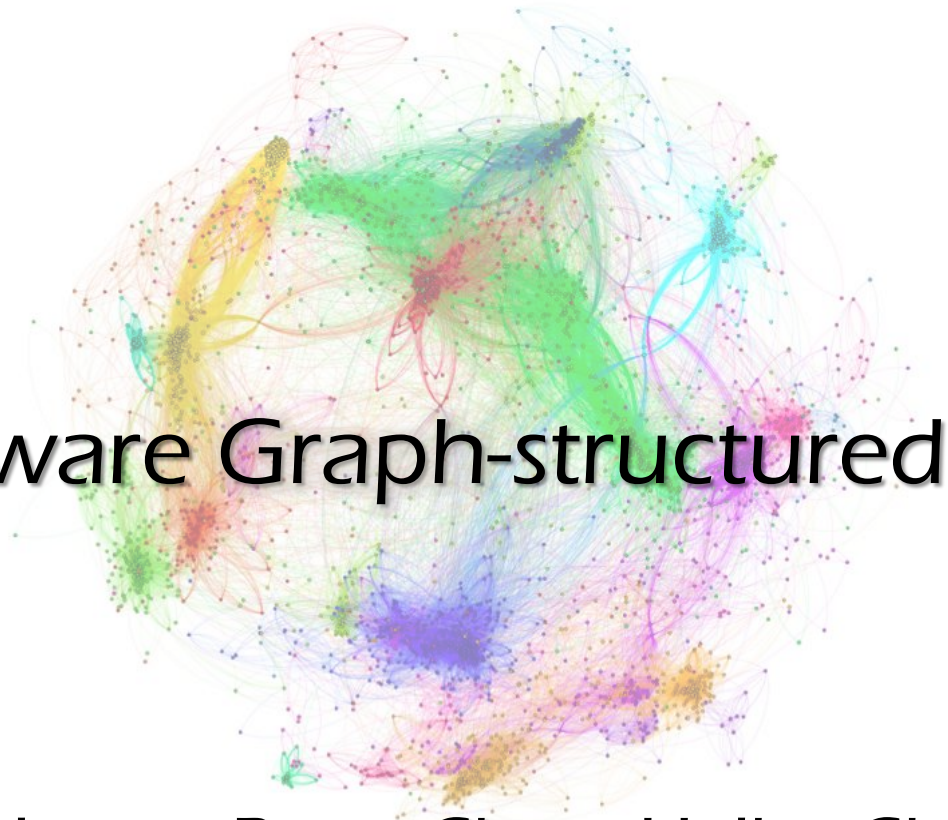
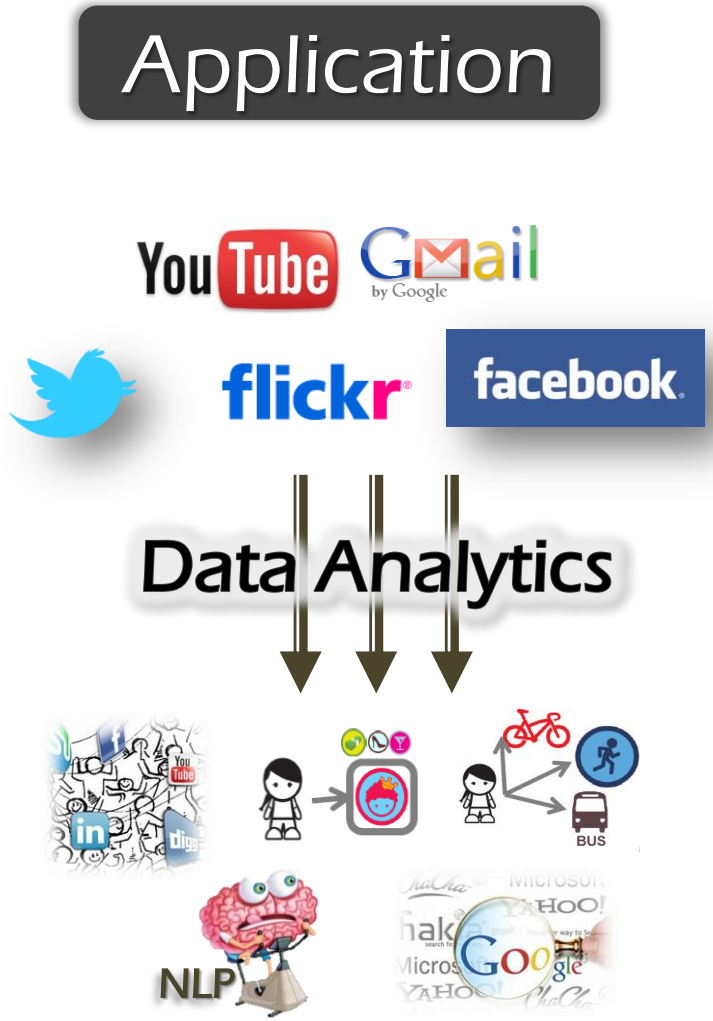


NUMA-aware Graph-structured Analytics

Kaiyuan, Rong Chen, Haibo Chen

Institute of Parallel and Distributed Systems
Shanghai Jiao Tong University, China

Graph-analytics and NUMA



Graph-analytics and NUMA

Application

Graph-analytics systems
for single machine

- GraphChi OSDI'12
  - out-of-core access
- Ligra PPoPP'13
  - appropriate exec-modes
- Galois SOSP'13
  - efficient task scheduler
- X-Stream SOSP'13
  - w/o rand ops on edges

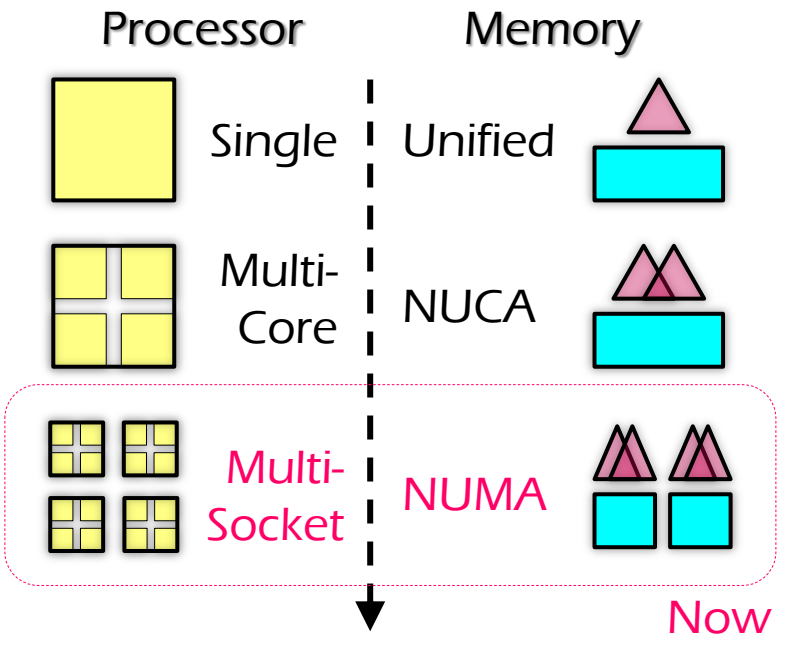
Graph-analytics and NUMA

Application

Graph-analytics systems
for single machine

- GraphChi OSDI'12
  - out-of-core access
- Ligra PPoPP'13
  - appropriate exec-modes
- Galois SOSP'13
  - efficient task scheduler
- X-Stream SOSP'13
  - w/o rand ops on edges

Hardware



e.g. 80 Cores with 1TB RAM

8 Sockets X (10 Cores with128GB local RAM)

Graph-analytics and NUMA

Application

Graph-analytics systems
for single machine

- GraphChi OSDI'12
  - out-of-core access
- Ligra PPoPP'13
  - appropriate exec-modes
- Galois SOSP'13
  - efficient task scheduler
- X-Stream SOSP'13
  - w/o rand ops on edges

