Towards a
Science of Parallel Programming

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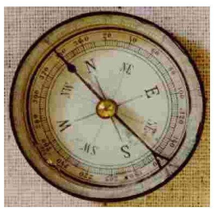
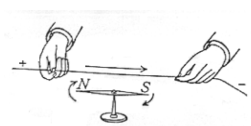
Problem Statement

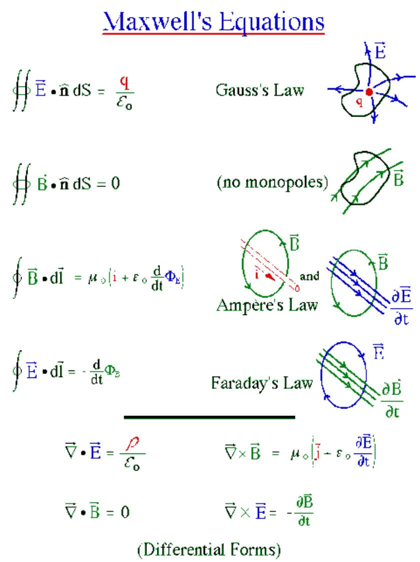
- Community has worked on parallel programming for more than 30 years
  - programming models
  - machine models
  - programming languages
  - ….
- However, parallel programming is still a research problem
  - matrix computations, stencil computations, FFTs etc. are fairly well-understood
  - few insights for irregular applications
    - each new application is a “new phenomenon”
- Thesis: we need a science of parallel programming
  - analysis: framework for thinking about parallelism in application
  - synthesis: produce an efficient parallel implementation of application

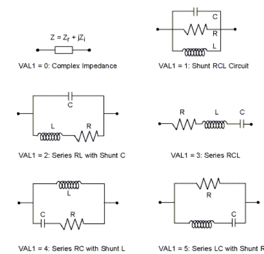
“The Alchemist” Cornelius Bega (1663)

Analogy: science of electro-magnetism









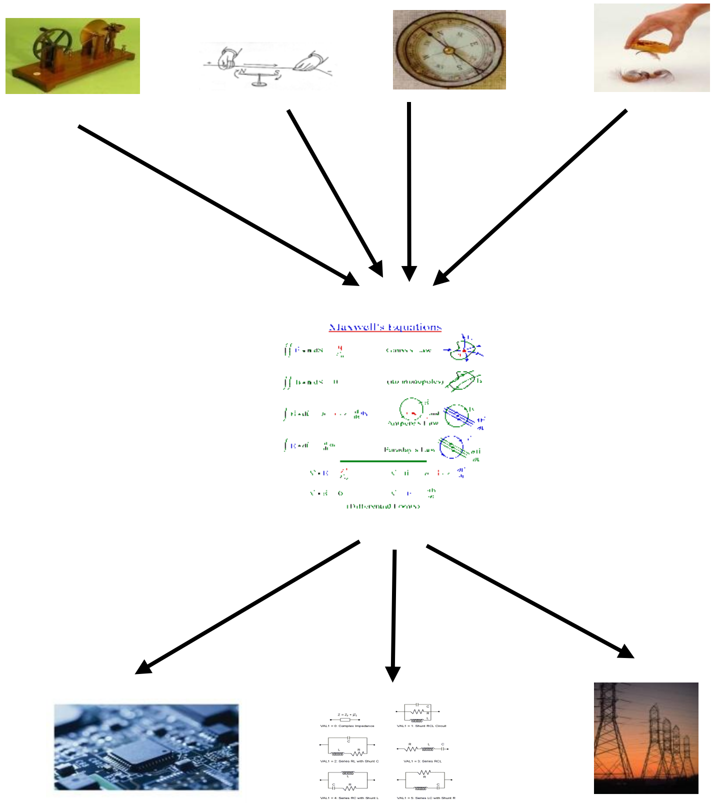
Seemingly unrelated phenomena

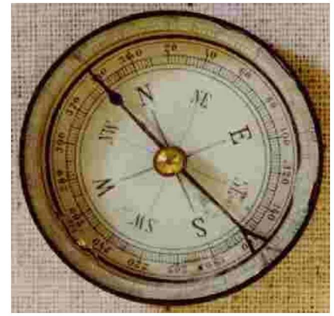
Unifying abstractions

Specialized models that exploit structure

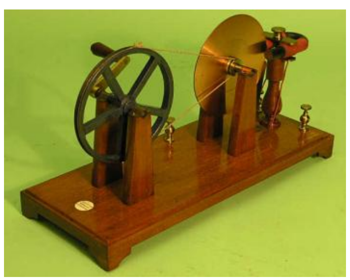
Organization of talk

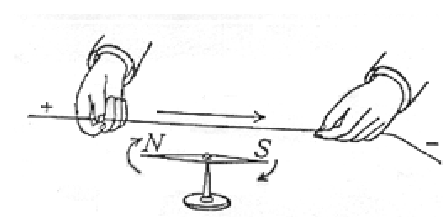
- Seemingly unrelated parallel algorithms and data structures
  - Stencil codes
  - Delaunay mesh refinement
  - Event-driven simulation
  - Graph reduction of functional languages
  - ………
- Unifying abstractions
  - Operator formulation of algorithms
  - Amorphous data-parallelism
  - Galois programming model
  - Baseline parallel implementation
- Specialized implementations that exploit structure
  - Structure of algorithms
  - Optimized compiler and runtime system support for different kinds of structure
- Ongoing work





Seemingly unrelated algorithms



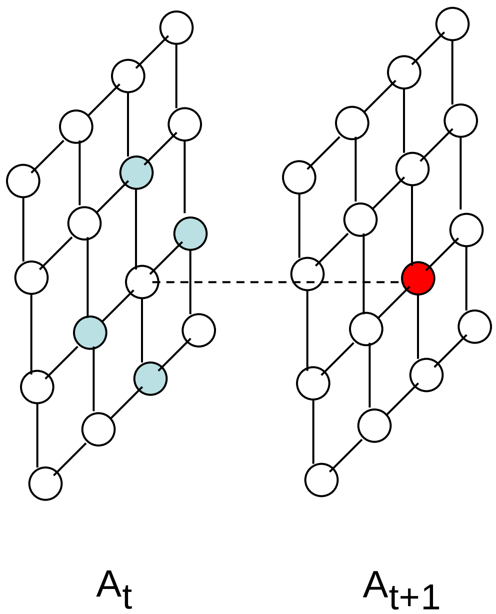


Examples

Application/domain		Algorithm
Meshing		Generation/refinement/partitioning
Compilers		Iterative and elimination-based dataflow algorithms
Functional interpreters		Graph reduction, static and dynamic dataflow
Maxflow		Preflow-push, augmenting paths
Minimal spanning trees		Prim, Kruskal, Boruvka
Event-driven simulation		Chandy-Misra-Bryant, Jefferson Timewarp
AI		Message-passing algorithms
Stencil computations		Jacobi, Gauss-Seidel, red-black ordering
Data-mining		Clustering

