CR²: Community-aware Compressed Regular Representation for Graph Processing on a GPU

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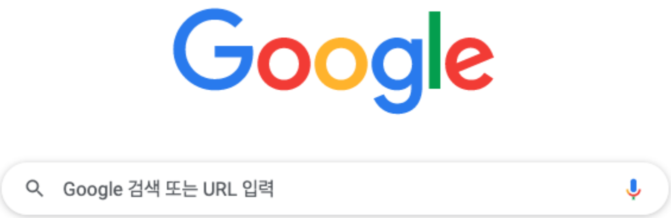
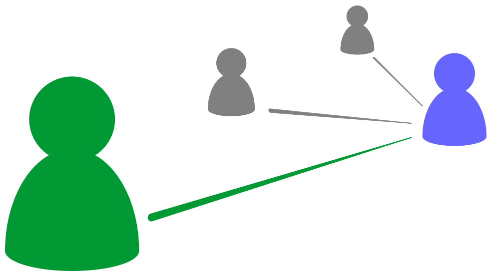
Graphs are One of the Important Data Structures to Abstract and Analyze Real-World Data

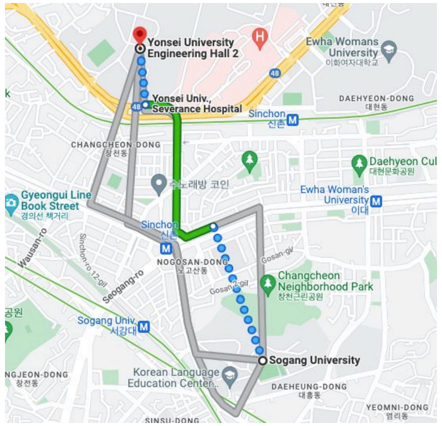


Web Search



Social Network

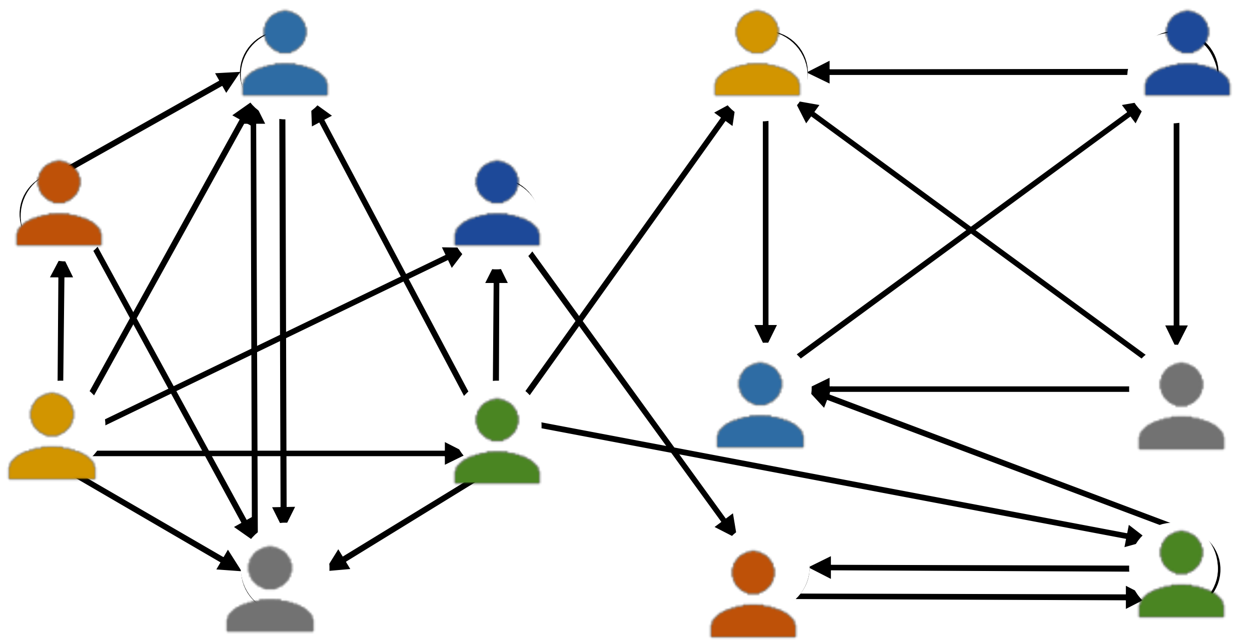
Neuroscience



Path Finding

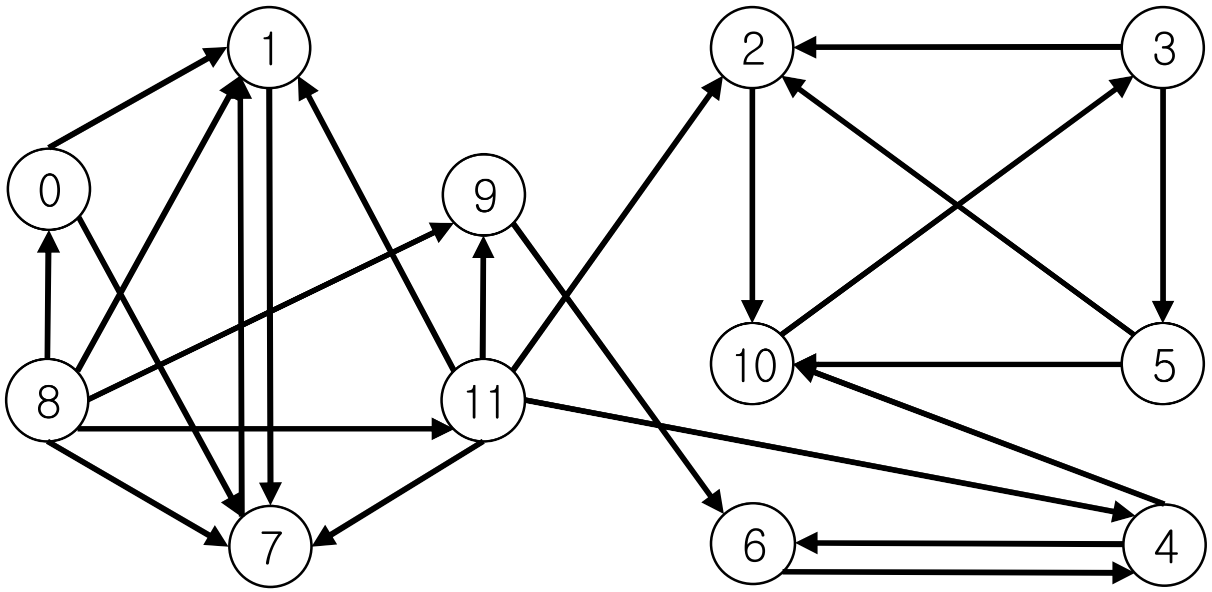
What is Graph?

