Easy and Efficient Graph Analysis: A DSL-based Approach

Sungpack Hong and Kunle Olukotun

Pervasive Parallelism Laboratory
Stanford University

Graph Analysis

- Graph
  - Fundamental data representation
  - Captures random relationship between data entities
  - You learned about it in CS 101
- Why graph once again?
  - New applications (in lucrative markets) use graph analysis– social networks, computational biology, …
    - e.g> Analyze molecular interaction graph in your body cells to identify key proteins
  - Requires significant processing power
    - Underlying graph size is large and growing
    - Some algorithms are expensive, i.e. O(n^2) or more
    - Classic ILP, Vector Units, FLOPs does not help much

➔ Let’s use parallelism

Parallel graph analysis

- Opportunities
  - Plenty of inherent (data-) parallelism in large graph instances
  - 100+ years of studies in graph theory
  - Parallel machines are now and everywhere

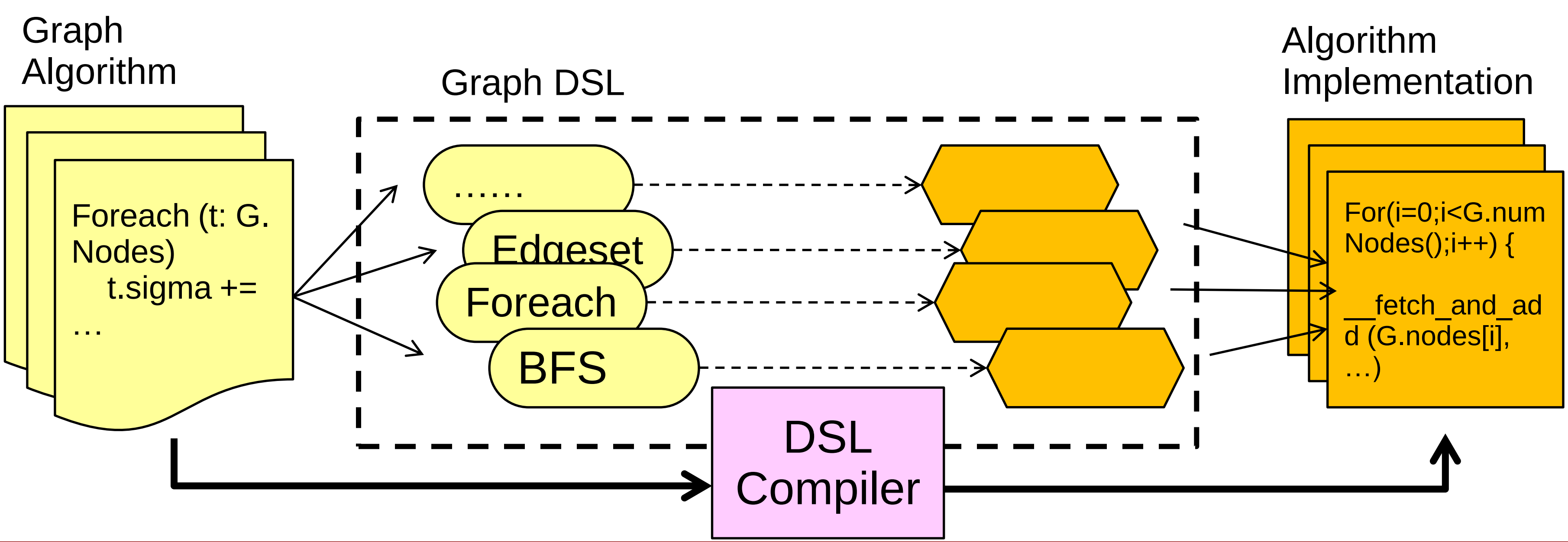
  (Multi-core CPU and GPU)
- Challenges
  - Hard to get correct implementation
  - Performance depends on implementation (even with the same algorithm)
  - The best implementation differs from machine to machine
  - Algorithms need to be *customized*

What's wrong with libraries?

- There are 30+ graph libraries/packages
- Issues in fixed library implementation
  - Parallelism?
  - Portability?
  - New/customized algorithm?
    - What if someone finds a better implementation for the un-customized algorithm?

Our approach: DSL for graph analysis

1. Identify key components in graph algorithms as define them language constructs.
2. Find (the best / a good) implementation of those constructs.
3. Let the compiler translate high-level algorithm written in DSL into a high-performing low-level implementation.
   - Possibly, apply high-level optimization on the way



Approaches

- DSL design
- Implementation of language constructs
  - BFS for GPU
  - BFS for CPU
- Compiler development

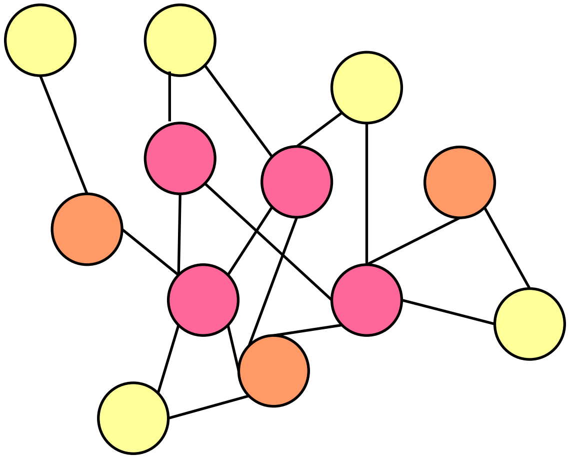
Language Design

- Domain property
  - The graphs are *sparse*, *small-world*, *scale-free*
    - Graph is not mesh-like!
  - Graph modification is less frequent than graph analysis
- Language Design: an inductive process
  - Examine existing algorithms ➔ Extract language constructs
  - Check if these algorithms can be naturally expressed with the language
  - Check if the compiler can figure out inherent parallelism from the description.

*The DSL is named as Green-Marl which means graph language (그림 말) in Korean.

