optimistic execution of Galois iterators

Implementation:

- Master thread begins execution of program
- When it encounters iterator, worker threads help by executing iterations concurrently
- Iterations may enqueue new tasks
- Barrier synchronization at end of iterator

Independence of neighborhoods:

- Concurrency managed by data structure library
- Logical locks on nodes and edges
- Implemented using CAS operations



```
main()
….
for each …..{
…….
…….
}
…..
```

Joe Program

Concurrent Data structure

“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

Lonestar

- Collection irregular algorithms

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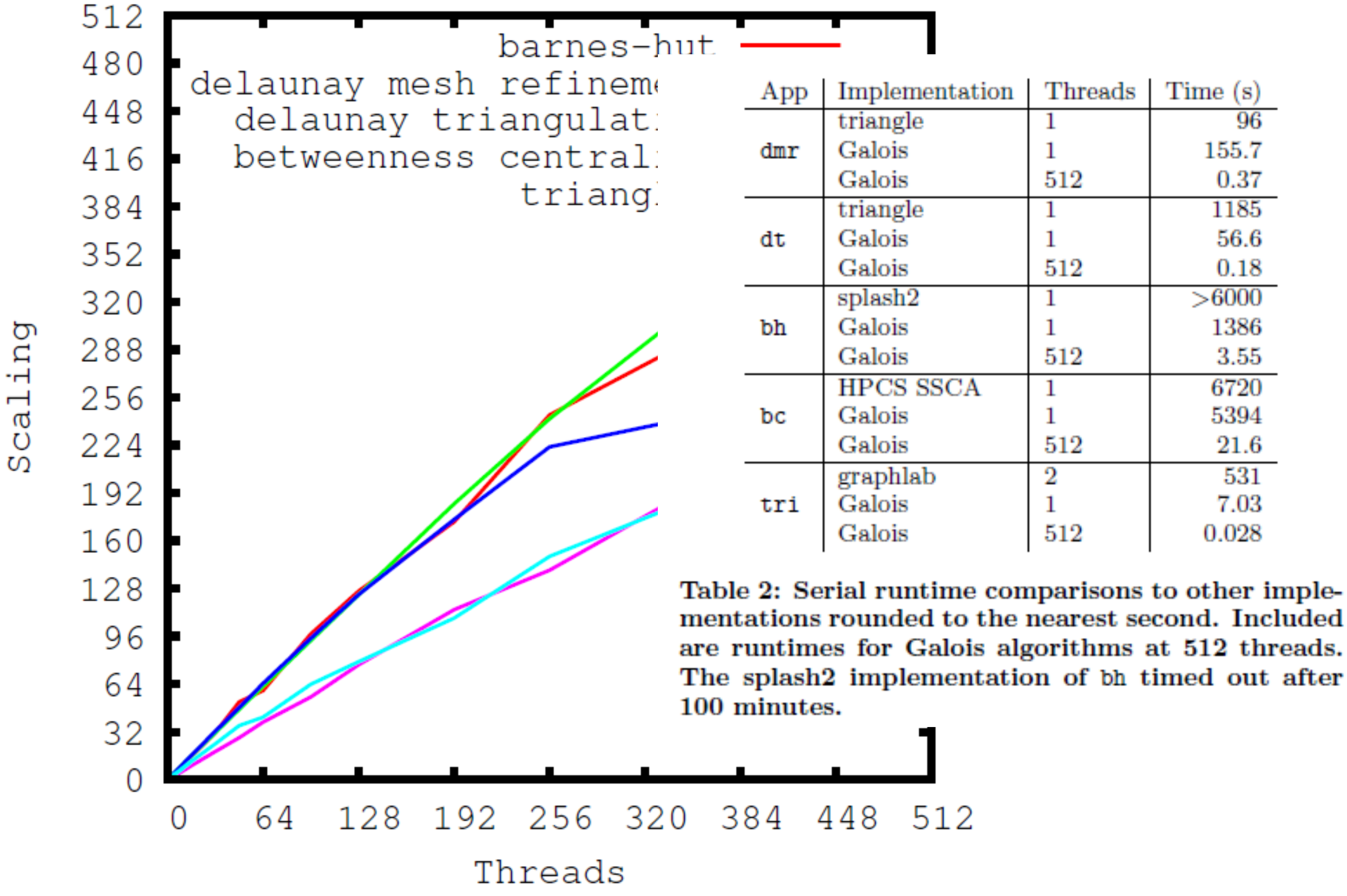
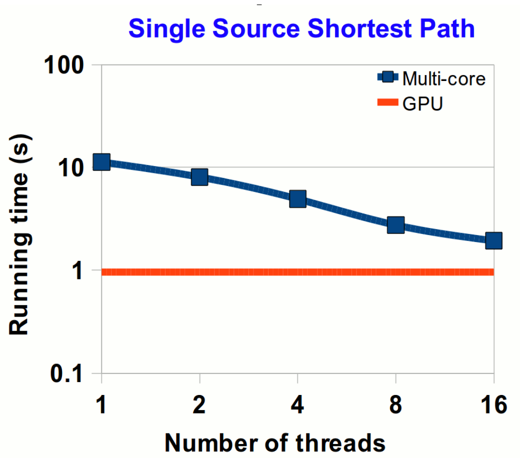
Galois: Performance on SGI Ultraviolet

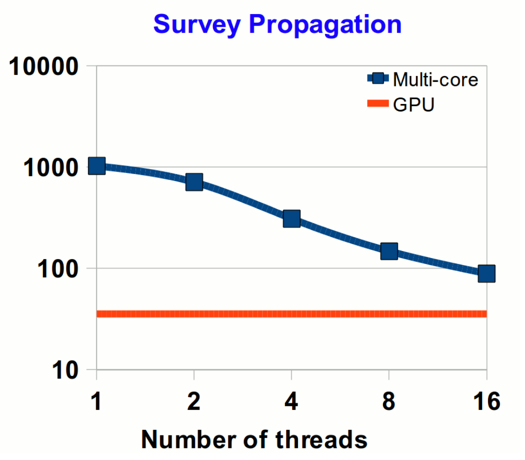


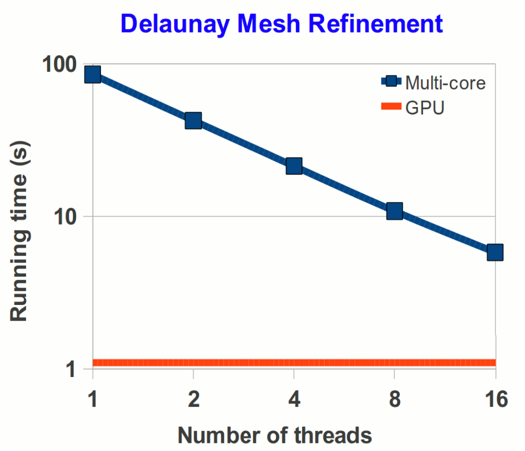
App	Implementation	Threads	Time (s)
dmr	triangle	1	96
	Galois	1	155.7
	Galois	512	0.37
dt	triangle	1	1185
	Galois	1	56.6
	Galois	512	0.18
bh	splash2	1	>6000
	Galois	1	1386
	Galois	512	3.55
bc	HPCS SSCA	1	6720
	Galois	1	5394
	Galois	512	21.6
tri	graphlab	2	531
	Galois	1	7.03
	Galois	512	0.028

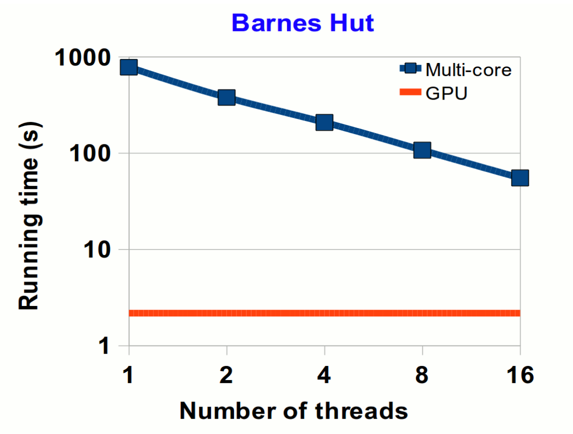
Table 2: Serial runtime comparisons to other implementations rounded to the nearest second. Included are runtimes for Galois algorithms at 512 threads. The splash2 implementation of bh timed out after 100 minutes.

