R244

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Green-Marl

A DSL for Easy and Efficient Graph Analysis

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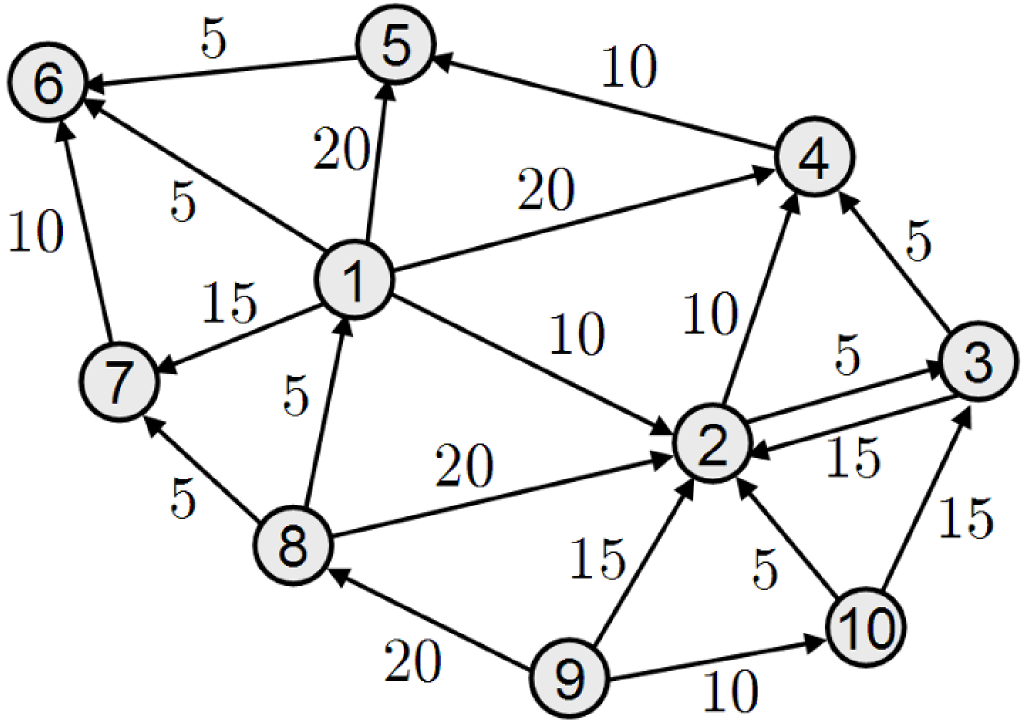
Background

