Revisiting Link Prioritization for Efficient Traversal in Structured Decentralized Environments

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October 14, 2025

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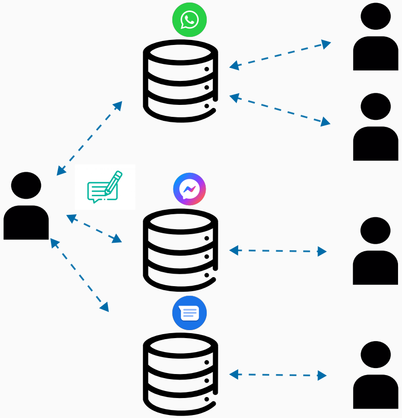
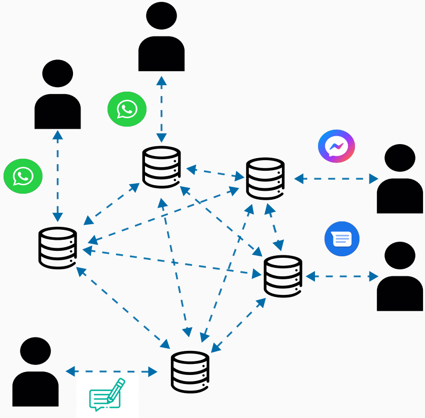
The Need for Decentralized Personal Data Storage



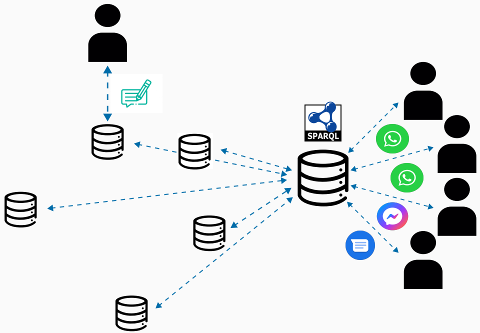
- Each application has its own data
- Stifles innovation
- Causes vendor lock-in

The Need for Decentralized Personal Data Storage



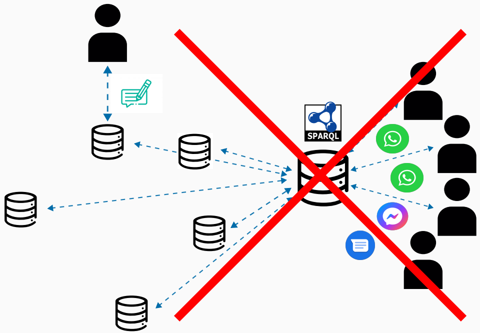
- Each application uses common data storage
- Easy to switch vendors
- Promotes innovation

The Problem with Centrally Aggregating and Querying



- Why not aggregate data and query it?
- Impossible in case of personal data due to privacy concerns

The Problem with Centrally Aggregating and Querying



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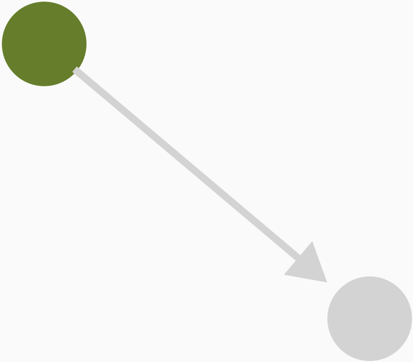
Link Traversal-based Query Processing

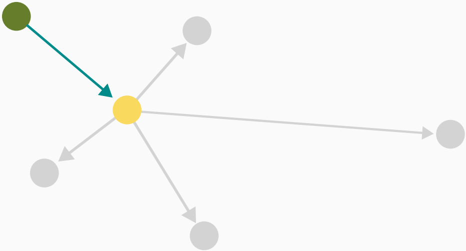
- Link Traversal iteratively dereferences data to query over
- Continuously produces results
- Can enforce fine-grained (document-level) access-control

Link Traversal: Seed Document

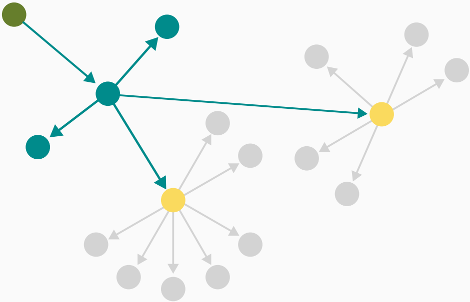


- Link Traversal starts from seed documents (URIs)
- These are provided by the user or in the query.

