

# Context-Free Path Querying Can be Fast if Cooked Properly

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## ABSTRACT

Recently proposed matrix multiplication based algorithm for context-free path querying (CFPQ) offloads the most performance-critical parts onto boolean matrices multiplication. Thus, it is possible to achieve high performance of CFPQ by means of modern parallel hardware and software. In this paper, we provide results of empirical performance comparison of different implementations of this algorithm on both real-world data and synthetic data for the worst cases.

## KEYWORDS

Context-free path querying, transitive closure, graph databases, linear algebra, context-free grammar, GPGPU, CUDA, boolean matrix, matrix multiplication

## 1 INTRODUCTION

Graph data bases !!!!!

Graph querying is !!! One way to formulate constraints on paths is to use formal language: concatenation of the labels along the path is treated as a word, and a specification of the language which should contain specific words is a constraint. Language-constrained path querying [3]. The most popular is a regular path querying (RPQ) [?]. Context-Free Path Querying (CFPQ) [17], CFPQ is widely used for graph-structured data analysis in such domains as biological data analysis, RDF, network analysis. Huge amount of the real-world data makes performance of CFPQ critical for practical tasks. Several algorithms for CFPQ based on such parsing techniques as (G)LL, (G)LR, and CYK are proposed recently [6, 8, 11, 13, 14, 18].

Recent research shows that [10] — all is bad, performance is poor, not applicable.

RedisGraph [4]<sup>1</sup> GraphBLAS [9]

One of the most promising algorithms is a matrix-based algorithm, proposed by Rustam Azimov [2]. This algorithm offloads the most critical computations onto boolean matrices multiplication. As a result, it is easy to implement, and allows one to utilize modern massive-parallel hardware for CFPQ. The implementation provided by the authors utilizes GPGPU by using cuSPARSE<sup>2</sup> library which is a floating point sparse matrices multiplication library. Although it does not use advanced algorithms for boolean matrices, it outperforms existing algorithms.

<sup>1</sup>RedisGraph project webpage: <https://oss.redislabs.com/redisgraph/>. Access date: 12.11.2019

<sup>2</sup>cuSparse is a library for sparse matrices multiplication on GPGPU. Official documentation: <https://docs.nvidia.com/cuda/cusparse/index.html>. Access date: 12.11.2019

In this work we !!! We make the following contributions in this paper.

- (1) We provide a number of implementations of the matrix multiplication based CFPQ algorithm, which utilizes different modern software and hardware. The source code is available on GitHub: !!!.
- (2)
- (3) We provide evaluation which shows that !!!.

## 2 MATRIX-BASED ALGORITHM FOR CFPQ

Matrix-based algorithm for CFPQ was proposed by Rustam Azimov [2]. This algorithm can be expressed in terms of operations over matrices (see listing 1), and it is a sufficient advantage for implementation. It was shown that the utilization of GPGPU improves the context-free path querying performance significantly in comparison to other implementations [2] even if float matrices are used instead of boolean matrices.

### Listing 1 Context-free path querying algorithm

```
1: function CONTEXTFREEPATHQUERYING(D, G)
2:    $n \leftarrow$  the number of nodes in  $D$ 
3:    $E \leftarrow$  the directed edge-relation from  $D$ 
4:    $P \leftarrow$  the set of production rules in  $G$ 
5:    $T \leftarrow$  the matrix  $n \times n$  in which each element is  $\emptyset$ 
6:   for all  $(i, x, j) \in E$  do ▷ Matrix initialization
7:      $T_{i,j} \leftarrow T_{i,j} \cup \{A \mid (A \rightarrow x) \in P\}$ 
8:   while matrix  $T$  is changing do
9:      $T \leftarrow T \cup (T \times T)$  ▷ Transitive closure calculation
10:  return  $T$ 
```

Here  $D = (V, E)$  is the input graph and  $G = (N, \Sigma, P)$  is the input grammar. Each cell of the matrix  $T$  contains the set of nonterminals such that  $N_k \in T[i, j] \iff \exists p = v_i \dots v_j$ —path in  $D$ , such that  $N_k \xrightarrow[G]{*} \omega(p)$ , where  $\omega(p)$  is a word formed by the labels along the path  $p$ . Thus, this algorithm solves reachability problem, or, according to Hellings [7], processes CFPQs by using relational query semantics.