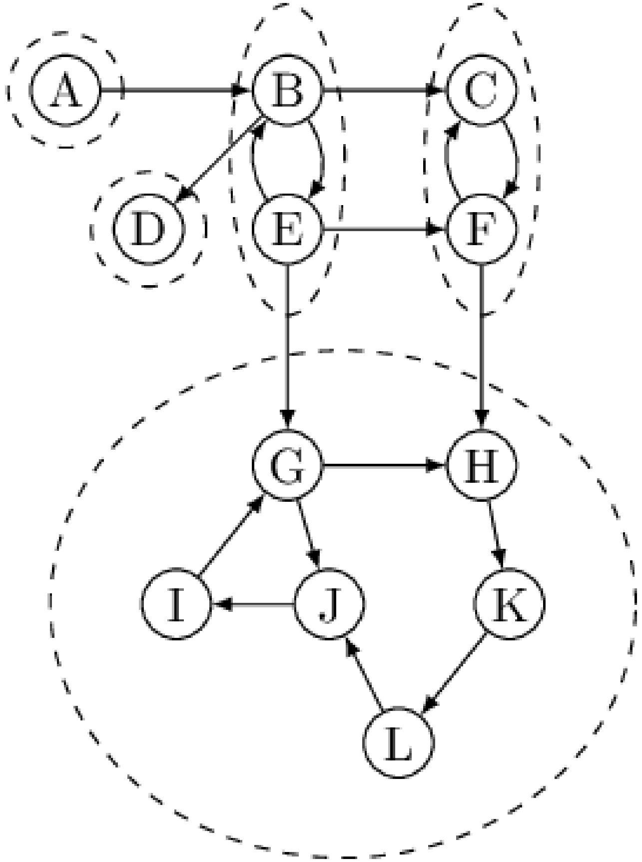
Background

- Graph Analysis - Extract information from a graph dataset



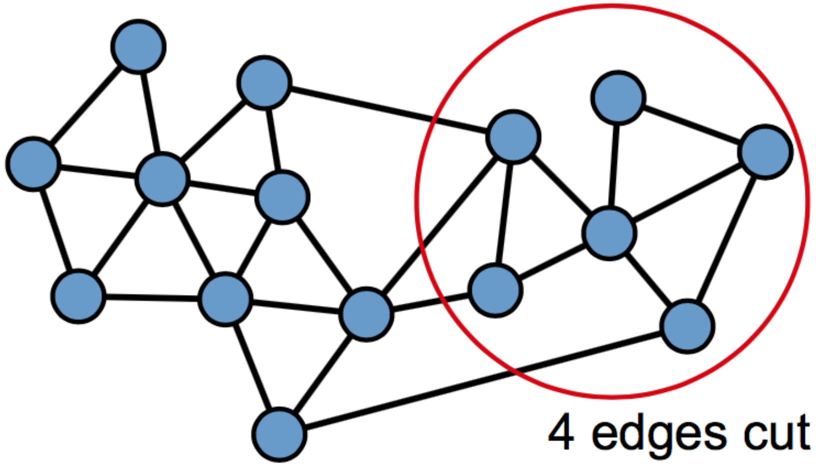
Background – Graph Analysis

Strongly Connected Components



Background – Graph Analysis

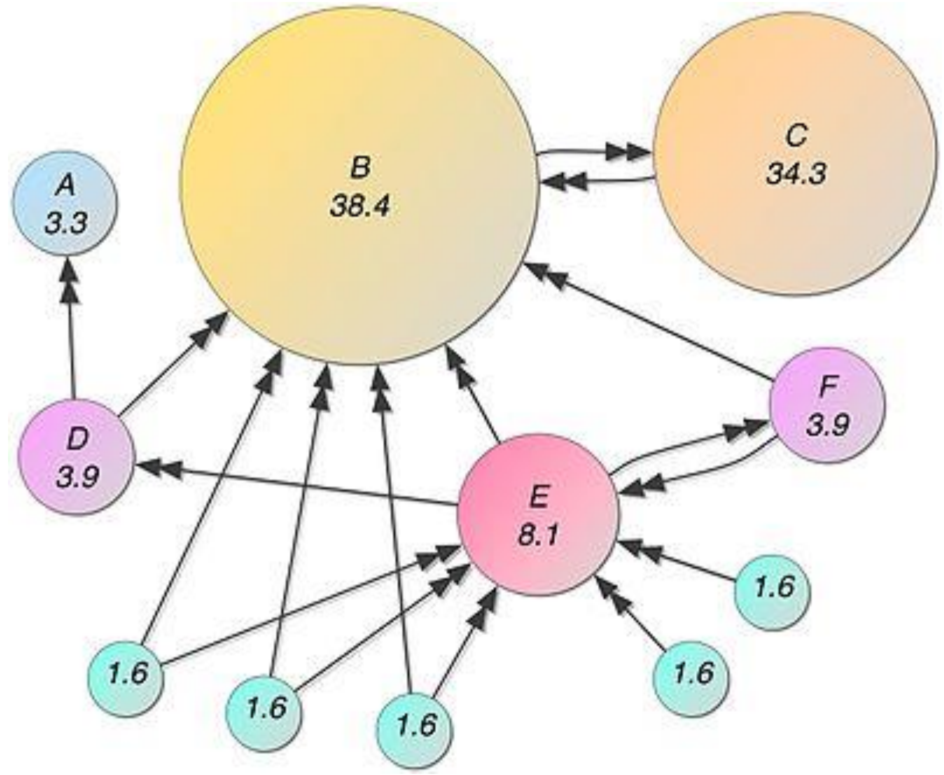
Conductance



4 edges cut
20 edge end points
edge conductance = 4 / 20

Background – Graph Analysis

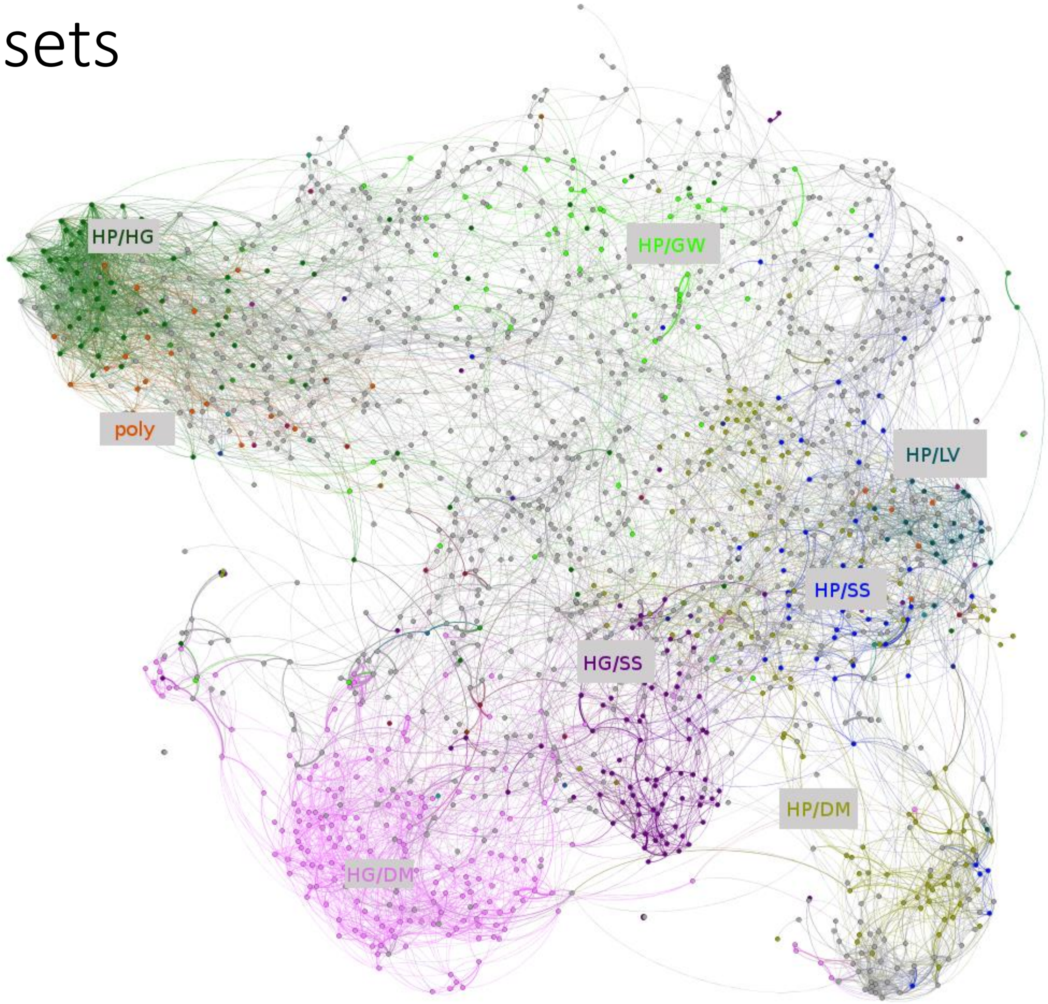
PageRank



Motivation

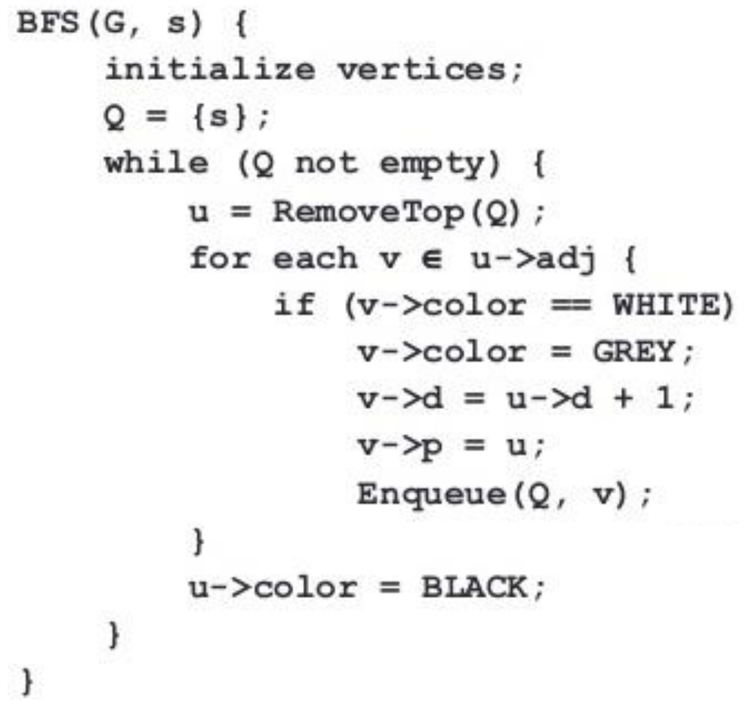
Motivation

- Large graph datasets

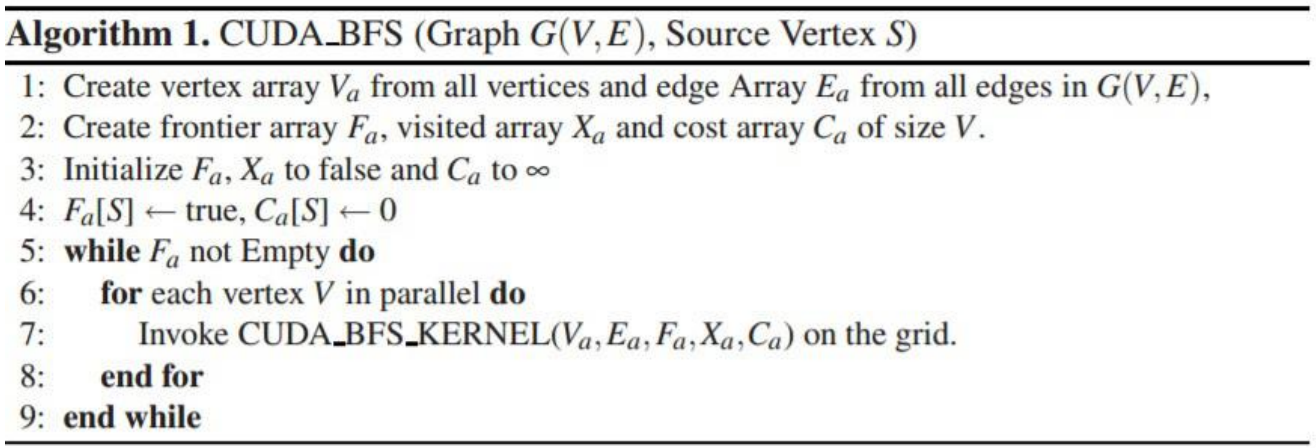


Motivation

- Intuitive Implementation vs Capturing Parallelism



```
BFS(G, s) {
    initialize vertices;
    Q = {s};
    while (Q not empty) {
        u = RemoveTop(Q);
        for each v ∈ u->adj {
            if (v->color == WHITE)
                v->color = GREY;
                v->d = u->d + 1;
                v->p = u;
                Enqueue(Q, v);
        }
        u->color = BLACK;
    }
}
```



Algorithm 1. CUDA_BFS (Graph $G(V,E)$, Source Vertex S)

```
Create vertex array $V_a$ from all vertices and edge Array $E_a$ from all edges in $G(V,E)$,
Create frontier array $F_a$, visited array $X_a$ and cost array $C_a$ of size $V$.
Initialize $F_a$, $X_a$ to false and $C_a$ to $\infty$
$F_a[S] \leftarrow$ true, $C_a[S] \leftarrow 0$
while $F_a$ not Empty do
    for each vertex $V$ in parallel do
        Invoke CUDA_BFS_KERNEL($V_a, E_a, F_a, X_a, C_a$) on the grid.
    end for
end while
```

