Context-Free Path Querying: Obstacles on the Way to Adoption

Semyon Grigorev

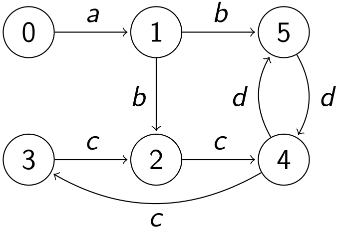
JetBrains Research, Programming Languages and Tools Lab
St. Petersburg State University

https://research.jetbrains.org/groups/plt_lab/

16.07.2021

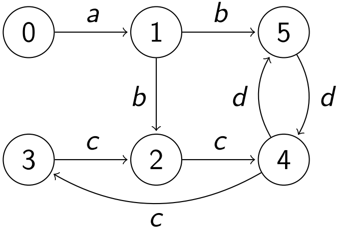
Formal Language Constrained Path Querying

Navigational queries in edge-labelled graph



Formal Language Constrained Path Querying

Navigational queries in edge-labelled graph

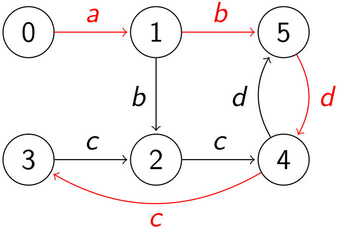


- Path to find:

$$0 \xrightarrow{a} v_0 \xrightarrow{b} v_1 \underbrace{\xrightarrow{d} v_2 \xrightarrow{c} v_3 \dots v_k \xrightarrow{c}}_{c \text{ or } d \text{ in arbitrary order}} v$$

Formal Language Constrained Path Querying

Navigational queries in edge-labelled graph

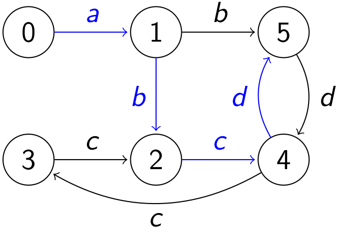


- Path to find:

$$0 \xrightarrow{a} v_0 \xrightarrow{b} v_1 \underbrace{\xrightarrow{d} v_2 \xrightarrow{c} v_3 \ldots v_k \xrightarrow{c}}_{c \text{ or } d \text{ in arbitrary order}} v$$

Formal Language Constrained Path Querying

Navigational queries in edge-labelled graph

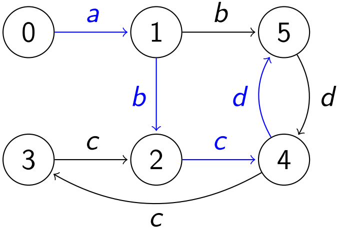


- Path to find:

$$0 \xrightarrow{a} v_0 \xrightarrow{b} v_1 \underbrace{\xrightarrow{d} v_2 \xrightarrow{c} v_3 \dots v_k \xrightarrow{c}}_{c \text{ or } d \text{ in arbitrary order}} v$$

Formal Language Constrained Path Querying

Navigational queries in edge-labelled graph



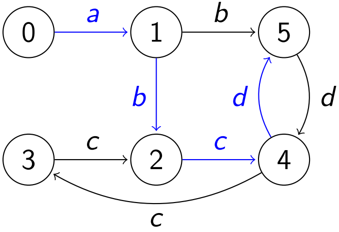
- $w(v_0 \xrightarrow{l_0} v_1 \xrightarrow{l_1} \ldots \xrightarrow{l_{k-1}} v_k) = l_0 l_1 \ldots l_{k-1}$
- $Q = \{(v_i, v_j) \mid \exists \pi = v_i \to \ldots \to v_j; w(\pi) \in \mathcal{L}\}$, where $\mathcal{L}$ — formal language
  - Regular, RPQ ($ab(c \mid d)^*$)
  - **Context-Free**, CFPQ ($a^n b^n$)
  - Multiple Context-Free ($a^n c^m b^n d^m$)

- Path to find:

$$0 \xrightarrow{a} v_0 \xrightarrow{b} v_1 \underbrace{\xrightarrow{d} v_2 \xrightarrow{c} v_3 \ldots v_k \xrightarrow{c}}_{c \text{ or } d \text{ in arbitrary order}} v$$

Formal Language Constrained Path Querying

Navigational queries in edge-labelled graph



- Path to find:

$$0 \xrightarrow{a} v_0 \xrightarrow{b} v_1 \underbrace{\xrightarrow{d} v_2 \xrightarrow{c} v_3 \dots v_k \xrightarrow{c}}_{c \text{ or } d \text{ in arbitrary order}} v$$

- $w(v_0 \xrightarrow{l_0} v_1 \xrightarrow{l_1} \dots \xrightarrow{l_{k-1}} v_k) = l_0 l_1 \dots l_{k-1}$
- $Q = \{(v_i, v_j) \mid \exists \pi = v_i \to \dots \to v_j; w(\pi) \in \mathcal{L}\}$, where $\mathcal{L}$ — formal language
  - ✔ Regular, RPQ ($ab(c \mid d)^*$)
  - **Context-Free**, CFPQ ($a^n b^n$)
  - Multiple Context-Free ($a^n c^m b^n d^m$)

Variations:

- All-pairs
- Multiple source
- Reachability
- All paths
- ...