Stencil computation: Jacobi iteration

- Finite-difference method for solving pde's
  - discrete representation of domain: grid
- Values at interior points are updated using values at neighbors
  - values at boundary points are fixed
- Data structure:
  - dense arrays
- Parallelism:
  - values at next time step can be computed simultaneously
  - parallelism is not dependent on runtime values
- Compiler can find the parallelism
  - spatial loops are DO-ALL loops

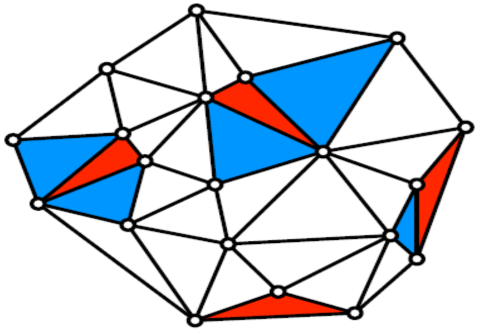


Jacobi iteration, 5-point stencil

```
//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)
```

Delaunay Mesh Refinement

```
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(e);//determine new cavity
        c.expand();
        c.retriangulate();
        m.update(c);//update mesh
        wl.add(c.badTriangles());
}
```



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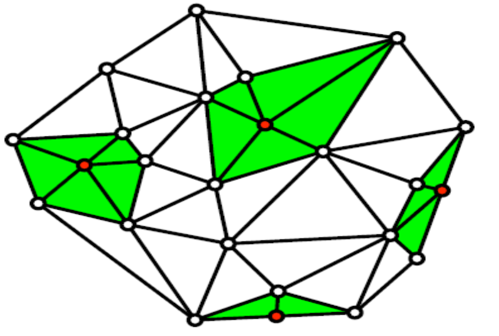
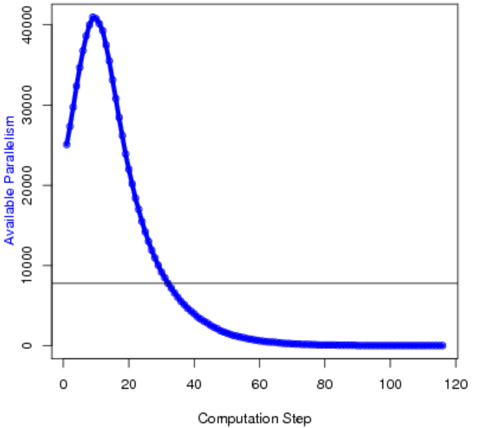


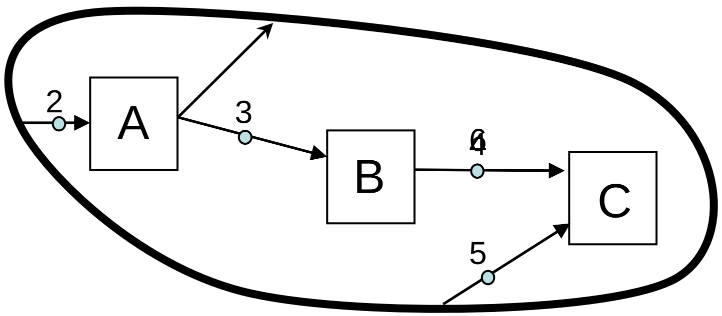
After

Available parallelism



Event-driven simulation

- Stations communicate by sending messages with time-stamps on FIFO channels
- Stations have internal state that is updated when a message is processed
- Messages must be processed in time-order at each station
- Data structure:
  – Messages in event-queue, sorted in time-order
- Parallelism:
  – activities created in future may interfere with current activities
  ➔ static parallelization and interference graph technique will not work
  – Jefferson time-warp
    - station can fire when it has an incoming message on *any* edge
    - requires roll-back if speculative conflict is detected
  – Chandy-Misra-Bryant
    - conservative event-driven simulation
    - requires null messages to avoid deadlock



Remarks on algorithms

- Algorithms:
  - parallelism can be dependent on runtime values
    - DMR, event-driven simulation, graph reduction,….
  - don't-care non-determinism
    - nothing to do with concurrency
    - DMR, graph reduction
  - activities created in the future may interfere with current activities
    - event-driven simulation…
- Data structures:
  - relatively few algorithms use dense arrays
  - more common: graphs, trees, lists, priority queues,…
- Parallelism in irregular algorithms is very complex
  - static parallelization usually does not work
  - static dependence graphs are the wrong abstraction
  - finding parallelism: most of the work must be done at runtime