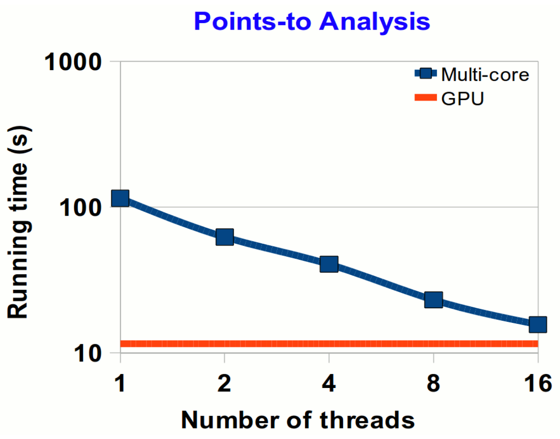
GPU implementation


Single Source Shortest Path


Survey Propagation


Delaunay Mesh Refinement

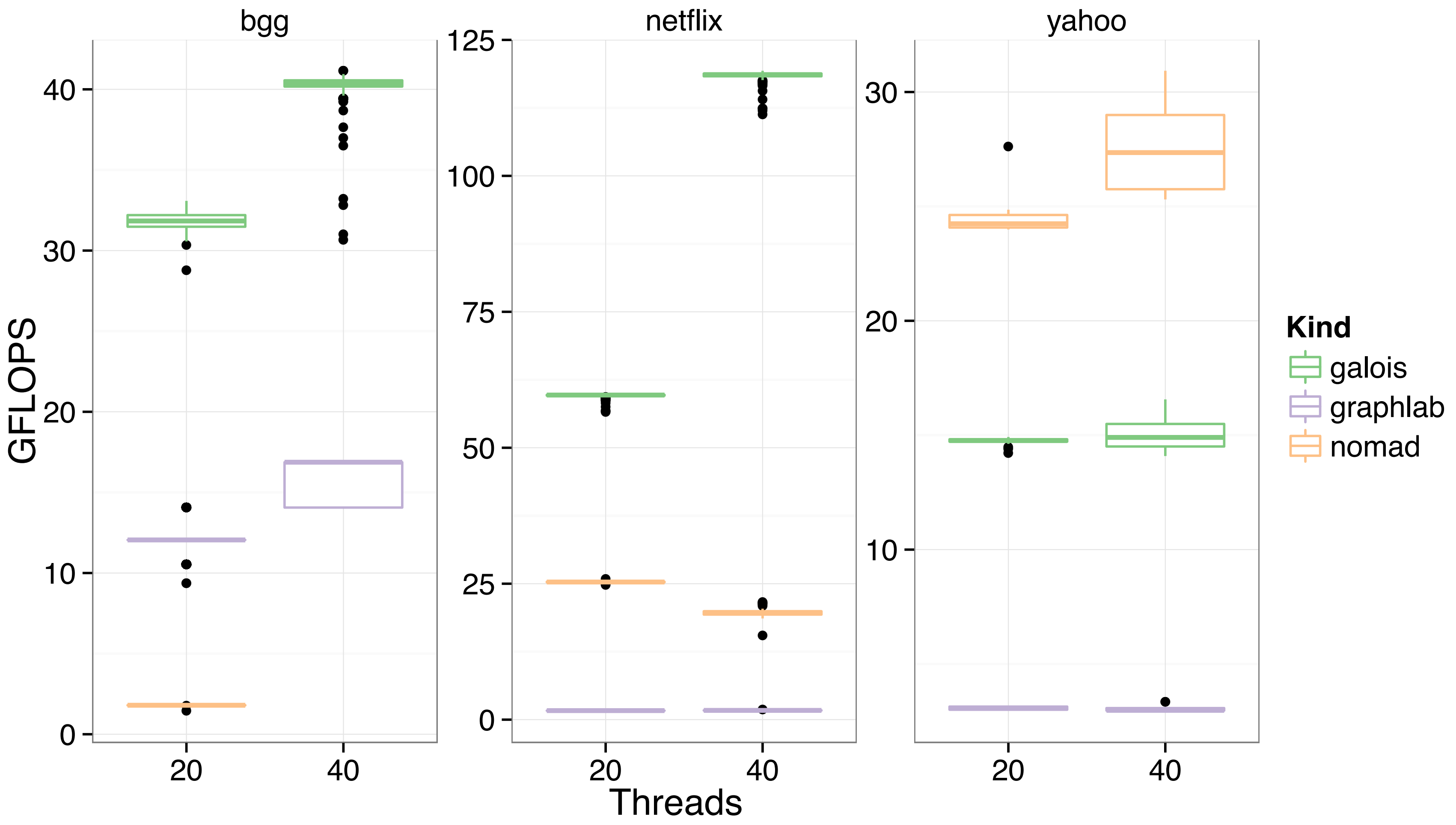

Barnes Hut


Points-to Analysis

Multicore: 24 core Xeon
GPU: NVIDIA Tesla

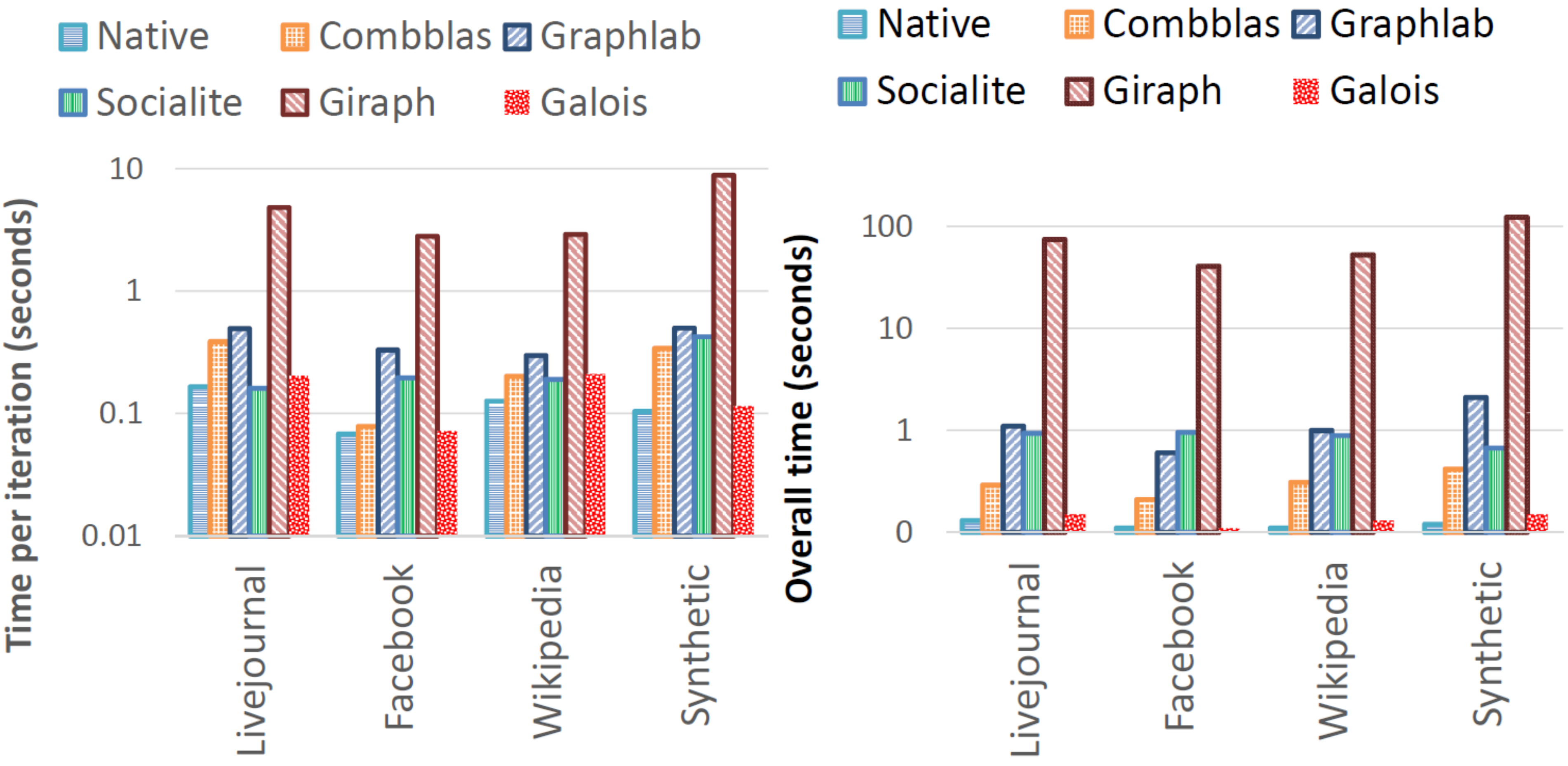
Inputs:	SSSP: 23M nodes, 57M edges	SP: 1M literals, 4.2M clauses	DMR: 10M triangles
	BH: 5M stars	PTA: 1.5M variables, 0.4M constraints	