Applications of Context-Free Path Querying

Hierarchy analysis: variations of the *same-generation queries* is the essence of CFPQ

[1] Mihalis Yannakakis. 1990. "Graph-theoretic Methods in Database Theory".
[2] Thomas Reps. 1997. "Program Analysis via Graph Reachability".

Hierarchy analysis: variations of the *same-generation queries* is the essence of CFPQ

Graph structured data analysis

- Introduced by M. Yannakakis in 1990[1]
- Biological data analysis
- Data provenance analysis
- ...

[1] Mihalis Yannakakis. 1990. "Graph-theoretic Methods in Database Theory".
[2] Thomas Reps. 1997. "Program Analysis via Graph Reachability".

Applications of Context-Free Path Querying

Hierarchy analysis: variations of the *same-generation queries* is the essence of CFPQ

Graph structured data analysis

- Introduced by M. Yannakakis in 1990[1]
- Biological data analysis
- Data provenance analysis
- ...

Static code analysis

- Introduced by T. Reps in 1997[2]
- Interprocedural points-to analysis
- Interprocedural alias analysis
- Type inference related tasks
- ...

[1] Mihalis Yannakakis. 1990. "Graph-theoretic Methods in Database Theory".
[2] Thomas Reps. 1997. "Program Analysis via Graph Reachability".

Applications of Context-Free Path Querying

Hierarchy analysis: variations of the *same-generation queries* is the essence of CFPQ

Graph structured data analysis

- Introduced by M. Yannakakis in 1990[1]
- Biological data analysis
- Data provenance analysis
- ...

Static code analysis

- Introduced by T. Reps in 1997[2]
- Interprocedural points-to analysis
- Interprocedural alias analysis
- Type inference related tasks
- ...

Graph databases

[1] Mihalis Yannakakis. 1990. "Graph-theoretic Methods in Database Theory".
[2] Thomas Reps. 1997. "Program Analysis via Graph Reachability".

There is No Unified Infrastructure to Compare CFPQ Solutions

- ? Which algorithm is better for the specific problem?
- ? How to assess if a newly developed algorithm is better than the existing ones?
- ? . . .

[3] Jochem Kuijpers, George Fletcher, Nikolay Yakovets, and Tobias Lindaaker. 2019

There is No Unified Infrastructure to Compare CFPQ Solutions

- ? Which algorithm is better for the specific problem?
- ? How to assess if a newly developed algorithm is better than the existing ones?
- ? ...
- **Unified benchmarks**: dataset, workflow, ...

[3] Jochem Kuijpers, George Fletcher, Nikolay Yakovets, and Tobias Lindaaker. 2019

There is No Unified Infrastructure to Compare CFPQ Solutions

- ? Which algorithm is better for the specific problem?
- ? How to assess if a newly developed algorithm is better than the existing ones?
- ? ...
- **Unified benchmarks**: dataset, workflow, ...
- ! The only attempt to compare different algorithms: "An Experimental Study of Context-Free Path Query Evaluation Methods"[3]

[3] Jochem Kuijpers, George Fletcher, Nikolay Yakovets, and Tobias Lindaaker. 2019

There is No Unified Infrastructure to Compare CFPQ Solutions

- ? Which algorithm is better for the specific problem?
- ? How to assess if a newly developed algorithm is better than the existing ones?
- ? . . .
- **Unified benchmarks**: dataset, workflow, . . .
- ! The only attempt to compare different algorithms: "An Experimental Study of Context-Free Path Query Evaluation Methods"[3]
  - ☹ "We conclude that state of the art solutions are not able to cope with large graphs as found in practice."

[3] Jochem Kuijpers, George Fletcher, Nikolay Yakovets, and Tobias Lindaaker. 2019

There is No Unified Infrastructure to Compare CFPQ Solutions

- ? Which algorithm is better for the specific problem?
- ? How to assess if a newly developed algorithm is better than the existing ones?
- ? ...
- **Unified benchmarks**: dataset, workflow, ...
- ! The only attempt to compare different algorithms: "An Experimental Study of Context-Free Path Query Evaluation Methods"[3]
  - ☹ "We conclude that state of the art solutions are not able to cope with large graphs as found in practice."