Organization of talk

- Seemingly unrelated parallel algorithms and data structures
  - Stencil codes
  - Delaunay mesh refinement
  - Event-driven simulation
  - Graph reduction of functional languages
  - ....
- Unifying abstractions
  - Operator formulation of algorithms
  - Amorphous data-parallelism
  - Baseline parallel implementation for exploiting amorphous data-parallelism
- Specialized implementations that exploit structure
  - Structure of algorithms
  - Optimized compiler and runtime system support for different kinds of structure
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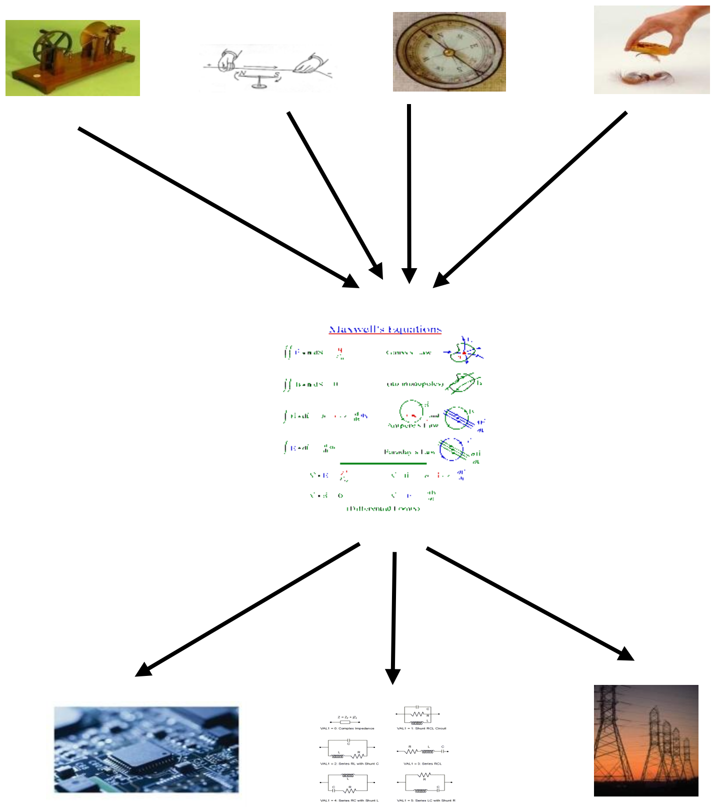
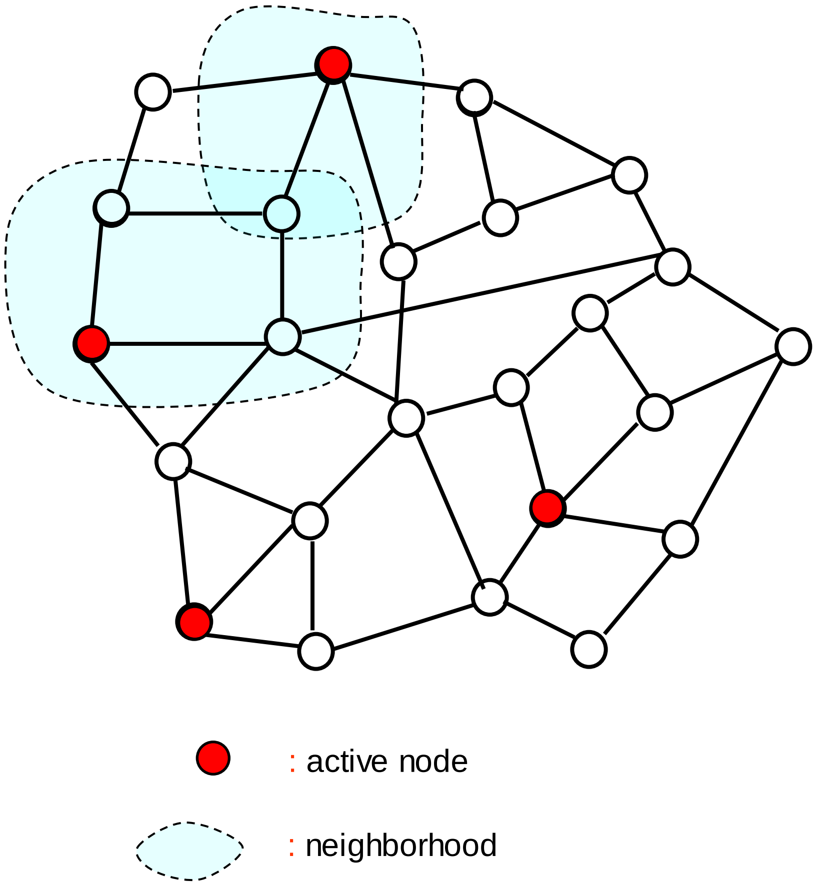


Operator formulation of algorithms

- Algorithm formulated in data-centric terms
  - active element:
    - node or edge where computation is needed
      - DMR: nodes representing bad triangles
      - Event-driven simulation: station with incoming message
      - Jacobi: nodes of mesh
  - activity:
    - application of operator to active element
  - neighborhood:
    - set of nodes and edges read/written to perform computation
      - DMR: cavity of bad triangle
      - Event-driven simulation: station
      - Jacobi: nodes in stencil
    - distinct usually from neighbors in graph
  - ordering:
    - order in which active elements must be executed in a sequential implementation
      - any order (Jacobi,DMR, graph reduction)
      - some problem-dependent order (event-driven simulation)
- Amorphous data-parallelism
  - active nodes can be processed in parallel, subject to
    - neighborhood constraints
    - ordering constraints



Galois programming model

- Joe programmers
  - sequential, OO model
  - Galois set iterators: for iterating over unordered and ordered sets of active elements
    - *for each e in Set S do B(e)*
      - evaluate B(e) for each element in set S
      - no a priori order on iterations
      - set S may get new elements during execution
    - *for each e in OrderedSet S do B(e)*
      - evaluate B(e) for each element in set S
      - perform iterations in order specified by OrderedSet
      - set S may get new elements during execution
- Stephanie programmers
  - Galois concurrent data structure library
- (Wirth) Algorithms + Data structures = Programs
  - (cf) SQL database programming

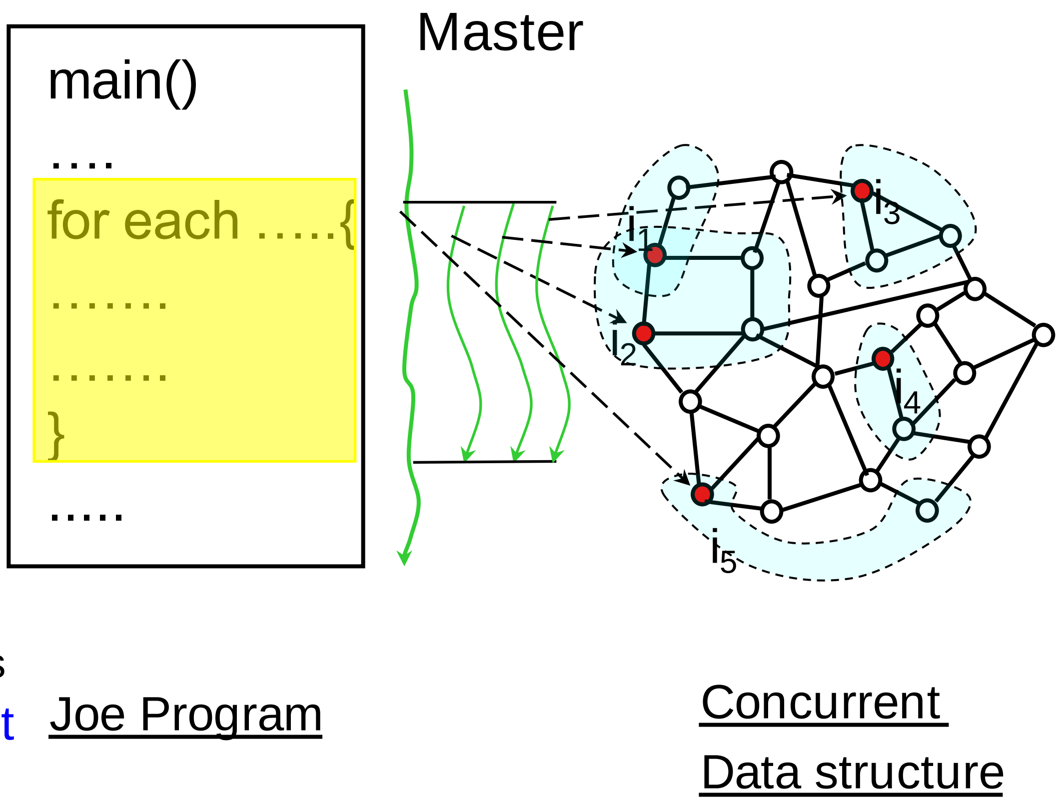
```
Mesh m = /* read in mesh */
Set ws;
ws.add(m.badTriangles());//initialize ws

for each tr in Set ws do {
      //unordered Set iterator
  if (tr no longer in mesh) continue;
  Cavity c = new Cavity(tr);
  c.expand();
  c.retriangulate();
  m.update(c);
  ws.add(c.badTriangles());
}
```