The performance-critical part of the algorithm is matrix multiplication. Note, that the set of nonterminals is finite, and we can represent the matrix  $T$  as a set of boolean matrices: one for each nonterminal. In this case the operation of matrix update is  $T_{N_i} \leftarrow T_{N_i} + (T_{N_j} \times T_{N_k})$  for each production  $N_i \rightarrow N_j N_k$  in  $P$ . Thus we can reduce CFPQ to boolean matrices multiplication. After such transformation, we can apply the next optimization: we can skip update if the matrices  $T_{N_j}$  and  $T_{N_k}$  have not been changed at the previous iteration.

Thus, the most important part is the efficient implementation of operations over boolean matrices. In this paper, we compare the effects of different approaches to matrices multiplication. All

our implementations are based on the optimized version of the algorithm.

### 3 IMPLEMENTATION

Previous works show [2, 12] that existing linear algebra libraries utilization is a right way to get high-performance CFPQ implementation in minimal effort. But non of these works do not provide evaluation with data storage, only pure time of algorithm execution was measured.

We provide a number of implementations of matrix-based CFPQ algorithm. All of them are based on RedisGraph — we use RedisGraph as a storage and implement CFPQ as an extension by using provided mechanism.

**CPU-based implementation.** Details on CPU implementation

**GPGPU-based implementation.** Details on GPGPU implementation

### 4 DATASET DESCRIPTION

We created and published a dataset for CFPQ algorithms evaluation. This dataset contains both the real-world data and synthetic data for different specific cases, such as the theoretical worst case, or the worst cases specific to matrices representations.

Our goal is to evaluate querying algorithms, not graph storages or graph databases, so all data is presented in a text-based format to simplify usage in different environments. Grammars are in Chomsky Normal Form, and graphs are represented as a list of triples (edges). Some details of the data representation can be found in the Appendix.

The variants of the *same generation query* [1] are an important example of queries that are context-free but not regular, so we use this type of queries in our evaluation. The dataset includes data for the following cases. Each case is a pair of a set of graphs and a set of grammars: each query (grammar) should be applied to each graph.

**[RDF]** The set of the real-world RDF files (ontologies) from [18] and two variants of the same generation query which describes hierarchy analysis. The first query is the grammar  $G_4$ :

$$\begin{aligned} s &\rightarrow SCOR s SCO & s &\rightarrow TR s T \\ s &\rightarrow SCOR SCO & s &\rightarrow TR T \end{aligned}$$

The second one is the grammar  $G_5$ :  $s \rightarrow SCOR s SCO \mid SCO$ .

**[Worst]** The theoretical worst case for CFPQ time complexity proposed by Hellings [8]: the graph is two cycles of coprime lengths with a single common vertex. The first cycle is labeled by the open bracket and the second cycle is labeled by the close bracket. Query is a grammar for the  $A^n B^n$  language. The example of such graph and grammar is presented in figure 1.

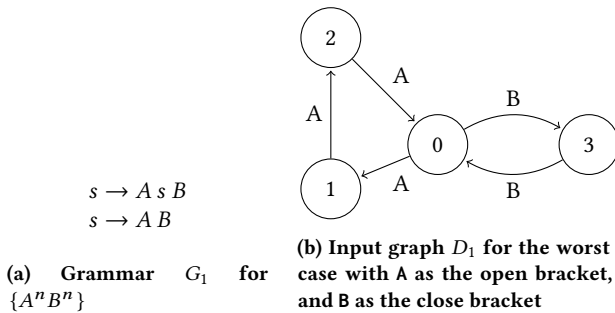


Figure 1: Graph and grammar for the worst case

**[Full]** The case when the input graph is sparse, but the result is a full graph. Such a case may be hard for sparse matrices representations. As an input graph, we use a cycle, all edges of which are labeled by the same token. As a query we use two grammars which describe the sequence of tokens of arbitrary length: the simple ambiguous grammar  $G_2$ :  $s \rightarrow s s \mid A$ , and the highly ambiguous grammar  $G_3$ :  $s \rightarrow s s s \mid A$ .

**[Sparse]** Sparse graphs from [5] are generated by the GTgraph graph generator, and emulate realistic sparse data. Names of these graphs have the form  $G_n-p$ , where  $n$  corresponds to the total number of vertices, and  $p$  is the probability that some pair of vertices is connected. The query is the same generation query represented by the grammar  $G_1$  (figure 1).

### 5 EVALUATION

We evaluate all the described implementations on all the datasets and the queries presented. We compare our implementations with [2]. We exclude the time required to load data from files. The time required for data transfer is included.

For evaluation, we use a PC with Ubuntu 18.04 installed. It has Intel core i7 8700k 3,7HGz CPU, DDR4 32 Gb RAM, and Geforce 1080Ti GPGPU with 11Gb RAM.