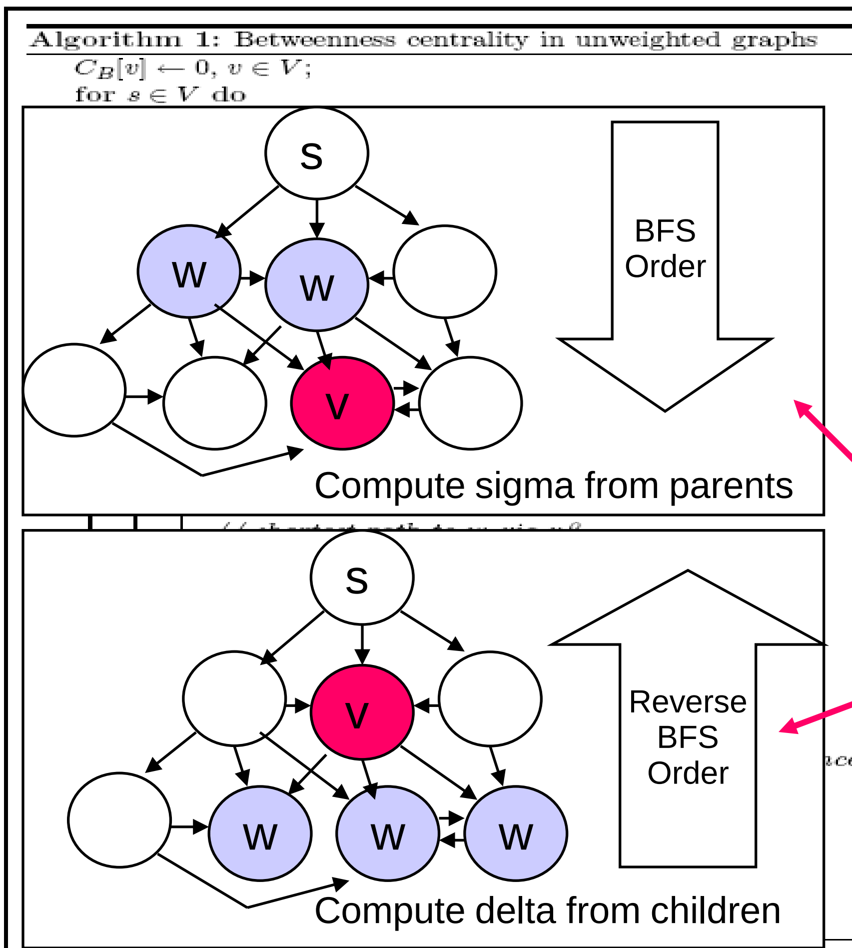
A Glimpse of DSL Syntax

- Example> Betweenness Centrality
  - A measure that tells how center a node is located in the graph
  - Frequently used in social network analysis
  - Computationally expensive: O(NM)



A Glimpse of DSL Syntax

- Original Algorithm




```
Procedure comp_BC(G: Graph, BC: Node_Property<Float>(G))
{
  G.BC = 0; // Initialize

  Foreach (s: G.Nodes) {
    // temporary values per Node
    Node_Property<Float>(G) sigma;
    Node_Property<Float>(G) delta;

    G.sigma = 0; // Initialize
    G.delta = 0;
    s.sigma = 1;

    // BFS order iteration from s
    InBFS(v: G.Nodes From s) {
      v.sigma =  // Summing over BFS parents
        Sum (w:v.UpNbrs) {w.sigma};
    }

    // Reverse-BFS order iteration to s
    InRBFS(v:G.Nodes To s)(v!=s) {
      v.delta =  // Summing over BFS children
        Sum (w:v.DownNbrs) {
          v.sigma / w.sigma * (1+ w.delta) };

    v.BC += v.delta @ s; // accumulate BC
    }
  }
}
```

Customized BFS Iteration
➔ Need good BFS implementation

Language Philosophy

- Goal is not to magically parallelize your sequential graph algorithm
  - Would you believe it, if I claim so?
  - People have devoted their entire career in developing parallel graph algorithms
- Instead, it allows you to express your algorithm (sequential or parallel) in a natural way
- The compiler grabs out the inherent parallelism in the algorithm and exploit it in the implementation
  - e.g. Betweenness Centrality is not designed for parallel execution

Consistency Model

- We are targeting different architectures: CPU, GPU, (Cluster)
- The language, thus, assumes the most relaxed form of consistency

```
Foreach (t: G.nodes) {
  Int z =  Sum (v: t.Nbrs) {v.Val};
  t.Val = z;
}
```

- Conceptually, **Foreach** is instantiated all at the same time.
- There is no guarantee update to **Val** will be visible (or not) to other instances, until the end of foreach
- It's not even Total Store Ordering

- Enforcing order out of chaos
  - High-level operations are atomic (e.g. add to a set)
  - Reduction and Deferred assignments

Consistency Model

- Deferred assignment

```
Foreach (t: G.Nodes) {
   Int z =  Sum (v: t.Nbrs) {v.Val};
   t.Val <= z @ t;
}
```

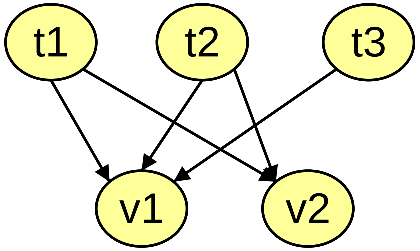
Write to **Val** happens at the end of iteration bound by t.

- Reduction assignment

```
Foreach (v: G.Nodes) {
   v.B = Min (t: v.Nbrs) {t.Val };
}
```

If the grap
we can ex
order to re
reduction

Reduction by minimum is resolved at the end of foreach iteration bound by t.



CPU: comp & swap
GPU: atomicMin
Cluster: MapReduce

I need Sequential Consistency!