DMR using Galois iterators

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
  - barrier synchronization at end of iterator
- Independence of neighborhoods:
  - logical locks on nodes and edges
  - implemented using CAS operations
- Ordering constraints for ordered set iterator:
  - execute iterations out of order but commit in order
  - cf. out-of-order CPUs

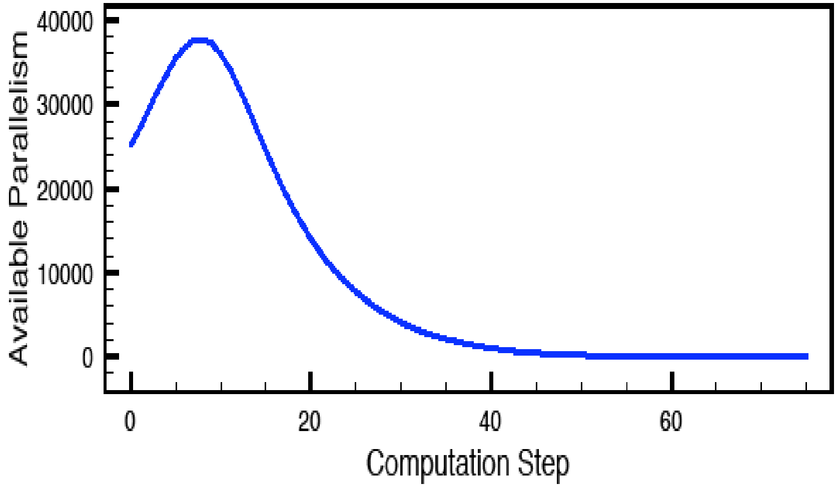


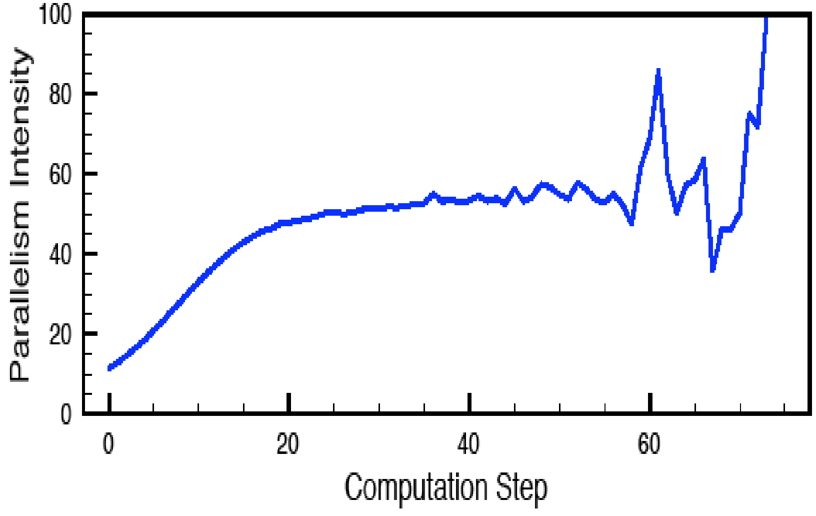
Parameter tool

- Measures amorphous data-parallelism in irregular program execution
- Idealized execution model:
  - unbounded number of processors
  - applying operator at active node takes one time step
  - execute a maximal set of active nodes
  - perfect knowledge of neighborhood and ordering constraints
- Useful as an analysis tool

Example: DMR

- Input mesh:
  - Produced by Triangle (Shewchuck)
  - 550K triangles
  - Roughly half are badly shaped
- Available parallelism:
  - How many non-conflicting triangles can be expanded at each time step?
- Parallelism intensity:
  - What fraction of the total number of bad triangles can be expanded at each step?





Example:Barnes-Hut

- Four phases:
  - build tree
  - center-of-mass
  - force computation
  - push particles
- Problem size:
  - 1000 particles
- Parallelism profile of tree build phase similar to that of DMR
  - why?

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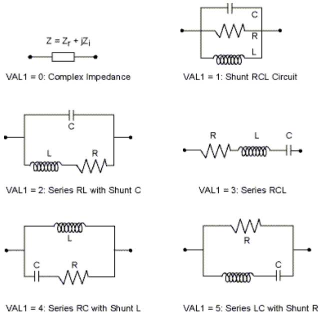
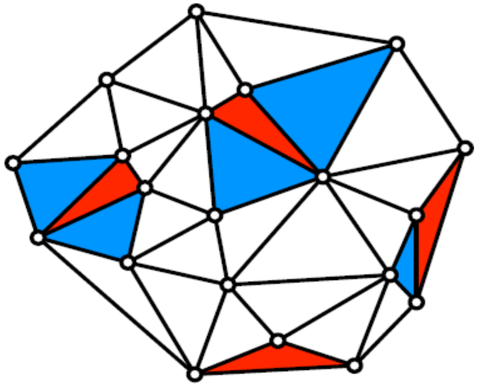


Cautious operators

- Cautious operator implementation:
  - reads all the elements in its neighborhood before modifying any of them
  - (eg) Delaunay mesh refinement
- Algorithm structure:
  - cautious operator + unordered active elements
- Optimization: optimistic execution w/o buffering
  - grab locks on elements during read phase
    - conflict: someone else has lock, so release your locks
  - once update phase begins, no new locks will be acquired
    - update in-place w/o making copies
    - zero-buffering
  - note: this is not two-phase locking



