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SGV: Spatial Graph Visualization

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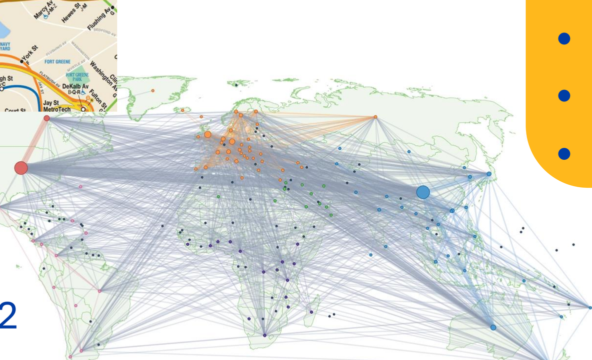
Background and Motivation

New York City Subway Map



Collaboration Network of Geoscience in 2022

Spatial Graph Visualization:

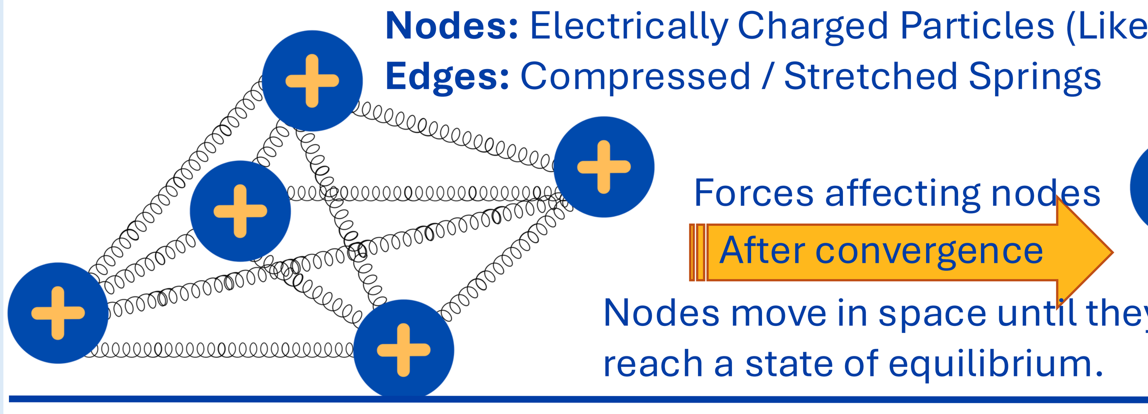
The **underlying space information** is also important. **Examples:**

- Railroad network
- Social Media Network
- Acaedemic Collaboration Network

Spatial Graph Model:
Nodes : Associated with geographic information.
Edges: Undirected – Only Show Connectivity

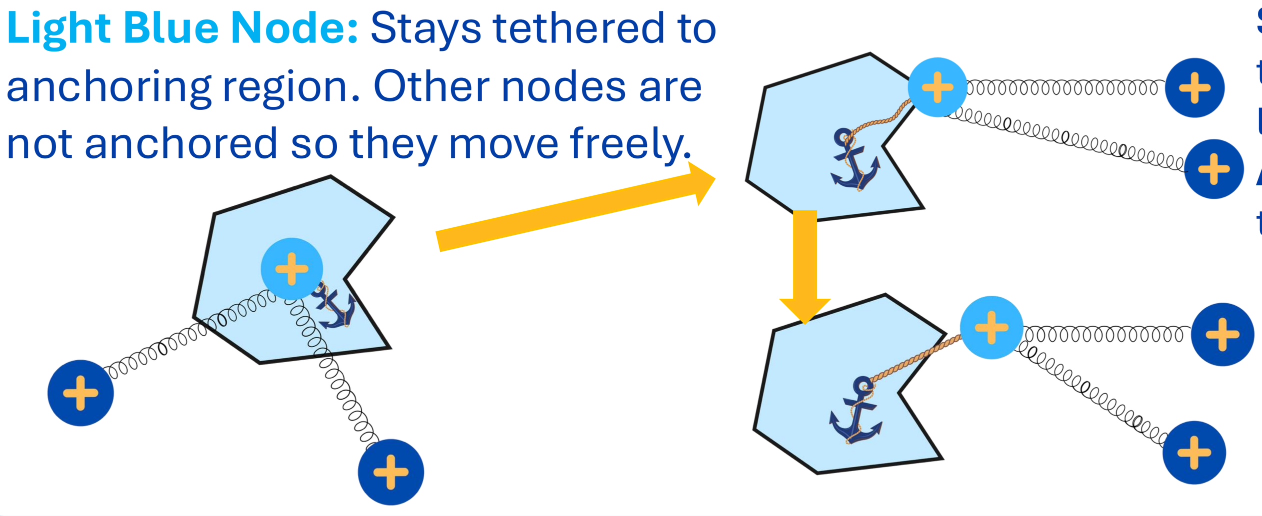
Force Directed Graph Model:

Nodes: Electrically Charged Particles (Like-charged)
Edges: Compressed / Stretched Springs



Nodes move in space until they reach a state of equilibrium.

Light Blue Node: Stays tethered to anchoring region. Other nodes are not anchored so they move freely.



Spatial Graph: Nodes have a true geographic location. In final layout, should not move too far. **Anchoring force** keeps nodes tethered to anchor regions.

Anchor Region Types:

- Point
- Linestring
- Polygon
- Multi-point

Relational Query Modeling

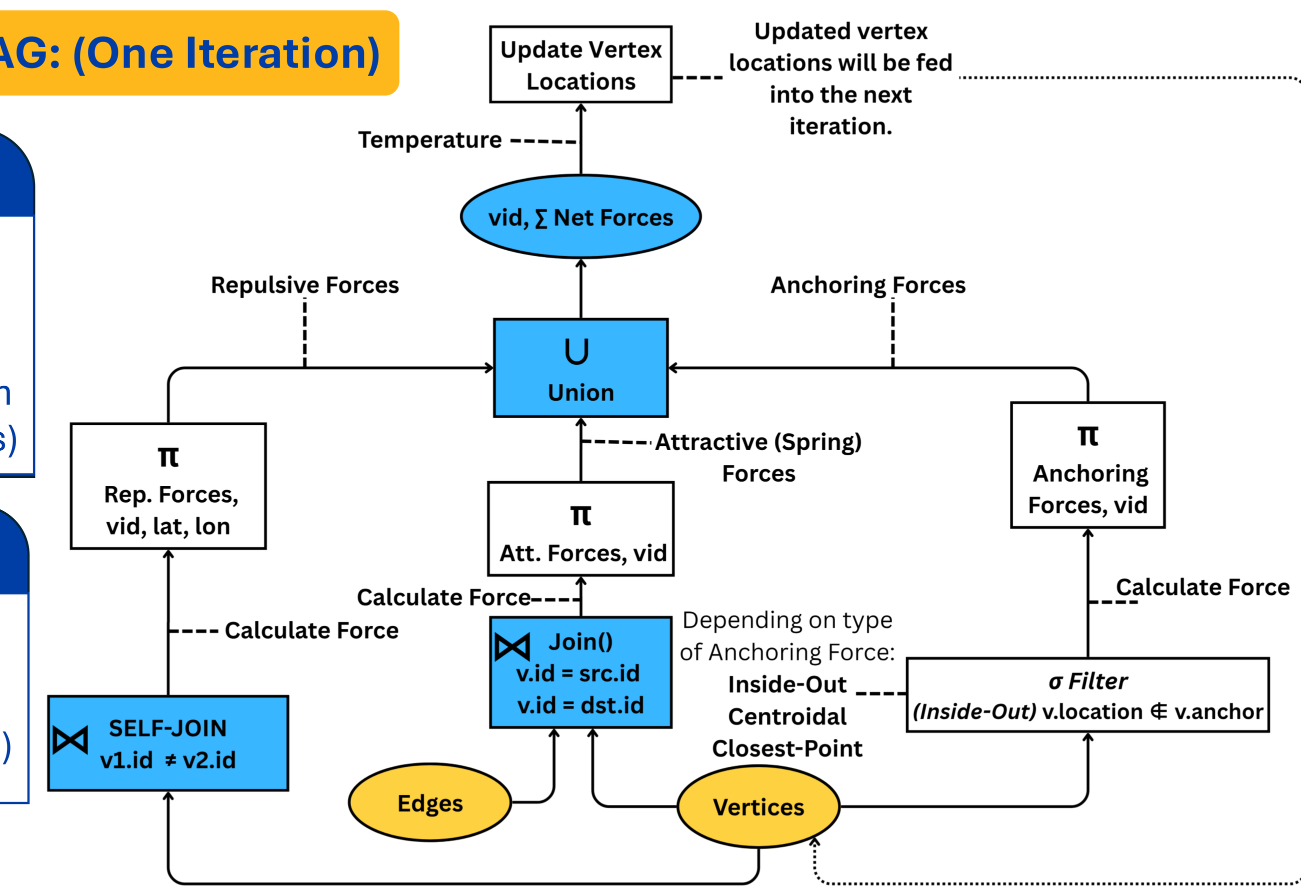
Relational Query DAG: (One Iteration)