SGD – Recommender System



nomad with 40 threads on bgg does not converge

Intel Study: Galois vs. Graph Frameworks

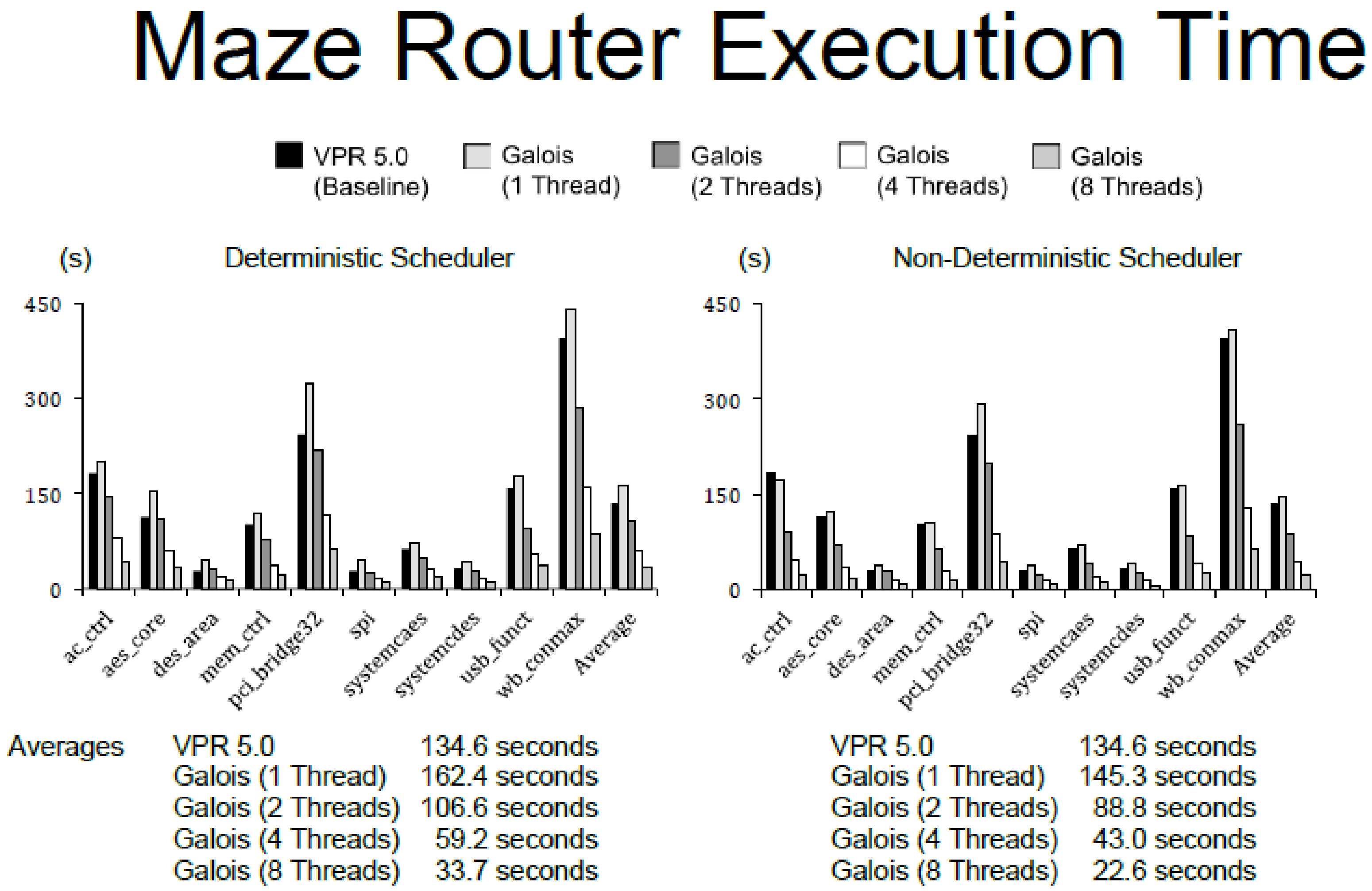


(a) PageRank

(b) Breadth-First Search

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

FPGA Tools



Maze Router Execution Time

Averages	VPR 5.0	134.6 seconds	VPR 5.0	134.6 seconds
	Galois (1 Thread)	162.4 seconds	Galois (1 Thread)	145.3 seconds
	Galois (2 Threads)	106.6 seconds	Galois (2 Threads)	88.8 seconds
	Galois (4 Threads)	59.2 seconds	Galois (4 Threads)	43.0 seconds
	Galois (8 Threads)	33.7 seconds	Galois (8 Threads)	22.6 seconds

Moctar & Brisk, "Parallel FPGA Routing based on the Operator Formulation" DAC 2014

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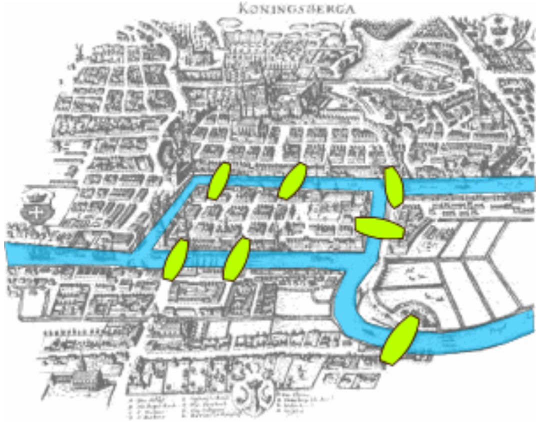
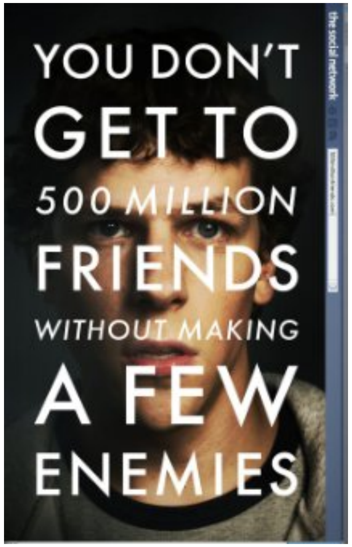
What is Graph Analytics?

- Algorithms to compute properties of graphs
  - Connected components, shortest paths, centrality measures, diameter, PageRank, …
- Many applications
  - Google, path routing, friend recommendations, network analysis
- Difficult to implement on a large scale
  - Data sets are large, data accesses are irregular
  - Need parallelism and efficient runtimes



Bridges of Konigsberg



The Social Network

Graph Analytics DSLs

GraphLab	Low et al. (UAI ’10)
PowerGraph	Gonzalez et al. (OSDI ’12)
GraphChi	Kyrola et al. (OSDI ’12)
Ligra	Shun and Blelloch (PPoPP ’13)
Pregel	Malewicz et al. (SIGMOD ‘10)
…	

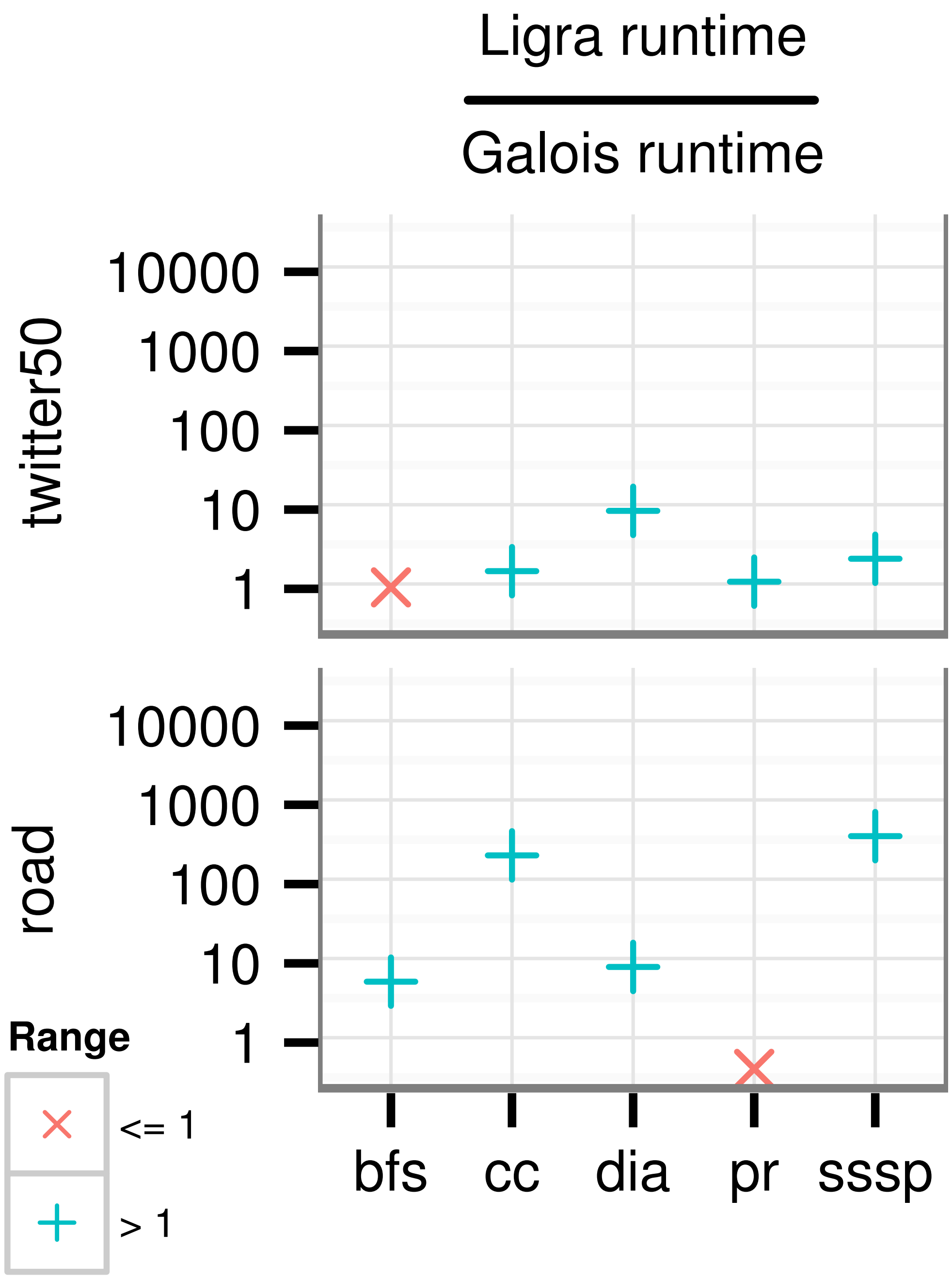
- Easy to implement their APIs on top of Galois system
  - Galois implementations called PowerGraph-g, Ligra-g, etc.
  - About 200-300 lines of code each