- An abstract data structure with vertices and their pairs(edges)
- Graph = (Vertex, Edge)



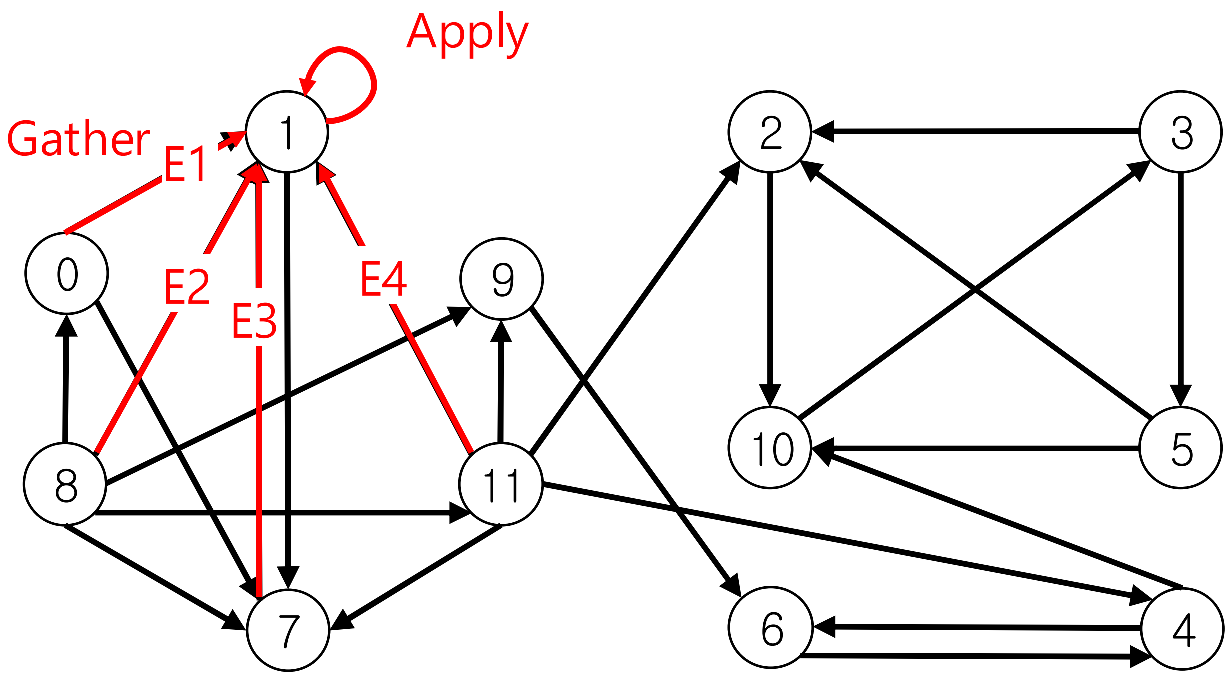
What is Graph?

- An abstract data structure with vertices and their pairs(edges)
- Graph = (Vertex, Edge)



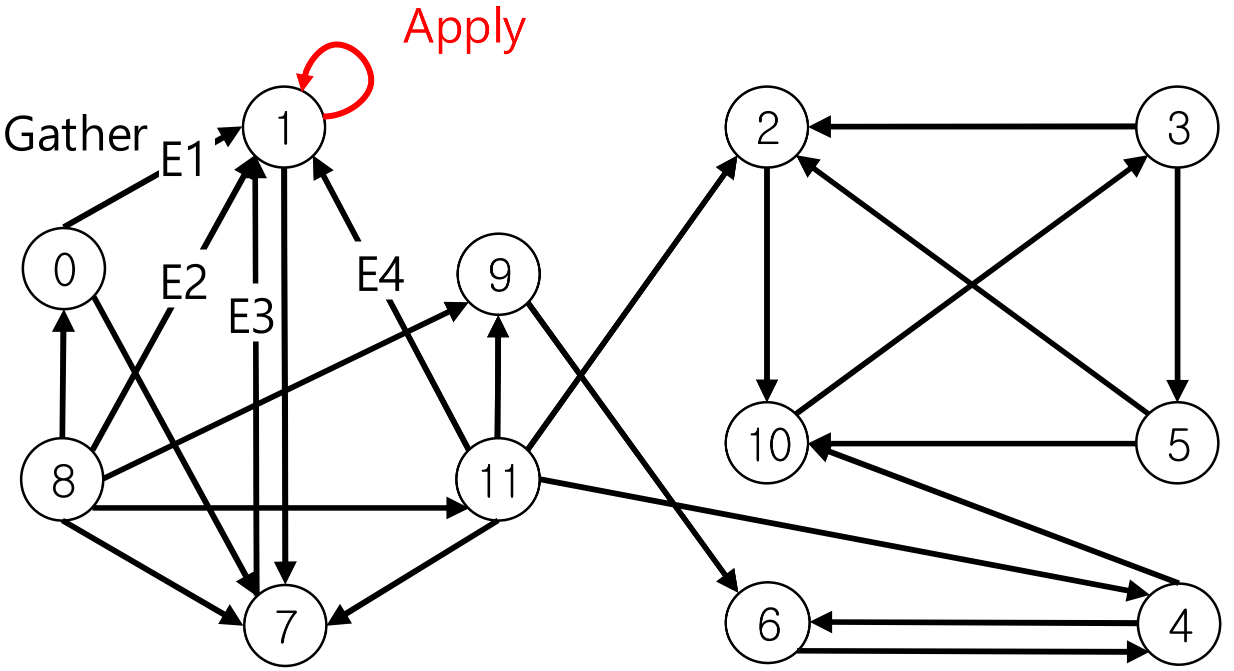
What is the Graph Processing?

- Update vertex data by **gather**ing neighbor edge data
- **Apply** computation on vertex data after finishing gathering
- Perform the same algorithm to each vertex and to each edge



GPU is a Promising Platform for Graph Processing

- Real-world graphs become larger and apply the same algorithms to each vertex and edges
- GPU is designed for Single Instruction Multiple Data(SIMD) processing



Map to each thread

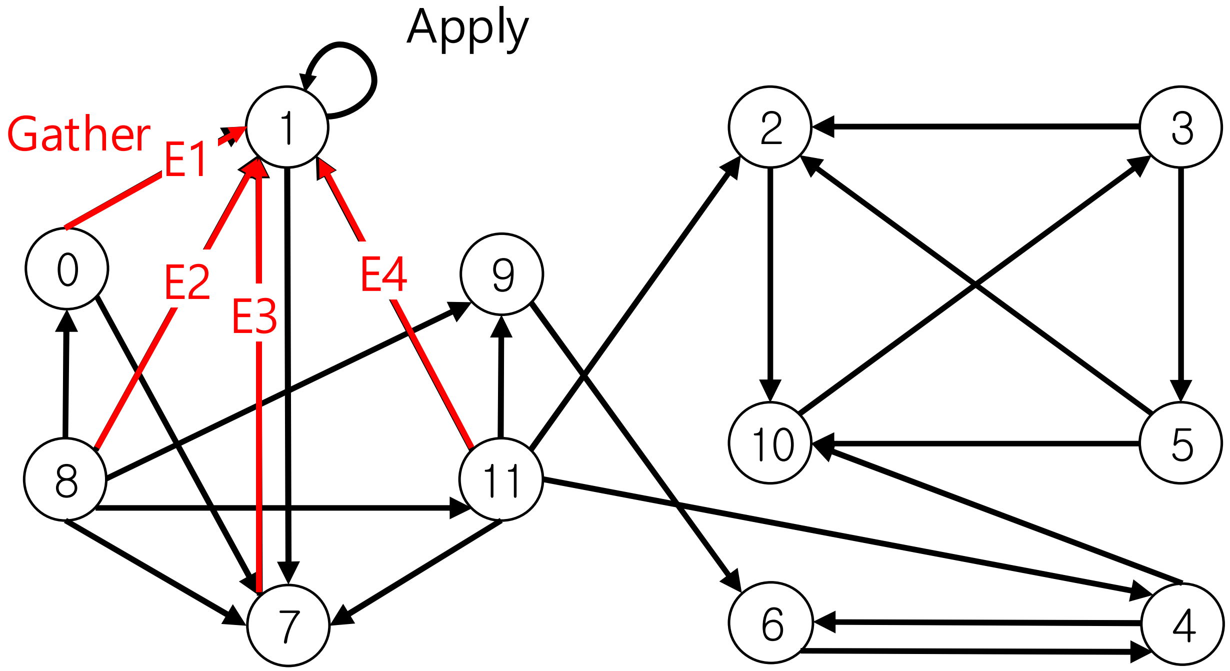
Apply Processing on GPU

T0	T1	T2	T3	T4	T5	T6	T7
V0	V1	V2	V3	V4	V5	V6	V7
V8	V9	V10	V11				

Time

However, Graph Processing on GPU is Still Challenging!

