Neo4j Keys

Entity Integrity on Property Graphs

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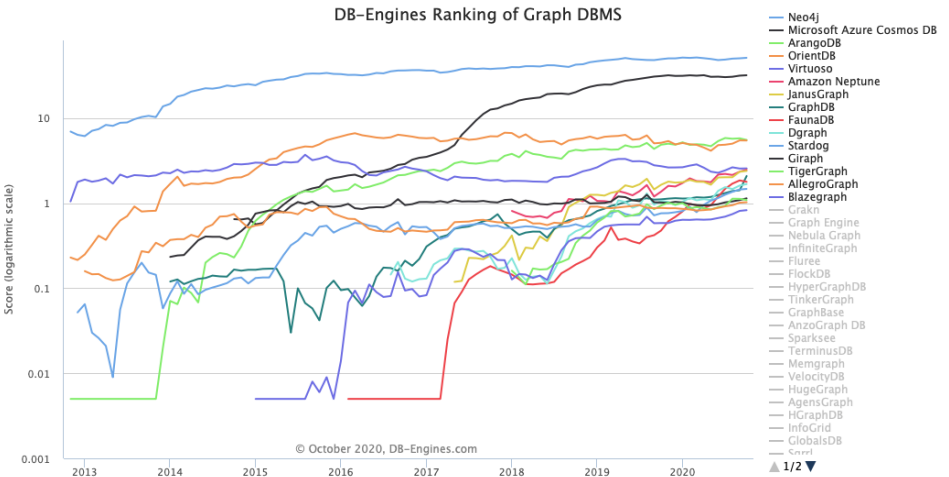
Vienna, Austria

Popularity of Neo4j



https://db-engines.com/en/ranking_trend/graph+dbms

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- Incomplete data (Codd keys, Key sets, Embedded Uniques, Possible and strongly possible and certain keys):
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entity integrity, referential integrity, database design, query processing, etc.

Overview

- Introduce a notion of keys
  - compliant with the one used by Neo4j
  - extended to make the most of the multi-label property graph model of Neo4j
- Use Cases
- Characterize the implication problem
  - axiomatically
  - algorithmically

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Entity Integrity on (Neo4j) Property Graphs

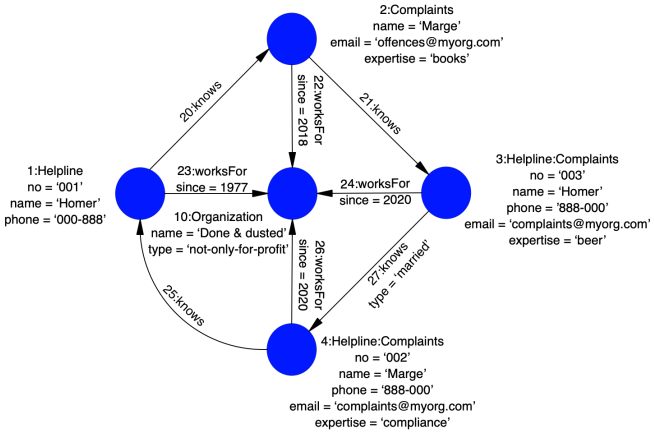
The (Neo4j) Property Graph Model

Disjoint Sets:

- $\mathcal{O}$ set of objects
- $\mathcal{L}$ finite set of labels
- $\mathcal{K}$ set of property attributes
- $\mathcal{N}$ set of values

Property Graph $G = (V, E, \eta, \lambda, \nu)$

- $V \subseteq \mathcal{O}$, eg. $V = \{1, 2, 3, 4, 10\}$
- $E \subseteq \mathcal{O}$, eg. $E = \{20, \ldots, 27\}$
- $\eta : E \to V \times V$, eg. $20 \mapsto (1, 2)$
- $\lambda : V \cup E \to \mathcal{P}(\mathcal{L})$,
  eg. $3 \mapsto \{:\text{Helpline}, :\text{Complaints}\}$
- $\nu : (V \cup E) \times \mathcal{K} \to \mathcal{N}$,
  eg. $(23, \text{since}) \mapsto 1977$



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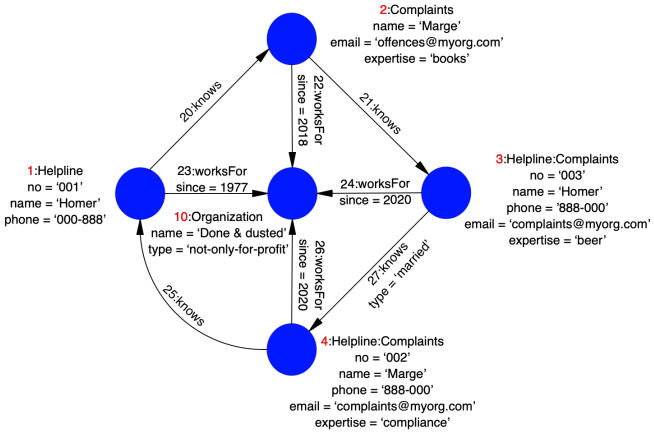