Hardware

NUMA-aware research

- Profiler, Analyzer, etc.
  - MemProf USENIX ATC'12
  - SSYNC SOSP'13
  - HPCToolkit-NUMA PPoPP'14
- Malloc, Schd., Sync. etc.
  - Lock-cohorting PPoPP'12
  - Carrefour ASPLOS'13
  - THP USENIX ATC'14
- Runtime (e.g. MapReduce)
  - Phoenix2 IIWSC'09
  - Ostrich PACT'10

Graph-analytics and NUMA

Graph-analytics + NUMA systems

Outline

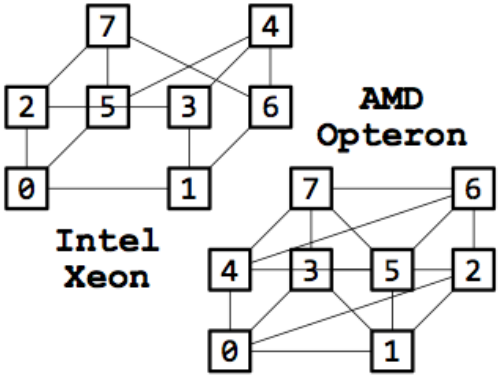
Background & Issues

Design of Polymer

Evaluation

- Background & Issues
- Design of Polymer
- Evaluation

NUMA Characteristics



A commodity NUMA machine

- Multiple processor nodes (i.e., socket)
- Processor = multiple cores + a local DRAM
- A globally shared memory abstract (cache-coherence)
- Hallmark: Non-uniform memory access

Latency (Cycle)

Inst.	0-hop	1-hop	2-hop
80-core Intel Xeon machine			
Load	**117**	271	**372**
Store	**108**	304	**409**

Bandwidth (MB/s)

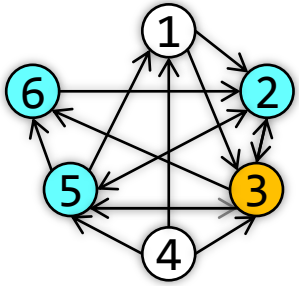
Access	0-hop	1-hop	2-hop	IL
80-core Intel Xeon machine				
SEQ	3207	2455	**2101**	2333
RAND	**720**	348	**307**	344

Graph-analytics

The scatter-gather model

- "scatter": propagate the current value of a vertex to its neighbors along edges
- "gather": accumulate values from neighbors to compute the next value of a vertex

Graph-analytics

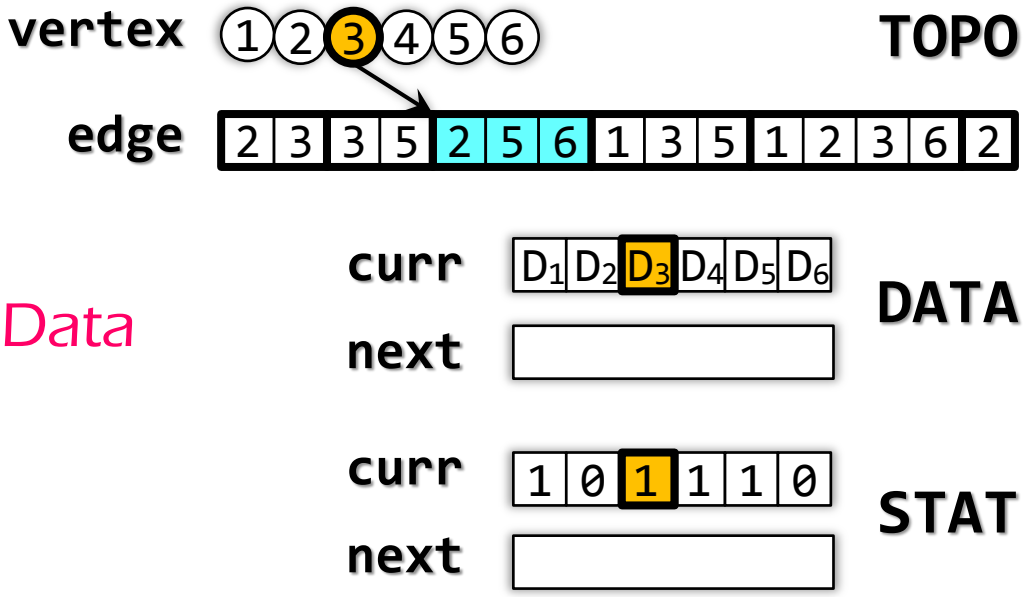


The scatter-gather model

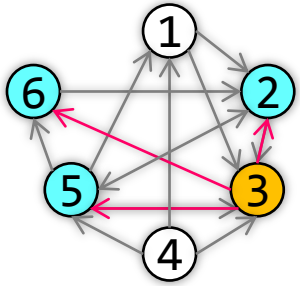
- "scatter": propagate the current value of a vertex to its neighbors along edges
- "gather": accumulate values from neighbors to compute the next value of a vertex