- The characteristics of real-world graph are not fit for GPU, such as skewness and sparsity
- Cause irregular distribution inducing **workload imbalance** and reducing resource utilization



Gather Processing on GPU

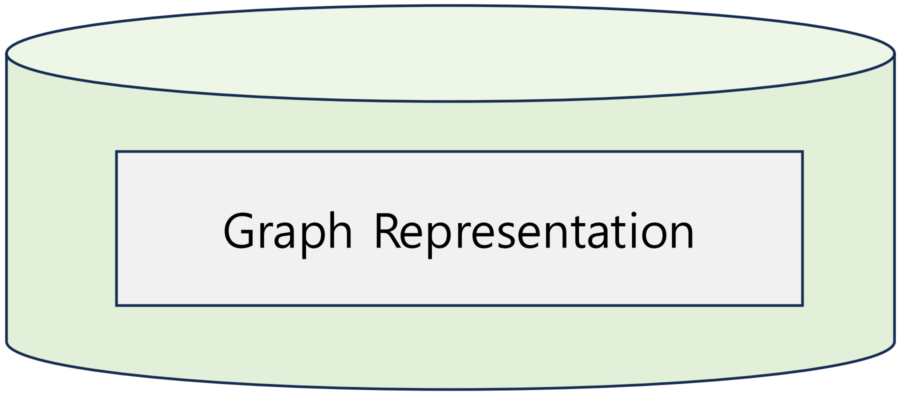
T0	T1	T2	T3	T4	T5	T6	T7
V0	V1	V2	V3	V4	V5	V6	V7
E0	E1	E5	E8	E9	E11	E12	E14
	E2	E6		E10		E13	E15
	E3	E7					E16
	E4						

Time

Map each vertex and its neighboring edges to each thread

Changing Graph Representation for GPU can be a Solution

- The graph representation defines how to store a given graph in GPU memory
- Since the graph is large, the graph representation affect to memory usage and perf



Read graph data from memory

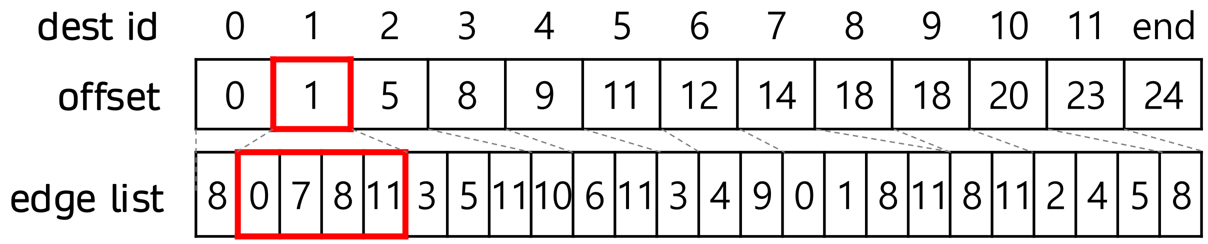
Gather Processing on GPU

T0	T1	T2	T3	T4	T5	T6	T7
V0	V1	V2	V3	V4	V5	V6	V7
E0	E1	E5	E8	E9	E11	E12	E14
	E2	E6		E10		E13	E15
	E3	E7					E16
	E4						

Time

Changing Graph Representation for GPU can be a Solution

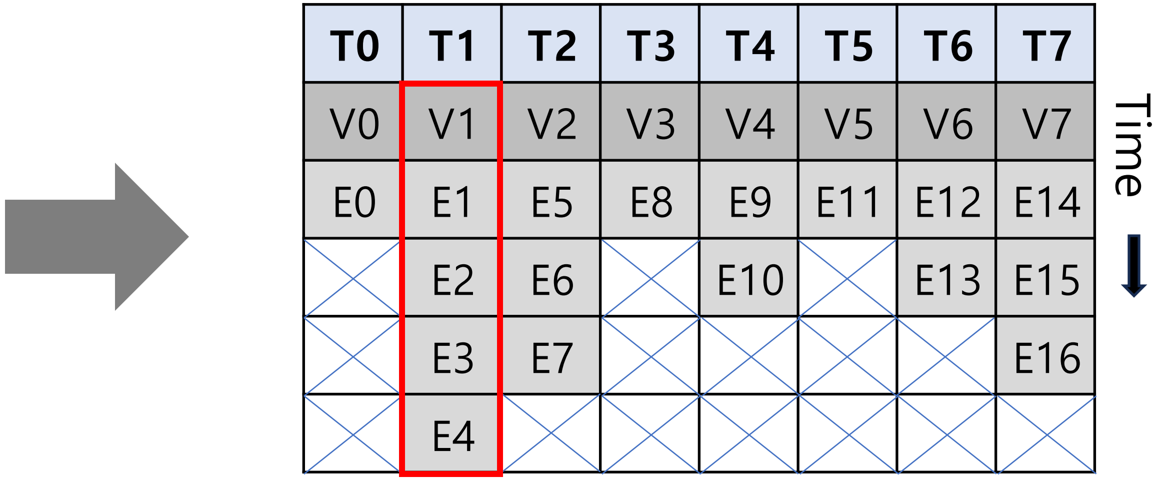
- CSR can reduce memory usage and enable neighbor list friendly access



Compressed Sparse Row (CSR) [1]

Neighbor list access friendly representation

Gather Processing on GPU



Changing Graph Representation for GPU can be a Solution

- CSR can reduce memory usage and enable neighbor list friendly access
- Graph representation affects **workload imbalance, locality, and memory access pattern**

dest id	0	1	2	3	4	5	6	7	8	9	10	11	end
offset	0	1	5	8	9	11	12	14	18	18	20	23	24

edge list	8	0	7	8	11	3	5	11	10	6	11	3	4	9	0	1	8	11	8	11	2	4	5	8

Compressed Sparse Row (CSR) [1]