The results of the evaluation are summarized in the tables below. Time is measured in seconds unless specified otherwise. The result for each algorithm is averaged over 10 runs. The cell is left blank if the time limit is exceeded, or if there is not enough memory to allocate the data.

The results of the first dataset **[RDF]** are presented in table 1. We can see, that in this case the running time of all our implementations is smaller than of the reference implementation, and all implementations but **[CuSprs]** demonstrate similar performance. It is obvious that performance improvement in comparison with the first implementation is huge and it is necessary to extend the dataset with new RDFs of the significantly bigger size.

Table 2: Evaluation results for the worst case

#V	Scipy	M4RI	GPU4R	GPU_N	GPU_Py	CuSprs
16	0.032	< 1	0.008	0.002	0.027	0.309
32	0.118	0.001	0.034	0.008	0.136	0.441
64	0.476	0.041	0.133	0.032	0.524	0.988
128	2.194	0.226	0.562	0.129	2.751	3.470
256	15.299	1.994	3.088	0.544	11.883	15.317
512	121.287	23.204	13.685	2.499	43.563	102.269
1024	1593.284	528.521	88.064	19.357	217.326	1122.055
2048	-	-	-	325.174	-	-

Results of the theoretical worst case (**[Worst]** dataset) are presented in table 2. This case is really hard to process: even for a graph of 1024 vertices, the query evaluation time is greater than 10 seconds even for the most performant implementation. We can see, that the running time grows too fast with the number of vertices.

**Table 1: RDFs querying results (time in milliseconds)**

RDF			Query $G_4$						Query $G_5$					
Name	#V	#E	Scipy	M4RI	GPU4R	GPU_N	GPU_Py	CuSprs	Scipy	M4RI	GPU4R	GPU_N	GPU_Py	CuSprs
atm-prim	291	685	3	2	2	1	5	269	1	< 1	1	< 1	2	267
biomed	341	711	3	5	2	1	5	283	4	< 1	1	< 1	5	280
foaf	256	815	2	9	2	< 1	5	270	1	< 1	1	< 1	2	263
funding	778	1480	4	7	4	1	5	279	2	< 1	3	< 1	4	274
generations	129	351	3	3	2	< 1	5	273	1	< 1	1	< 1	2	263
people_pets	337	834	3	3	3	1	7	284	1	< 1	1	< 1	3	277
pizza	671	2604	6	8	3	1	6	292	2	< 1	2	< 1	5	278
skos	144	323	2	4	2	< 1	5	273	< 1	< 1	1	< 1	2	265
travel	131	397	3	5	2	< 1	6	268	1	< 1	1	< 1	3	271
unv-bnch	179	413	2	4	2	< 1	5	266	1	< 1	1	< 1	3	266
wine	733	2450	7	6	4	1	7	294	1	< 1	3	< 1	3	281

**Table 3: Sparse graphs querying results**

Graph	Scipy	M4RI	GPU4R	GPU_N	GPU_Py	CuSprs
G5k-0.001	10.352	0.647	0.113	0.041	0.216	5.729
G10k-0.001	37.286	2.395	0.435	0.215	1.331	35.937
G10k-0.01	97.607	1.455	0.273	0.138	0.763	47.525
G10k-0.1	601.182	1.050	0.223	0.114	0.859	395.393
G20k-0.001	150.774	11.025	1.842	1.274	6.180	-
G40k-0.001	-	97.841	11.663	8.393	37.821	-
G80k-0.001	-	1142.959	88.366	65.886	-	-

The next is the **[Sparse]** dataset presented in table 3. The evaluation shows that sparsity of graphs (value of parameter  $p$ ) is important both for implementations which use sparse matrices and for implementations which use dense matrices. Note that the behavior of the sparse matrices based implementation is as expected, but for dense matrices we can see, that more sparse graphs are processed faster. Reasons for such behavior demand further investigation. Note that we estimate only the query execution time, so it is hard to compare our results with the results presented in [5]. Nevertheless, the running time of our **[GPU\_N]** implementation is significantly smaller than the one provided in [5].

The last dataset is **[Full]**, and results are shown in table 4. As we expect, this case is very hard for sparse matrices based implementations: the running time grows too fast. This dataset also demonstrates the impact of the grammar size. Both queries specify the same constraints, but the grammar  $G_3$  in CNF contains 2 times more rules than the grammar  $G_2$ , so, the running time for big graphs differs by more than twice.