- Is this what you want?

```
Foreach (t: G.nodes) {
   Atomic {
      Int z =  Sum (v: t.Nbrs) {v.Val};
      t.Val = z;
   } @ t
}
```

- Your algorithm is not deterministic, you know
- We may add it to the language, though
  - Coloring like Listz [Big setup overhead]
  - Grab a lock of neighbors
  - Performance is not guaranteed; due to the graph shape (i.e. not mesh)

Reduction Assignment vs. Reduction Operator

- Reduction Assignment (spread-out)

```
Int z = 0;
Foreach(n:G.Nodes) {
  If (n.color == 0) { z += n.val @ n;}
  Else {
    Foreach (t: n.Nbrs)(t.color == 1)
      z += t.val @ n;
}}
```

+=	Sum
*=	Product
min=	Min
max=	Max
argmax=	Argmax
argmin=	Argmin
+= 1	Count

- Reduction Operator (in-place)

```
Int z = 0;
Foreach(n:G.Nodes) {
  z = Sum (t:n.Nbrs)(t.color==0) {t.val};
}}
```

A Few More on Syntax

- Nodes(Edges) are bound to a graph

```
Graph G1, G2;
Node(G1) t1;
Node(G2) t2;
t1 = t2; // Type Error!
```

- Fields can be defined dynamically and passed as arguments

```
Graph G;
While (…) {
   Node_Property<Int>(G) cap;
   …
   Foo(G, cap);
} // cap has static scop
```

Call common routines with different fields.

```
Procedure Foo
(G:Graph, d:Node_Property<Int>(G))
{
  // …
}
```

A Few More on Syntax

- Sets
  - Operation to a set is atomic: Add/Remove/IsIn
  - Set: bound to a graph

```
NodeSet(G) NSet;
EdgeSet(G) ESet;
NbrSet(G)  NBSet;
NbrEdgeSet(G) NBESet;
```

```
Foreach (t: G.Nodes)
  Foreach(n: t.Nbrs)
    If (n.value > THRESHOLD) {
        t->NBSet.Add(n);
    }
```

A Few More on Syntax

- Static Scope
  - Variable name shadowing is not allowed.

```
Foreach (t: G.Nodes){
   Int k;
   Foreach(n: t.Nbrs) {
         Int t; // Error;
   }
   Int n; // Okay;
}
```

Some Rules to be Enforced

- Cannot write to an iterator

```
Node(G) n;
Foreach(t: G.Nodes) {
    n = t;  // Okay
    t = n;  // Error
}
```

- Cannot write to a property reference

```
N_P<Int> (G) val;
N_P<Int> (G) cap;
Node(G) n;
n.val = n.cap // Okay;
G.val = G.cap // Okay;
cap = val; // Error;
```

Some Rules to be Enforced

- Reduce (Defer) Assignment should be bound once and only once.

```
Int z = 0;
Foreach(t: G.Nodes) {
    z += t.val @ t;
    Foreach (n: t. Nbrs) {
        z += n.val @ t; // Okay
        z += n.val @ n; // Error
        z min= n.val @t; // Error
    }
    z = 3; // Error
}
Z += 3; // Error
```

Parallelization

- Assumption
  - Graph is large
  - Otherwise uninteresting.
  - One operation is enough to consume all the cache & memory bandwidth
- Strategy
  - CPU: Parallelize inner-most graph-wide iteration
  - *GPU: two-level parallelization: sub-warp + thread*

```
Foreach(t: G.Nodes) {
    …
    Foreach (n: G.Nodes) {
        …
        Foreach (r: n.Nbrs) {
        }
    }
}
```

GPU:
subwarp (outer)
thread(inner)

Parallelization

- Optimization after Parallel Region Decision

```
Foreach(s: G.Nodes) {
    Foreach(t: G.Nodes) {
        t.val += …  @ s;
    }
}
```

Reduction can be implemented with normal write

```
Foreach(s: G.Nodes) {
    N_P<Int> temp;
    Foreach(t: G.Nodes) {
        t.temp += …  @ t;
    }
    s.val += s.temp @ s;
}
```

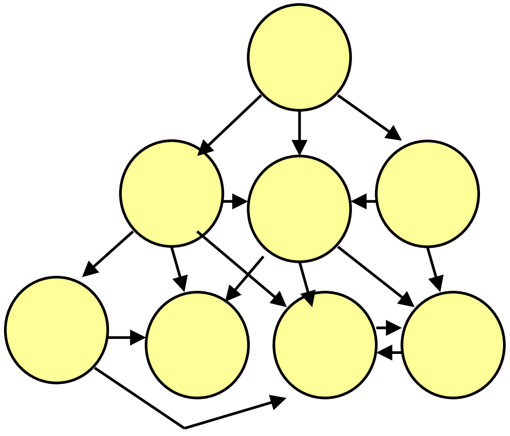
No need to create (and delete) temp, O(N) times. (Move temp-define out of s-loop)

Language Implementation

- Breadth-First Search (BFS)
  - An systematical way of traversing a graph
  - Enforces a natural (partial) ordering of the graph
  - Serves as a building block for other algorithms

    (Connected components, Betweenness centrality, Max flow computation…)
  - Many papers about efficient BFS implementation

    (Multi-Core CPU, GPU, Cell, Cray XMT, Cluster) …



BFS on GPU

- Potentials of GPU in graph analysis
  - Large memory bandwidth (but with limited capacity)
    + Latency hiding scheme
  - Massively parallel hardware
- Previous implementation [Harish and Narayanan 2007]
  - Level synchronous, frontier-expansion method.
  - PRAM-style; each thread processes a node.
  - *Problem*:

  ➔ Performance dropped heavily when applied to scale-free graphs (i.e. skewed degree distribution)

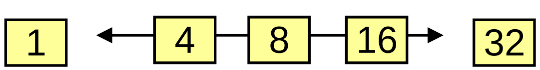
BFS on GPU

- What causes this?
  - The trait of GPU architecture ➔ Threads in a warp are executed in a synchronous way
  - Skewed degree distribution ➔ Intra-warp workload imbalance
- Our implementation