Neighbor list access friendly representation

Gather Processing on GPU

T0	T1	T2	T3	T4	T5	T6	T7
V0	V1	V2	V3	V4	V5	V6	V7
E0	E1	E5	E8	E9	E11	E12	E14
	E2	E6		E10		E13	E15
	E3	E7					E16
	E4						

Time

Existing Graph Representation for GPU: G-shards

Shard 0

src id	0	3	3	0	1	2
dest id	1	2	4	7	7	10
src value	v_1	v_2	v_4	v_7	v_7	v_{10}

Shard 1

src id	7	4	6	5	4	5
dest id	1	2	5	6	10	10
src value	v_1	v_2	v_5	v_6	v_{10}	v_{10}

Shard 3

src id	8	8	11	11	10	11	9	8	11	8	11	8
dest id	0	1	1	2	3	5	6	7	7	9	9	11
src value	v_0	v_1	v_1	v_2	v_3	v_5	v_6	v_7	v_7	v_9	v_9	v_{11}

G-Shards[2]

- Achieve balanced execution
- Improve vertex value access locality
- **Cause more memory usage** than CSR

Rep	Edge Rep	Value	
		Vertex	Edge
CSR	|E| + |V| + 1	|V|	|E|
G-Shards	2|E|	|V| + |E|	|E|

[2] R. Gupta F. Khorasani et al. 2014. CuSha: Vertex-centric Graph Processing on GPUs. HPCA’14

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Existing Graph Representation for GPU: Tigr

dest id	0	1	1	2	2	3	4	5	6	7	7	8	9	10	10	11	end
offset	0	1	3	5	7	8	9	11	12	14	16	18	18	20	22	23	24

edge list	8	0	7	8	11	3	5	11	10	6	11	3	4	9	0	1	8	11	8	11	2	4	5	8

Tigr[3]

- Reduce imbalance by vertex split
- Still remain balancing opertunity
- Cause more memory usage
- Do not address vertex value access locality

Rep	Edge Rep	Value	
		Vertex	Edge
CSR	|E| + |V| + 1	|V|	|E|
G-Shards	2|E|	|V| + |E|	|E|
Tigr	|E| + (**2 + Ft**)|V|	|V|	|E|

[3] Q. Junqiao N. Sabet et al. 2018. Tigr: Transforming Irregular Graphs for GPU-Friendly Graph Processing. ASPLOS'18

Existing Graph Representation for GPU: Tigr

dest id	0	1	1	2	2	3	4	5	6	7	7	8	9	10	10	11	end
offset	0	1	3	5	7	8	9	11	12	14	16	18	18	20	22	23	24

Existing graph representation for GPUs fails to **balance workload** and to improve **locality** while **reducing memory size**

- Still remain workload imbalance
- Cause more memory usage
- Do not address vertex value access locality

Tigr	|E| + (**2 + Ft**)|V|	|V|	|E|

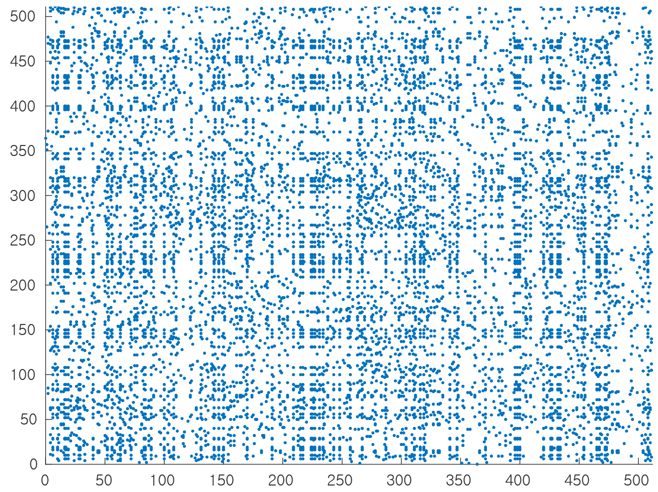
[3] Q. Junqiao N. Sabet et al. 2018. Tigr: Transforming Irregular Graphs for GPU-Friendly Graph Processing. ASPLOS'18

Need a New Graph Representation!

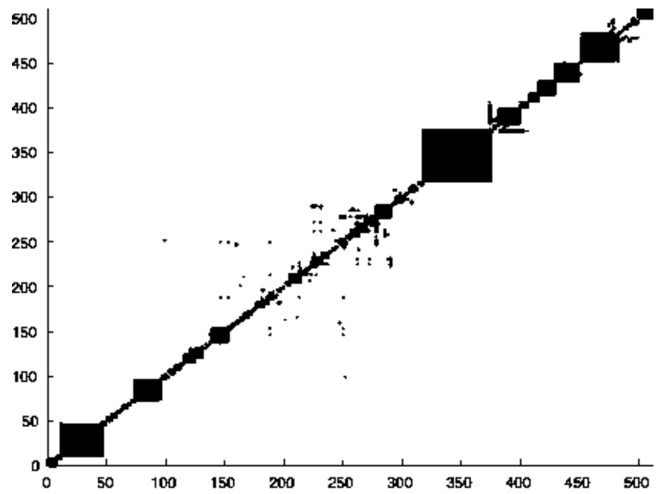
- Leverage the **high locality**
- **Minimize memory usage** to support larger graphs
- **Align with GPU architecture** to maximize performance

Observation 1: The Reordered Graph Has a Community on a Diagonal

- Most vertices are densely connected within certain groups
- With reordering algorithms, real-world graphs can be reordered in diagonal lines



Random Order

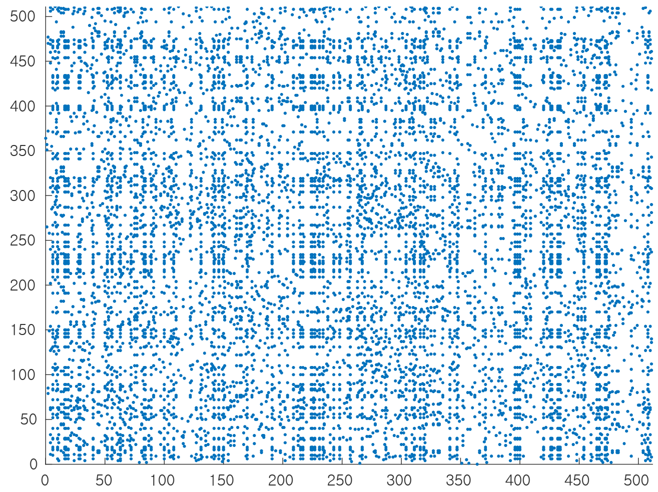


Community-based

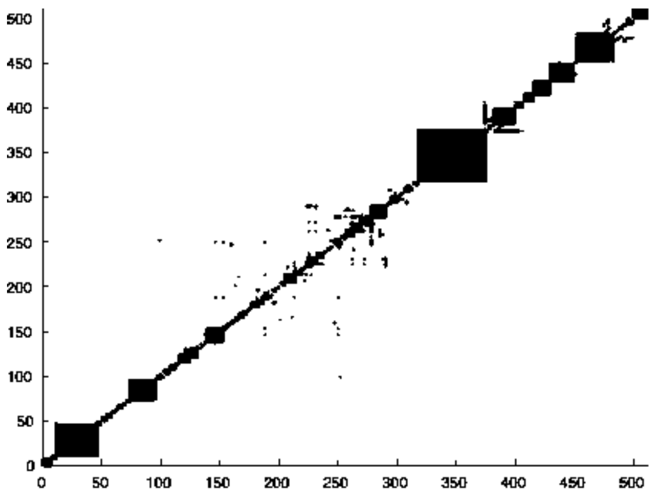
Solution 1: Community-aware Clustered Graph Representation

- Extract communities of real-world graph as clusters
- Execute edges in the same cluster on the same GPU core