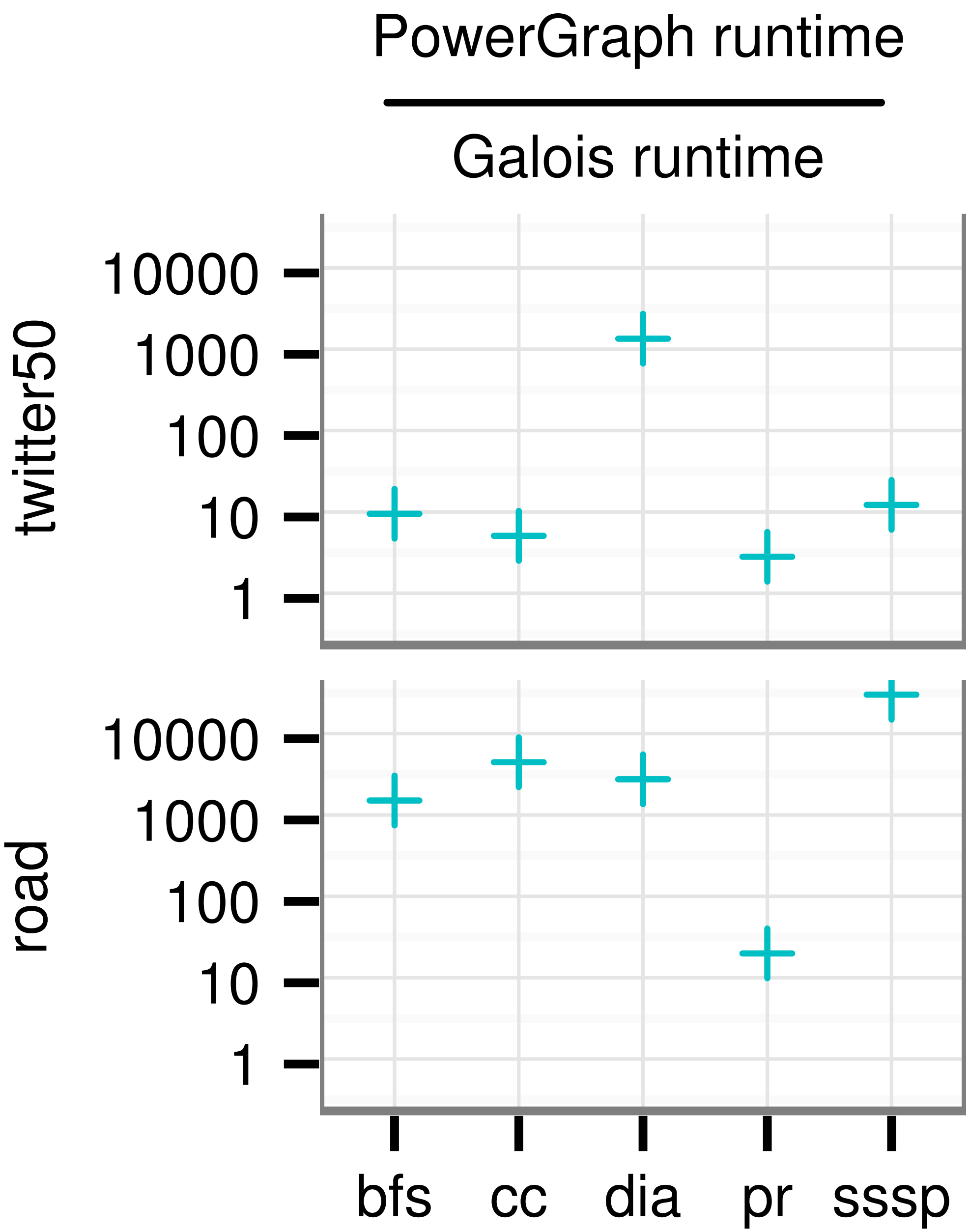
Evaluation

- Platform
  - 40-core system
    - 4 socket, Xeon E7-4860 (Westmere)
  - 128 GB RAM
- Applications
  - Breadth-first search (bfs)
  - Connected components (cc)
  - Approximate diameter (dia)
  - PageRank (pr)
  - Single-source shortest paths (sssp)

- Inputs
  - twitter50 (50 M nodes, 2 B edges, low-diameter)
  - road (20 M nodes, 60 M edges, high-diameter)
- Comparison with
  - Ligra (shared memory)
  - PowerGraph (distributed)
    - Runtimes with 64 16-core machines (1024 cores) does not beat one 40-core machine using Galois

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


Ligra runtime
Galois runtime
twitter50
road
10000
1000
100
10
1
bfs
cc
dia
pr
sssp
Range
× <= 1
+ > 1


PowerGraph runtime
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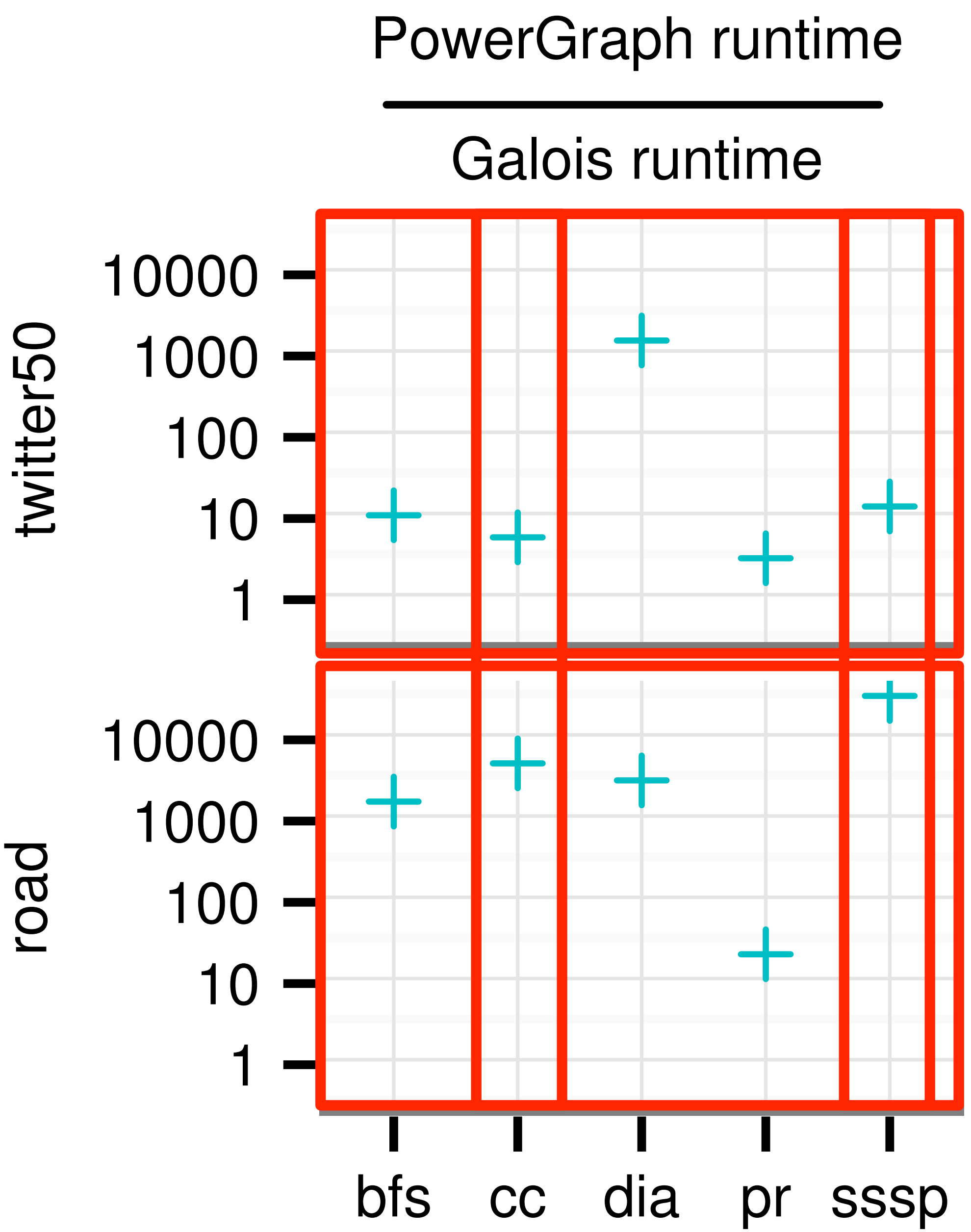