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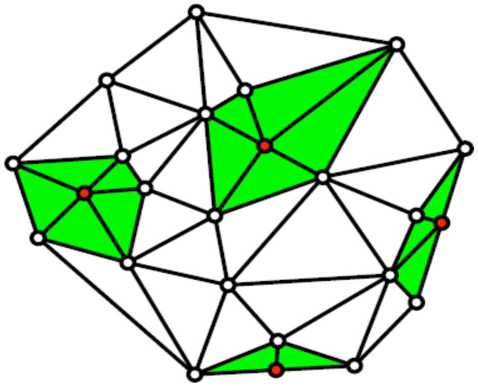
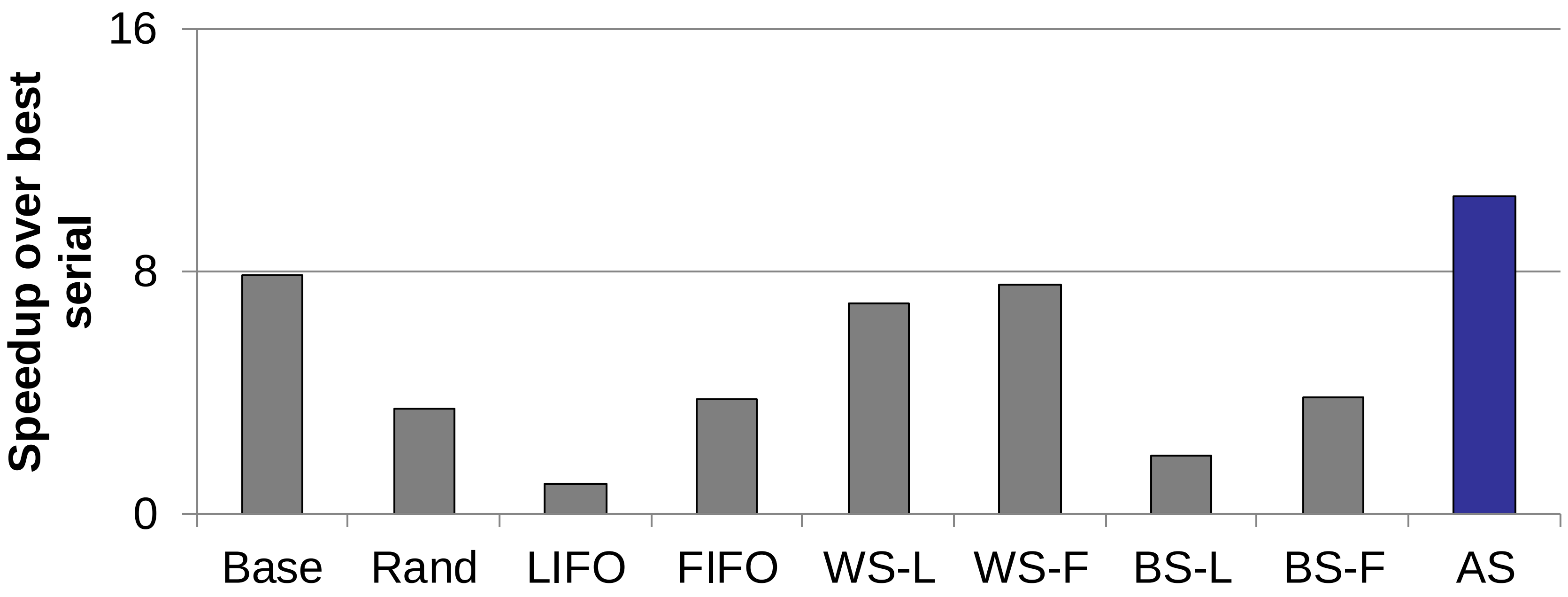


After

Scheduling for unordered algorithms

- Best serial policy for DMR: LIFO
  - Exploit temporal (and potentially spatial) locality
- Best parallel policy for DMR: ***not*** LIFO
  - LIFO increases conflicts
  - Best policy: per thread LIFOs with initial work placed in global queue of chunks
    - New work placed on creating thread's LIFO
    - When a local LIFO is empty, steal a chunk from global queue
  - Application-specific policy: exploit locality while maintaining scalability and reducing conflicts
- Scheduler is a parallel program
  - can be harder to write than the application

Scheduler Sensitivity: DMR



- **Rand**
- **LIFO**, **FIFO**: Global queue or stack
- **WS-L**, **WS-F**: Work-stealing with queue or stack
- **BS-L**, **BS-F**

- **Base**: FIFO of chunks of at most 32 elements
- **AS**: Application-specific policy

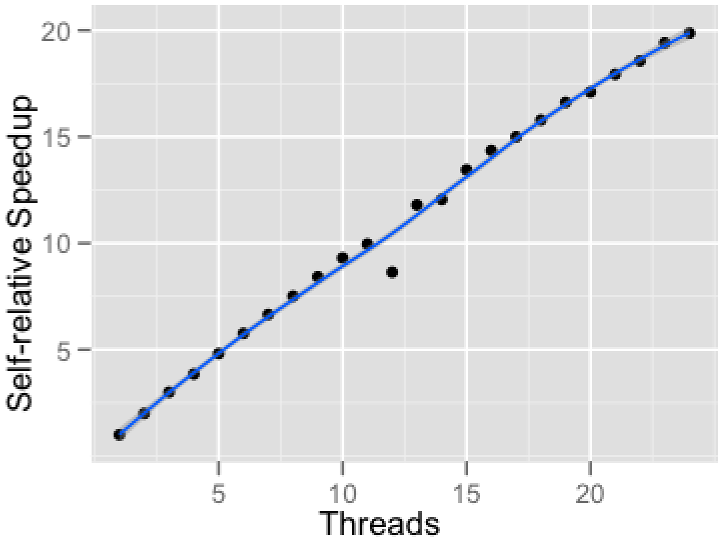
•4x4-core @ 2.7GHz (Opteron 8384), **Sun JDK 1.6.0**, 20 GB heap, time is last of 3 in same JVM instance

Scheduling language

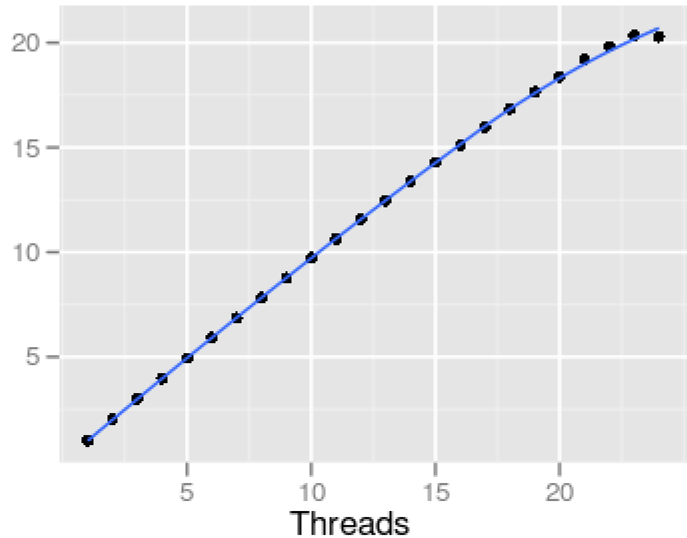
- A language for scheduling policies (Nguyen &Pingali, ASPLOS 2011)
  - *Declarative:* sophisticated schedulers w/o writing code
  - *Effective:* performance comparable to hand-written and often better than previous schedulers