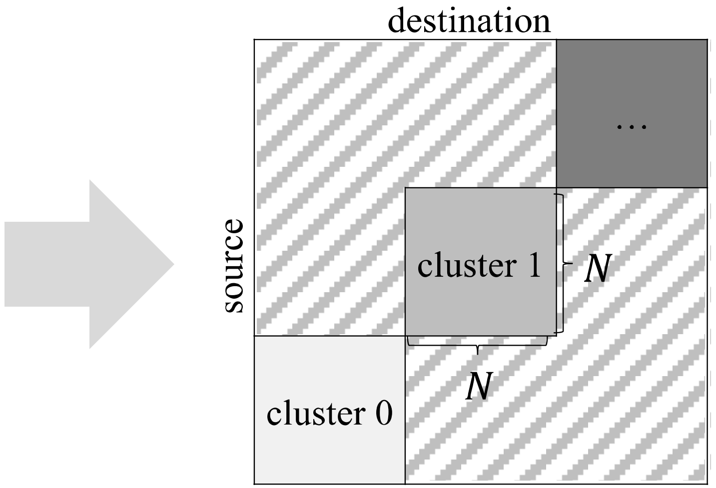
➔ CR² can **exploit the vertex locality**



Random Order



Community-based



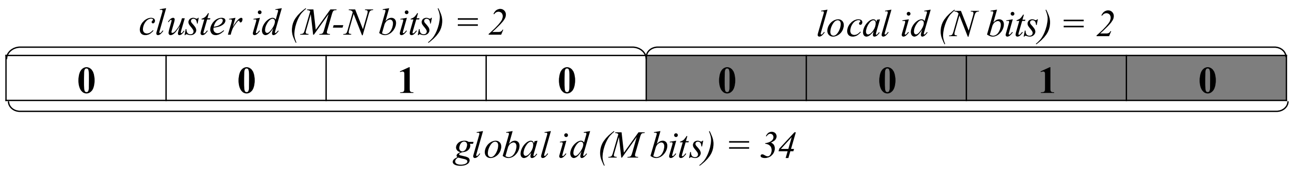
Clustering in CR²

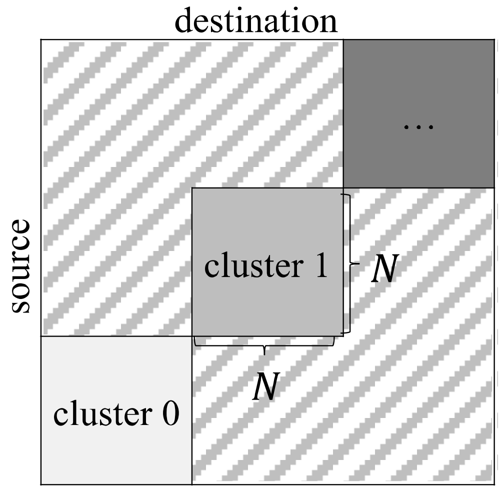
Solution 1: Community-aware Clustered Graph Representation

- Extract communities of real-world graph as clusters
- Execute edges in the same cluster on the same GPU core

➔ CR^2 can **exploit the vertex locality**

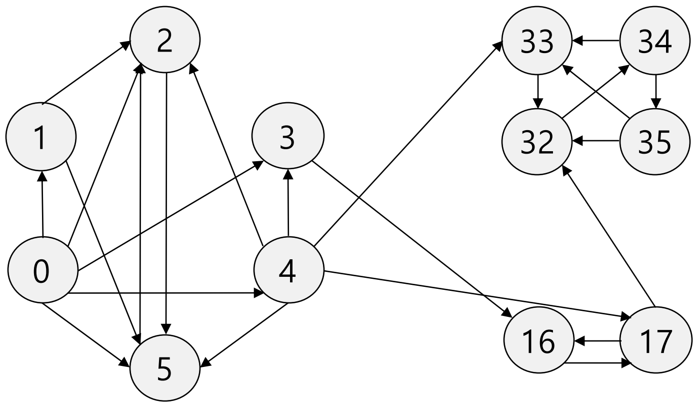
➔ **Reduce memory usage** by representing vertex id with local id





Clustering in CR^2

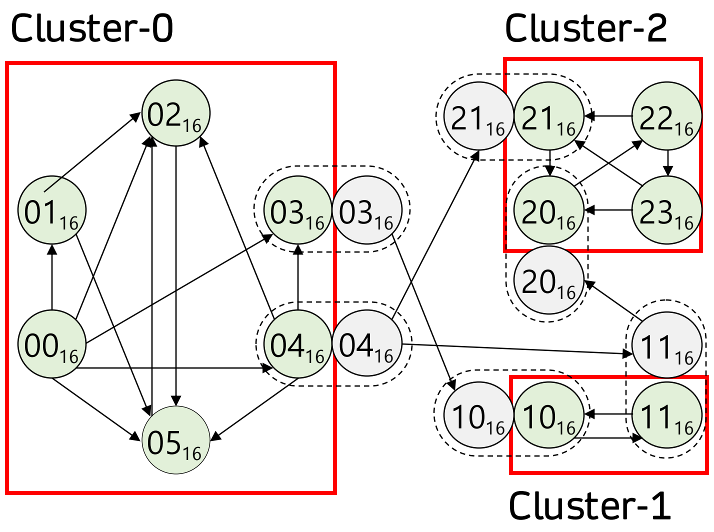
Solution 1: Community-aware Clustered Graph Representation



src id	0	1	2	3	4	5	6	…	16	17	18	…	32	33	34	35	36	…
offset_{8bit}	0	5	7	8	9	14	15	…	15	16	18	…	18	19	20	22	24	…

edge list_{8bit}																							
1	2	3	4	5	2	5	5	16	2	3	5	17	33	2	17	16	32	34	32	33	35	32	33

Make clusters to improve locality
Reduce memory usage by using local id



Cluster-0 graph

src id_{4bit}	0	1	2	4	5						
offset_{8bit}	0	5	7	8	11	12					
edge list_{4bit}	1	2	3	4	5	2	5	5	2	3	5	2

Cluster-1 graph

src id_{4bit}	0	1	
offset_{8bit}	0	1	2
edge list_{4bit}	1	0	

Cluster-2 graph

src id_{4bit}	0	1	2	3		
offset_{8bit}	0	1	2	4	6	
edge list_{4bit}	2	0	1	3	0	1

Inter-cluster graph

src id_{8bit}	3	4	17	
offset_{8bit}	0	1	3	4
edge list_{8bit}	16	33	17	32

Seperated subgraph for inter cluster

Solution 1: Community-aware Clustered Graph Representation

Cluster-0 graph

src id_{4bit}	0 1 2 4 5
$offset_{8bit}$	0 5 7 8 11 12
edge $list_{4bit}$	1 2 3 4 5 2 5 5 2 3 5 2