- The best algorithm may require application-specific scheduling
  - Priority scheduling for SSSP
- The best algorithm may not be expressible as a vertex program
  - Connected components with union-find
- Autonomous scheduling required for high-diameter graphs
  - Coordinated scheduling uses many rounds and has too much overhead

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Galois in Practice

- C++ library
  - Galois::for_each(begin, end, functor)
  - Galois::Graph::*, Galois::Bag, …

- Currently supports
  - Cautious operators (i.e., no undos)
  - No static analysis (e.g., POPL 2011)

Building Galois Programs

- Requirements
  - Linux, modern compiler, Boost headers
    - Partial support for Solaris, Windows
    - Partial support for Intel MIC, Arm, Power
  - Hugepages (optional)

- As easy as gcc…

```
g++ -I${GDIR}/include –L${GDIR}/lib *.cpp –lgalois
```

- Galois distribution uses CMake to simplify build

```
cmake ${GDIR}; make
```

Baseline Runtime System

- Speculative execution-based runtime

- Provides hooks (Joe++) to allow user to optimize performance

- Once program works correctly in parallel, then optimize

“Hello graph” in Galois

```
#include “Galois/Galois.h”
#include “Galois/Graphs/LCGraph.h”

using namespace Galois;

struct Data { int value; float f; };

typedef Graph::LC_Linear_Graph<Data,void> Graph;
typedef Graph::GraphNode Node;

Graph graph;

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

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

Includes

Graph Declarations

Galois Iterator

A Galois Program

- Operator
  - The Context
- Iterator
  - Topology-Driven
  - Data-Driven
- Data Structures
  - Api for graphs, etc
- Scheduling
  - Priorities, etc
- Miscellaneous directives

Example Operator

```
//Operators are any valid C++ functor with the correct signature
struct P {
  Graph& g;
  P(Graph& g) :g(g) {}
  void operator()(const Node& n, UserContext<Node>& ctx) {
    graph.getData(n).value += 1;
  }
};
Galois::for_each(ii,ee,P(graph));

//Or as a lambda
Galois::for_each(ii,ee, [&graph] (const Node& n,
                                  UserContext<Node>& ctx) {
                         graph.getData(n).value += 1;
                });
```

The Operator Context

```
void operator()(const Node& n, UserContext<Node>& ctx);
```

- Context is a handle to the loop-runtime
- UserContext<WorkItemType> has
  - breakLoop(); //Break out of the current parallel loop (eventually)
  - PerIterAllocTy& getPerIterAlloc(); //A per-iteration region allocator
  - void push(Args&&... args); //Add a new item to the worklist (forwards args to WorkItemType constructor)

Fast Local Memory

```
void operator()(const Node& n, UserContext<Node>& ctx) {
 //This vector uses scalable allocation
std::vector<Node,Galois::PerIterAllocTy::rebind<Node>::other> vec(ctx.getPerIterAlloc());
  for (…) { vec.push_back(graph.getEdgeDst(ii)); }
}
```

Applying an Operator: Topology

```
//Standard Topology driven fixedpoint
while (!fixedpoint()) {
  //Apply op to each node in the graph
  Galois::for_each(graph.begin(), graph.end(),Op(graph));
}

//Standard Topology driven initialization
Galois::for_each(graph.begin(), graph.end(),
         [&graph] (const Node& n, UserContext<Node>& ctx) {
                   graph.getData(n).value = 0;
                });
```

Applying an Operator: Data-driven

```
struct P {
  void operator()(int n, UserContext<int>& ctx) {
    if (n < 100) {
      ctx.push(n+1);
      ctx.push(n+2);
    }
}
};
//For_each has a single work item form
//1 is the initial work item
//Yes, you can work on abstract iteration spaces
Galois::for_each(1,P());
```

Data Structures

- In Galois/Graph/*
- General Graph: FirstGraph.h
- Specialized graphs: LC_*.h
  - No edge/node creation/removal
  - Variants for different memory layouts
  - Except LC_Morph: allows new nodes with declared number of edges
- Others: Trees, Bags, Reducers

LC_CSR_Graph

- Local Computation, Compressed Sparse Row
- Key Typedefs:
  - GraphNode: node handle
  - edge_iterator
  - iterator
- Key Functions:
  - nodeData& getData(GraphNode)
  - edgeData& getEdgeData(edge_iterator)
  - GraphNode getEdgeDst(edge_iterator)
  - iterator begin()
  - iterator end()
  - edge_iterator edge_begin(GraphNode)
  - edge_iterator edge_end(GraphNode)

LC_CSR_Graph Example

```
//sum values on edges and nodes
LC_CSR_Graph<double, double> graph;
…
double sum;
for (auto N : graph) {
  sum = graph.getData(N);
  for (auto ii = graph.edge_begin(N),
            ee = graph.edge_end(N);
       ii != ee; ++ii) {
    sum += graph.getEdgeData(ii);
  }
}
```

Scheduling

- In Galois/WorkList/*
- Scheduling specified by mini language in optional argument to for_each loops

```
using namespace Galois::WorkList;
typedef dChunkedLIFO<256> Sched;
Galois::for_each(g.begin(), g.end, Op(),
                 Galois::wl<Sched>());
```

Standard Scheduling Options

Most have options (including sub-schedulers)

- Lifo (Fifo) Like:
  - LIFO, ChunkedLIFO, dChunkedLIFO
  - AltChunkedLIFO
- No worklist pushes:
  - StableIterator
- Round Based:
  - BulkSynchronous
- New Work stays local:
  - LocalQueue
- Priority Scheduling:
  - OrderedByIntegerMetric

Useful Directives

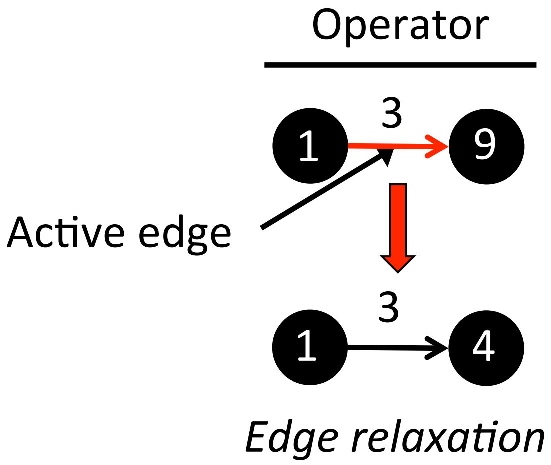
- Loopname: report statistics by loop
  - for_each(…, loopname(“name”));
- Timers: Galois::StatTimer
  - May be named
- PAPI measurements
- reportpageAlloc: report pages allocated
- setActiveThreads(n) : limit threads to n

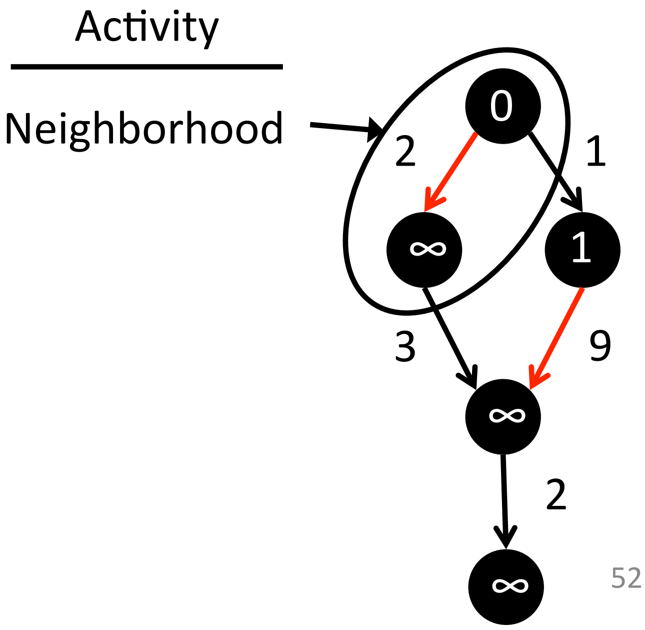
Outline

- Current State of Parallel programming
- Amorphous data parallelism / Operator formulation
- High Level Galois
- Current state of the system
- Implementing Graph Analytic DSLs on Galois
- Practical Galois
- **Extended Example: SSSP**
- Scheduling
- Active research

Example: SSSP

- Find the shortest distance from source node to all other nodes in a graph
  - Label nodes with tentative distance
  - Assume non-negative edge weights
- Algorithms
  - Chaotic relaxation O(2^V)
  - Bellman-Ford O(VE)
  - Dijkstra's algorithm O(E log V)
    - Uses priority queue
  - Δ-stepping
    - Uses sequence of bags to prioritize work
    - Δ=1, O(E log V)
    - Δ=∞, O(VE)
- Different algorithms are different schedules for applying relaxations
  - SSSP needs priority scheduling for work efficiency





Algorithmic Variants == Scheduling

- Chaotic Relaxation:
  - Specify a non-priority scheduler
    - E.g. dChunkedFIFO
- Dijkstra:
  - Use Ordered Executor
- Delta-Stepping Like:
  - Specify OBIM priority scheduler
- Bellman-Ford
  - Push every edge in non-priority scheduler
  - Execute
  - Repeat #nodes times

Simple (PUSH) SSSP in Galois