  [PPOPP 2011]
  - Work assignment

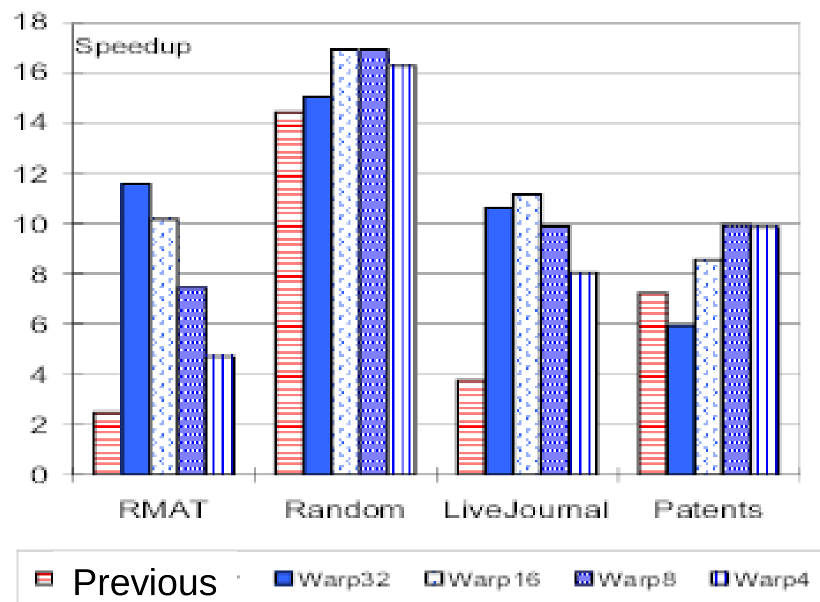
    ➔ per a subset of warp

    ➔ Trade off under-utilization and workload imbalance



A unit of work
per each thread

A unit of work
per each warp



Measured on GTX275 (Tesla GPU)

BFS on Multi-core CPU

- Level-synchronous Parallel BFS

Algorithm 1 Level Synchronous Parallel BFS

```
procedure BFS(r:Node)
    V = C = ∅; N = {r}                        ▷ Visited, Current, and Next set
    r.lev = level = 0
    repeat
        C = N; N= Ø
        for Node c ∈ C do                      ▷ in parallel
            for Node n ∈ Nbr(c) do             ▷ in parallel
                if n ∉ V then
                    N = N ∪ {n}; V = V ∪ {n}
                    n.lev = level + 1
        level++
    until N = ∅
```

- Previous Implementation [Agarwal et al 2010]
  - Adopted a few techniques: prefetech, bitmap (Visited), non-blocking queue (Next/Curr Set)
  - Non-blocking queue: sophisticated implementation
    - Reduce synchronization and cache-cache coherence traffic.
    - Not much implementation details revealed in the paper.

BFS on Multi-core CPU

for Node $c \in C$ do

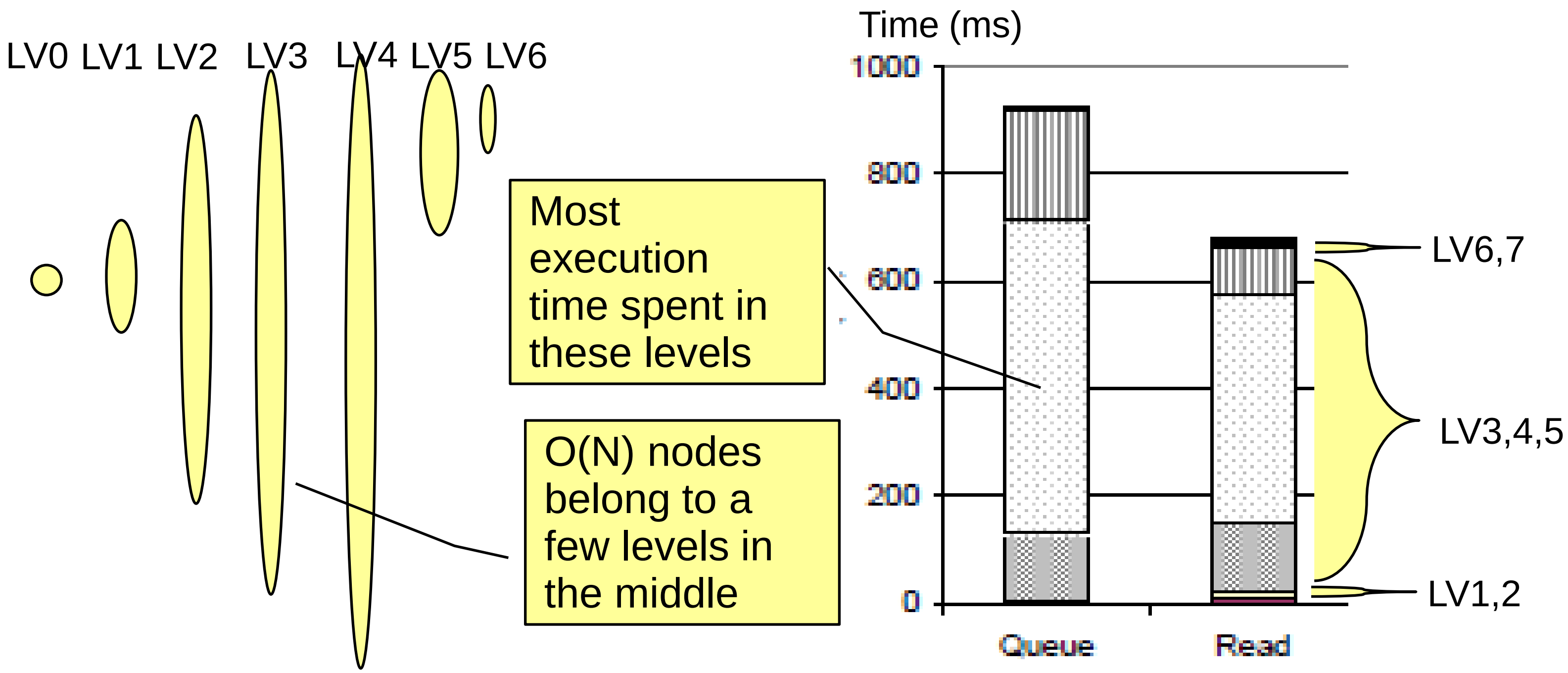
```
for (i=0;i<N;i++) {
   if (C[i] == curr) {
      ...
   }
}
```

