GRADES-NDA 2019

# Evaluation of the Context-Free Path Querying Algorithm Based on Matrix Multiplication

Nikita Mishin, Iaroslav Sokolov, Egor Spirin, Vladimir Kutuev, Egor Nemchinov, Sergey Gorbatyuk, **Semyon Grigorev**

JetBrains Research, Programming Languages and Tools Lab
Saint Petersburg University

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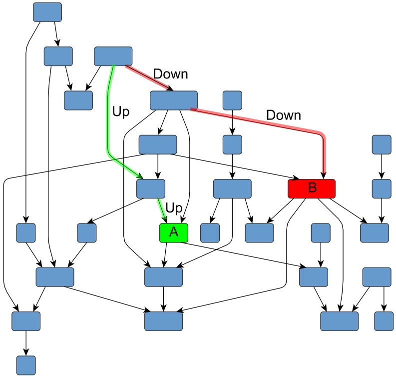
# Context-Free Path Querying




Navigation through a graph

- Are nodes A and B on the same level of hierarchy?
- Is there a path of form **Up**$^n$ **Down**$^n$?
- Find all paths of form **Up**$^n$ **Down**$^n$ which start from the node A

# Context-Free Path Querying: Relational Query Semantics

- $\mathbb{G} = (\Sigma, N, P)$ — context-free grammar in normal form
  - $A \to BC$, where $A, B, C \in N$
  - $A \to x$, where $A \in N, x \in \Sigma$
  - $L(\mathbb{G}, A) = \{\omega \mid A \to^* \omega\}$
- $G = (V, E, L)$ — directed graph
  - $v \xrightarrow{l} u \in E$
  - $L \subseteq \Sigma$
- $\omega(\pi) = \omega(v_0 \xrightarrow{l_0} v_1 \xrightarrow{l_1} \cdots \xrightarrow{l_{n-2}} v_{n-1} \xrightarrow{l_{n-1}} v_n) = l_0 l_1 \cdots l_{n-1}$
- $R_A = \{(n, m) \mid \exists n \pi m$, such that $\omega(\pi) \in L(\mathbb{G}, A)\}$

# Matrix-Based Algorithm

**Algorithm** Context-Free Path Querying by Matrix Multiplication

**function** CONTEXTFREEPATHQUERYING(D, G)
    $n \leftarrow$ the number of nodes in $D$
    $E \leftarrow$ the directed edge-relation from $D$
    $P \leftarrow$ the set of production rules in $G$
    $T \leftarrow$ the matrix $n \times n$ in which each element is $\varnothing$
    **for all** $(i, x, j) \in E$ **do** ▷ Matrix initialization
        $T_{i,j} \leftarrow T_{i,j} \cup \{A \mid (A \to x) \in P\}$
    **while** matrix $T$ is changing **do**
        $T \leftarrow T \cup (T \times T)$ ▷ Transitive closure $T^{cf}$ calculation
    **return** $T$

# Matrix-Based Algorithm: Technical Details

- $T$ can be represented as e set of Boolean matrices: one matrix for each nonterminal
- The algorithm can be implemented in terms of Boolean matrices multiplication
- All matrices can be allocated in memory statically

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- Can GPGPUs utilization for CFPQ improve performance in comparison with the CPU version?
- Is it possible to achieve higher performance by means of existing libraries for matrices operations or do we need to create our own solution to get more control?
- Can we achieve high performance with high-level languages such as Python?
- Can we improve performance by using sparse matrix representation for CFPQ?

# CPU-Based Implementations

**[Scipy]** Sparse matrices multiplication by using **Scipy** in **Python** programming language

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**[Scipy]** Sparse matrices multiplication by using **Scipy** in **Python** programming language

**[M4RI]** Dense matrices multiplication by using **m4ri2** library which implements the Method of Four Russians in **C** language

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**[GPU_N]** Our own implementation of the naïve boolean matrix multiplication in **CUDA C**

**[GPU_Py]** Manual implementation of naïve boolean matrix multiplication in **Python** by using **numba** compiler

# Reference Implementations

**[CuSprs]**

- Rustam Azimov, 2018, "Context-free Path Querying by Matrix Multiplication"
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**[CYK]**
- X. Zhang et al, 2016, "Context-free path queries on RDF graphs"
- CYK-based algorithm implemented in **Java** (CPU)

# Dataset

**[RDF]**

- The set of the real-world RDF files (ontologies)
- Queries:
  $G_4 : s \to SCOR\ s\ SCO \mid TR\ s\ T \mid SCOR\ SCO \mid TR\ T$,
  $G_5 : s \to SCOR\ s\ SCO \mid SCO$

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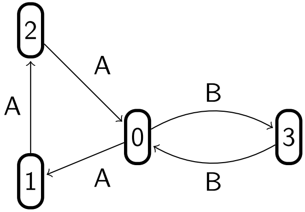
**[Worst]**

- The input graph is a two cycles of coprime lengths with a single common vertex




- Queries: $G_1 : s \to A\ s\ B \mid A\ B$

# Dataset

**[Full]**

- The input graph is sparse, but the result is a full graph
- Queries:
  $G_2 : s \to s\ s \mid A$,
  $G_3 : s \to s\ s\ s \mid A$