Cluster-1 graph

src id_{4bit}	0 1
$offset_{8bit}$	0 1 2
edge $list_{4bit}$	1 0

Cluster-2 graph

src id_{4bit}	0 1 2 3
$offset_{8bit}$	0 1 2 4 6
edge $list_{4bit}$	2 0 1 3 0 1

Inter-cluster graph

src id_{8bit}	3 4 17
$offset_{8bit}$	0 1 3 4
edge $list_{8bit}$	16 33 17 32

Gather Processing
Execute edges in the same cluster on the same GPU core

Cluster-0

T0	T1	T2	T3	T4	T5	T6	T7
0	1	2	4	5			
0	5	7	8	11			
5	7	8	11	12			
1	2	5	2	2			
2	5		3				
3			5				
4							
5							

Cluster-1

T0	T1	T2	T3	T4	T5	T6	T7
0	1						
0	1						
1	2						
1	0						

Cluster-2

T0	T1	T2	T3	T4	T5	T6	T7
0	1	2	3				
0	1	2	4				
1	2	4	6				
2	0	1	0				
		3	1				

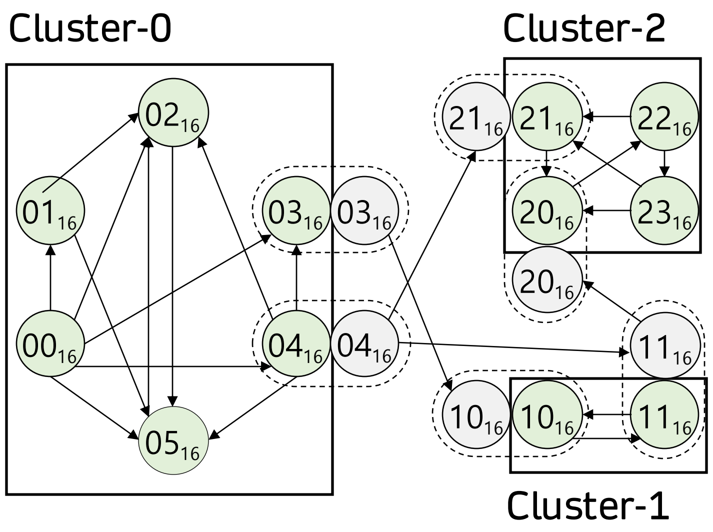
Inter-cluster

T0	T1	T2	T3	T4	T5	T6	T7
3	4	17					
0	1	3					
1	3	4					
16	33	32					
	17						

- Improve locality
- Reduce memory usage with local id
- But, **still suffered from workload imbalance**

Observation 2: Degree Regulation can Remove Offest Array

- Offset array indicates the number of neighboring edges
- If graph representation has a fixed number of edges per vertex,
  - Can remove offset array
  - Can balance workload



Cluster-0 graph

src id_{4bit}	0	1	2	4	5							
$offset_{8bit}$	0	5	7	8	11	12						
edge $list_{4bit}$	1	2	3	4	5	2	5	5	2	3	5	2

Cluster-1 graph

src id_{4bit}	0	1	
$offset_{8bit}$	0	1	2
edge $list_{4bit}$	1	0	

Cluster-2 graph

src id_{4bit}	0	1	2	3		
$offset_{8bit}$	0	1	2	4	6	
edge $list_{4bit}$	2	0	1	3	0	1

Inter-cluster graph

src id_{8bit}	3	4	17	
$offset_{8bit}$	0	1	3	4
edge $list_{8bit}$	16	33	17	32

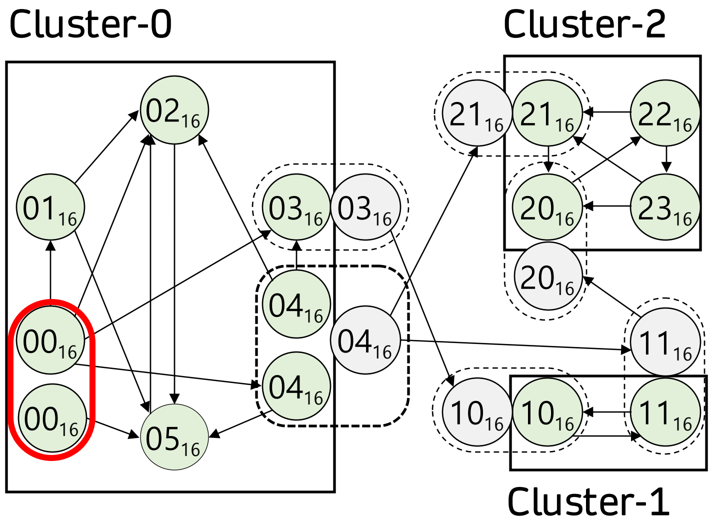
Solution 2: Degree-ordered Subgraph

- Partition the graph into multiple degree-ordered subgraphs in which all the vertices have the **Degree-n regularized number of edges**
- Enable **fine-grained workload balancing** across GPU warps with less memory usage

Degree-1	E0															
Degree-2	E1	E2														
Degree-4	E3	E4	E5	E6												
Degree-8	E7	E8	E9	E10	E11	E12	E13	E14								
Degree-16	E15	E16	E17	E18	E19	E20	E21	E22	E23	E24	E25	E26	E27	E28	E19	E30

⋮

Solution 2: Degree-ordered Subgraph



Cluster-0 graph

src id_{4bit}	0	0	1	2	4	4	5											
$offset_{8bit}$	0	4	5	7	8	10	11	12										
edge $list_{4bit}$	1	2	3	4	5	2	5	5	2	3	5	2						

Cluster-1 graph

src id_{4bit}	0	1	
$offset_{8bit}$	0	1	2
edge $list_{4bit}$	1	0	

Cluster-2 graph

src id_{4bit}	0	1	2	3		
$offset_{8bit}$	0	1	2	4	6	
edge $list_{4bit}$	2	0	1	3	0	1

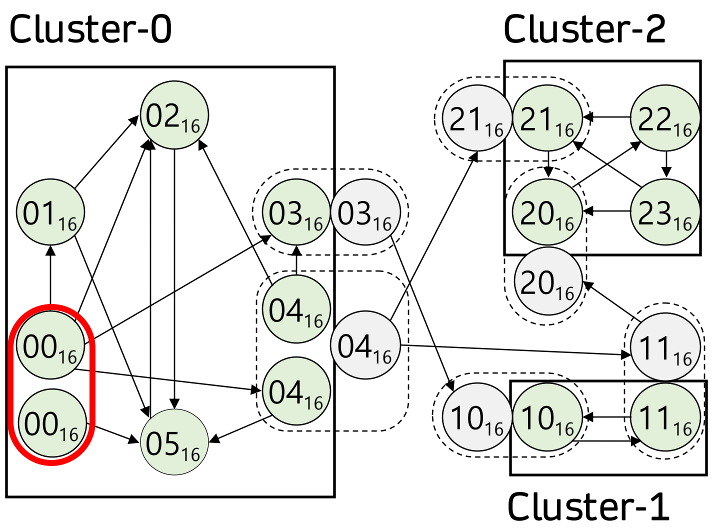
Inter-cluster graph

src id_{8bit}	3	4	17	
$offset_{8bit}$	0	1	3	4
edge $list_{8bit}$	16	33	17	32

Vertex-split graph & representation

Split vertex to make it a power-of-two

Solution: CR² Representation



Cluster-0 graph

src id$_{4bit}$	0	0	1	2	4	4	5					
offset$_{8bit}$	0	4	5	7	8	10	11	12				
edge list$_{4bit}$	1	2	3	4	5	2	5	5	2	3	5	2

Cluster-1 graph

src id$_{4bit}$	0	1	
offset$_{8bit}$	0	1	2
edge list$_{4bit}$	1	0	

Cluster-2 graph

src id$_{4bit}$	0	1	2	3		
offset$_{8bit}$	0	1	2	4	6	
edge list$_{4bit}$	2	0	1	3	0	1