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

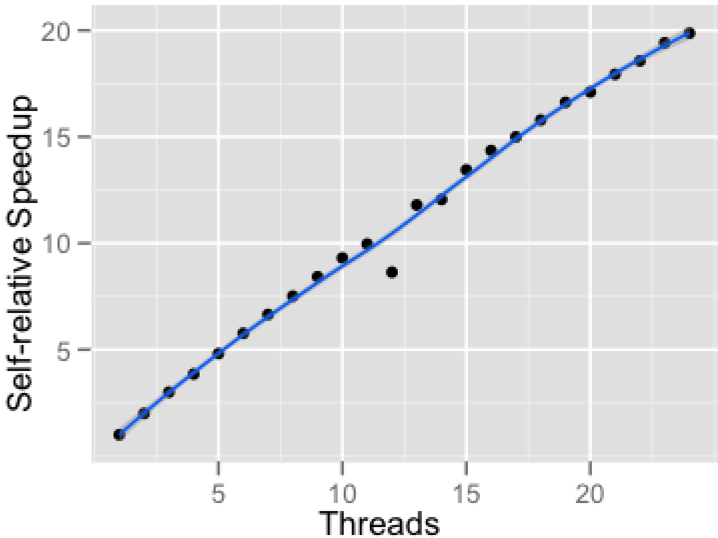
Performance of Galois system (I)