Motivation

- Challenges - Capacity, Performance, Implementation

Green-Marl

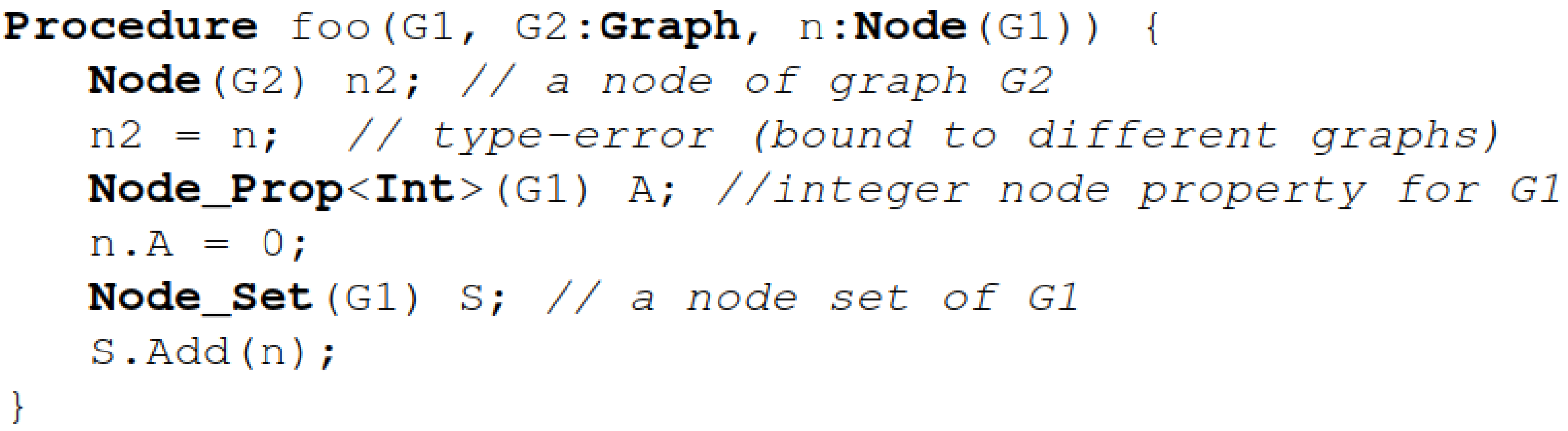
Green-Marl

- DSL (Domain-specific language)
    - Separation of programming and optimization
    - Intuitive implementation of graph algorithms
    - Exposes data-level parallelism

```
//---------------------------------------------------------------------------------------------------------
// Computing Conductance
//---------------------------------------------------------------------------------------------------------
Procedure conductance(G: Graph, member: N_P<Int>(G), num: Int) : Double {
  Int Din, Dout, Cross;
  Din  = Sum(u:G.Nodes)(u.member==num){u.Degree()};              // Compute degree sum of inside nodes.
  Dout = Sum(u:G.Nodes)(u.member!=num){u.Degree()};              // Compute degree sum of outside nodes.
  Cross = Sum(u:G.Nodes)(u.member==num){                          // Count number of crossing edges.
            Count(j:u.Nbrs)(j.member!=num)};                      // (Count is a syntactic sugar to Sum(..){1}
  Double m = (Din < Dout) ? Din : Dout;
  If (m ==0) Return (Cross == 0) ? 0.0 : +INF;
  Else Return (Cross / m);
}
```

Green-Marl

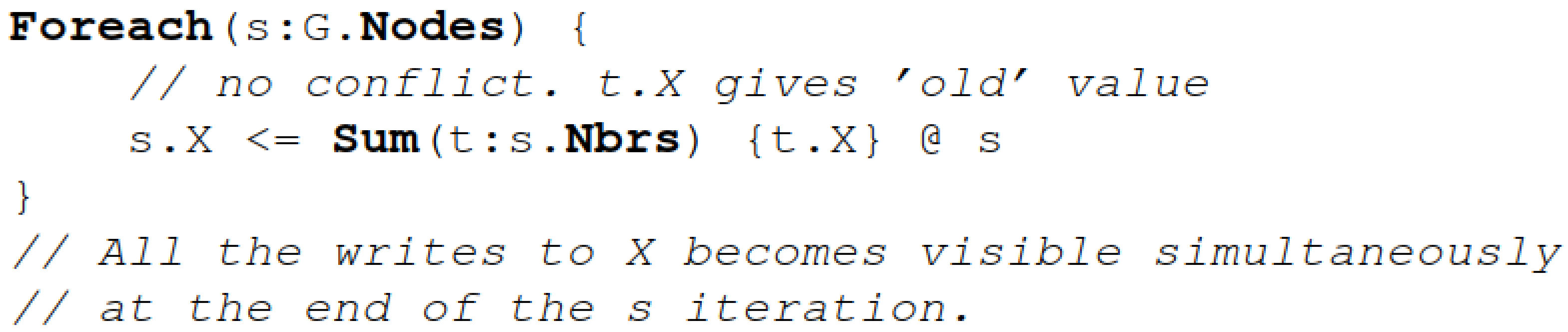
- Simple language constructs
    - Primitive types: Bool, Int, Long, Float, Double
    - Graph types: Undirected, Directed
    - Types bounded to graphs: Node, Edge
    - Collection types: Set, Order, Sequence
    - Traversal Schemes: BFS, DFS



```
Procedure foo(G1, G2:Graph, n:Node(G1)) {
   Node(G2) n2; // a node of graph G2
   n2 = n;  // type-error (bound to different graphs)
   Node_Prop<Int>(G1) A; //integer node property for G1
   n.A = 0;
   Node_Set(G1) S; // a node set of G1
   S.Add(n);
}
```