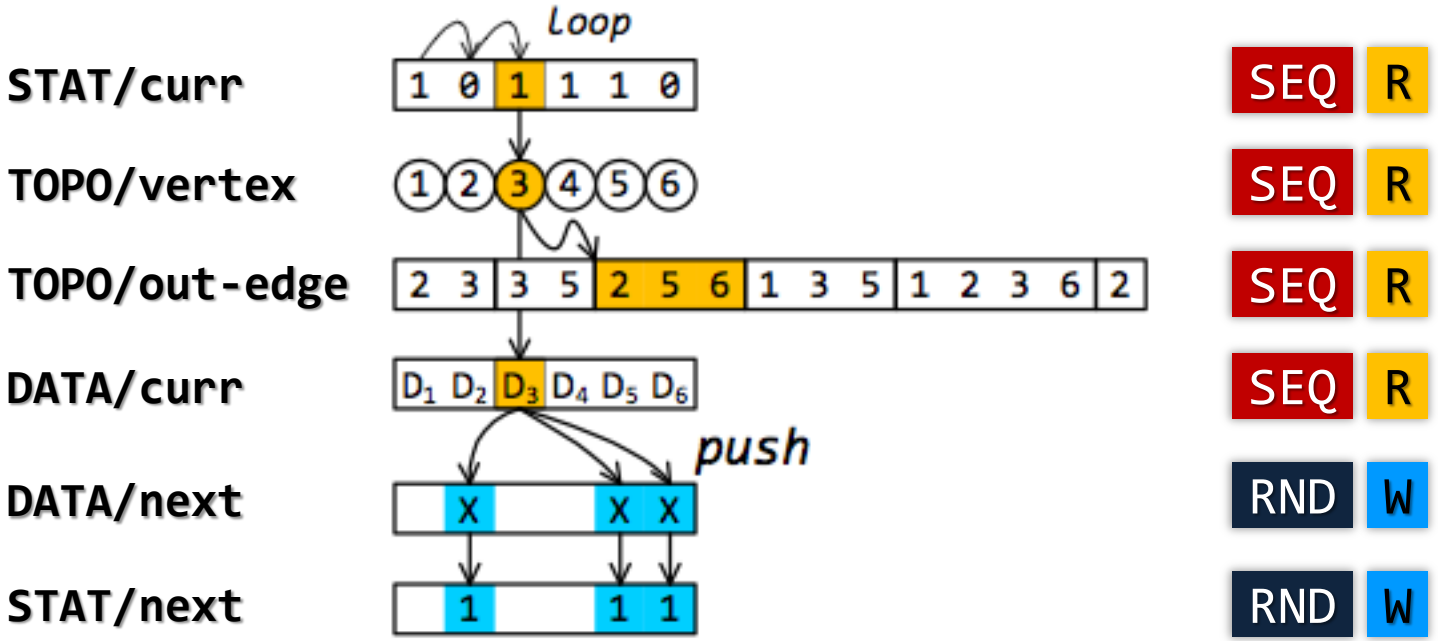
In-memory data

- Graph Topology
- Application-specific Data
- Runtime State

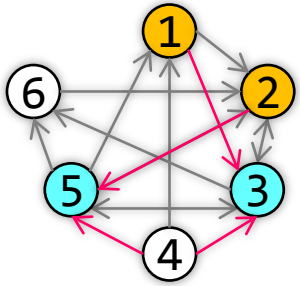


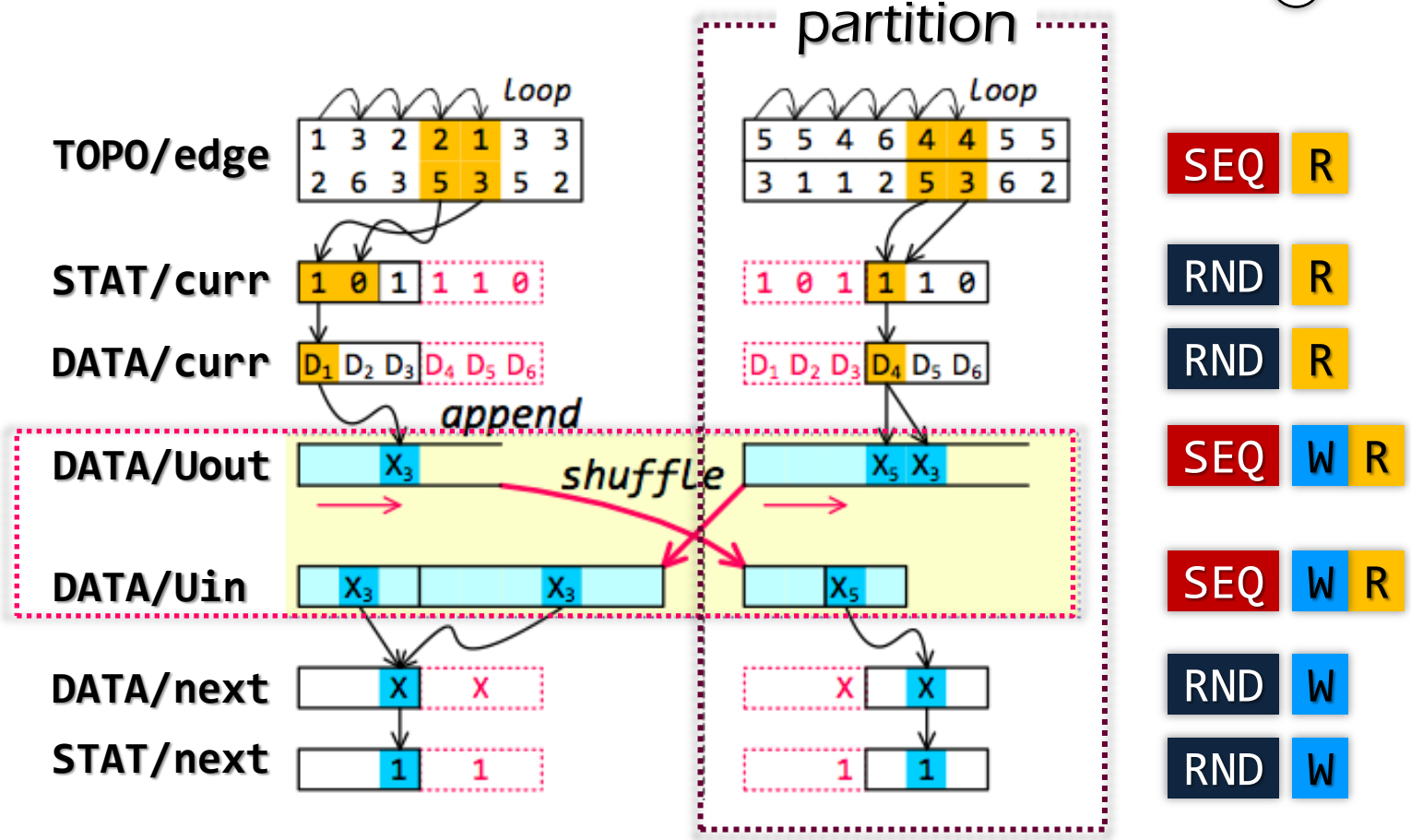
Vertex-centric (e.g. Ligra)





Edge-centric (e.g. X-Stream)

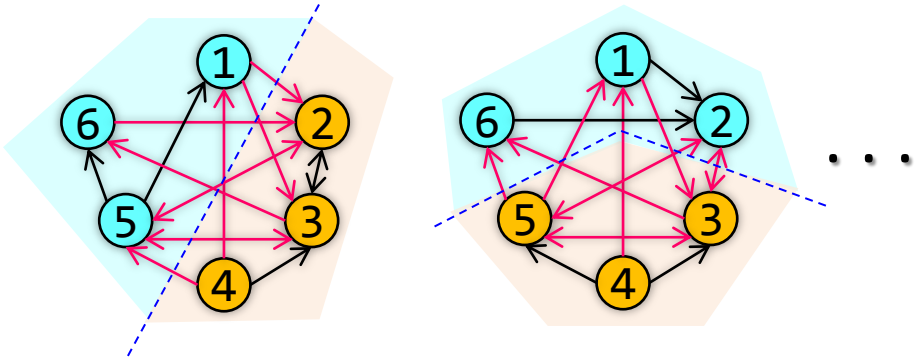




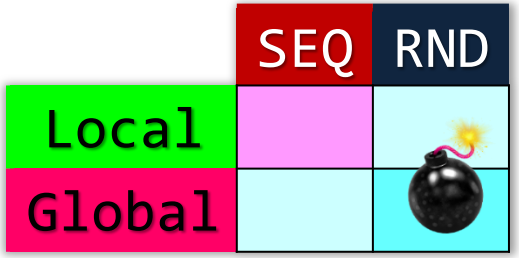
Access Strategy on NUMA

Lack of locality (access neighboring vertices)

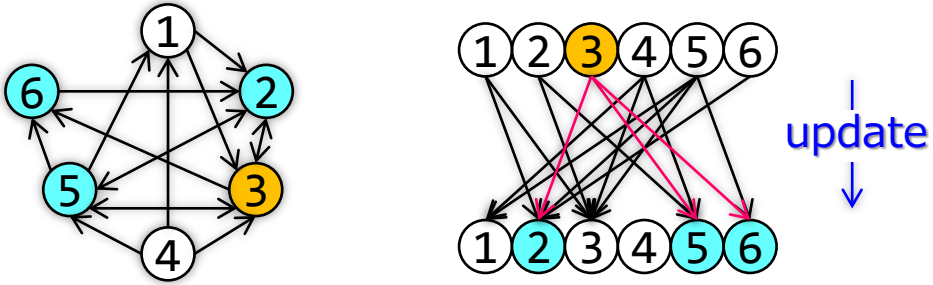
- It is inevitable to access remote memory



How to mix ??



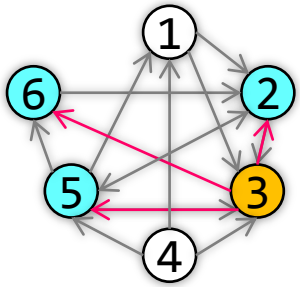
- Random access is always there

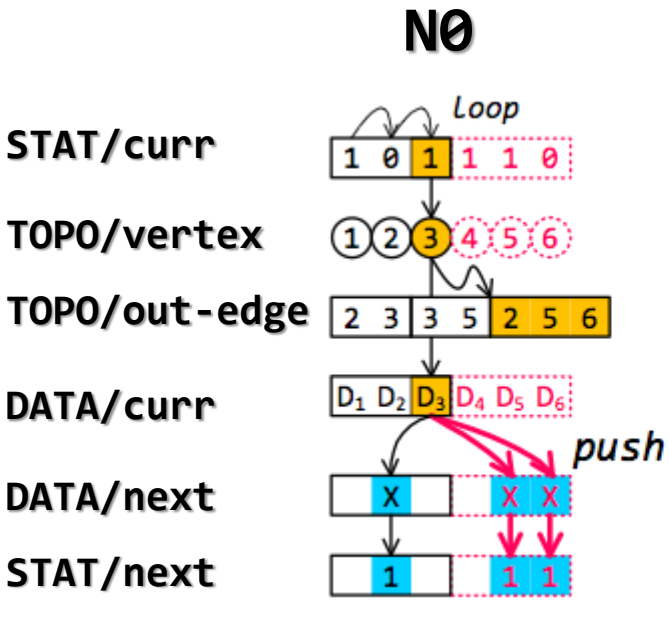


Access Strategy on NUMA

Vertex-centric Model

- Completely overlooked (e.g. Ligra)