```
struct SSSP {
 void operator()(UpdateRequest& req,
      Galois::UserContext<UpdateRequest>& ctx) const {
  unsigned& data = graph.getData(req.second);
  if (req.first > data) return;

  for (Graph::edge_iterator ii
=graph.edge_begin(req.second),
     ee = graph.edge_end(req.second); ii != ee; ++ii)
   relax_edge(data, ii, ctx);
 }
};
```

Relax Edge (PUSH)

```
void relax_edge(unsigned src_data, Graph::edge_iterator ii,
              Galois::UserContext<UpdateRequest>& ctx) {
  GNode dst = graph.getEdgeDst(ii);
  unsigned int edge_data = graph.getEdgeData(ii);
  unsigned& dst_data = graph.getData(dst);
  unsigned int newDist = dst_data + edge_data;
  if (newDist < dst_data) {
    dst_data = newDist;
    ctx.push(std::make_pair(newDist, dst));
  }
}
```

Specifying Schedule and Running

Load

```
Galois::Graph::readGraph(graph, filename);
Galois::for_each(graph.begin(), graph.end(), Init());
```

WorkList

```
using namespace Galois::WorkList;
typedef dChunkedLIFO<16> dChunk;
typedef OrderedByIntegerMetric<UpdateRequestIndexer,dChunk>
OBIM;
```

SSSP

```
graph.getData(*graph.begin()) = 0;
Galois::for_each(std::make_pair(0U, *graph.begin()), SSSP(),
                             Galois::wl<OBIM>());
```

Implementation Variants: Push V.S. Pull

- Simple optimization to control concurrency costs, locks, etc.
- Push: Look at node and update neighbors
- Pull: Look at neighbors and update self
- Pull seems “obviously” better, but in practice it depends on algorithm, scheduling, and data

Pull SSSP

```
struct SSSP {
  void operator()(GNode req, Galois::UserContext<UpdateRequest>& ctx) {
//update self
    for (auto ii = graph.edge_begin(req),  ee = graph.edge_end(req); ii != ee; ++ii) {
      auto edist = graph.getEdgeData(ii), ndist = graph.getData(graph.getEdgeDst(ii));
      if (edist + ndist < data)
         data  = edist + ndist;
    }
//push higher neighbors
 for (auto ii = graph.edge_begin(req),  ee = graph.edge_end(req); ii != ee; ++ii) {
      auto edist = graph.getEdgeData(ii), ndist = graph.getData(graph.getEdgeDst(ii));
      if (ndist  > data + edist)
          ctx.push(graph.getEdgeDst(ii));
    }
};
```

SSSP Demo

- Start with chaotic algorithm and vary scheduling policy
  - Different policies give different amounts of work and scalability but all policies produce correct executions

- Policies
  - FIFO
  - ChunkedFIFO
    - FIFO of fixed size chunks of items
  - dChunkedFIFO
    - A ChunkedFIFO per package with stealing between ChunkedFIFOs
  - OBIM
    - Generalization of sequence of bags when sequence is sparse

Demo SSSP variants

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Best Scheduling Policies

1. Exploit locality
2. Control the total amount of work
3. Use architecture-aware concurrent data structures that must scale to many threads
4. Vary according to application

Require sophisticated implementations

Contribution

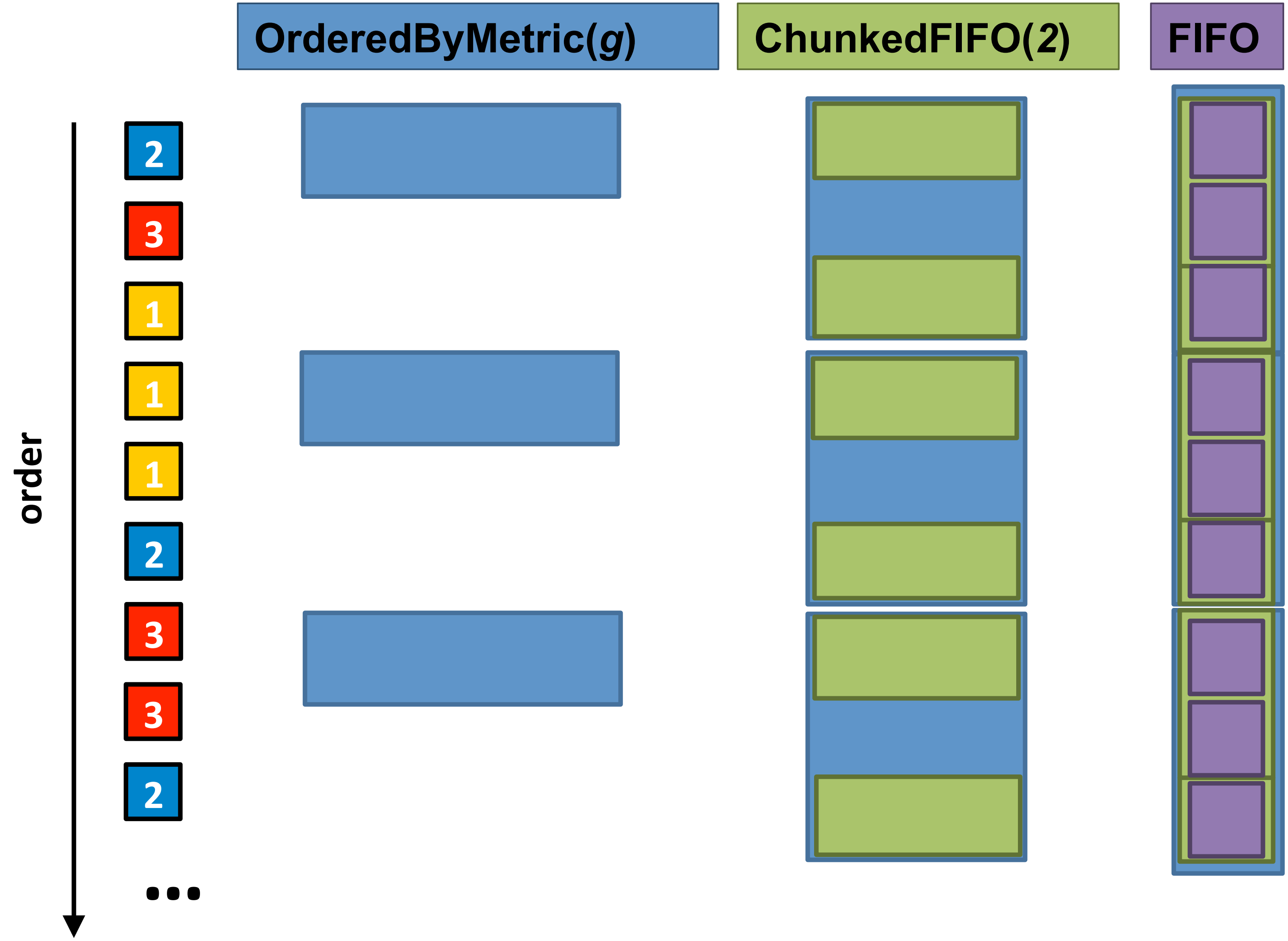
- A language for scheduling policies
  - *Declarative:* sophisticated schedulers w/o writing code
  - *Effective:* performance comparable to hand-written and often better than previous schedulers

Get good performance without users writing (serial or concurrent) scheduling code

Rules and their composition

FIFO | LIFO | ChunkedLIFO(*k*) | Ordered(*f*)

Random | OrderedByMetric(*g*) | ChunkedFIFO(*k*)



Application-specific Policies

App	Order	Scheduling Policy	
PFP	FIFO	**FIFO**	[Goldberg88]
PFP	HL	**OrderedByMetric**(□*n. -n.height*) **FIFO**	[Cherkassy95]
SSSP	D-stepping	**OrderedByMetric**(□n. □*n.w* / D□ + …) **FIFO**	[Meyer98]
SSSP	Dijkstra	**Ordered**(□*a,b. a.w* □ *b.w*)	[Dijkstra59]
DMR	Local stack	**ChunkedFIFO**(*k*) Local: **LIFO**	[Kulkarni08]
DT	BRIO	**OrderedByMetric**(□*p. p.rnd*) **ChunkedFIFO**(*k*)	[Amenta03]
MATCHING	ABMP	**OrderedByMetric**(□*n. n.lvl*) **FIFO**	[ABMP91]
BP	RBP	**Ordered**(□*a,b. a.old-a.new* □ *b.old-b.new*)	[Elidan06]

Synthesis

- Generate scheduler implementation from specification

- Assemble atoms that implement individual rules into final implementation
  - Tricky depending on overall behavior that needs to be maintained

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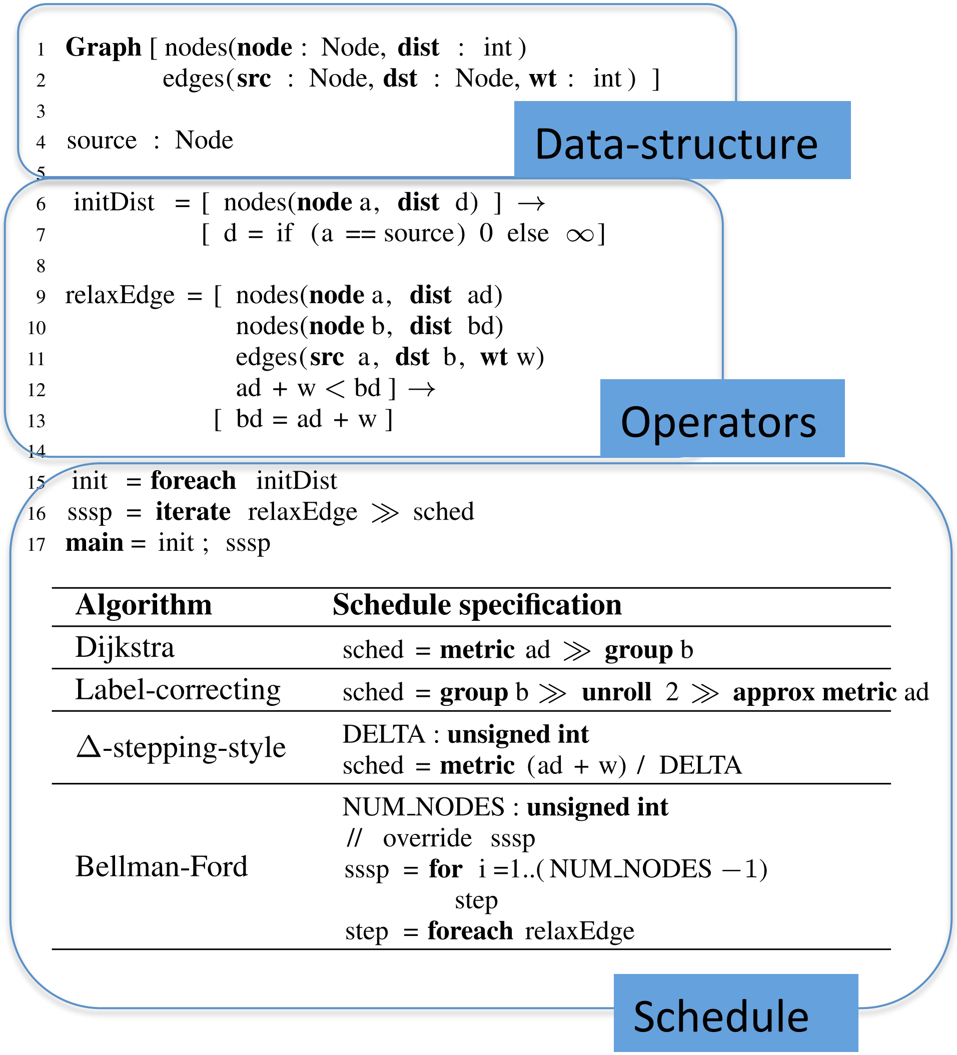
Interesting Problems

- Algorithm implementation synthesis
- GPU execution
- Hybrid execution
- Hardware mapping
- Development tools
- Distributed memory

Elixir: Synthesizing parallel graph algorithms