Vertices

vertex_id	*int*
lat	float
lon	float
anchor	geom
(optional extra attributes)	

Edges

src_id	*int*
dst_id	*int*
(optional extra attributes)	



Attractive Forces:
JOIN: Edges ⋈ Vertices → Spring force alpha L (ideal spring length) applied to both dst and src vertices.
Repulsive Forces:
SPATIAL SELF-JOIN: Vertices ⋈ Vertices (within theta) → Repulsive force applied to both vertices.
Anchoring Forces:
VERTICES → pull-to-anchor (centroid / closest-point) (**σ** Filter inside-out: skip if inside region) → per-vertex f
Net Force Aggregation:
∪ **UNION ALL** (attractive, repulsive, anchoring) → Σ by vid → F_{total} → Updater

Method

Force Formulas:

Three types of forces between nodes:

Attractive (Spring) Forces:

$$\mathbf{F}^{\mathrm{att}}_{u\leftarrow v} = -\frac{d}{L}\Delta\mathbf{r}_{uv},$$

Repulsive Forces:

$$d^2 = \max\left(\|\mathbf{r}_{uv}\|^2,\ \varepsilon^2\right), \qquad \mathbf{F}^{\mathrm{rep}}_{u\leftarrow v} = c_{\mathrm{rep}}\frac{\mathbf{r}_{uv}}{d^2}.$$

$$\mathbf{F}^{\mathrm{rep}}_{i} = \sum_{j\in\mathcal{N}_r(i)} c_{\mathrm{rep}}\frac{\mathbf{p}_i-\mathbf{p}_j}{\max(\|\mathbf{p}_i-\mathbf{p}_j\|^2,\varepsilon^2)}.$$

Anchoring Forces:

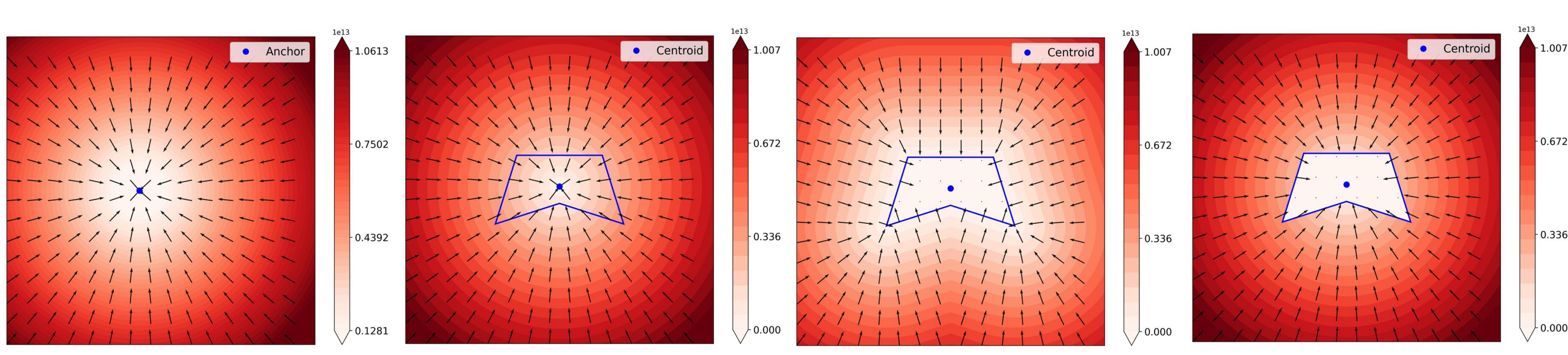
$$\mu(A_u) = \begin{cases} 1, & A_u \text{ is a point,} \\ |A_u|, & A_u \text{ is a finite set of points,} \\ \mathrm{Length}(A_u), & A_u \text{ is a linestring,} \\ \mathrm{Area}(A_u), & A_u \text{ is a polygon,} \end{cases}$$