Finally, we can conclude that GPGPU utilization for CFPQ can significantly improve performance, but more research on advanced optimization techniques should be done. On the other hand, the high-level implementation (**[GPU\_Py]**) is comparable with other GPGPU-based implementations. So, it may be a balance between implementation complexity and performance. Highly optimized existing libraries can be of some use: the implementation based on m4ri is faster than the reference implementation and the other CPU-based implementation. Moreover, it is comparable with some GPGPU-based implementations in some cases. Sparse matrices utilization demands more thorough investigation. The main question is if we can create an efficient implementation for sparse boolean matrices multiplication.

## 6 DISCUSSION

Zeros in sparse matrices.

Overhead on matrices conversion and transferring when run on GPGPU.

No conversion when run on CPU. Better than Neo4j and other BD with non-matrix representation of graphs.

## 7 CONCLUSION AND FUTURE WORK

We provide an CPU and GPGPU based context-free path querying implementations for RedisGraph and show that CFPQ can be fast enough to analyze real-world data. But our implementations are on prototype stage and we should provide full integration of CFPQ to RedisGraph. First of all it is necessary to extend Cupher graph query language, which uses in RedisGraph, to support respective syntax for context-free constraints specification. There is a proposal which describes such syntax extension<sup>3</sup> and we plan to support proposed syntax in libcypher-parser<sup>4</sup> which uses in RedisGraph.

In current version we use CUSP matrix multiplication library for GPGPU utilization, but it may be better to use GraphBLAST<sup>5</sup> [16] — Gunrock<sup>6</sup> [15] based implementation of GraphBLAS API for GPGPU. First of all, we should evaluate GraphBlast based implementation of CFPQ. Also, we should investigate to implement multi-GPU support for GraphBlast, because it should improve performance of huge real-world data processing.

Our implementations calculate queries in respect to relational semantics, but in some cases it is necessary to provide a path which satisfied constraints. As we know, matrix based algorithm for single path or all paths semantix is not provided yet, and it is a direction for future research.

Another important question for future research is how to update query result dynamically when data changes. Mechanism for result updating allows one to recalculate query faster and use result as an index for other queries.

Also, further improvements of the dataset are required. For example, it is necessary to include real-world cases from static code analysis [?].

<sup>3</sup>Proposal with path pattern syntax for openCypher: <https://github.com/thobe/openCypher/blob/rpq/cip/1.accepted/CIP2017-02-06-Path-Patterns.adoc>. It is shown that context-free constraints are expressible in proposd syntax. Access date: 12.11.2019

<sup>4</sup>Web page of libcypher-parser project: <http://cleishm.github.io/libcypher-parser/>. Access date: 12.11.2019

<sup>5</sup>GraphBLAST project: <https://github.com/gunrock/graphblast>. Access date: 12.11.2019.

<sup>6</sup>Gunrock project web page: <https://gunrock.github.io/docs/>. Access date: 12.11.2019.

**Table 4: Full querying results**

#V	Query $G_2$						Query $G_3$					
	Scipy	M4RI	GPU4R	GPU_N	GPU_Py	CuSprs	Scipy	M4RI	GPU4R	GPU_N	GPU_Py	CuSprs
100	0.007	0.002	0.002	< 1	0.003	0.278	0.023	0.076	0.005	0.001	0.007	0.290
200	0.040	0.003	0.002	0.001	0.004	0.279	0.105	0.098	0.004	0.001	0.007	0.296
500	0.480	0.003	0.003	0.001	0.004	0.329	1.636	0.094	0.007	0.001	0.010	0.382
1000	3.741	0.007	0.005	0.001	0.006	0.571	13.071	0.106	0.009	0.001	0.009	0.839
2000	40.309	0.063	0.019	0.003	0.017	1.949	93.676	0.108	0.030	0.005	0.026	3.740
5000	651.343	0.366	0.125	0.038	0.150	99.651	1205.421	0.851	0.195	0.075	0.239	201.151
10000	-	1.932	0.552	0.315	0.840	1029.042	-	4.690	1.055	0.648	1.838	-
25000	-	33.236	7.252	5.314	15.521	-	-	70.823	15.240	10.961	36.495	-
50000	-	360.035	58.751	44.611	129.641	-	-	775.765	130.203	91.579	226.834	-
80000	-	1292.817	256.579	190.343	641.260	-	-	-	531.694	376.691	-	-

## ACKNOWLEDGMENTS

The research was supported by the Russian Science Foundation grant 18-11-00100 and a grant from JetBrains Research.

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