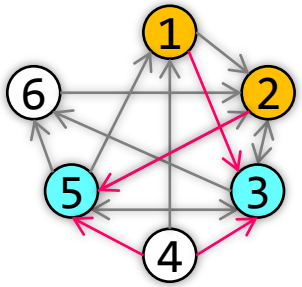


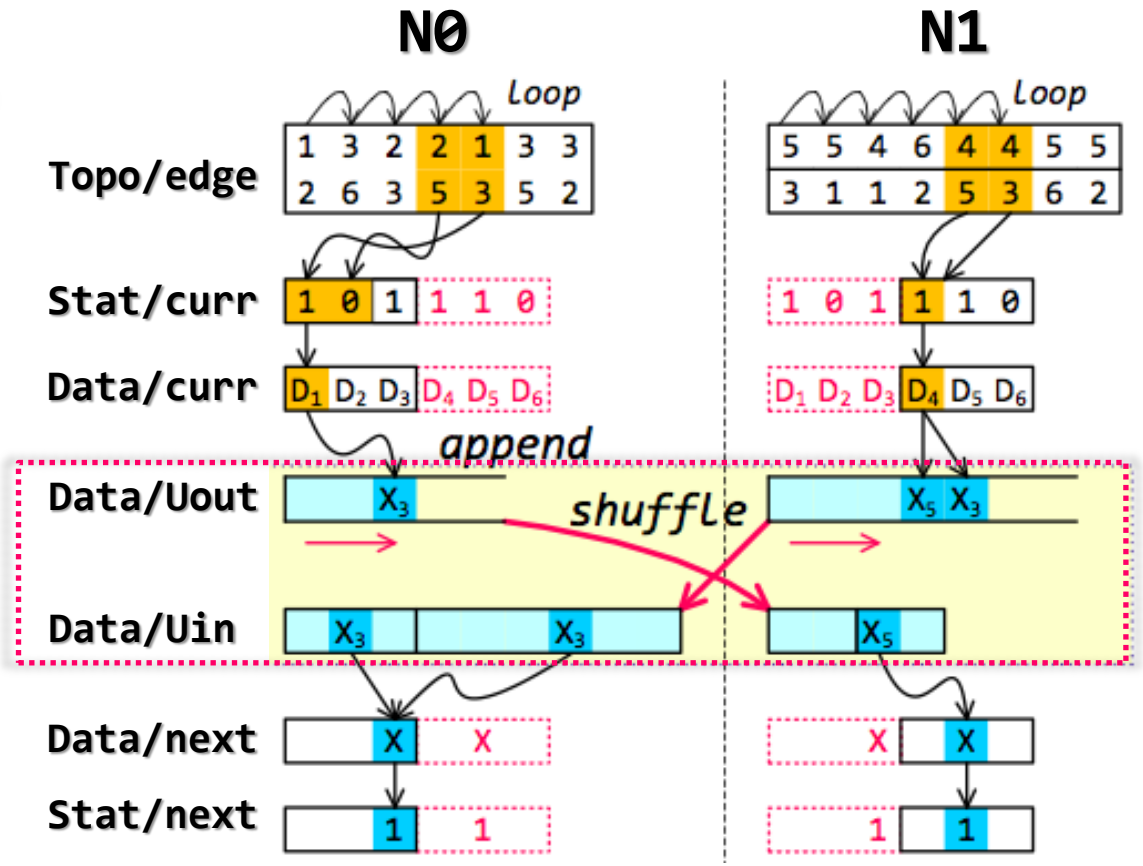


Access Strategy on NUMA

Edge-centric Model

- Inefficient way (e.g. X-Stream)

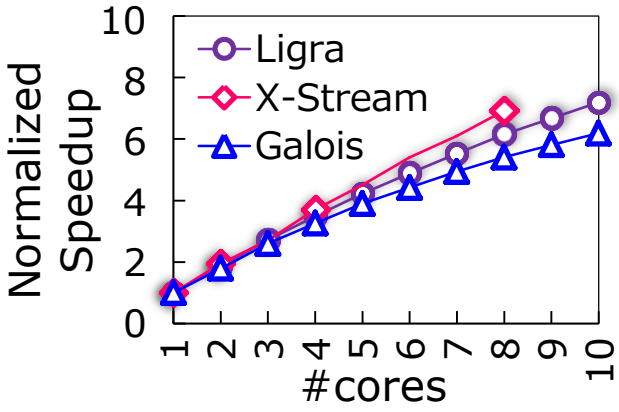


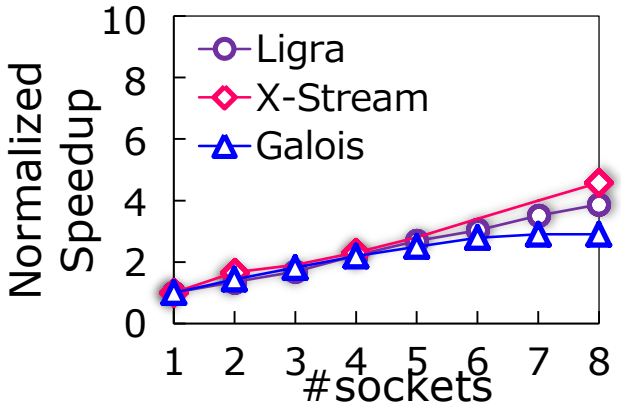


Scalability & Performance on NUMA

Scalability: #Cores vs. #sockets

Intel 80-cores (8Sx10C)





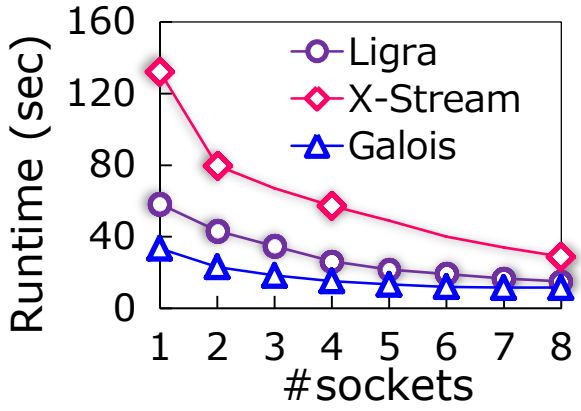
X-Stream
8C: 6.92X
8S: 4.58X

Galois
10C: 6.19X
8S: 2.90X

Performance (sec)

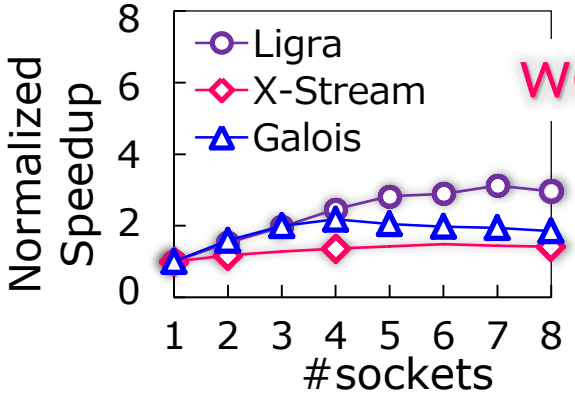
X-Stream
1S: 132s
8S: 29s

Galois
1S: 33s
8S: 12s



Intel 80-cores (8Sx10C)

Scalability: #sockets



worse !