# Dataset

**[Full]**

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**[Sparse]**

- Sparse graphs are generated by the GTgraph
- Queries: $G_1 : s \to A\ s\ B \mid A\ B$

# Evaluation

- OS: Ubuntu 18.04
- CPU: Intel core i7 8700k 3,7HGz
- RAM: DDR4 32 Gb
- GPGPU: Geforce 1080Ti (11Gb RAM)

# Evaluation: [RDF][2]

| RDF | | | Query $G_4$ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Name | #V | #E | Scipy | M4RI | GPU4R | GPU_N | GPU_Py | CuSprs | CYK [1] |
| atm-prim | 291 | 685 | 3 | 2 | 2 | 1 | 5 | 269 | 515285 |
| biomed | 341 | 711 | 3 | 5 | 2 | 1 | 5 | 283 | 420604 |
| foaf | 256 | 815 | 2 | 9 | 2 | $< 1$ | 5 | 270 | 5027 |
| funding | 778 | 1480 | 4 | 7 | 4 | 1 | 5 | 279 | 499 |
| generations | 129 | 351 | 3 | 3 | 2 | $< 1$ | 5 | 273 | 6091 |
| people_pets | 337 | 834 | 3 | 3 | 3 | 1 | 7 | 284 | 82081 |
| pizza | 671 | 2604 | 6 | 8 | 3 | 1 | 6 | 292 | 3233587 |
| skos | 144 | 323 | 2 | 4 | 2 | $< 1$ | 5 | 273 | 1044 |
| travel | 131 | 397 | 3 | 5 | 2 | $< 1$ | 6 | 268 | 13971 |
| unv-bnch | 179 | 413 | 2 | 4 | 2 | $< 1$ | 5 | 266 | 20981 |
| wine | 733 | 2450 | 7 | 6 | 4 | 1 | 7 | 294 | 4075319 |

[1] Results from X. Zhang et al, 2016, "Context-Free Path Queries on RDF Graphs"

[2] Time in milliseconds

# Evaluation: [Worst][3]

| #V | Scipy | M4RI | GPU4R | GPU_N | GPU_Py | CuSprs |
|---|---|---|---|---|---|---|
| 16 | 0.032 | $< 0.001$ | 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 | - | - |

[3] Time in seconds

# Evaluation: [Sparse][4]

| 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 | - | - |

[4] Time in seconds

# Evaluation: [Full][5]

| #V | Query $G_2$ | | | | | |
|---|---|---|---|---|---|---|
| | Scipy | M4RI | GPU4R | GPU_N | GPU_Py | CuSprs |
| 100 | 0.007 | 0.002 | 0.002 | $<$ 0.001 | 0.003 | 0.278 |
| 200 | 0.040 | 0.003 | 0.002 | 0.001 | 0.004 | 0.279 |
| 500 | 0.480 | 0.003 | 0.003 | 0.001 | 0.004 | 0.329 |
| 1000 | 3.741 | 0.007 | 0.005 | 0.001 | 0.006 | 0.571 |
| 2000 | 40.309 | 0.063 | 0.019 | 0.003 | 0.017 | 1.949 |
| 5000 | 651.343 | 0.366 | 0.125 | 0.038 | 0.150 | 99.651 |
| 10000 | - | 1.932 | 0.552 | 0.315 | 0.840 | 1029.042 |
| 25000 | - | 33.236 | 7.252 | 5.314 | 15.521 | - |
| 50000 | - | 360.035 | 58.751 | 44.611 | 129.641 | - |
| 80000 | - | 1292.817 | 256.579 | 190.343 | 641.260 | - |

[5] Time in seconds

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- High level languages + translator to GPGPU may be a good balance between performance ad implementation complexity

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- High performnce libraries utilizzation is a good idea
  - But it should be an appropriate libraries: M4RI (CPU) is better then cuSPARSE (GPGPU)
- High level languages + translator to GPGPU may be a good balance between performance ad implementation complexity
- Sparse matrix representation is important for performance ([Scipy] for [Sparse])
  - We should try to implement sparse boolean matrix operations for GPGPU

# Future Research

- Detailed investigation of implemented algorithms
- Create open extensible platform for CFPQ algorithms comparison
- Evaluate other CFPQ algorithms
  - Sparse matrices
  - Destributed matrix multiplication
  - LL and LR parsing algorithms
- Add new data and queries
  - Big RDFs
  - Static code analysis

# Contact Information


- Semyon Grigorev:
  - s.v.grigoriev@spbu.ru
  - Semen.Grigorev@jetbrains.com
- Nikita Mishin: mishinnikitam@gmail.com
- Iaroslav Sokolov: sokolov.yas@gmail.com
- Egor Spirin: egor@spirin.tech
- Vladimir Kutuev: vladimir.kutuev@gmail.com
- Egor Nemchinov: nemchegor@gmail.com
- Sergey Gorbatyuk: sergeygorbatyuk171@gmail.com


- Dataset and algorithm implementations: https://github.com/SokolovYaroslav/CFPQ-on-GPGPU

Thanks!