$$\mathbf{c}_u = \frac{1}{\mu(A_u)}\int_{A_u}\mathbf{x}\,d\mu(\mathbf{x}), \quad \mathbf{p}_u = \arg\min_{\mathbf{y}\in A_u}\|\mathbf{r}_u-\mathbf{y}\|.$$

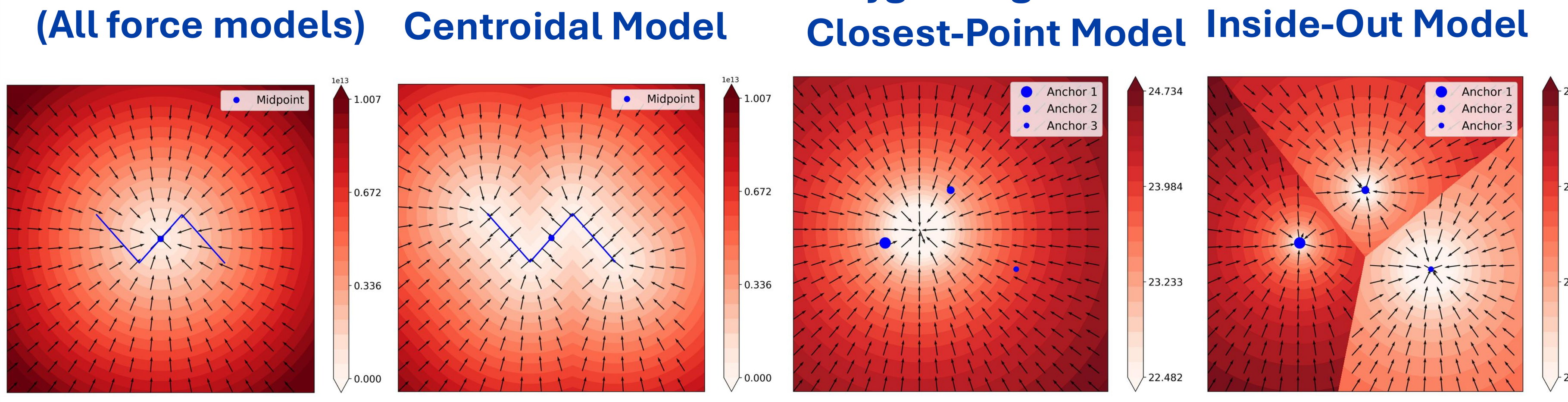
Anchoring Force Models:

- Centroidal: $\mathbf{F}^{\mathrm{anchor}}_u = \alpha\left(\mathbf{c}_u - \mathbf{r}_u\right).$
- Inside-Out: $\mathbf{F}^{\mathrm{anchor}}_u = \begin{cases} \alpha\left(\mathbf{c}_u-\mathbf{r}_u\right), & \mathbf{r}_u \notin A_u, \\ \mathbf{0}, & \mathbf{r}_u \in A_u. \end{cases}$
- Closest-Point: $\mathbf{F}^{\mathrm{anchor}}_u = \begin{cases} \alpha\left(\mathbf{p}_u-\mathbf{r}_u\right), & \mathbf{r}_u \notin A_u, \\ \mathbf{0}, & \mathbf{r}_u \in A_u. \end{cases}$

Anchoring Force Fields:



Point Region (All force models) | Polygon Region Centroidal Model | Polygon Region Closest-Point Model | Polygon Region Inside-Out Model



Linestring Region Centroidal Model | Linestring Region Closest-Point Model | Multi-point Region Centroidal Model | Multi-point Region Closest-Point Model

Scalability:

Problem: Spatial Graphs can grow arbitrarily large
Naïve Calculation of Repulsive forces between all nodes: O(N²) → Bottleneck
Spark SQL: Parallelize the computations in distributed form → Increases Scalability

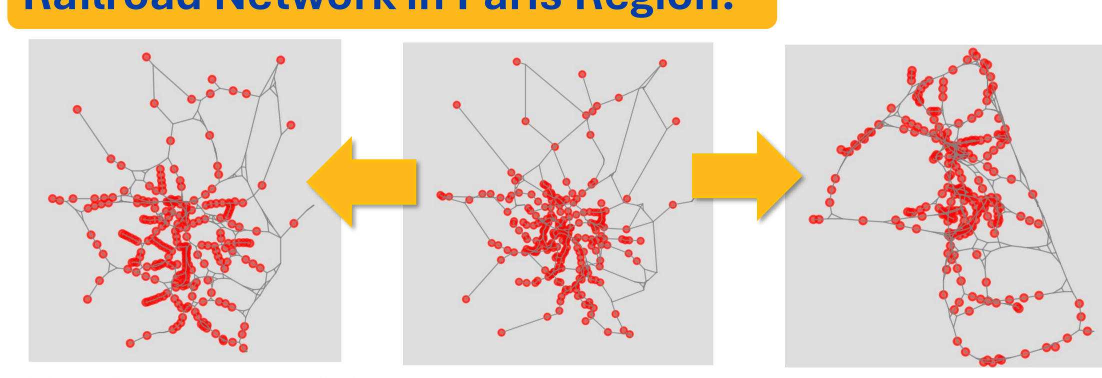
Future Work:
Use a Spatial Index (QuadTree partitioning of the space) and approximate effect of nodes that are further than the **distance threshold theta**. Based on well-separated pairs.

Related Work:

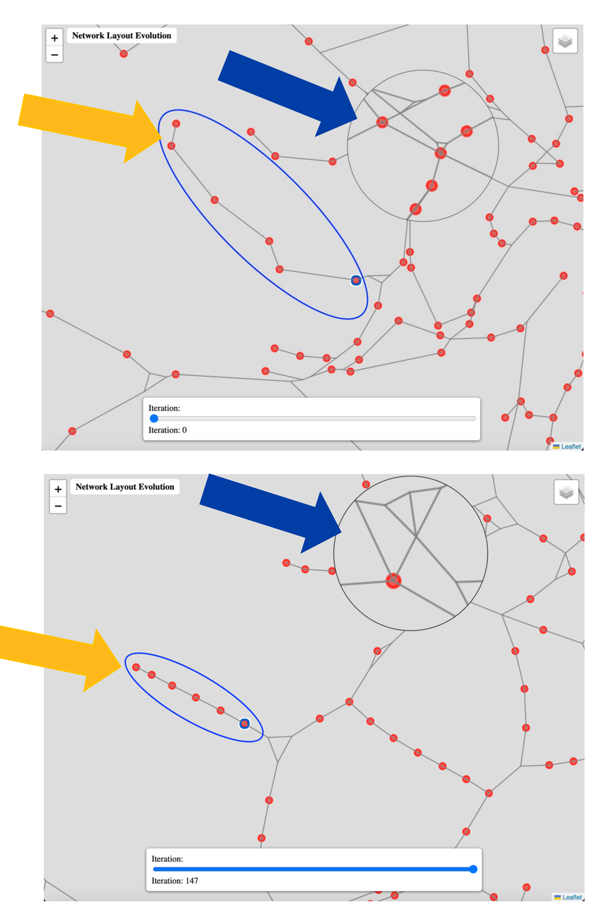
Polygonally Anchored Graph Drawing (Extended Abstract) (Chiu et al – 2024)
Well Separated Pair Decomposition (Chan - 2008)
A Potential-Field-Based Multilevel Algorithm for Drawing Large Graphs. (Hachul – 2005)

Use Cases

Railroad Network in Paris Region:

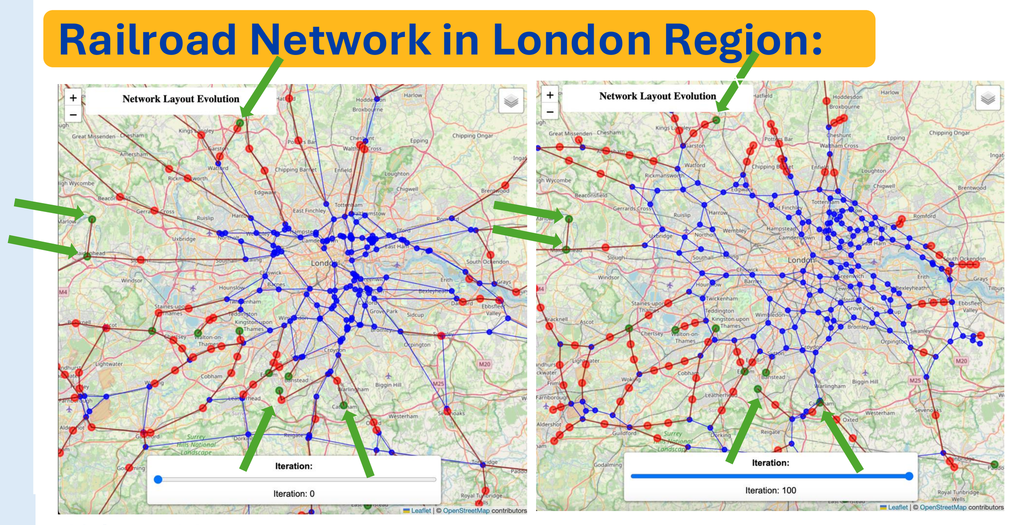


After Convergence (With Anchoring Forces) | Initial Layout | After Convergence (Without Anchoring Forces)



Zoomed in – Railroad network in Paris: Before (Top) vs After (Bottom) Convergence – Using Anchoring Forces. More **homogenous edge lengths** and **increased layout legibility**

Railroad Network in London Region:



A) Initial Layout | B) After Convergence (With Anchoring Forces)

Green Nodes: Main stations

Strong Anchoring Forces → Nodes stay tethered to their true geographic locations.

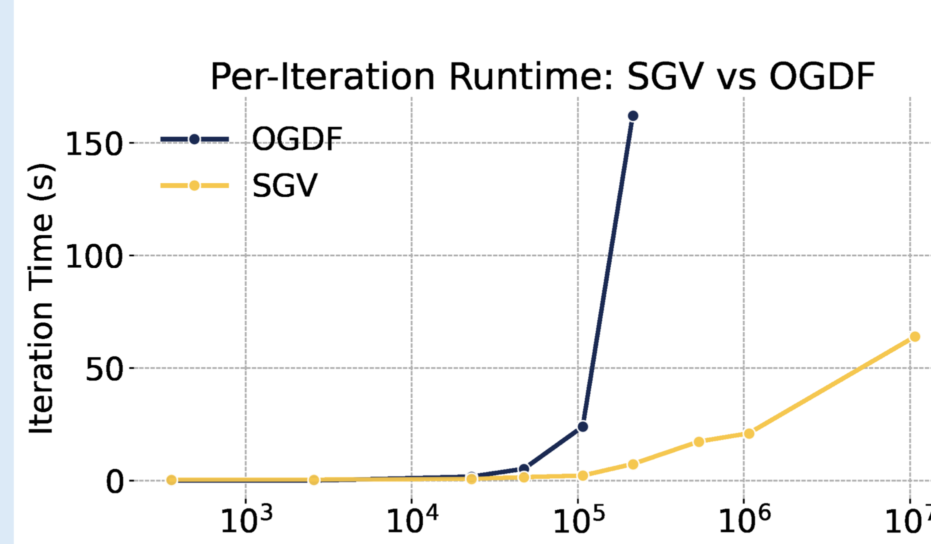
Results and Conclusion

Experiment Setup:

We conducted experiments on a 12-node Spark cluster. The master node has two 8-core Intel Xeon E5-2609 v4 (1.7 GHz) CPUs and 128 GB RAM; each worker has two 6-core Xeon E5-2603 v4 CPUs and 64 GB RAM. All nodes run CentOS 7.5 with local SSDs for the OS and HDDs for data.