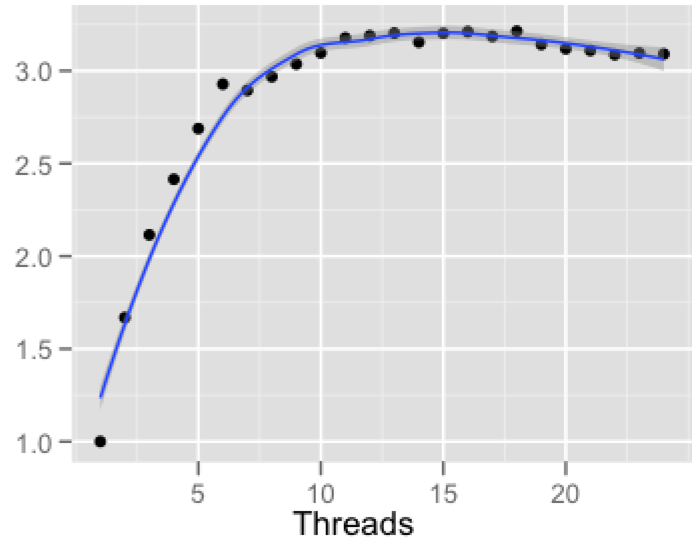
•Betweenness Centrality



•Delaunay Mesh Refinement



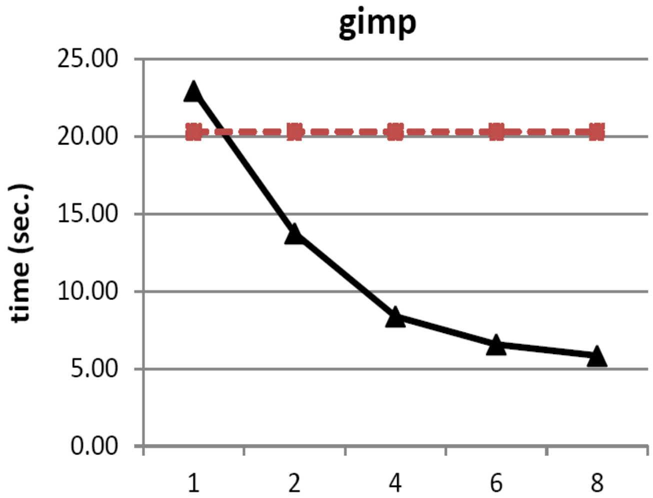
•Asynchronous Variational Integrator

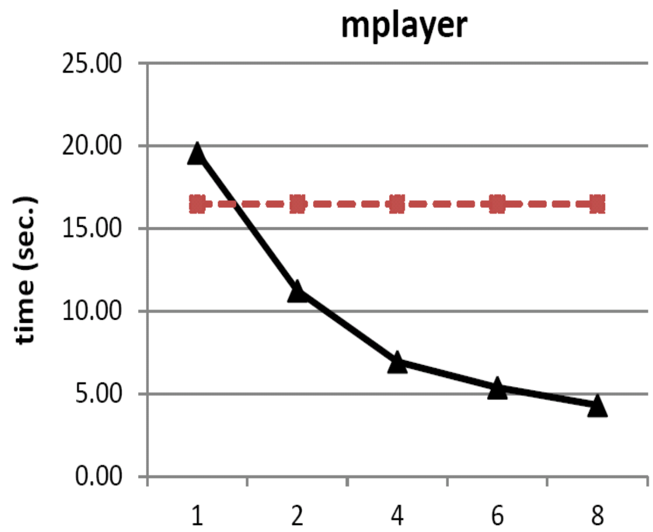


•Metis

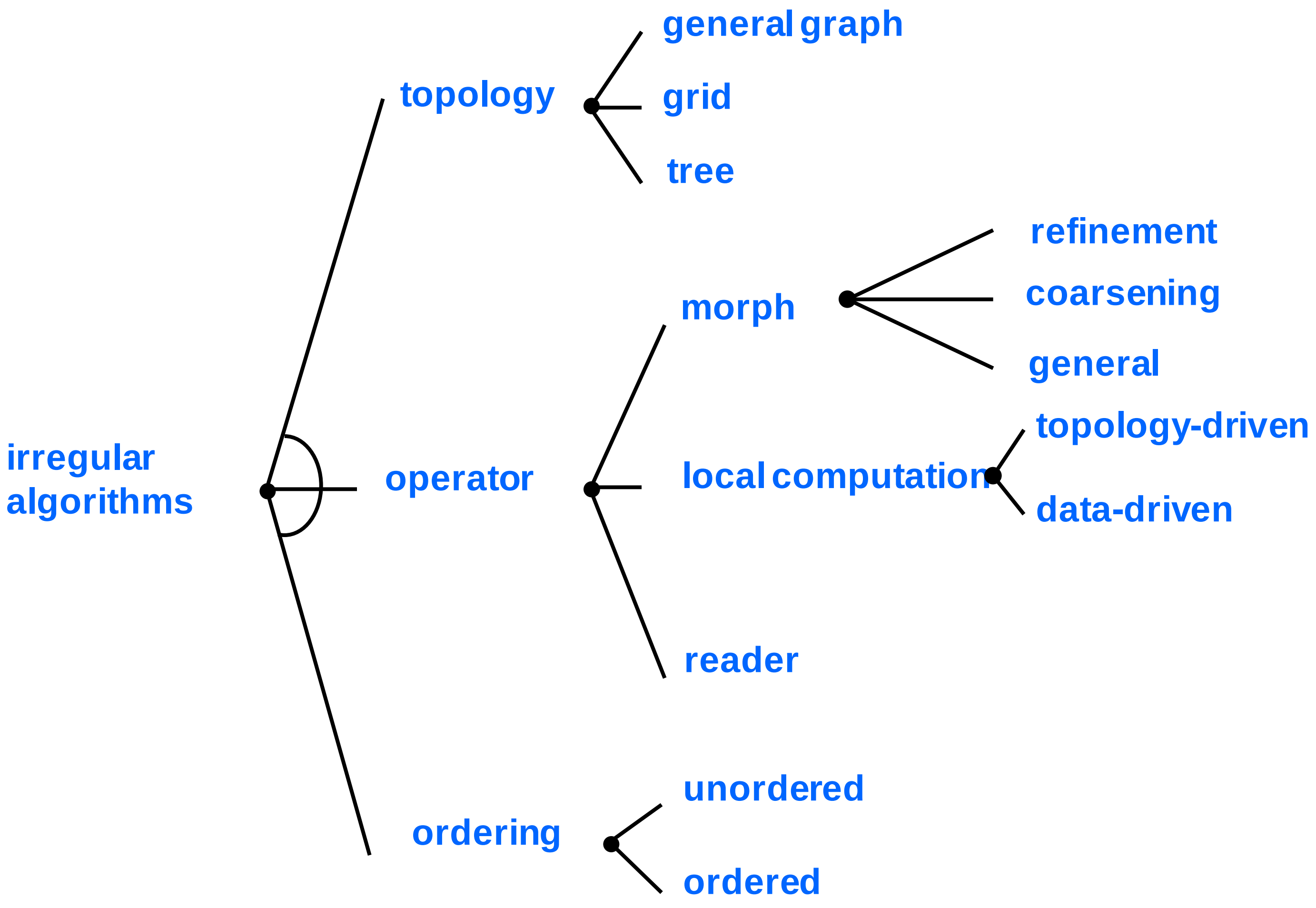
Performance of Galois system (II)

- Andersen-style points-to analysis
- Algorithm formulation
  - solution to system of set constraints
  - 3 graph rewrite rules
  - speedup algorithm by collapsing cycles in constraint graph
- State of the art C++ implementation
  - Hardekopf & Lin
  - red lines in graphs
- "Parallel Andersen-style points-to analysis" Mendez-Lojo et al (OOPSLA 2010)





Structural analysis of irregular algorithms



Jacobi: topology: grid, operator: local computation, ordering: unordered

DMR, graph reduction: topology: graph, operator: morph, ordering: unordered

Event-driven simulation: topology: graph, operator: local computation, ordering: ordered

Exploiting structure to eliminate speculation

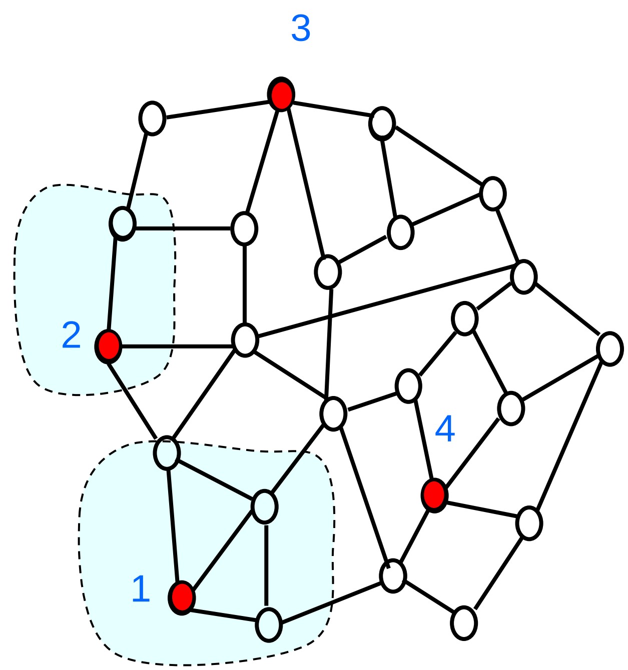
Compile-time — **Static parallelization**

After input is given but before execution — **Inspector-executor**

During program execution — **Interference graph**

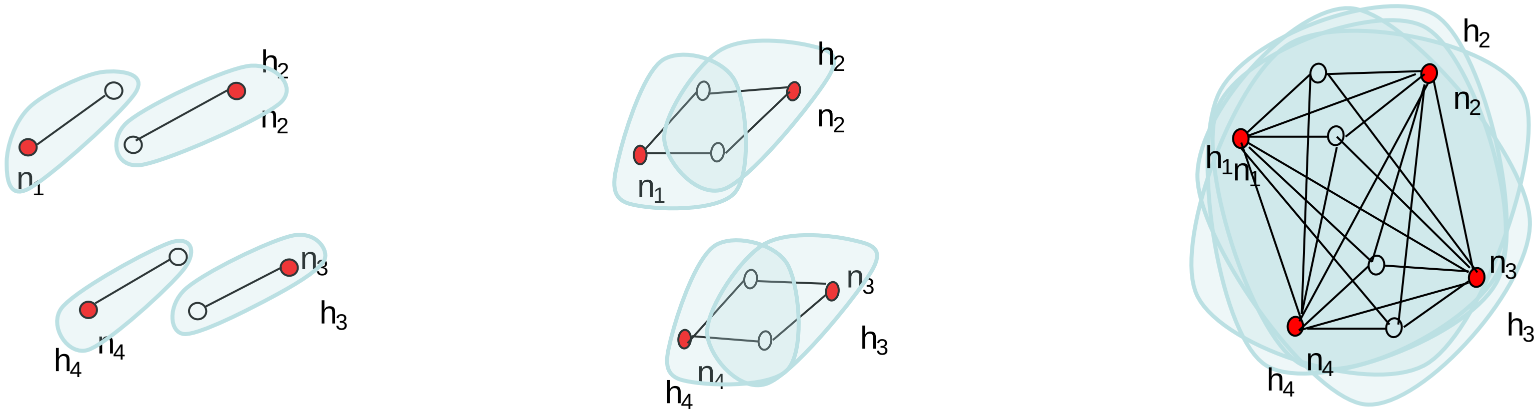
After program is finished — **Optimistic parallelization**

Structured topology, topology-driven algorithms
(dense linear algebra,FFT,finite-differences,..)