Difficulties

- Data is spread over projects and papers in different communities
- There is a huge number of different subclasses of the problem
  - all-pairs, single source, multiple source, ...
  - reachability, single path, all path, ...

[3] Jochem Kuijpers, George Fletcher, Nikolay Yakovets, and Tobias Lindaaker. 2019

There is No Support of CFPQ in Real-World Graph Databases

- ? Which database or graph analysis system should you choose?
  - ☹ H. Miao and A. Deshpande: “Though the problem has been first studied in our community [40], there is little follow up and support in the context of modern graph databases ...”[4]

[4] H. Miao and A. Deshpande, “Understanding Data Science Lifecycle Provenance via Graph Segmentation and Summarization”, 2019

There is No Support of CFPQ in Real-World Graph Databases

- ? Which database or graph analysis system should you choose?
  - ☹ H. Miao and A. Deshpande: “Though the problem has been first studied in our community [40], there is little follow up and support in the context of modern graph databases ...”[4]

Difficulties

- ? How to choose an appropriate algorithm for query engine?
  - Benchmarks for querying algorithms
- ? How to express context-free constraints in graph query language?
  - ? Syntactic features to express context-free language constraints
  - ? Semantics of quey language

[4] H. Miao and A. Deshpande, “Understanding Data Science Lifecycle Provenance via Graph Segmentation and Summarization”, 2019

There is No Support of CFPQ in Real-World Graph Databases

- ? Which database or graph analysis system should you choose?
  - ☹ H. Miao and A. Deshpande: "Though the problem has been first studied in our community [40], there is little follow up and support in the context of modern graph databases ..."[4]

Difficulties

- ? How to choose an appropriate algorithm for query engine?
  - Benchmarks for querying algorithms
- ? How to express context-free constraints in graph query language?
  - ? Syntactic features to express context-free language constraints
  - ? Semantics of quey language
  - GQL standard

[4] H. Miao and A. Deshpande, "Understanding Data Science Lifecycle Provenance via Graph Segmentation and Summarization", 2019

Our Results

- Collection of linear algebra based algorithms for CFPQ
  - SuiteSparse is utilized for sparse linear algebra subroutines
  - Published: `https://github.com/JetBrains-Research/CFPQ_PyAlgo`

[5] Arseniy Terekhov et al. 2019. "Multiple-Source Context-Free Path Querying in Terms of Linear Algebra".

Our Results

- Collection of linear algebra based algorithms for CFPQ
  - SuiteSparse is utilized for sparse linear algebra subroutines
  - Published: `https://github.com/JetBrains-Research/CFPQ_PyAlgo`
- Full-stack support of CFPQ[5]
  - On top of RedisGraph: query engine is extended with CFPQ algorithm
  - openCypher is extended to support CFPQ

[5] Arseniy Terekhov et al. 2019. "Multiple-Source Context-Free Path Querying in Terms of Linear Algebra".

Our Results

- ✔ Collection of linear algebra based algorithms for CFPQ
  - SuiteSparse is utilized for sparse linear algebra subroutines
  - Published: `https://github.com/JetBrains-Research/CFPQ_PyAlgo`
- ✔ Full-stack support of CFPQ[5]
  - On top of RedisGraph: query engine is extended with CFPQ algorithm
  - openCypher is extended to support CFPQ
- ⚙ Dataset for CFPQ benchmarking: early stages
  - Synthetic graphs
    - ★ Theoretical worst case
    - ★ Complicated cases
  - Real-world graphs
    - ★ Static code analysis
    - ★ Biological data analysis
  - Published: `https://github.com/JetBrains-Research/CFPQ_Data`

[5] Arseniy Terekhov et al. 2019. "Multiple-Source Context-Free Path Querying in Terms of Linear Algebra".

Our Results Evaluation

- All-pairs reachability queries
- *geospecies*, *taxonomy* — biological data
- *crypto*, *drivers*, *fs* — points-to analysis
- Time in seconds

- GPU: Geforce GTX 1070, 1.5GHz, 8Gb RAM, 1920 CUDA cores
- CPU: Intel core i7-6700 CPU, 3.4GHz, DDR4 64Gb RAM

Graph	#V	#E	Neo4j[6]	RedisGraph[7]	Lin.al. CPU[8]	Lin.al. GPU[9]
geospecies	450 609	2 311 461	6 953.9	80.1	7.1	0.8
taxonomy	5 728 398	14 922 125	n.a.	⚙	1.1	0.7
crypto	3 464 970	5 976 774	n.a.	⚙	84.8	28.1
drivers	4 273 803	7 415 538	n.a.	⚙	269.9	62.5
fs	4 177 416	7 218 746	n.a.	⚙	165.1	47.7

[6] Jochem Kuijpers et al. 2019. "An Experimental Study of Context-Free Path Query Evaluation Methods".
[7] Arseniy Terekhov et al. 2019. "Multiple-Source Context-Free Path Querying in Terms of Linear Algebra".
[8] Standalone linear algebra based algorithm on CPU, using SuiteSparse.
[9] Standalone linear algebra based algorithm on GPU, using spbla.