Inter-cluster graph

src id$_{8bit}$	3	4	17	
offset$_{8bit}$	0	1	3	4
edge list$_{8bit}$	16	33	17	32

Remove offset array & Generate Degree-n Subgraph

Cluster-0 degree-4

src id$_{4bit}$	0			
edge list$_{4bit}$	1	2	3	4

Cluster-0 degree-2

src id$_{4bit}$	1	4		
edge list$_{4bit}$	2	5	2	3

Cluster-0 degree-1

src id$_{4bit}$	0	2	4	5
edge list$_{4bit}$	5	5	5	2

Cluster-1 degree-1

src id$_{4bit}$	0	1
edge list$_{4bit}$	1	0

Cluster-0 degree-2

src id$_{4bit}$	2	3		
edge list$_{4bit}$	1	3	0	1

Cluster-2 degree-1

src id$_{4bit}$	0	1
edge list$_{4bit}$	2	0

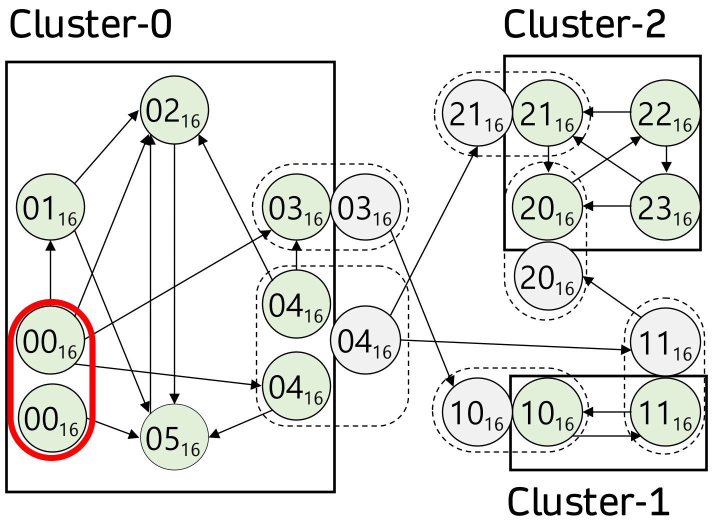
Inter-Cluster degree-1

src id$_{8bit}$	4	
edge list$_{8bit}$	33	17

Inter-Cluster degree-1

src id$_{8bit}$	3	17
edge list$_{8bit}$	16	32

Solution: CR² Representation



Cluster-0 graph

- src id_{4bit}: 0 0 1 2 4 4 5
- $offset_{8bit}$: 0 4 5 7 8 10 11 12
- edge $list_{4bit}$: 1 2 3 4 5 2 5 5 2 3 5 2

Cluster-1 graph

- src id_{4bit}: 0 1
- $offset_{8bit}$: 0 1 2
- edge $list_{4bit}$: 1 0

Cluster-2 graph

- src id_{4bit}: 0 1 2 3
- $offset_{8bit}$: 0 1 2 4 6
- edge $list_{4bit}$: 2 0 1 3 0 1

Inter-cluster graph

- src id_{8bit}: 3 4 17
- $offset_{8bit}$: 0 1 3 4
- edge $list_{8bit}$: 16 33 17 32

Remove offset array & Generate Degree-n Subgraph

Cluster-0 degree-4

- src id_{4bit}: 0
- edge $list_{4bit}$: 1 2 3 4

Cluster-0 degree-2

- src id_{4bit}: 1 4
- edge $list_{4bit}$: 2 5 2 3

Cluster-0 degree-1

- src id_{4bit}: 0 2 4 5
- edge $list_{4bit}$: 5 5 5 2

Cluster-1 degree-1

- src id_{4bit}: 0 1
- edge $list_{4bit}$: 1 0

Cluster-0 degree-2

- src id_{4bit}: 2 3
- edge $list_{4bit}$: 1 3 0 1

Cluster-2 degree-1

- src id_{4bit}: 0 1
- edge $list_{4bit}$: 2 0

Inter-Cluster degree-1

- src id_{8bit}: 4
- edge $list_{8bit}$: 33 17

Inter-Cluster degree-1

- src id_{8bit}: 3 17
- edge $list_{8bit}$: 16 32

- High locality
- Minimize memory usage
- Align with GPU architecture

Solution: CR^2 Representation

Cluster-0 degree-4
src id$_{4bit}$: 0
edge list$_{4bit}$: 1 | 2 | 3 | 4

Cluster-0 degree-2
src id$_{4bit}$: 1 | 4
edge list$_{4bit}$: 2 | 5 | 2 | 3

Cluster-0 degree-1
src id$_{4bit}$: 0 | 2 | 4 | 5
edge list$_{4bit}$: 5 | 5 | 5 | 2