Data-driven, ordered algorithms
(discrete-event simulation, Dijkstra SSSP,..)

Ongoing work



- System building
  - current version of Galois, Lonestar: http://iss.ices.utexas.edu/galois
- Algorithm studies:
  - other kinds of structure
  - intra-operator parallelism
  - locality
- Specializing data structure implementations to particular algorithms
  - can this be done semi-automatically?
- Program synthesis from high-level specification of algorithm
- Architectural support for irregular applications
  - joint work with Derek Chiou (ECE, UT)

Summary of Galois system

Galois system =

Abstract Data Types (permit Joe/Stephanie separation)

+

Don't-care non-determinism (unordered set iterator)

+

Scheduling directives (synthesis)

+

Optimistic parallelization (runtime system)

+

Exploitation of structure in algorithms and data (compiler)

Related work

- Transactional memory (TM)
  - Programming model:
    - TM: explicitly parallel (threads)
      - transactions: synchronization mechanism for threads
      - mostly memory-level conflict detection
    - Galois: Joe programs are sequential OO programs
      - ADT-level conflict detection
  - Where do threads come from?
    - TM: someone else's problem
    - Galois project: focus on sources of parallelism in algorithm
- Thread-level speculation
  - Programming model:
    - Galois: separation between ADT and its implementation is critical
      - permits separation of Joe and Stephanie layers (cf. relational databases)
      - permits more aggressive conflict detection schemes like commutativity relations
    - TLS: FORTRAN/C, so no separation between ADT and implementation
  - Programming model:
    - Galois: don't-care non-determinism plays a central role
    - TLS: FORTRAN/C, so only ordered algorithm

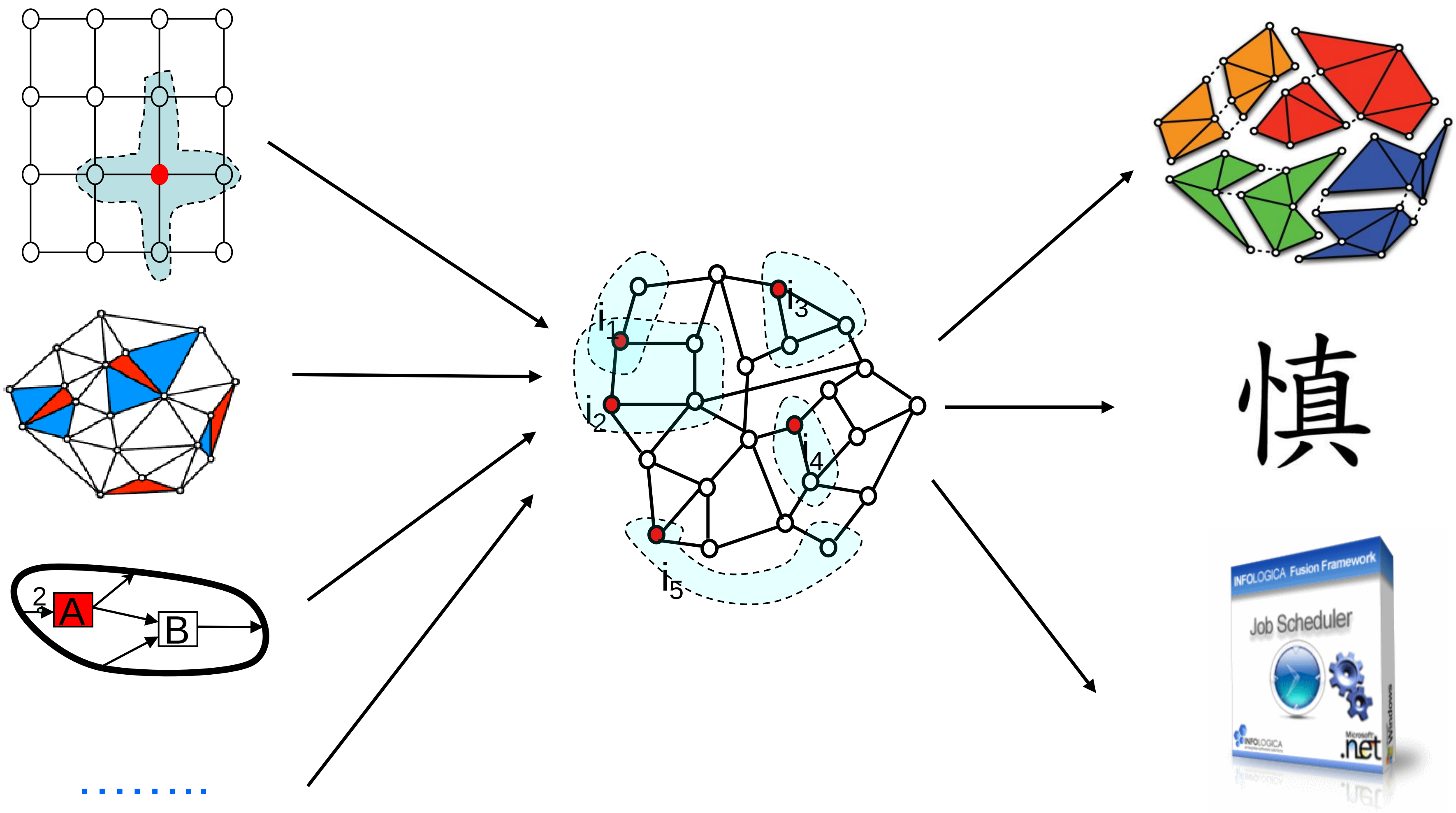
Summary of high-level message

- Current approach
  1. Static parallelization is the norm
  2. Inspector-executor, optimistic parallelization, etc.
     - needed only for weird programs, crutch for dumb programmers
     - they are expensive: (eg) high abort ratio
  3. Dependence graphs are the right abstraction for parallelism
     - program-centric abstraction

- Galois approach
  1. Optimistic parallelization is the baseline
  2. Static parallelization, inspector-executor etc.
     - possible only for weird programs, early-binding of scheduling decisions,
     - overheads of optimistic parallelization can be controlled
  3. Operator formulation of algorithms is the right abstraction
     - data-centric abstraction

structure

Science of Parallel Programming



Seemingly unrelated algorithms

Unifying abstractions

Specialized models that exploit structure