Green-Marl

- Deferred assignment and Reductions

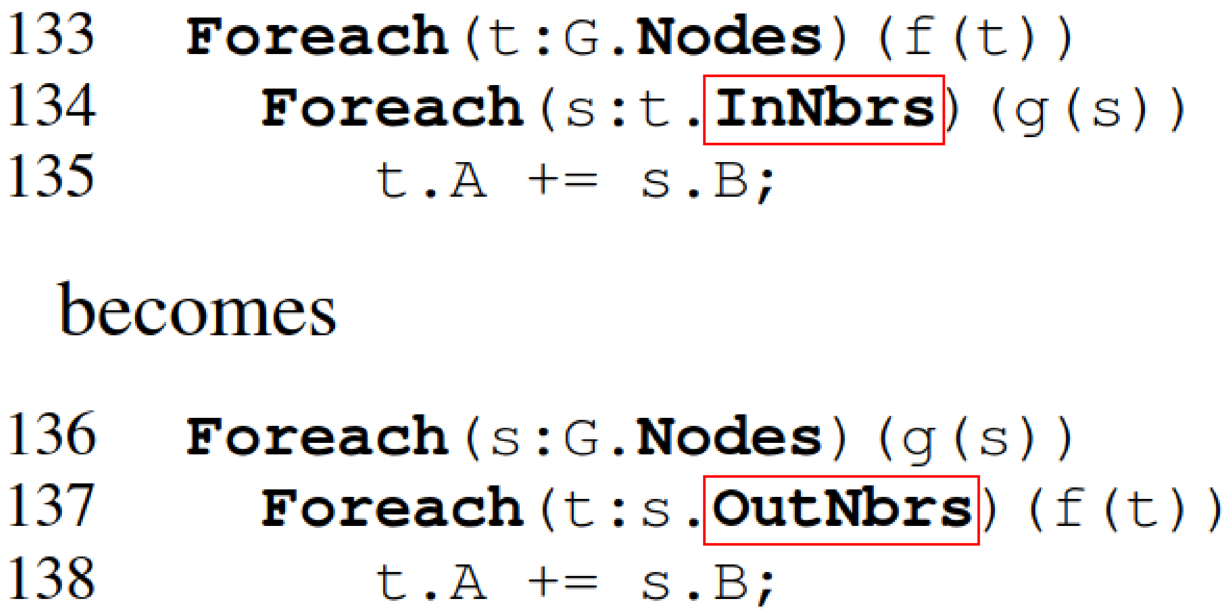


```
Foreach(s:G.Nodes) {
    // no conflict. t.X gives 'old' value
    s.X <= Sum(t:s.Nbrs) {t.X} @ s
}
// All the writes to X becomes visible simultaneously
// at the end of the s iteration.
```

Optimizations & Compilation

Optimizations

- Architecture independent optimizations
    - Loop Fusion, Hoisting Definitions, Reduction Bound Relaxation, Flipping Edges



```
Foreach(t:G.Nodes)(f(t))
  Foreach(s:t.InNbrs)(g(s))
    t.A += s.B;
```

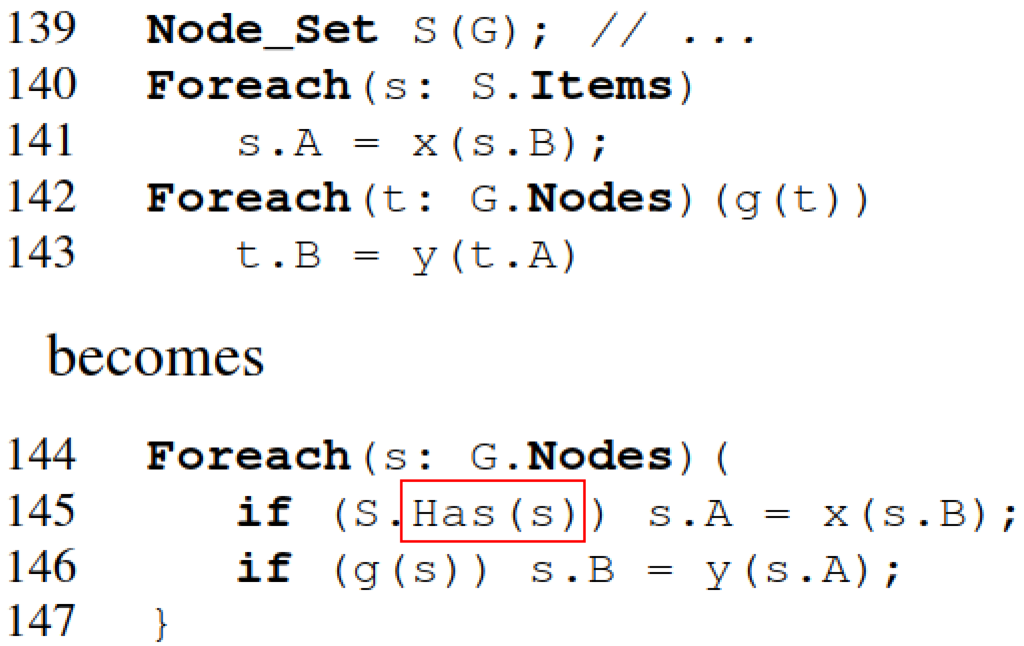
becomes

```
Foreach(s:G.Nodes)(g(s))
  Foreach(t:s.OutNbrs)(f(t))
    t.A += s.B;
```

Example of Flipping Edges Optimization

Optimizations

- Architecture dependent optimizations
  - Selection of Parallel Regions, Deferred Assignment and Saving BFS Children, Set-Graph Loop Fusion



```
Node_Set S(G); // ...
Foreach(s: S.Items)
    s.A = x(s.B);
Foreach(t: G.Nodes)(g(t))
    t.B = y(t.A)
```