Dataset	# Vertices	# Edges
Gowalla Subset	22,803	381,384
Gowalla	107,092	913,660
Gowalla x2	214,184	1,827,320
Gowalla x5	535,460	4,568,300
Gowalla x10	1,070,920	9,136,600
Gowalla x 100	10,709,200	91,366,000

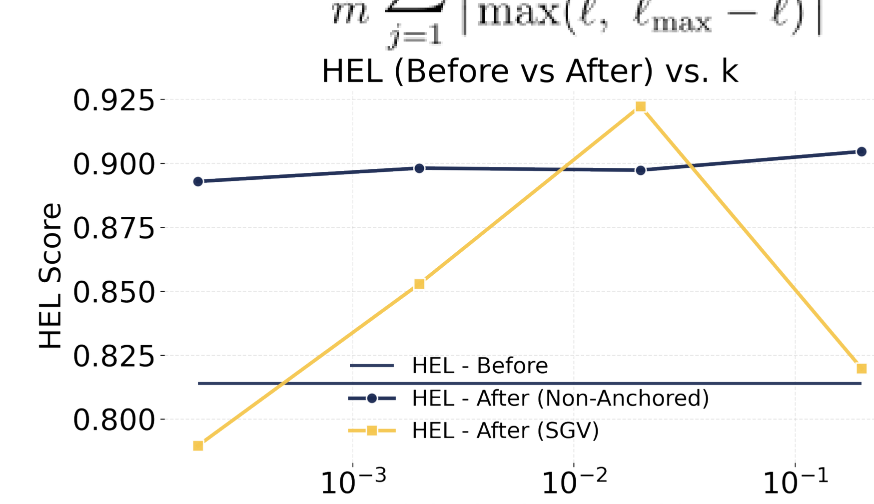
Goal: find a balance between **edge length homogeneity** and **average distance from anchor** of nodes in final layout.



Evaluation Metrics:

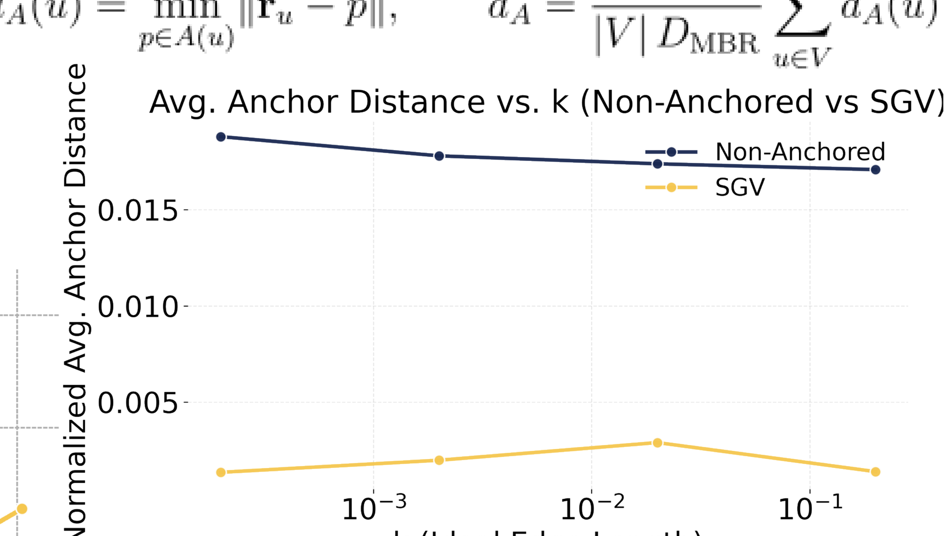
HEL: *(Homogenous Edge Lengths)*
Higher value is desired

$$\mathrm{HEL} = 1 - \frac{1}{m}\sum_{j=1}^{m}\left|\frac{\ell_j-\bar{\ell}}{\max(\bar{\ell},\ \ell_{\max}-\bar{\ell})}\right|$$



NAD: *(Normalized Anchor Distance)*
Lower value is desired

$$d_A(u) = \min_{p\in A(u)}\|\mathbf{r}_u - p\|, \qquad \tilde{d}_A = \frac{1}{|V|\,D_{\mathrm{MBR}}}\sum_{u\in V} d_A(u)$$



LEARN MORE:
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