Link Traversal: Traversal

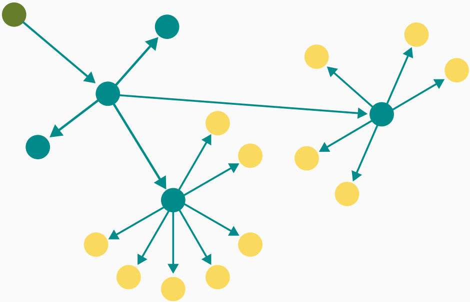


- New URIs are extracted from the seed document
- URIs are extracted in accordance with reachability criterions



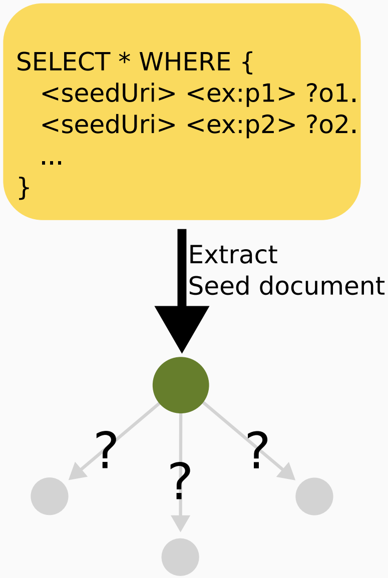
- New URIs are dereferenced and the process is repeated

Link Traversal: Termination



- This continues untill all links are dereferenced

Query Optimization for Link Traversal

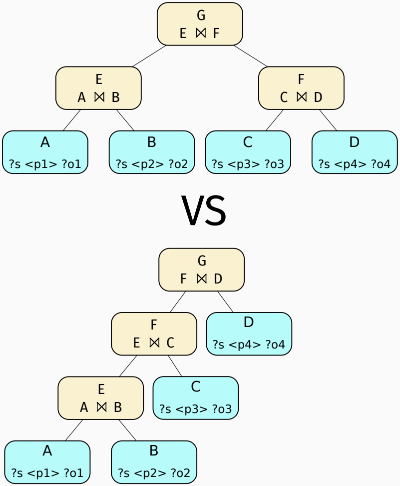


The query (partly) determines:

- The queried data
- The topology of the queried data
- The query-relevant documents

Result: limited prior knowledge for query optimization

Query Optimization for Link Traversal: Traditional Query Planning

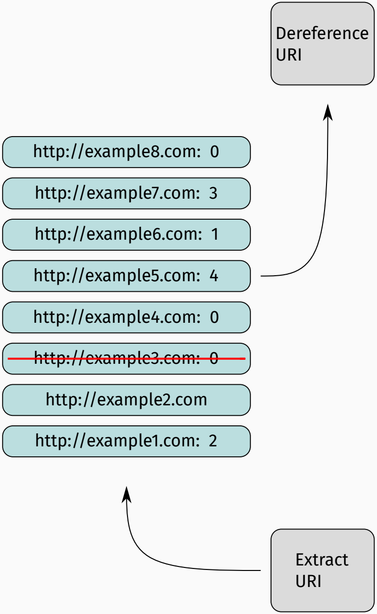


- Query optimization for link traversal involves traditional (zero knowledge) query planning

Query Optimization for Link Traversal: Traversal optimization

- URIs are put into a link queue
- Link traversal uses a FiFo queue by default

Query Optimization for Link Traversal: Traversal optimization



Optimizations:

- Prioritize query-relevant URIs
- Prune irrelevant URIs
- Pruning can lead to missing results without prior knowledge

Problem Statement

Investigate the performance of link prioritization algorithms in literature in new structured decentralized environments

Problem Statement

- These algorithms are implemented in an engine that is no longer maintained
- The baseline performance depends on design choices orthogonal to the prioritization algorithm
- The baseline should measure marginal prioritization performance

R^3 metric: Motivation

Context
During link traversal, the engine traverses a fixed topology entirely

Goal
The goal of prioritization is to find query-relevant (where-provenance) documents as soon as possible.

Challenge
Find the optimal traversal order of a given query in hindsight to compare the traversal order taken by the engine to.

R^3 metric: Steiner trees

- Directed graph steiner tree over traversed directed graph $\mathrm{G} = (\mathrm{V}, \mathrm{A})$ with root r
- Query-relevant documents $\mathrm{D_T}$ serve as terminals $\mathrm{T} \subseteq \mathrm{V}$
- Find minimum cost sub-graph $\mathrm{X} = (\mathrm{V}', \mathrm{A}')$ starting at root r and spanning all vertexes T.
- With cost: $\mathrm{C(X)} = \sum_{\mathrm{a} \in \mathrm{A}'} \mathrm{c(a)}$,, with c(a) the cost of an edge in the topology

R^3 metric

Definition

$$R^3 = \frac{C(X)}{C(O_{\mathcal{T}})}$$

- X: the optimal traversal order (minimal-cost path)
- $O_{\mathcal{T}}$: traversal order produced by the link prioritization algorithm
- $C(\cdot)$: The total cost of all arcs in the traversal path

Interpretation

- $R^3 = 1$ perfect match with the optimal traversal
- $R^3 < 1$ deviation from optimal performance
- Higher values indicate better prioritization quality.