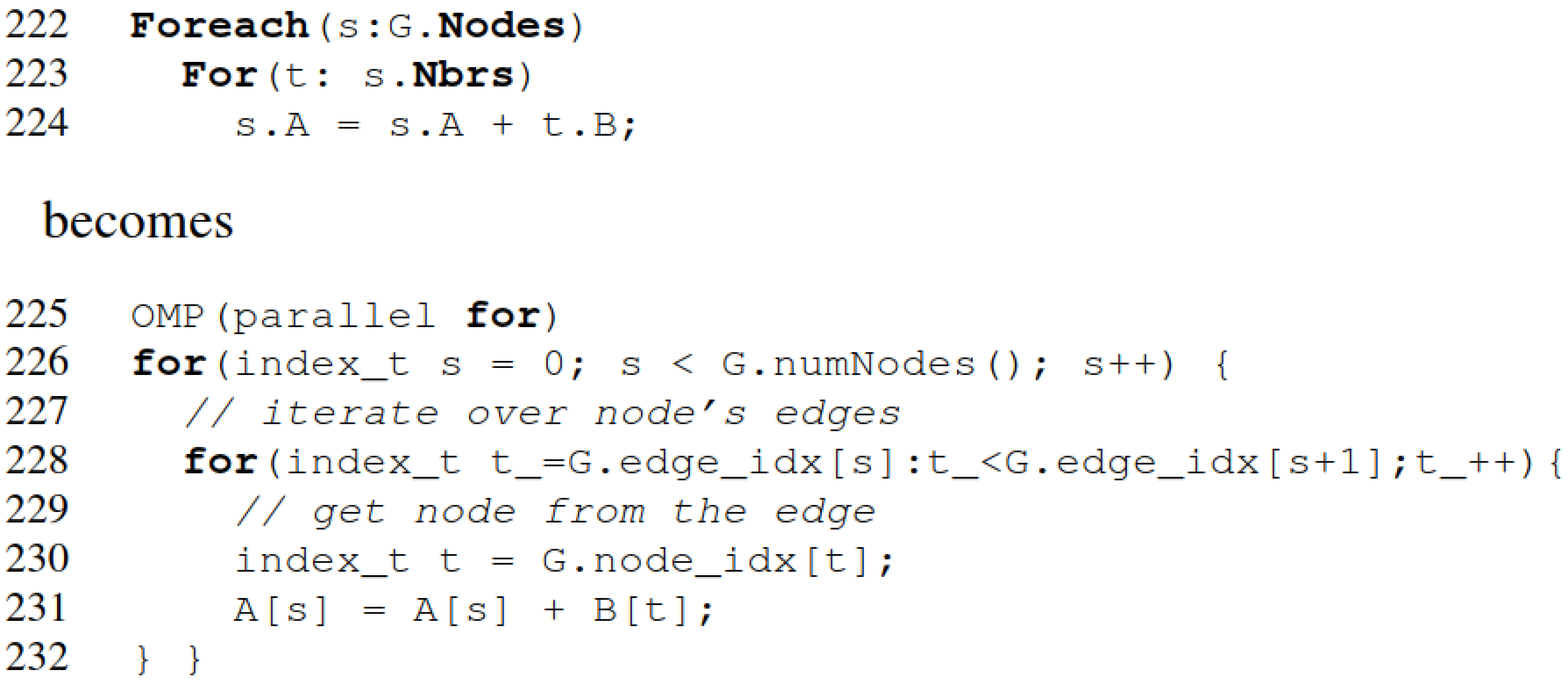
becomes

```
Foreach(s: G.Nodes)(
    if (S.Has(s)) s.A = x(s.B);
    if (g(s)) s.B = y(s.A);
}
```

Example of Set-Graph Loop Fusion Optimization

Compilation

- Into general-purpose languages, e.g. C++ (using graph library)



```
Foreach(s:G.Nodes)
  For(t: s.Nbrs)
    s.A = s.A + t.B;
```

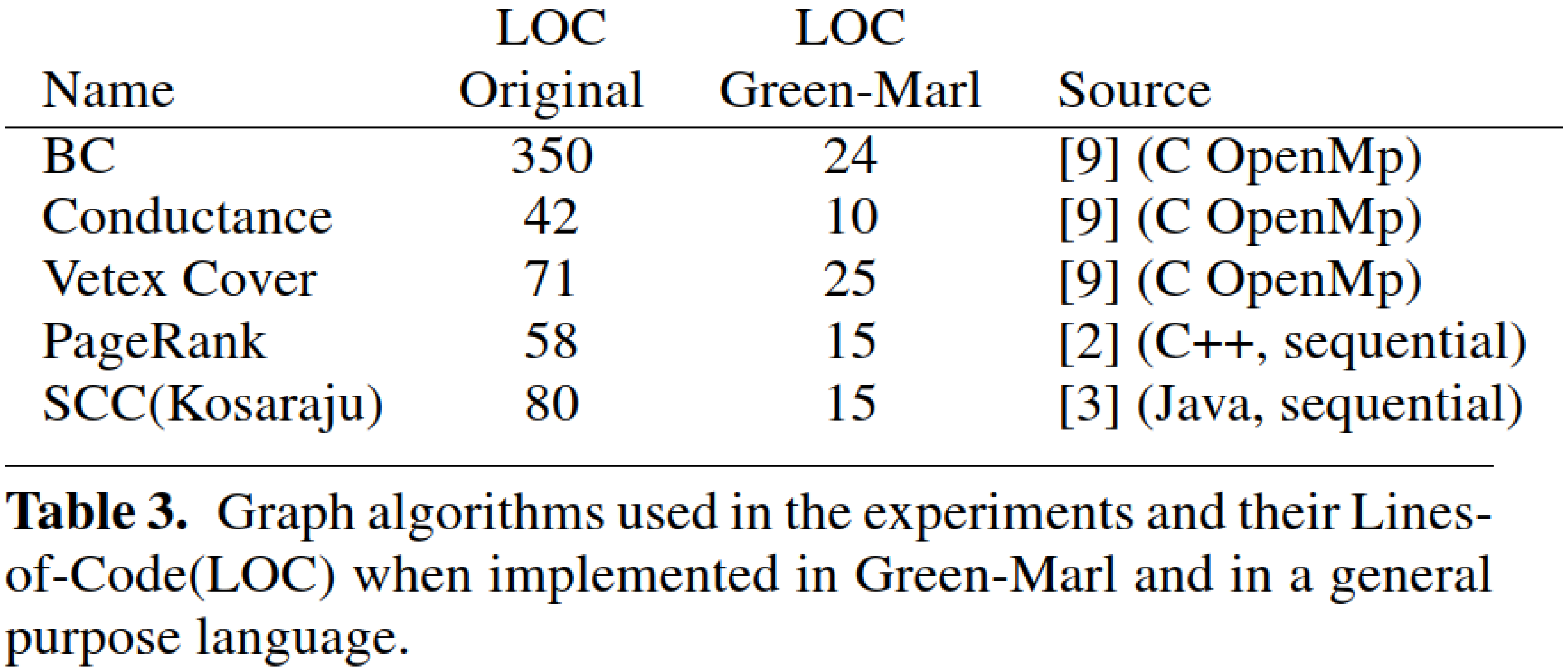
becomes

```
OMP(parallel for)
for(index_t s = 0; s < G.numNodes(); s++) {
  // iterate over node's edges
  for(index_t t_=G.edge_idx[s]:t_<G.edge_idx[s+1];t_++){
    // get node from the edge
    index_t t = G.node_idx[t];
    A[s] = A[s] + B[t];
} }
```