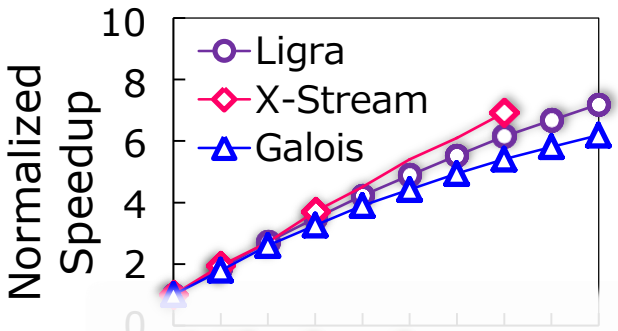
8 Socket
LG: 2.9X
XS: 1.4X

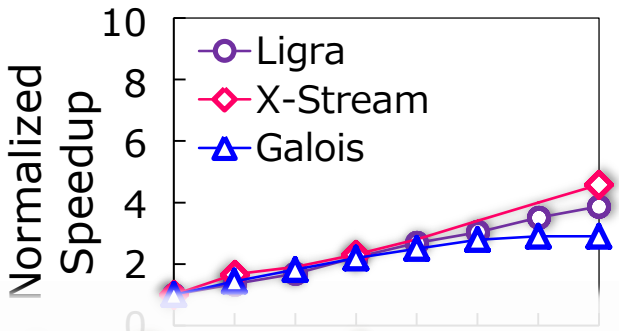
AMD 64-core (8Sx8C)

Scalability & Performance on NUMA

Scalability: #Cores vs. #sockets

Intel 80-cores (8Sx10C)





X-Stream
8C: 6.92X
8S: 4.58X

Galois
10C: 6.19X
8S: 2.90X

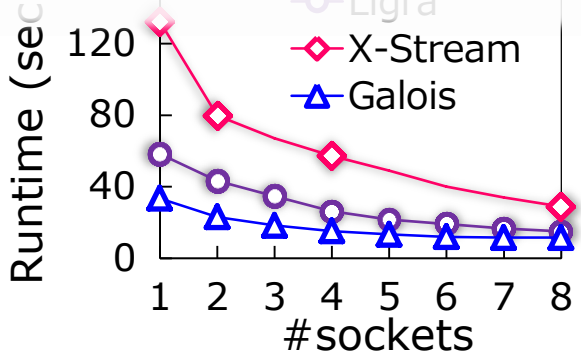
Minimize remote & random accesses

+

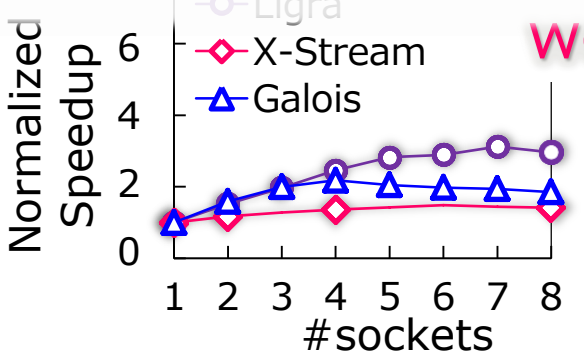
Eliminate the combination of them

X-Stream
1S: 132s
8S: 29s

Galois
1S: 33s
8S: 12s



Intel 80-cores (8Sx10C)



worse !

8 Socket
LG: 2.9X
XS: 1.4X

AMD 64-core (8Sx8C)

Background and Issues

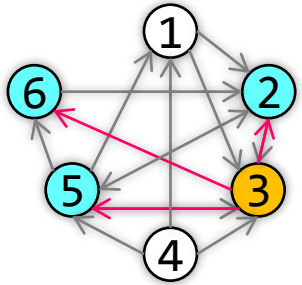
Design of Polymer

Evaluation

Goal#1: Reduce remote accesses

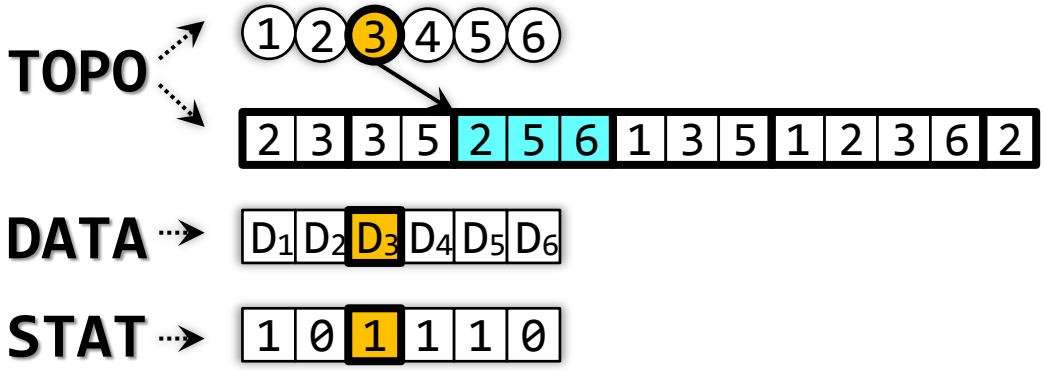
Co-locating data and computation within the same NUMA node

Graph-aware Data Layout

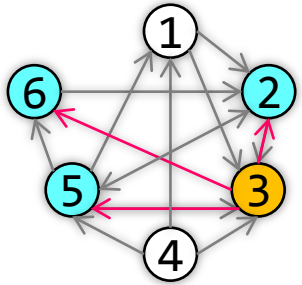


Co-locating *data and computation within the same NUMA node*

1. Graph-aware partitioning

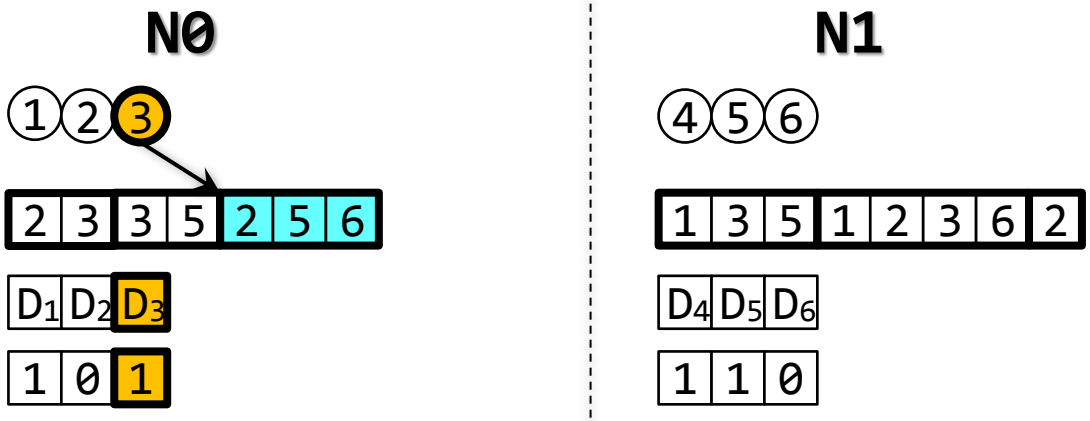


Graph-aware Data Layout



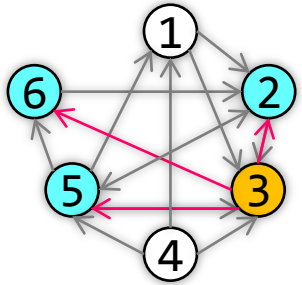
Co-locating *data and computation within the same NUMA node*