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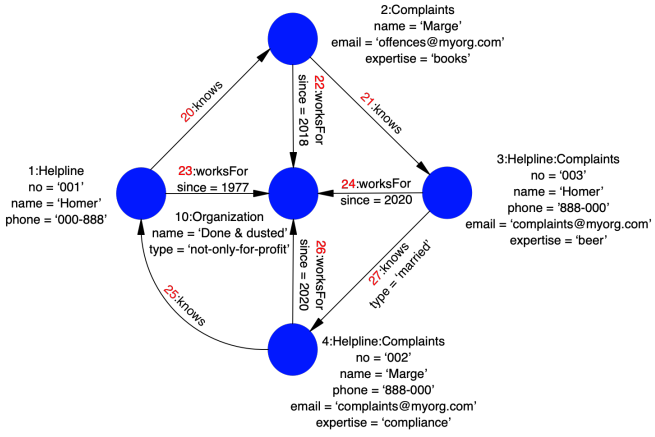

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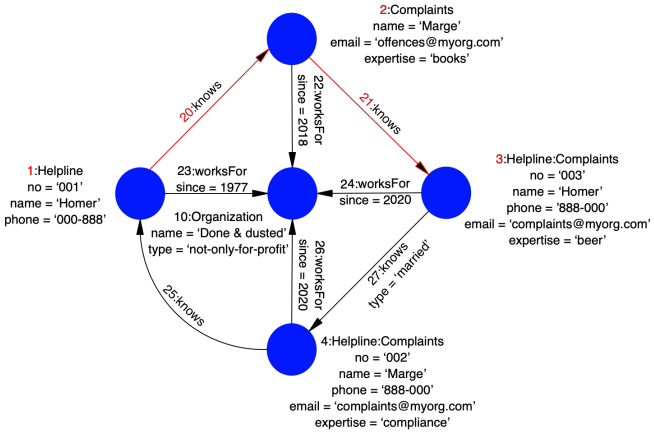

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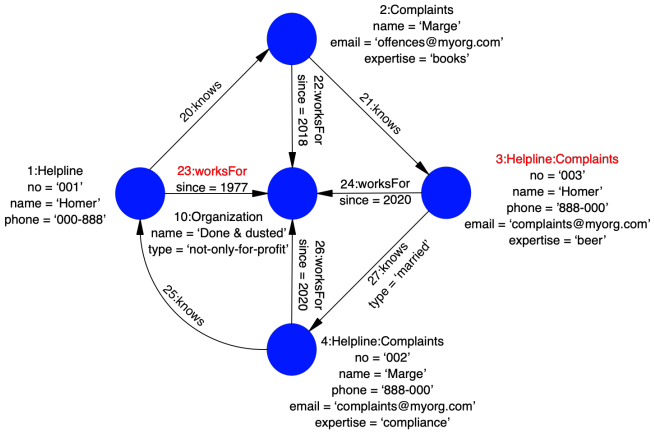

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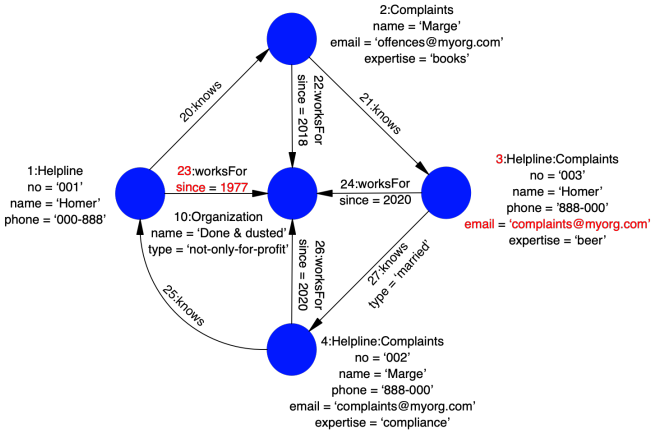

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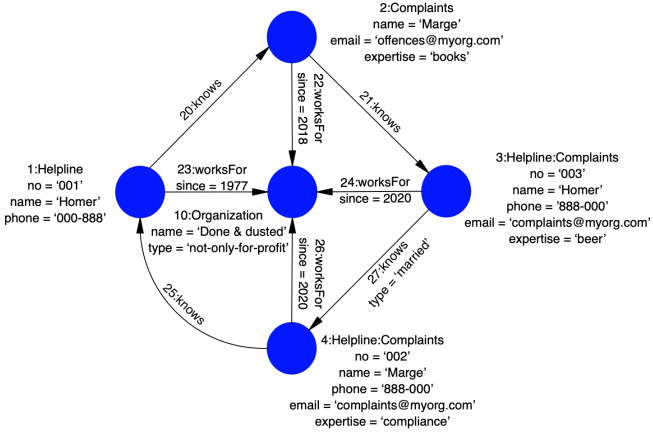