```
Graph [ nodes(node : Node, dist : int )
        edges(src : Node, dst : Node, wt : int ) ]

source : Node

initDist = [ nodes(node a, dist d) ] →
           [ d = if (a == source) 0 else ∞]

relaxEdge = [ nodes(node a, dist ad)
              nodes(node b, dist bd)
              edges(src a, dst b, wt w)
              ad + w < bd ] →
            [ bd = ad + w ]

init = foreach initDist
sssp = iterate relaxEdge ≫ sched
main = init ; sssp
```

Algorithm	Schedule specification
Dijkstra	sched = **metric** ad ≫ **group** b
Label-correcting	sched = **group** b ≫ **unroll** 2 ≫ **approx metric** ad
Δ-stepping-style	DELTA : **unsigned int** sched = **metric** (ad + w) / DELTA

Bellman-Ford	NUM_NODES : **unsigned int**
	// override sssp
	sssp = **for** i =1..(NUM_NODES − 1)
	step
	step = **foreach** relaxEdge

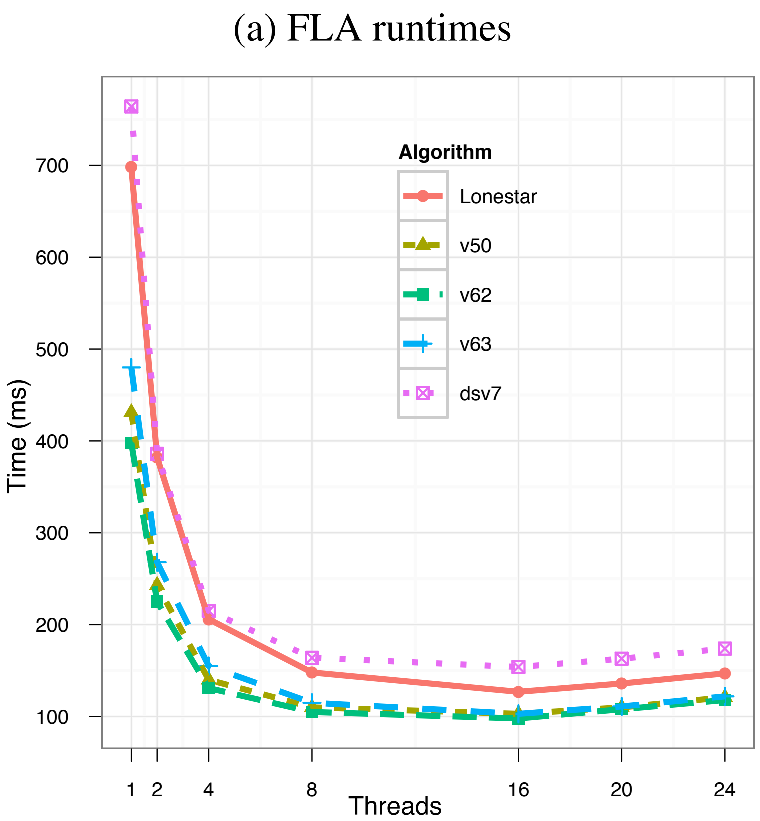
Data-structure

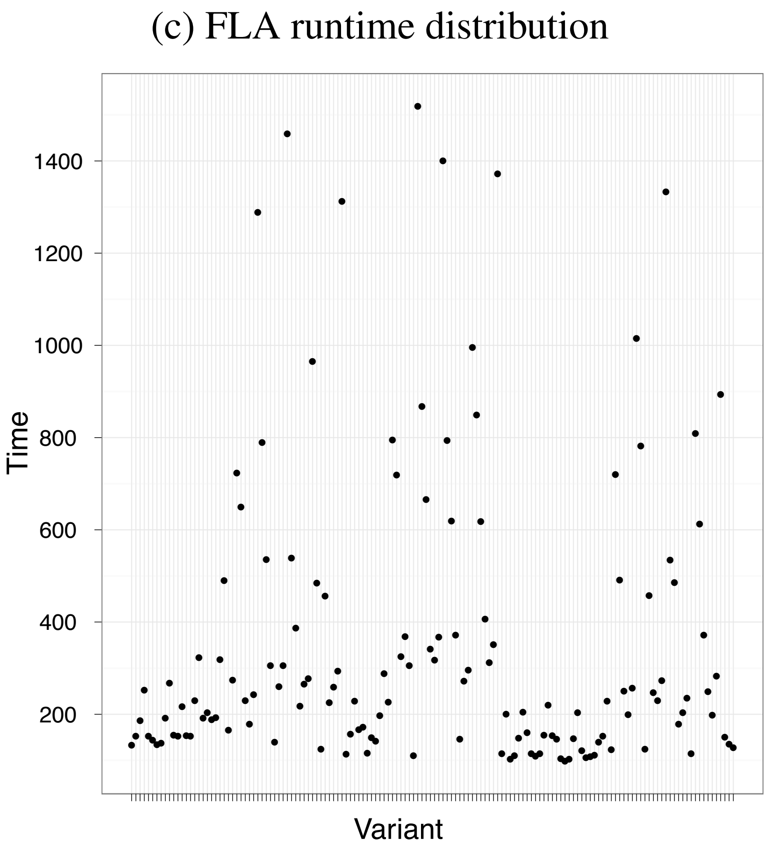
Operators

Schedule

- Elixir DSL:
  - Relational data-structure spec
  - Operators as rewrite rules
  - Schedule specified declaratively
- Compiler synthesizes fixpoint computation
- Inserts synchronization automatically
- Allows quick experimentation with many algorithm variants

SSSP : synthesized vs. handwritten





- Input graph: Florida road network, 1M nodes, 2.7M edges

Irregular Algorithms on the GPU

- GPUs offer hundreds of concurrent threads for computation
- Discrete GPUs possess higher memory bandwidths and allow more throughput than CPUs
- GPUs can be used solely or share work with the CPU

Key Challenges

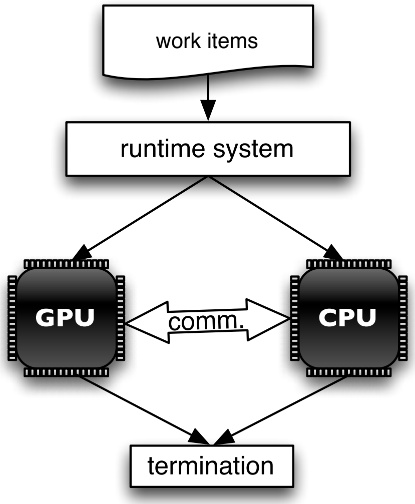
- GPU hardware is optimized for *regular* code
- Dynamic scheduling is hard because GPU threads are hardware-scheduled
- Limited synchronization primitives with little to no communication allowed between threads
- No standard library, code reuse is hard
- Autotuning necessary for performance portability

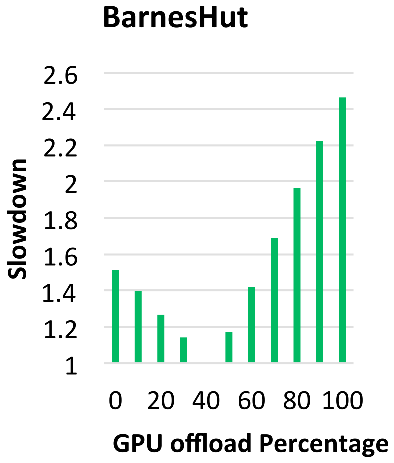
The LonestarGPU Suite and beyond

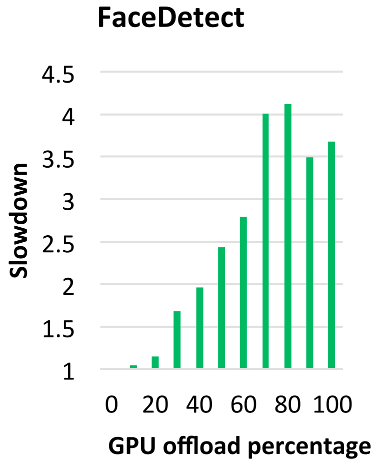