- Our approach [under submission]
  - Implement Curr/Next set as a (single) byte-array.
    - Visited set is still a bitmap
  - Cons
    - (Iteration over set) == (Read the whole byte array)
  - Pros
    - No synchronization when writing
    - Sequential read when iterating

Turns out to be okay,
due to small-world property

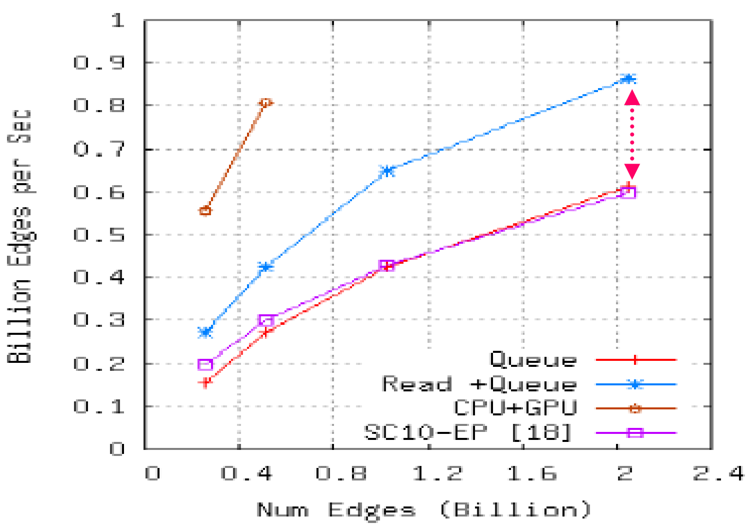
BFS on Multi-core CPU

- Small world property?
  - A.k.a. six-degrees of separation
  - Diameter (maximum hop count between any two nodes) is small even with large graphs
  - ➔ (# Nodes) in each BFS level grows, exponentially

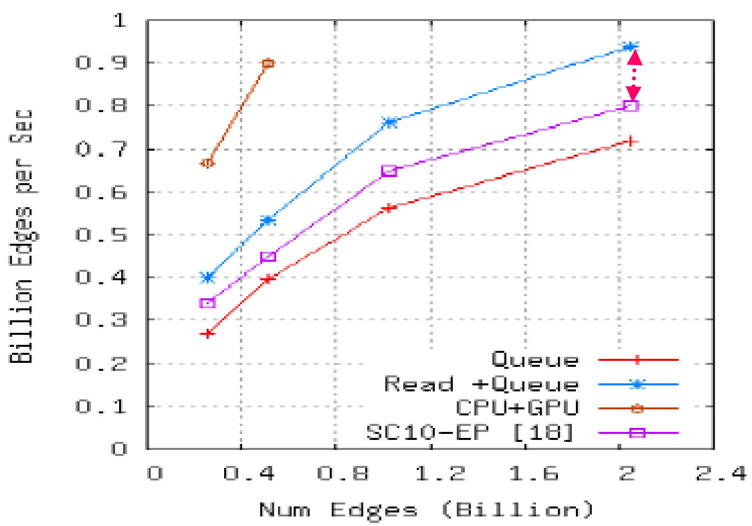


BFS on Multi-core CPU

- Results
  - 1.2x ~ 1.5x performance improvement
  - Performance gap widens as graph size grows
  - (+ Our algorithm is easier to implement)



(c) Edges (Uniform)