1. Graph-aware partitioning



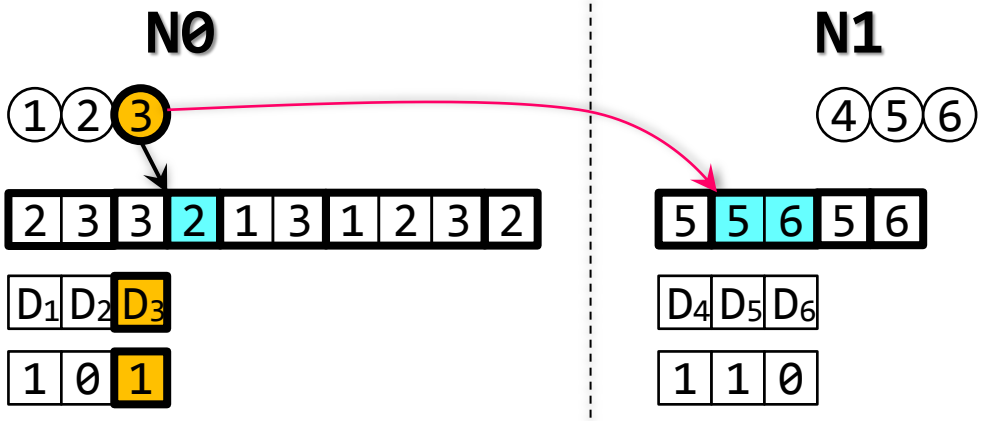
Intuitive

Graph-aware Data Layout



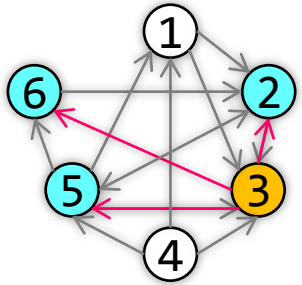
Co-locating *data and computation within the same NUMA node*

1. Graph-aware partitioning



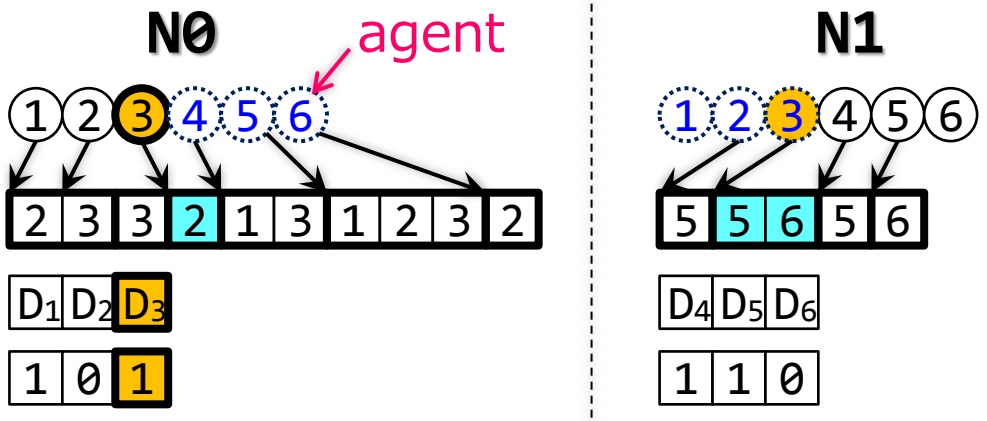
sophisticated

Graph-aware Data Layout



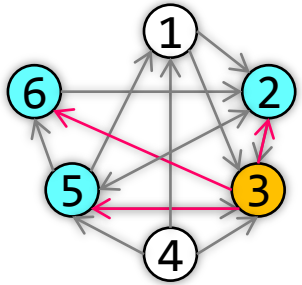
Co-locating *data and computation within the same NUMA node*

1. Graph-aware partitioning



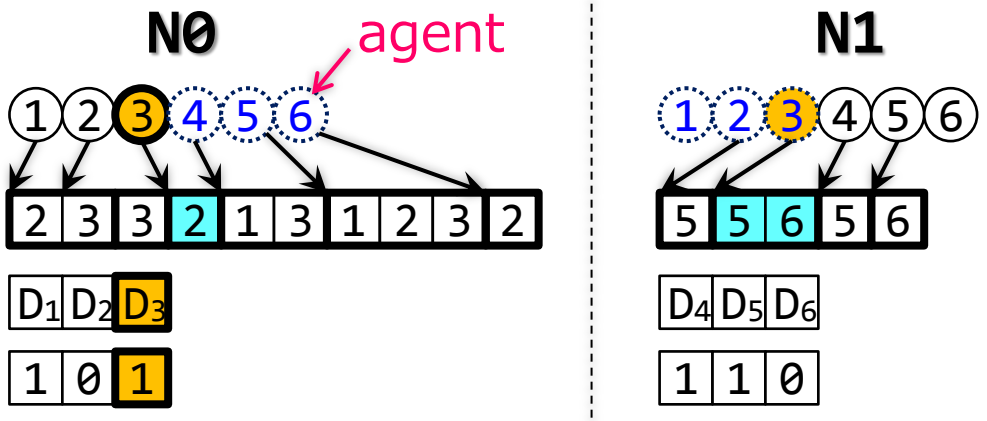
sophisticated

Graph-aware Data Layout



Co-locating *data and computation within the same NUMA node*

1. Graph-aware **partitioning**

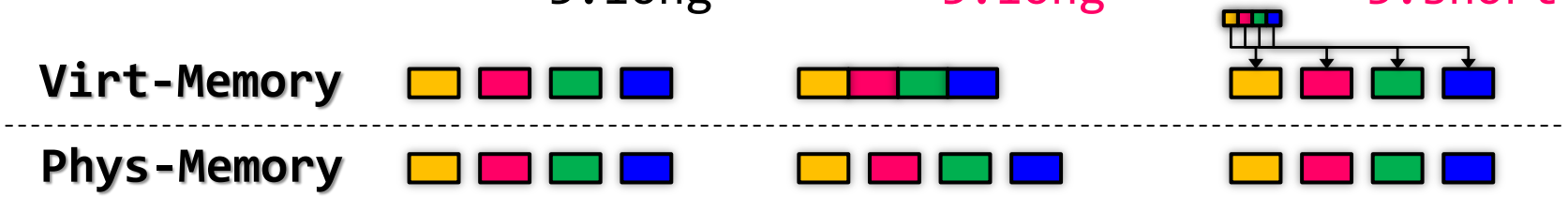


2. NUMA-aware **allocation**

TOPO 1.seq 2.local 3.long

DATA 1.seq/rnd 2.global 3.long

STAT 1.seq/rnd 2.global 3.short



Goal#2: Eliminate “random + remote”