Experiments & Comparisons

Concise Representation

- Fewer lines-of-code (LOC) for many problems

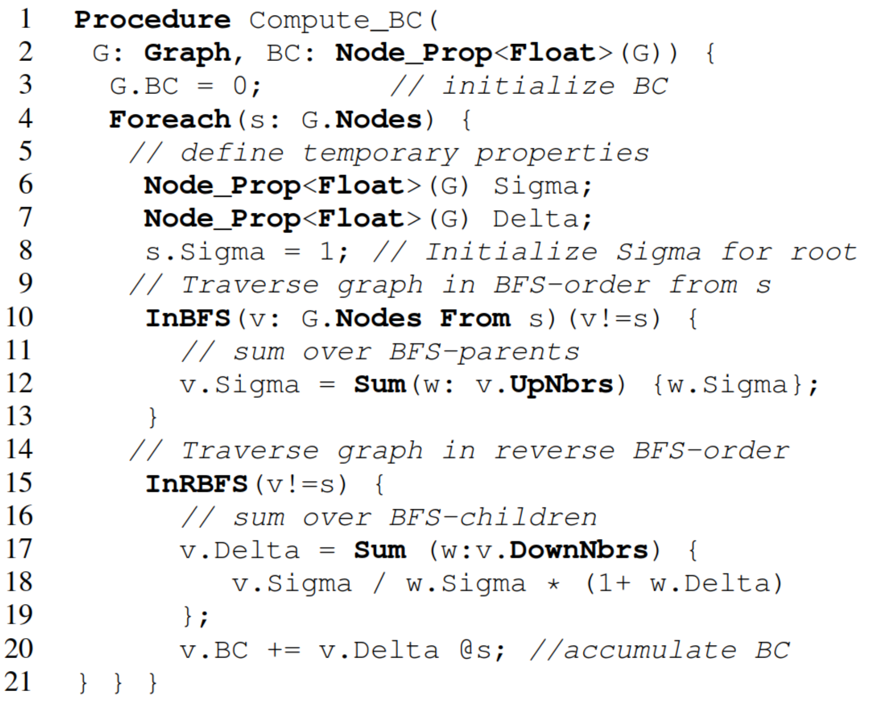


Name	LOC Original	LOC Green-Marl	Source
BC	350	24	[9] (C OpenMp)
Conductance	42	10	[9] (C OpenMp)
Vetex Cover	71	25	[9] (C OpenMp)
PageRank	58	15	[2] (C++, sequential)
SCC(Kosaraju)	80	15	[3] (Java, sequential)

Table 3. Graph algorithms used in the experiments and their Lines-of-Code(LOC) when implemented in Green-Marl and in a general purpose language.

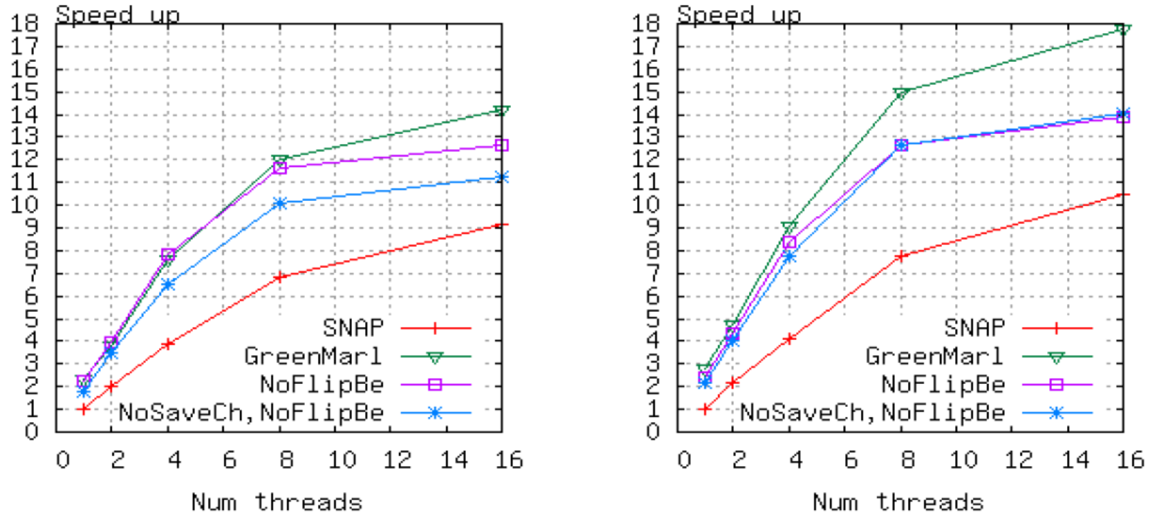
Experiments

- Betweenness Centrality
  - Compared to SNAP library



```
Procedure Compute_BC(
 G: Graph, BC: Node_Prop<Float>(G)) {
  G.BC = 0;        // initialize BC
  Foreach(s: G.Nodes) {
   // define temporary properties
    Node_Prop<Float>(G) Sigma;
    Node_Prop<Float>(G) Delta;
    s.Sigma = 1; // Initialize Sigma for root
   // Traverse graph in BFS-order from s
    InBFS(v: G.Nodes From s)(v!=s) {
      // sum over BFS-parents
      v.Sigma = Sum(w: v.UpNbrs) {w.Sigma};
    }
   // Traverse graph in reverse BFS-order
    InRBFS(v!=s) {
      // sum over BFS-children
      v.Delta = Sum (w:v.DownNbrs) {
         v.Sigma / w.Sigma * (1+ w.Delta)
      };
      v.BC += v.Delta @s; //accumulate BC
} } }
```