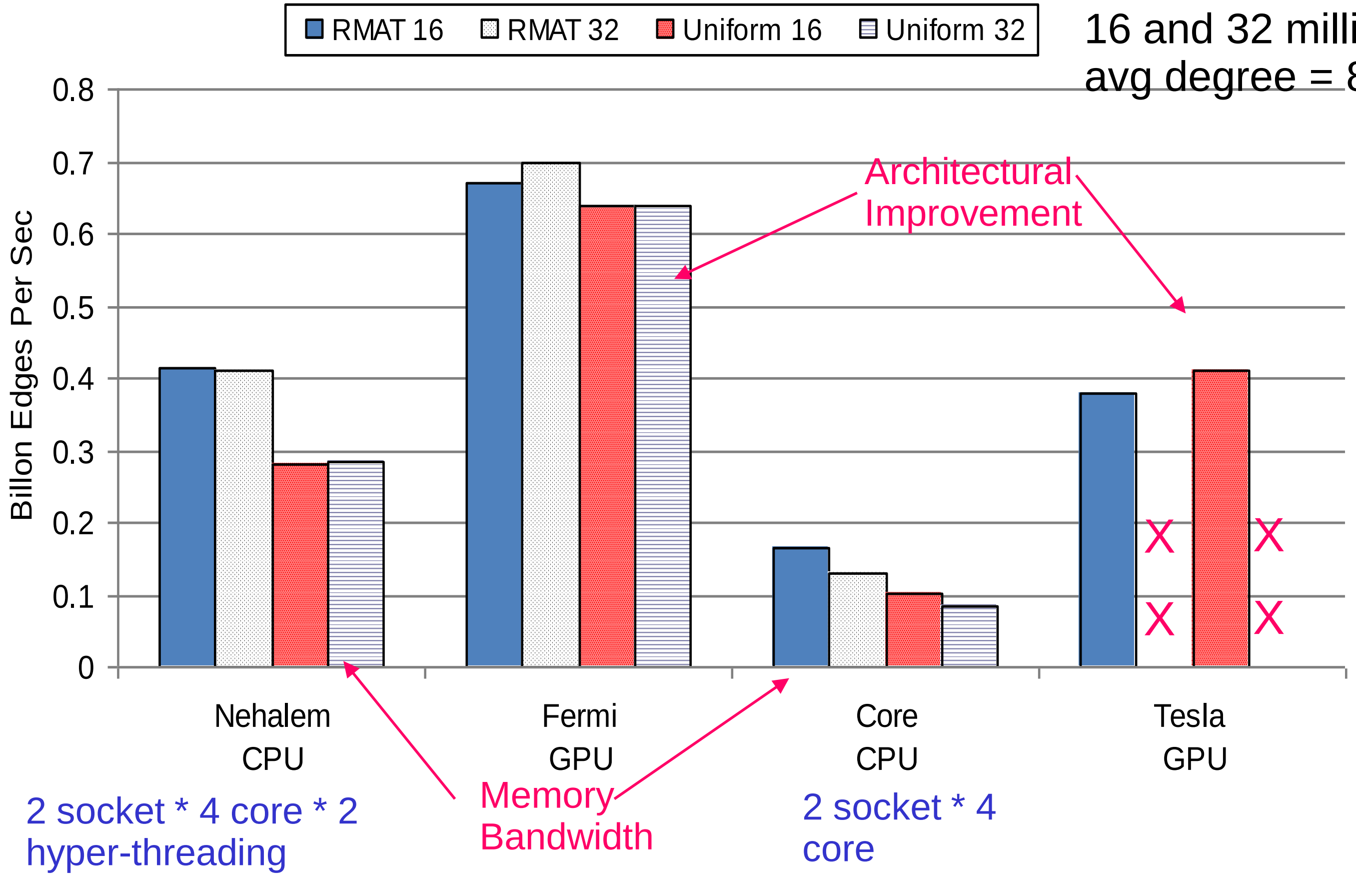
(d) Edges (RMAT)

Measured on Nehalem-EP CPU (2 socket x 4core x 2 HyperThread)

Architectural Effects

*For Fermi GPU, L1 has been disabled since it affected the performance negatively.

16 and 32 million nodes
avg degree = 8

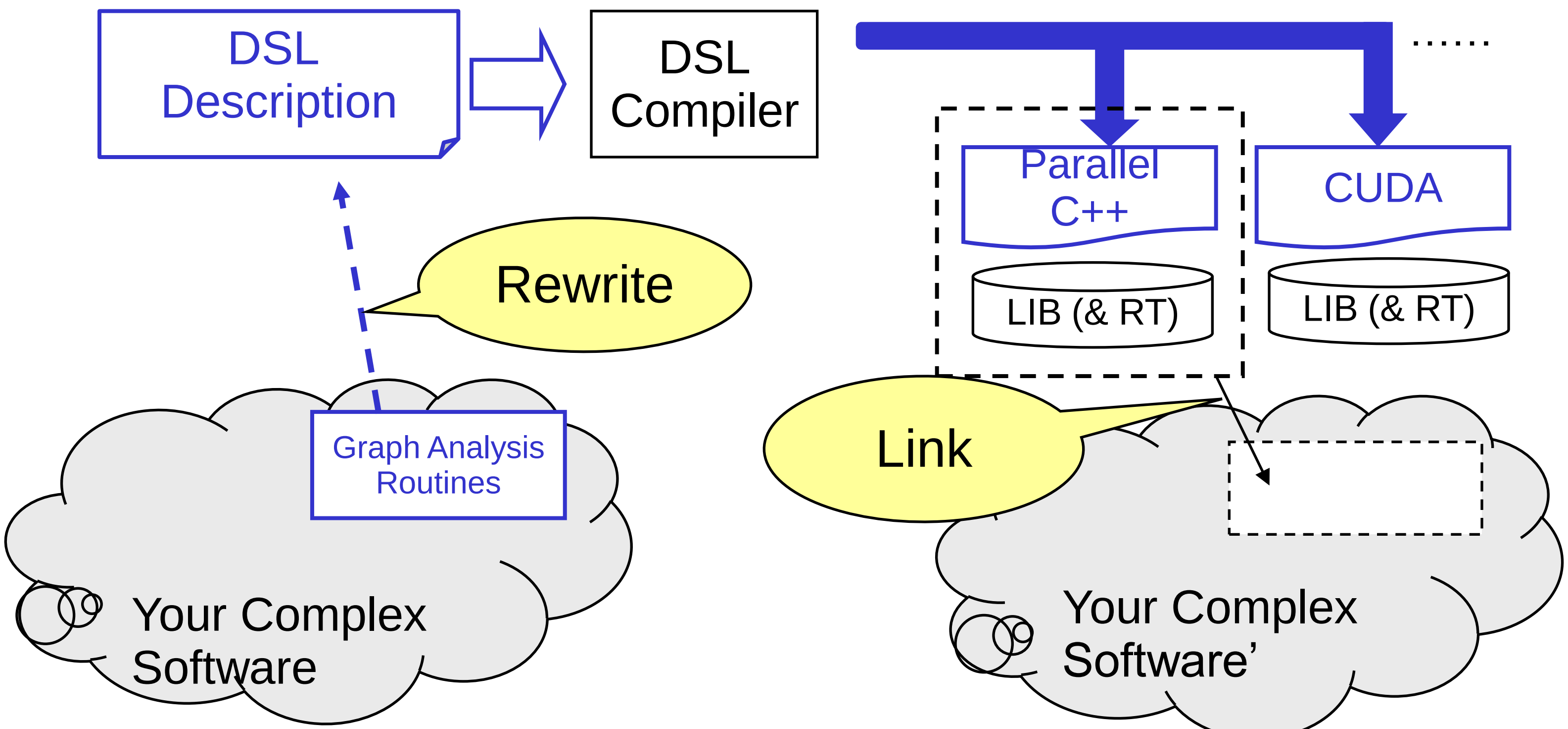


2 socket * 4 core * 2 hyper-threading

2 socket * 4 core

DSL Compiler

- Currently under development
- Goal:
  - Maps language constructs with their best impl.
  - Source-to-Source translation.