R^3 Metric Illustration

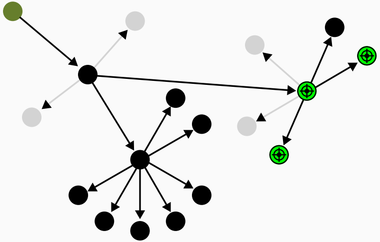


Figure 1: Actual traversal

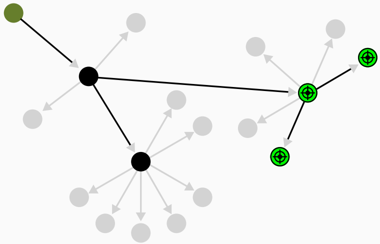


Figure 2: Optimal traversal: minimal cost path

$$R^3 = \frac{5}{13} = 0.38$$

Investigated Structered Decentralized Environment

Simulated Solid Environment: SolidBench Taelman and Verborgh 2023

- Data is stored in vaults
- Vaults use document-centric structure
- Vaults simulate a social media application

Data attributes

- Generates 158,233 RDF files
- Across 1,531 data vaults
- containing a total of 3,556,159 triples.

Analysed queries

- Use discover queries

Metrics Used

- Time until first result and last result
- Relative to breadth-first traversal baseline
- R^3

Prioritization algorithms (Hartig and Özsu 2016)

Non-adaptive

- Breadth-first (default), depth-first, random prioritization

Graph-based

- In-degree, PageRank score

Result-based

- Uses result contribution count (RCC) of each node (URI)
- Priority equal to the sum / count of non-zero RCC of the 1 or 2-hop in-neighbours of a node
- Called rcc-1, rcc-2, rel-1, rel-2 respectively.

Prioritization algorithms

Intermediate-results

- Uses intermediate solutions in the engine
- Priority of URI equal to the largest intermediate result with that URI bound
- IS sets initial priorities to 0, while ISdcr sets priority to the priority of the parent node - 1

Hybrid

- Multiply intermediate and full result scoring functions
- is-rcc1, is-rcc2, is-rel1, is-rel2

TypeIndex

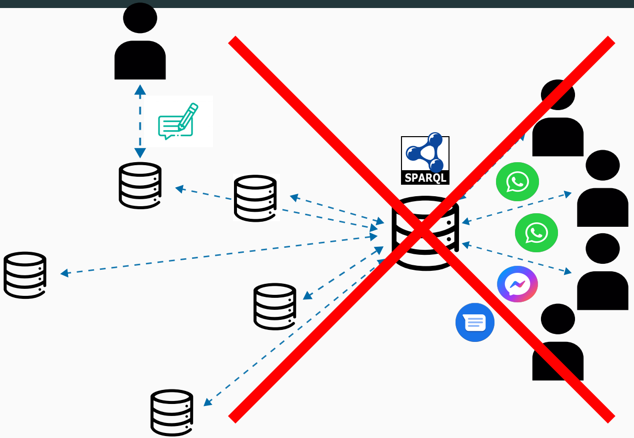
- TypeIndex points to location for resource of specific type
- Prioritize TypeIndex

Prioritization algorithms

Oracle

- Compute RCC in hindsight
- Scores are propegated through the shortest path
- Serves as optimal performance oracle

Results



- TODO: Insert image from paper here (discover 2 and 8)
- Breadth-first outperforms most algorithms
- Oracle has significantly better R^3, but not execution time

Results

	1st		Cmpl		R^3	
	better	worse	better	worse	better	worse
depth-first	15.7	17.1	14.3	17.1	7.5	12.5
random	4.3	68.6	5.7	74.3	15.0	15.0
is-rcc-1	4.3	57.1	5.7	60.0	7.5	5.0
type-index	15.7	18.6	10.0	15.7	12.5	20.0
oracle	18.6	11.4	18.6	12.9	25.0	2.5

Table 1: Percentage of queries for which an algorithm performs at least 10% better or worse than the breadth-first baseline.

- No algorithm improves performance, and the oracle only marginally improves performance

Link Prioritization in Structured Decentralized Environments

- Link prioritization in Solid environment will not significantly improve query performance
- Research should instead focus on query planning Hanski et al. (2025) or traversal pruning Tam et al. (2024)

- Hanski, J. et al. (2025). "Link Traversal over Decentralised Environments using Restart-Based Query Planning". In: International Conference on Web Engineering.
- Hartig, O. and M. T. Özsu (2016). "Walking without a map: Ranking-based traversal for querying linked data". In: International Semantic Web Conference. Springer, pp. 305–324.
- Taelman, R. and R. Verborgh (2023). "Link traversal query processing over decentralized environments with structural assumptions". In: International Semantic Web Conference. Springer, pp. 3–22.

Tam, B.-E. et al. (2024). “Opportunities for Shape-based Optimization of Link Traversal Queries”. In: arXiv preprint arXiv:2407.00998.