- All-pairs reachability queries
- *geospecies, taxonomy* — biological data
- *crypto, drivers, fs* — points-to analysis
- Time in seconds

- GPU: Geforce GTX 1070, 1.5GHz, 8Gb RAM, 1920 CUDA cores
- CPU: Intel core i7-6700 CPU, 3.4GHz, DDR4 64Gb RAM

Graph	#V	#E	Neo4j[6]	RedisGraph[7]	Lin.al. CPU[8]	Lin.al. GPU[9]
geospecies	450 609	2 311 461	6 953.9	80.1	7.1	0.8
taxonomy	5 728 398	14 922 125	n.a.	⚙	1.1	0.7
crypto	3 464 970	5 976 774	n.a.	⚙	84.8	28.1
drivers	4 273 803	7 415 538	n.a.	⚙	269.9	62.5
fs	4 177 416	7 218 746	n.a.	⚙	165.1	47.7

[6] Jochem Kuijpers et al. 2019. "An Experimental Study of Context-Free Path Query Evaluation Methods".
[7] Arseniy Terekhov et al. 2019. "Multiple-Source Context-Free Path Querying in Terms of Linear Algebra".
[8] Standalone linear algebra based algorithm on CPU, using SuiteSparse.
[9] Standalone linear algebra based algorithm on GPU, using spbla.

Our Results Evaluation

- All-pairs reachability queries
- *geospecies, taxonomy* — biological data
- *crypto, drivers, fs* — points-to analysis
- Time in seconds
- GPU: Geforce GTX 1070, 1.5GHz, 8Gb RAM, 1920 CUDA cores
- CPU: Intel core i7-6700 CPU, 3.4GHz, DDR4 64Gb RAM

Graph	#V	#E	Neo4j[6]	RedisGraph[7]	Lin.al. CPU[8]	Lin.al. GPU[9]
geospecies	450 609	2 311 461	6 953.9	80.1	7.1	0.8
taxonomy	5 728 398	14 922 125	n.a.	⚙	1.1	0.7
crypto	3 464 970	5 976 774	n.a.	⚙	84.8	28.1
drivers	4 273 803	7 415 538	n.a.	⚙	269.9	62.5
fs	4 177 416	7 218 746	n.a.	⚙	165.1	47.7

[6] Jochem Kuijpers et al. 2019. “An Experimental Study of Context-Free Path Query Evaluation Methods”.
[7] Arseniy Terekhov et al. 2019. “Multiple-Source Context-Free Path Querying in Terms of Linear Algebra”.
[8] Standalone linear algebra based algorithm on CPU, using SuiteSparse.
[9] Standalone linear algebra based algorithm on GPU, using spbla.

Ongoing Research

- Benchmarking of linear algebra based algorithms
  - Comparison of different algorithms for different query semantics
  - Investigation of scalability on multicore machines
  - Estimation of performance on GPGPU
- Developing and evaluating GLL-based CFPQ algorithm for Neo4j
  - Multiple-source
  - All paths and reachability-only

Ongoing Research

- Benchmarking of linear algebra based algorithms
  - Comparison of different algorithms for different query semantics
  - Investigation of scalability on multicore machines
  - Estimation of performance on GPGPU
- Developing and evaluating GLL-based CFPQ algorithm for Neo4j
  - Multiple-source
  - All paths and reachability-only
- Describing semantics of (subset of) openCypher in terms of linear algebra (in Coq)
- Utilizing multiple context-free languages as path constraints

What Should We Do?

- Publish unified benchmarks for formal language constrained path querying algorithms
  - Graphs: synthetic and real-world
  - Queries: templates and real-world queries
  - Tasks: all-pairs, single source, reachability, ...

What Should We Do?

- Publish unified benchmarks for formal language constrained path querying algorithms
  - Graphs: synthetic and real-world
  - Queries: templates and real-world queries
  - Tasks: all-pairs, single source, reachability, ...
- Organize language constrained path querying competition
  - Part of existing competition for graph processing systems
  - Involve static analysis community

What Should We Do?

- Publish unified benchmarks for formal language constrained path querying algorithms
  - Graphs: synthetic and real-world
  - Queries: templates and real-world queries
  - Tasks: all-pairs, single source, reachability, ...
- Organize language constrained path querying competition
  - Part of existing competition for graph processing systems
  - Involve static analysis community
- ? Provide graph database support
  - Different algorithms for different systems
  - Syntax and semantics of query languages