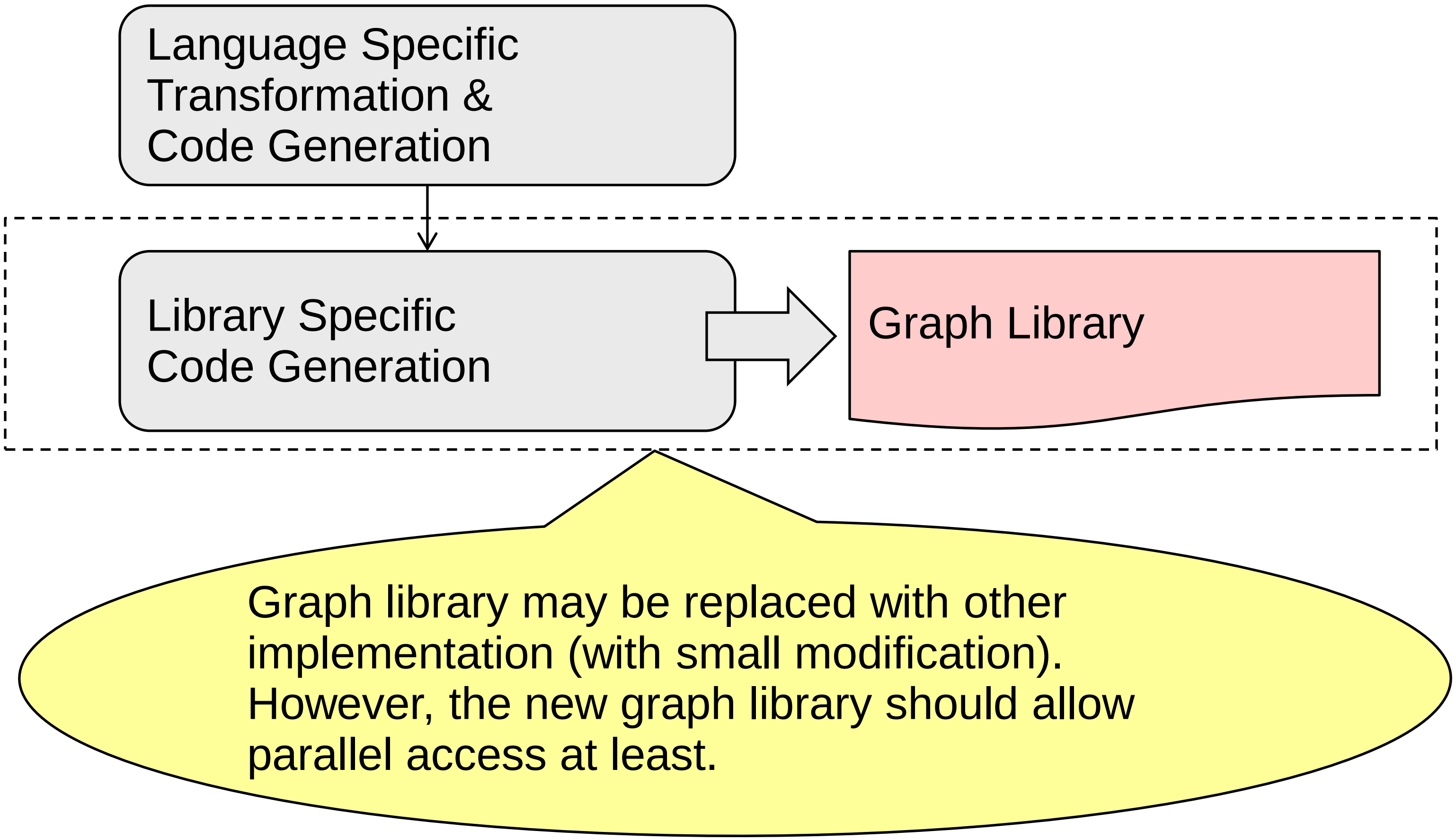
Interfacing with user-world

- Translate entry function(s)
  - Arguments translation
  - Int ➔ int32_t, Double ➔ double, Set ➔ Array, …
  - Node/Edge/Graph ➔ Library data type (node_t, edge_t, graph_t, …)
  - Entry function should be called in a single-thread context (+ Whole GPU is available)
- Adopting user-defined functions, data types.
  - Like ASM in the C/C++
  - Simple text transformation
  - Bypass type-checking

```
Procedure(G:Graph, val: N_P<Int>(G), z : $Utype){
  Foreach (t: G.Nodes)
      t.z = $UserFun (t.val, z);
}
```

Using other graph library

- Want to use other graph library?