- LonestarGPU 2.0 Suite contains fast implementations of many irregular algorithms
  - BFS, SSSP, MST, BH, PTA, SP, DMR
- LSG-next contains more algorithms and autotuning support
- Written by hand currently
- Working on a code generator for irregular algorithms

Heterogeneous execution

- Distribute work between multiple devices ; CPU (host) and accelerator (GPU, Xeon-Phi, FPGA etc.)
- Challenges:
  - Work division – how to divide workload between devices to minimize communication
  - Communication – reduce communication overhead by combining/overlapping
  - Data representation – preferred layouts different on different devices

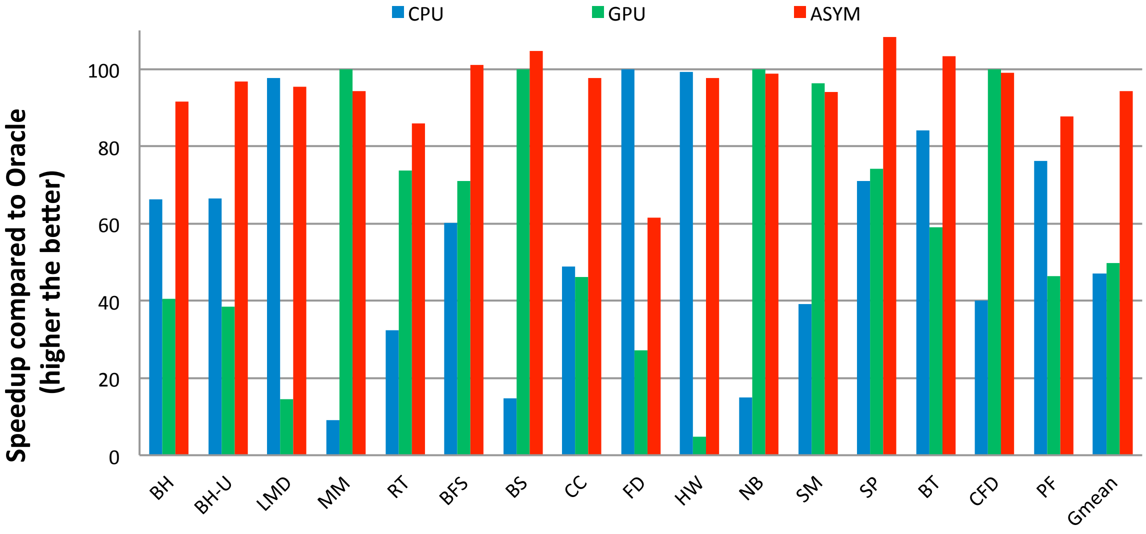






Integrated GPUs.

- Simpler problem:
  - Low communication overhead, Atomics b/w CPU-GPU
- Constrained:
  - GPUs not as powerful as discrete GPUs
  - Memory limit (less than 1G)
- Use runtime-profiling to determine work-distribution
  - Adaptive execution addresses load imbalance



Misc

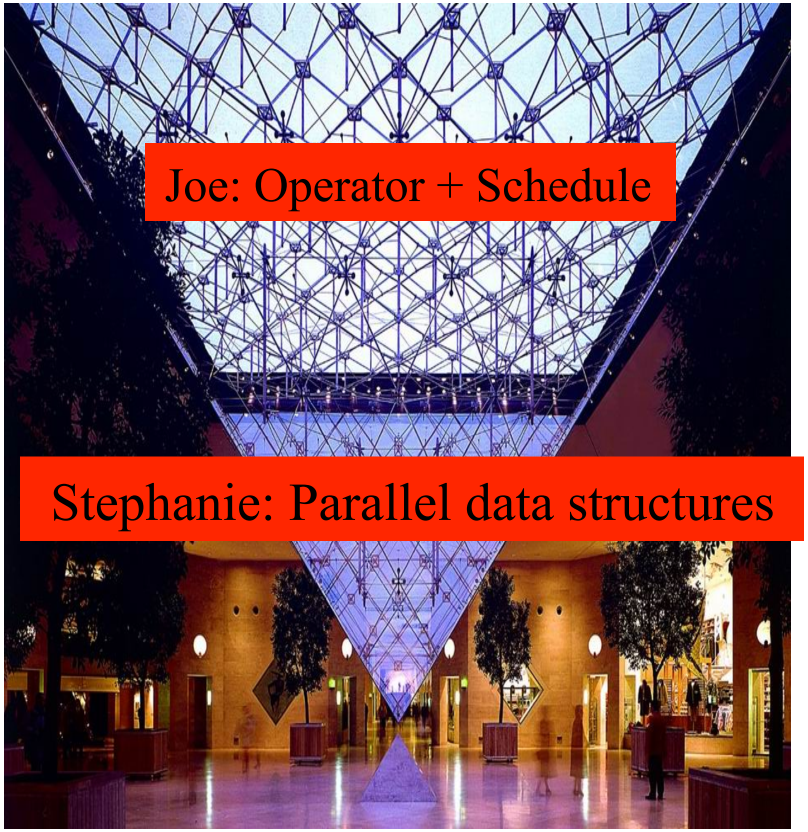
- Hardware transactional memory
  - How does it compare to Galois's conflict checking
  - How can it be improved to be used as basis for non-trivial runtimes
- Performance Prediction
  - Can we measure scaling without having to first write code?

Distributed Memory

- Source compatible DSM Galois
- Handles non-vertex programs
  - Add remove nodes and edges

Conclusions

- Yesterday:
  - Computation-centric view of parallelism
- Today:
  - Data-centric view of parallelism
  - Operator formulation of algorithms
  - Permits a unified view of parallelism and locality in algorithms
  - Joe/Stephanie programming model
  - Galois system is an implementation
- Tomorrow:
  - DSLs for different applications
  - Layer on top of Galois



Joe: Operator + Schedule

Stephanie: Parallel data structures

Parallel program = Operator + Schedule + Parallel data structure

More information

- Website
  - http://iss.ices.utexas.edu
- Download
  - Galois system for multicores
  - Lonestar benchmarks (CPU and GPU)
  - All our papers