Random remote access

→ ~~access neighboring vertices on other nodes~~

distribute the computations on
singe vertex over multiple NUMA-nodes

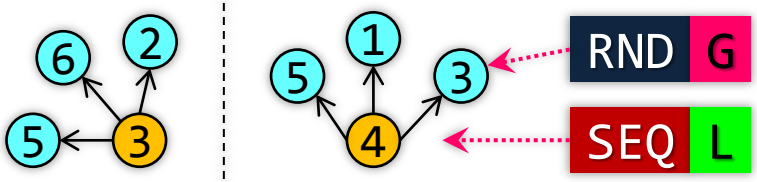
NUMA-aware Access Strategy

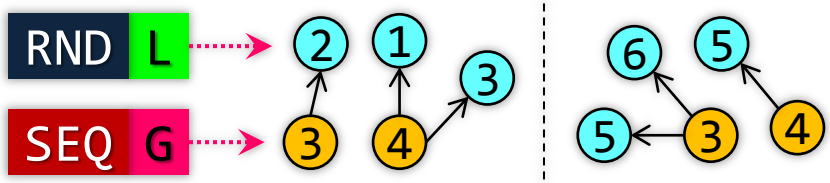
Random remote access

→ ~~access neighboring vertices on other nodes~~

distribute the computations on singe vertex over multiple NUMA-nodes

Each node handles
all edges of partial vertices

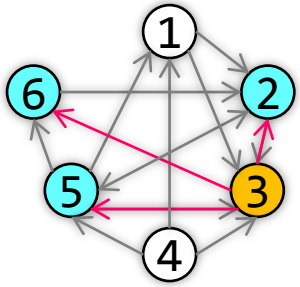




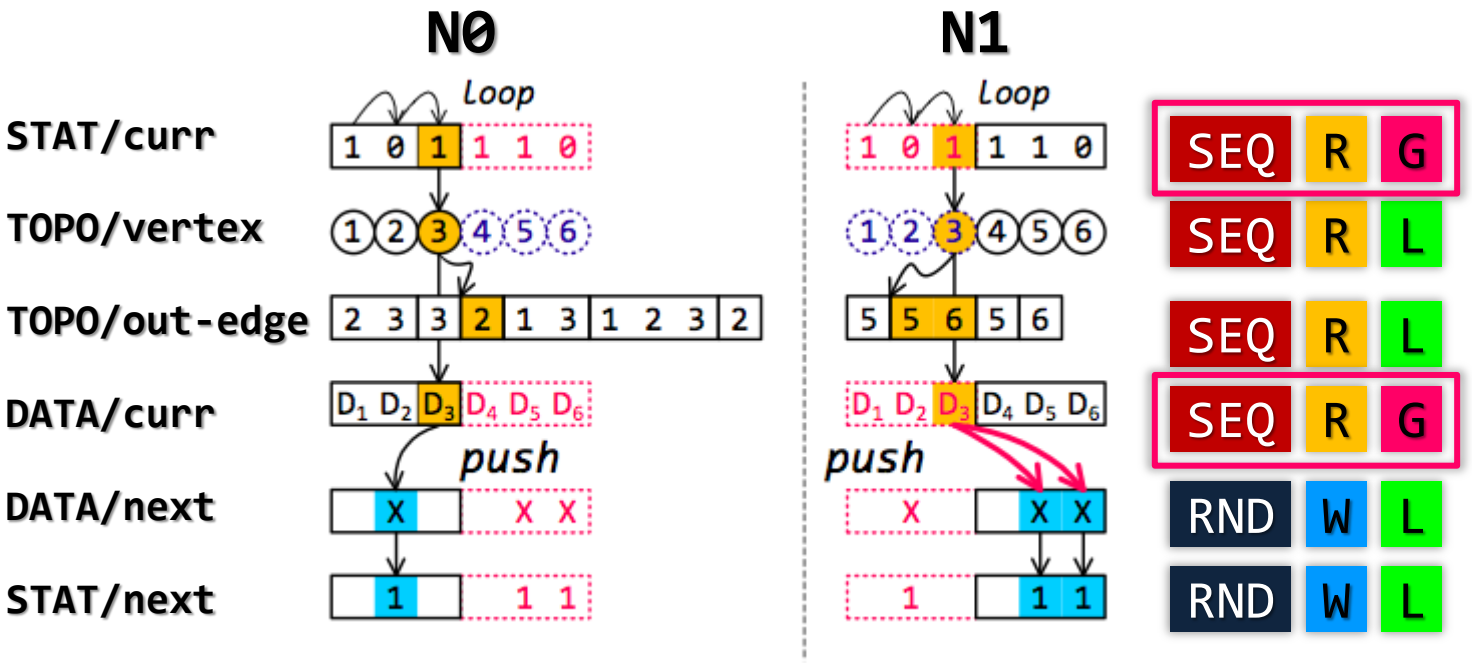
Each node handles
partial edges of all vertices

NUMA-aware Access Strategy

distribute the computations on singe vertex over multiple NUMA-nodes

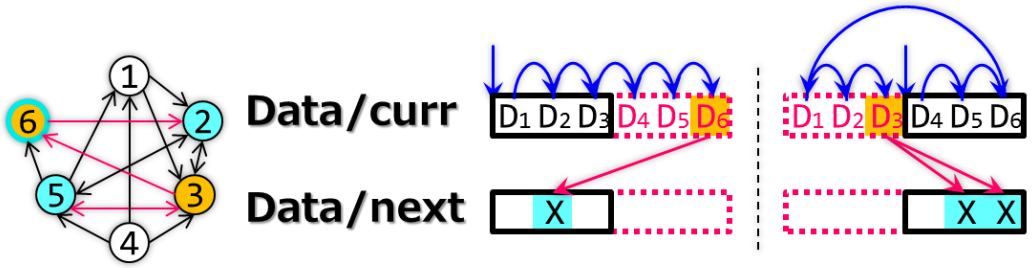


Push

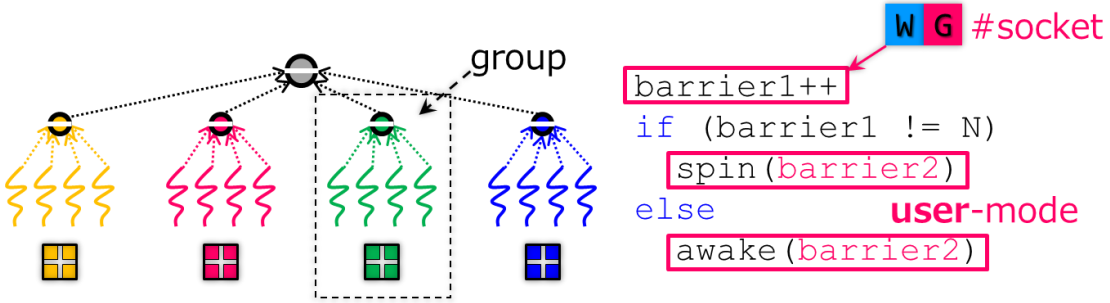


Optimizations

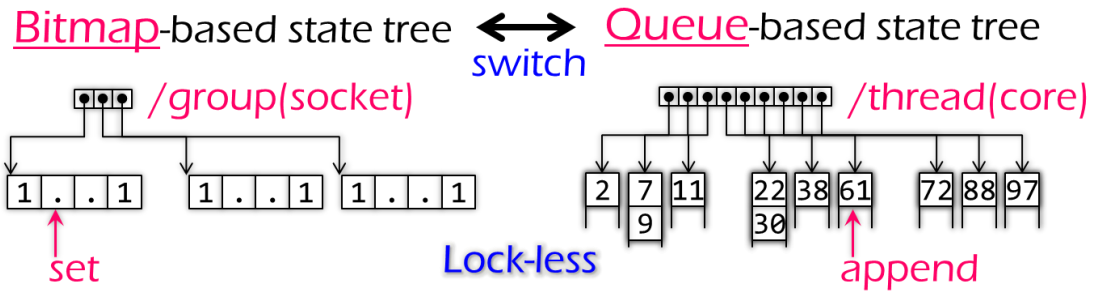
1. *Rolling* update



2. *Hierarchical* and *efficient* barrier



3. *Adaptive* data structure

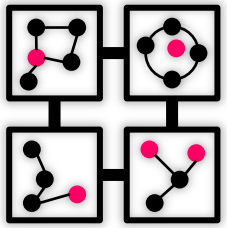


Background &Issues

Design of Polymer

Evaluation

Implementation



Polymer

- ~5,300 SLOCs of C++ code
- Based on scatter-gather iterative model
  - → Support both push and pull mode
  - → Use a synchronous scheduler
- Several typical graph applications
  - → Sparse MM: PageRank, SpMV and BP
  - → Graph Traversal: BFS, CC and SSSP

Open source

http://ipads.se.sjtu.edu.cn/projects/polymer.html

Experiment Settings

Baseline: Ligra v2014.3, X-Stream v0.9, and Galois v2.2

Platform Intel/8X10 AMD/8X8

- 80-core Intel machine (w/o Hyper-Threading)
  8 sockets (E7-8850: 10 cores and 128 GB local RAM)
- 64-core AMD machine (also 8 sockets)

Algorithms (6)

- 3 Spars MM algorithms
- 3 Traversal algorithms

Graphs (4)

- 2 real-world and
  2 synthetic graphs

Graph	|V|	|E|
Twitter	41.7 M	1.47B
rMat27	134.2M	2.14B
Powerlaw	10.0M	105M
roadUS	23.9M	58M

Overall Performance

Intel 80-cores (8Sx10C)

Algo.	|V|	Polymer	Ligra	X-Stream	Galois
PR (x5)	Twitter	5.3	15.0	28.9	11.6
	rMat27	9.6	28.0	18.2	19.6
	Power	1.6	30.5	6.1	6.6
	roadUS	1.2	2.3	2.8	1.4
SpMV (x5)	Twitter	7.6	29.0	59.6	11.7
	rMat27	19.2	54.3	52.5	41.9
	Power	1.8	31.0	5.5	6.2
	roadUS	1.3	2.8	3.0	3.6
BP (x5)	Twitter	38.0	63.1	2017	57.1
	rMat27	58.3	92.8	737	75.0
	Power	8.0	30.7	38.3	8.6
	roadUS	5.2	2.6	20.0	7.1