Cluster-1 degree-1
src id$_{4bit}$: 0 | 1
edge list$_{4bit}$: 1 | 0

Cluster-0 degree-2
src id$_{4bit}$: 2 | 3
edge list$_{4bit}$: 1 | 3 | 0 | 1

Cluster-2 degree-1
src id$_{4bit}$: 0 | 1
edge list$_{4bit}$: 2 | 0

Inter-Cluster degree-1
src id$_{8bit}$: 4
edge list$_{8bit}$: 33 | 17

Inter-Cluster degree-1
src id$_{8bit}$: 3 | 17
edge list$_{8bit}$: 16 | 32

Gather Processing

Intra-Cluster Execution

Degree-4 Execution

T0	T1	T2	T3	T4	T5	T6	T7
0	0	0	0				
1	2	3	4				

Degree-2 Execution

T0	T1	T2	T3	T4	T5	T6	T7
1	1	4	4	2	2	3	3
2	5	2	3	1	3	0	1

Degree-1 Execution

T0	T1	T2	T3	T4	T5	T6	T7
0	2	4	5	0	1	0	1
5	5	5	2	1	0	2	0

Execute the degree-n subgraphs of each cluster simultaneously

Inter-Cluster Execution

Degree-4 Execution

T0	T1	T2	T3	T4	T5	T6	T7

Degree-2 Execution

T0	T1	T2	T3	T4	T5	T6	T7
4	4						
33	17						

Degree-1 Execution

T0	T1	T2	T3	T4	T5	T6	T7
3	17						
16	32						

Solution: CR² Representation

Cluster-0 degree-4
src id$_{4bit}$: 0
edge list$_{4bit}$: 1 2 3 4

Cluster-0 degree-2
src id$_{4bit}$: 1 4
edge list$_{4bit}$: 2 5 2 3

Cluster-0 degree-1
src id$_{4bit}$: 0 2 4 5
edge list$_{4bit}$: 5 5 5 2

Cluster-1 degree-1
src id$_{4bit}$: 0 1
edge list$_{4bit}$: 1 0

Cluster-0 degree-2
src id$_{4bit}$: 2 3
edge list$_{4bit}$: 1 3 0 1

Cluster-2 degree-1
src id$_{4bit}$: 0 1
edge list$_{4bit}$: 2 0

Inter-Cluster degree-1
src id$_{8bit}$: 4
edge list$_{8bit}$: 33 17

Inter-Cluster degree-1
src id$_{8bit}$: 3 17
edge list$_{8bit}$: 16 32

Gather Processing

Intra-Cluster Execution

Degree-4 Execution

T0	T1	T2	T3	T4	T5	T6	T7
0	0	0	0				
1	2	3	4				

Degree-2 Execution

T0	T1	T2	T3	T4	T5	T6	T7
1	1	4	4	2	2	3	3
2	5	2	3	1	3	0	1

Degree-1 Execution

T0	T1	T2	T3	T4	T5	T6	T7
0	2	4	5	0	1	0	1
5	5	5	2	1	0	2	0

Inter-Cluster Execution

Degree-4 Execution

T0	T1	T2	T3	T4	T5	T6	T7

Degree-2 Execution

T0	T1	T2	T3	T4	T5	T6	T7
4	4						
33	17						

Degree-1 Execution

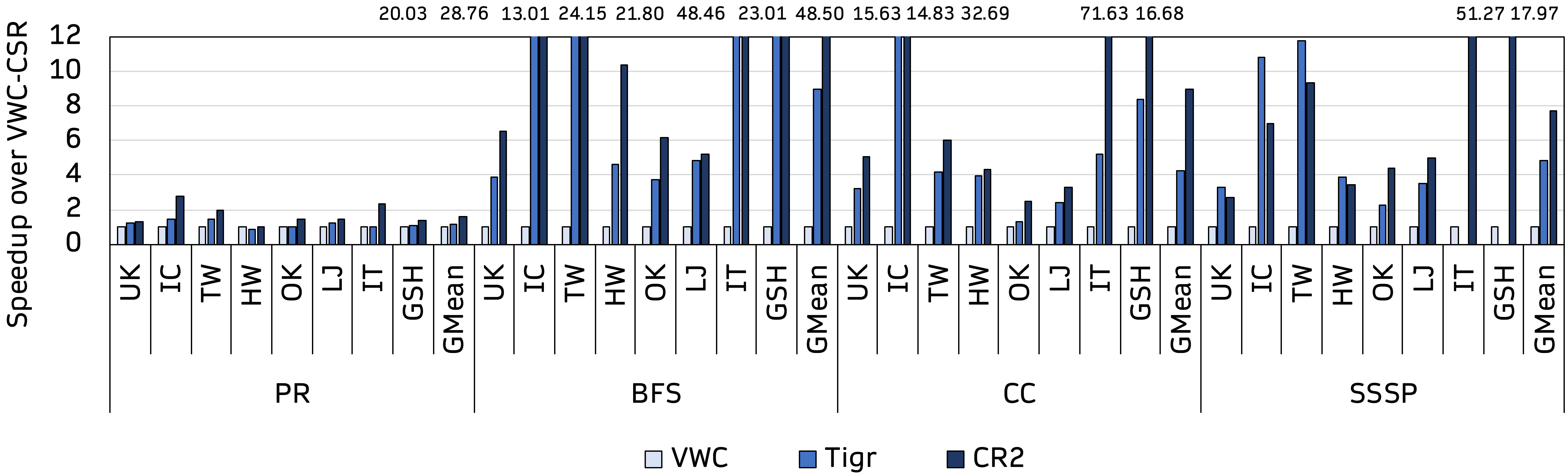
T0	T1	T2	T3	T4	T5	T6	T7
3	17						
16	32						

CSR Execution

T0	T1	T2	T3	T4	T5	T6	T7
0	5	7	8	9	14	15	15
5	7	8	9	14	15	15	15
1	2	5	5	2	2		
2	5			3			
3				5			
4				17			
5				33			
15	15	15	15	15	15	15	15
15	15	15	15	15	15	15	15
15	16	18	18	18	18	18	18
16	18	18	18	18	18	18	18
17	16						
	32						
18	18	18	18	18	18	18	18
18	18	18	18	18	18	18	18
18	19	20	22				
19	20	22	24				
34	32	33	32				
		35	33				

Overall Performance

- Achieve **6.47**x and **1.55**x performance geomean speedup compared to VWC-CSR and Tigr
- Use NVIDIA Geforce RTX 3090
- Use Four graph algorithms: PageRank(PR), Breadth-First Search(BFS), Connected Components(CC), and Single Source Shortest Path(SSSP)



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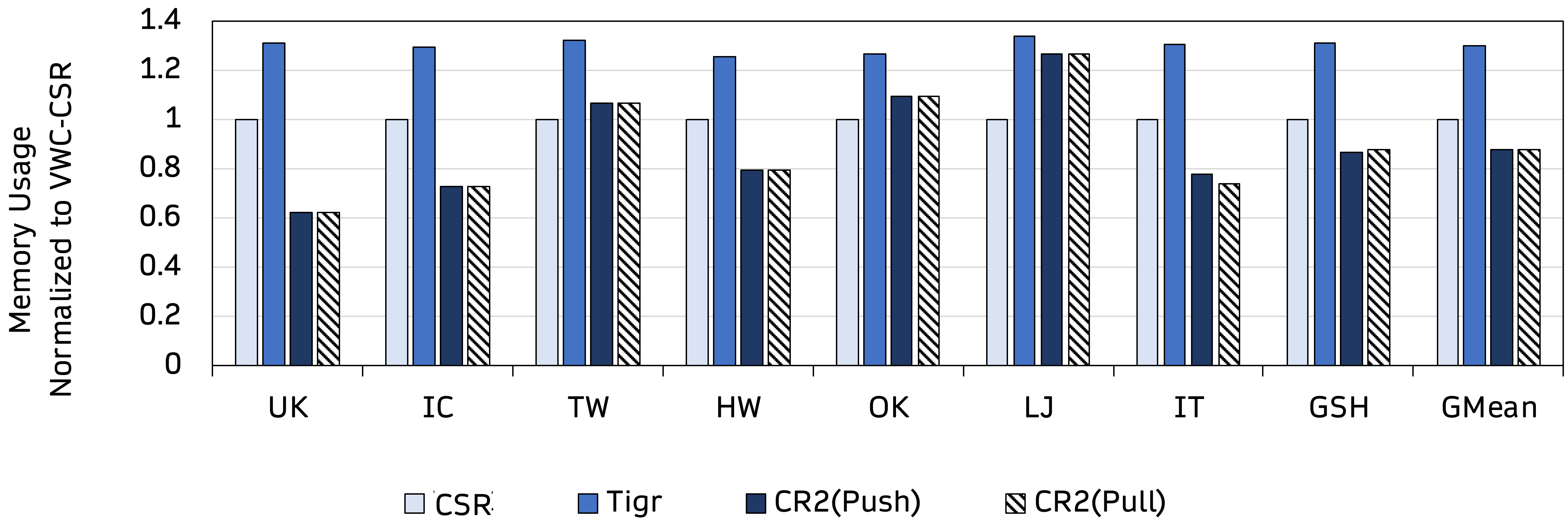
Memory Usage

- Achieve **12.3**% and **32.2**% less memory on geomean average compared with CSR and Tigr



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Conclusion

- This work proposes a new graph representation called **CR²**
- Based on two key solution,
  - Community-aware clustered subgraph
  - Degree-ordered subgraphs with vertex degree regulation

- CR² enhance graph processing on GPU by,
  - Improving locality
  - Minimizing memory usage
  - Aligning with GPU architecture

- Achieve 1.53 times performance speedup while using 32.1% less memory on the geomean average compared to the state-of-the-art techniques

Thank you 😊

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