Figure 1. Betweenness Centrality algorithm described in Green-Marl



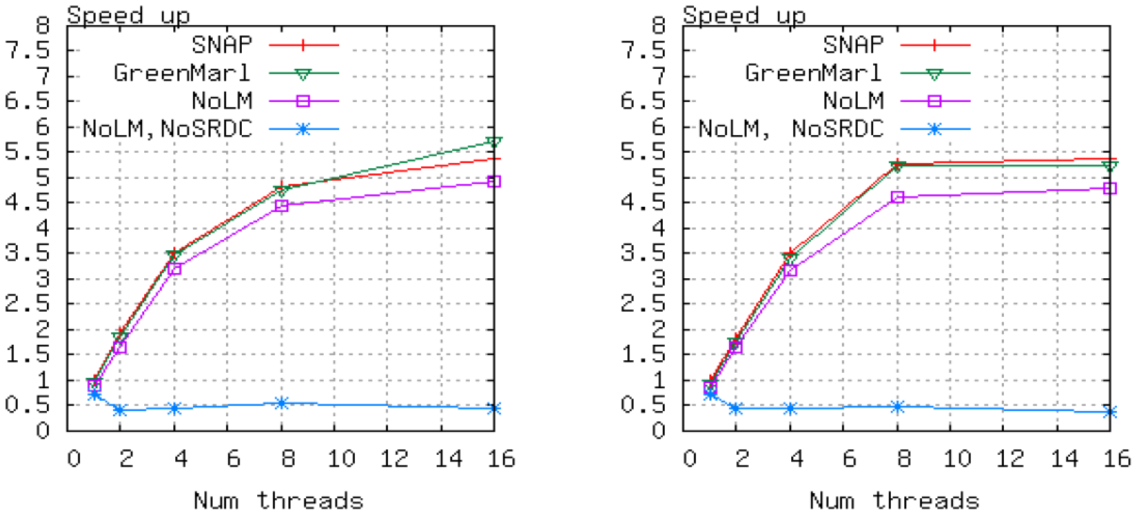
(a) RMAT

(b) Uniform

Figure 4. Speed-up of Betweenness Centrality. Speed-up is over the SNAP library [9] version running on a single-thread. NoFlipBE and NoSaveCh means disabling the *Flipping Edges* (Section 3.3) and *Saving BFS Children* (Section 3.5) optimizations respectively.

Experiments

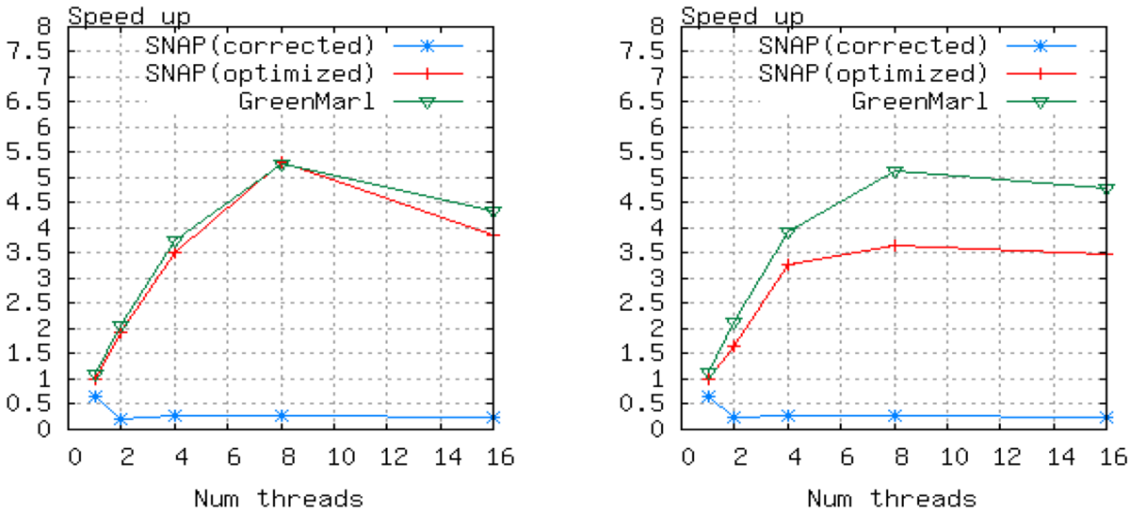
- Conductance



(a) RMAT (b) Uniform

Figure 5. Speed-up of Conductance. Speed-up is over the SNAP library [9] version running on a single-thread. NoLM and NoSRDC means disabling the *Loop Fusion* (Section 3.3) and *Reduction on Scalars* (Section 3.5) optimizations, respectively.

- Vertex Cover



(a) RMAT (b) Uniform

Figure 6. Speed-up of Vertex Cover implemented in Green-Marl and two versions of the corrected SNAP implementation SNAP which had a data-race. The first version, SNAP(correct) utilizes a simple locking approach. The second version, SNAP(optimized), uses a more advanced test and test-and-set scheme. A small instance (100k nodes, 800k edges) was used in this experiment.

Critique

Major Contributions

1. Intuitive, concise implementation of algorithms
2. Transparent, automatic optimizations through compilation
3. Wider range of optimizations using domain-specific knowledge
4. Architecture-dependent optimizations
5. High architecture portability
6. Easy integration into current workflow

Criticism

1. Limited to graphs which fits into RAM
2. Backend optimized for CPU execution only
3. Limited comparison with related works

Conclusion

- A domain-specific language that is
  - Portable
  - Concise and intuitive
  - Efficient
  - Easy to integrate into workflow

- Require more work on
  - Scalability
  - Performance evaluation