Result: Compiler Output

- Compiler is still under development

tayo@drink-1:~

Green-Marl

```
/* BLOCK COMMENT */

// LINE Comment

// test for general statements
Procedure foo
    (G: Graph, n: Node(G),
     d: Node_Property<Int>(G) ; o: Float) : Float
{
   G.d =  -((4 + 3 + 3) / 5) + 2;

   Int j,k;
   k = 0;
   j = k + 1;

   Foreach(q: G.Nodes ) (q.d > 0)
   {

      Node(G) t;
      Edge(G) e;
      N_P<Float>(G) A;     // Node_Property
      E_P<Float>(G) B;
      N_P<Bool>(G) C;
      n.d = 1;

      q.d = 1;
      q.d = n.d;
      t = q;

      Foreach(r: q.Nbrs)
      {
        t.d = 3+8;
        t.A = 1.0 + 7;
        e.B = 0.0;
        e.B = t.A;
        //r.C = z && (r.d > 3);

        // t.d = Sum (k: t.BFS_Parents) { k.d };

      }
   }
}
~
~
~
~
~
~
```

C++

```
#include "gm_graph.h"
#include "t1.h"


float foo(gm_graph& G, node_t n,
    int32_t* __G_d, float& o)
{
    int32_t _t1 =  -((4 + 3 + 3) / 5) + 2;
    for (int i=0;  i < G.numNodes(); i++) { __G_d[i] = _t1;}


    int32_t j,k;
    k = 0;
    j = k + 1;
    for (nodeiter_t q = 0; q < G.numNodes(); q ++)
    {
        if (__G_d[q] > 0)
        {

            node_t t;
            edge_t e;
            float* __G_A;
            __G_A = new float [ G.numNodes() ] ;
            float* __G_B;
            __G_B = new float [ G.numEdges() ] ;
            bool* __G_C;
            __G_C = new bool [ G.numNodes() ] ;
            __G_d[n] = 1;

            __G_d[q] = 1;
            __G_d[q] = __G_d[n];
            t = q;


            for (index_t _r0 = G.begin[q];_r0 < G.begin[q+1] ; _r0 ++)
            {
                nodeiter_t r = G.node_idx [_r0];

                __G_d[t] = 3 + 8;
                __G_A[t] = 1.000000 + 7;
                __G_B[e] = 0.000000;
                __G_B[e] = __G_A[t];
            }
            delete [] __G_A;
            delete [] __G_B;
            delete [] __G_C;
        }
    }
}
```

Result: Compiler Output

- Sanity check
  - Manual implementation of Betweenness Centrality
    (i.e. what the compiler should emit out.)
  - Showed ~2x improvement
    - over a publicly available *parallel* implementation (8-core CPU)
    - Gain comes from using a better BFS scheme

Issues with Delite Implementation

- Syntax
  - dynamic property declaration
  - @ syntax

```
N_P<Float>(G) X;
G.X = 0;
Foreach (t: G.Nodes) {
 If (t.flag) {
    Foreach (n: t.Nbrs) {
       n.X += t.cost @ t;
    }
 }
 t.X += t.cost @ t;
}
```

```
Val X = N_P[Float](X, G);
X = 0;
foreach (t <- Nodes(G)) {
  if (flag(t)) {
    foreach (n <- Nbrs(t)) {
      X(n) += (cost(t), t);
    }
  }
  X(t) += (cost(t), t);
}
```

- Rule Enforcing
  - Reduction rules
  - “UpNbrs” is only meaningful inside BFS.

Issues with Delite Implementation

- Transformation
  - Patterns that are far from each other
  - Lack of Symbol table
- Parallel Execution Strategy
- Code generation
  - CUDA
  - BFS Pattern

```
{ …
  InBFS (v: G.Nodes From s) {
  }
  … // some sentences
  If (…) {
     InRBFS(v:G.Nodes To s) {…}
  }
}
```

Issues with Delite Implementation

Lex → Parse → Type Check → Trans-formation → Opti-mization → Code Generation

Syntax has to be modified

Type check is free.

Any other rules I make, I have to enforce them by myself

Transformation should be described as pattern-matching.

Optimization and Parallelization are independent

Custom code generation patterns (e.g. BFS)

How many Delite-Ops do I use?

Distributed Graph Processing (Future Works)

- Fundamental Issue
  - Graph: random, small world, scale-free
    - ➔ Far from planar
    - ➔ Impossible to find a *good* partition
    - ➔ Surface to volume ratio is high
    - ➔ Communication overhead dominates
- Pregel
  - Google's *framework* for distributed graph processing
  - Conceptually similar to MapReduce
    - Let's just live with latency. Concentrate on bandwidth.
    - Bulk-Synchronous Consistency
    - A framework is provided - the user fills in custom computation.
    - However, the user function writing is not very intuitive.

Distributed Graph Processing (Future Works)

- PageRank Example

```
class PageRankVertex
    : public Vertex<double, void, double> {
 public:
  virtual void Compute(MessageIterator* msgs) {
    if (superstep() >= 1) {
      double sum = 0;
      for (; !msgs->Done(); msgs->Next())
        sum += msgs->Value();
      *MutableValue() =
          0.15 / NumVertices() + 0.85 * sum;
    }

    if (superstep() < 30) {
      const int64 n = GetOutEdgeIterator().size();
      SendMessageToAllNeighbors(GetValue() / n);
    } else {
      VoteToHalt();
    }
  }
};
```

Pregel Program

```
hongsup@drink-1:~/tcc/farm/driver
Procedure PageRank(G: Graph, e:Float, d:Float,
  p_rank: Node_Property<Float>(G)) {

  // Initialize
  Int N = G.NumNodes;
  G.p_rank = 1 / (Float) G.NumNodes;
  Float diff;
  Do {
    diff = 0;
    Foreach (t: G.Nodes) {
      Float new_val = (1-d) / N + d *
          Sum (w: t.InNbrs) {w.p_rank / w.NumOutNbrs} ;
      diff += | val - t.p_rank | @ t;  // reduction assignment
      t.p_rank <= val @ t;             // deferred assignment
    }
  } While (diff > e); // Iterate until converge
```

Green-Marl Program

Can we find automatic translations?

Summary

- DSL-based approach
  - Productivity: Enables elegant algorithm description
  - Performance: Maps (best/good) parallel implementation
  - Portability: Generates CPU and GPU version
  - Flexibility: Language constructs are more than a library
- Current Status
  - A draft of language specification
  - Studies on BFS implementation
  - Prototype compiler on the way

Questions?

"*Programs must be written for people to read, and only incidentally for machines to execute*."

– Abelson and Sussman

No more slides