Overall Performance

Intel 80-cores (8Sx10C)

Algo.	|V|	Polymer	Ligra	X-Stream	Galois
PR (x5)	Twitter	5.3	2.85X	5.48X	2.19X
	rMat27	9.6	2.91X	1.89X	2.04X
	Power	1.6	18.9X	3.76X	4.11X
	roadUS	1.2	1.92X	2.31X	1.14X
SpMV (x5)	Twitter	7.6	3.84X	7.89X	1.55X
	rMat27	19.2	2.83X	2.74X	2.19X
	Power	1.8	17.3X	3.08X	3.46X
	roadUS	1.3	2.18X	2.30X	2.74X
BP (x5)	Twitter	38.0	1.66X	53.1X	1.50X
	rMat27	58.3	1.59X	12.6X	1.29X
	Power	8.0	3.80X	4.74X	1.06X
	roadUS	5.2	2.01X	3.84X	1.36X

Overall Performance

Intel 80-cores (8Sx10C)

Algo.	|V|	Polymer	Ligra	X-Stream	Galois
BFS	Twitter	0.90	1.13	28.70	2.67
	rMat27	1.56	1.86	30.18	2.54
	Power	0.36	0.39	2.58	0.36
	roadUS	1.16	6.93	557.7	5.01
CC	Twitter	4.60	5.51	54.8	31.9
	rMat27	8.72	7.74	40.0	33.9
	Power	1.23	2.56	5.13	3.51
	roadUS	57.5	63.2	985	1.18*
SSSP	Twitter	2.26	3.17	165	26.3
	rMat27	5.78	5.26	17.9	28.5
	Power	0.85	1.12	126	26.6
	roadUS	341	338	1225	0.33*

Overall Performance

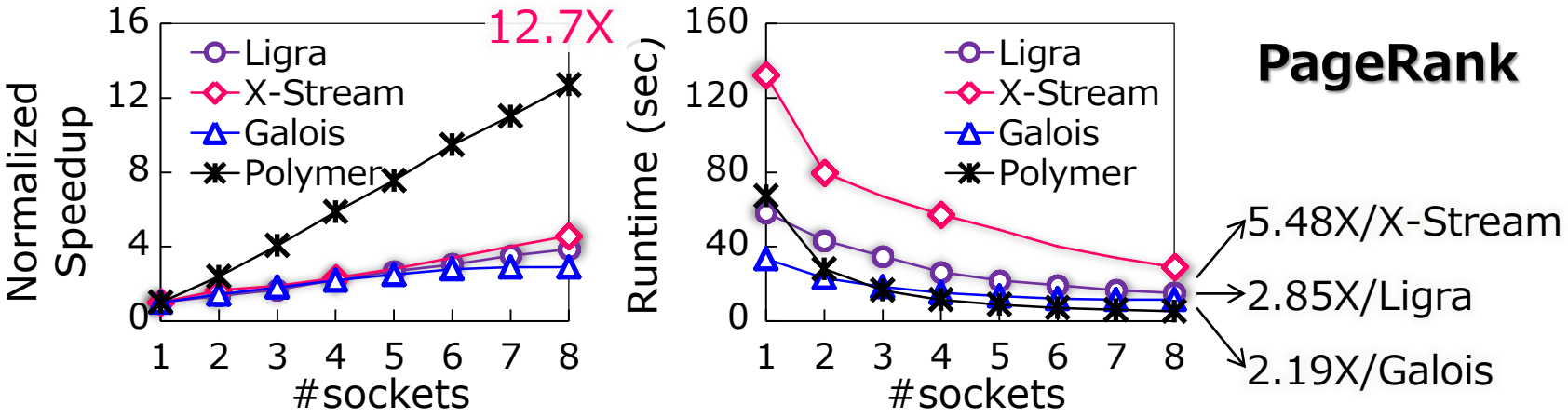
Intel 80-cores (8Sx10C)

Algo.	|V|	Polymer	Ligra	X-Stream	Galois
BFS	Twitter	0.90	1.26X	31.9X	2.97X
	rMat27	1.56	1.19X	19.4X	1.63X
	Power	0.36	1.08X	7.16X	1.02X
	roadUS	1.16	5.97X	481.X	4.32X
CC	Twitter	4.60	1.20X	11.9X	6.94X
	rMat27	8.72	1.12X	4.58X	3.88X
	Power	1.23	2.08X	4.17X	2.85X
	roadUS	57.5	1.10X	17.1X	1.18*
SSSP	Twitter	2.26	1.40X	73.1X	11.5X
	rMat27	5.78	1.09X	21.9X	4.93X
	Power	0.85	1.31X	14.5X	31.1X
	roadUS	341	1.01X	3.59X	0.33*

Scalability on NUMA

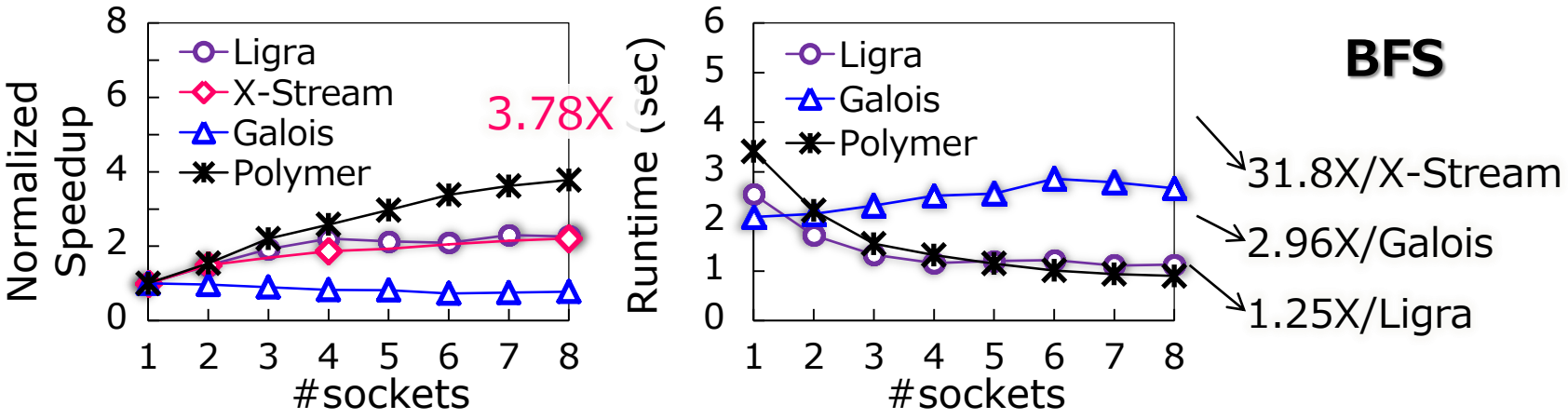
Performance & Scalability: #sockets

Intel 80-cores (8Sx10C)



Performance & Scalability: #sockets

Intel 80-cores (8Sx10C)

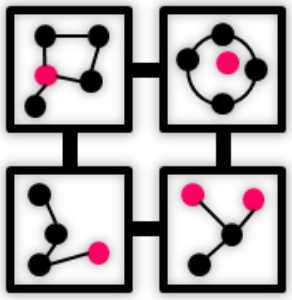


Conclusion

Polymer: NUMA-aware Graph-structured Analytics

- A comprehensive analysis that uncovers several NUMA characteristics and issues with existing NUMA-oblivious graph analytics systems
- A new system that exploits both NUMA- and graph-aware data layout and memory access strategies
  - → minimize remote access
  - → eliminate remote random access
- Three optimizations for global synchronization efficiency, load balance and data structure flexibility

Thanks



http://ipads.se.sjtu.edu.cn/projects/polymer.html

Institute of Parallel and Distributed Systems

Questions