Definition of Neo4j Keys

Syntax

- Given are finite sets $\mathcal{L}$ of labels and $\mathcal{K}$ of property attributes
- A *key* is an expression $\mathfrak{L} : \mathfrak{K}$ where $\mathfrak{L} \subseteq \mathcal{L}$ and $\mathfrak{K} \subseteq \mathcal{K}$
- If $\mathfrak{L}$ is a singleton, $\mathfrak{L} : \mathfrak{K}$ is a *single-labelled* key, and otherwise *multi-labelled*.

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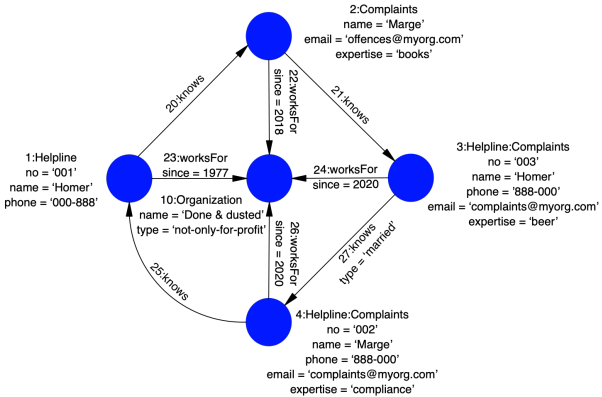
Semantics

- Given is a property graph $G = (V, E, \eta, \lambda, \nu)$ over $\mathcal{O}$, $\mathcal{L}$, $\mathcal{K}$, and $\mathcal{N}$
- G *satisfies* the key $\mathfrak{L} : \mathfrak{K}$ over $\mathcal{L}$ and $\mathcal{K}$, denoted by $\models_G \mathfrak{L} : \mathfrak{K}$, if and only if
  1. (Completeness) $V_{\mathfrak{L}} := \{v \in V \mid \mathfrak{L} \subseteq \lambda(v)\}$ is $\mathfrak{K}$-complete, that is, for all $v \in V_{\mathfrak{L}}$ and for all $A \in \mathfrak{K}$, $\nu(v, A)$ is defined
  2. (Uniqueness) For all $v_1, v_2 \in V_{\mathfrak{L}}$, if $v_1 \neq v_2$, then there is some $A \in \mathfrak{K}$ such that $\nu(v_1, A) \neq \nu(v_2, A)$

Examples

Keys satisfied by property graph

- $Helpline{:}\{no\}$
- $Helpline{:}\{name, phone\}$,
- $Complaints{:}\{name, email\}$
- $\{Helpline, Complaints\}{:}\{no, email\}$



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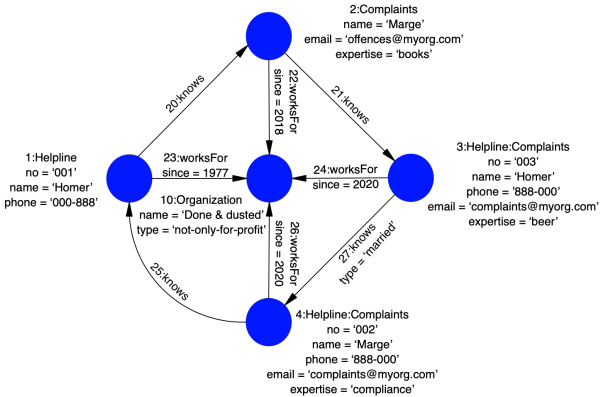
- $\{Helpline,Complaints\}{:}\{no,email\}$

Keys violated by property graph

- $Helpline{:}\{no,expertise\}$
- $Complaints{:}\{name\}$
- $\{Helpline,Complaints\}{:}\{phone,email\}$



Use Case 1: Updates under the key *Helpline:{name,phone}*

No node created due to violation of key

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No property removed due to violation of key

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MATCH (h:Helpline {name:'Homer', phone:'000-888'}) REMOVE h.phone
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No update of values due to violation of key

```
MATCH (h:Helpline {name:  'Homer', phone:'000-888'})
SET h.phone = '888-000'
RETURN h.name, h.phone
```

Use Case 2: Physical query optimization

```
MATCH (h:Helpline {name:'Homer',phone:'000-888'})
RETURN h.no, h.name
```

- will do a NodeByLabelScan, due to node label *Helpline*
- query would still take long on realistic property graphs

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```
CREATE INDEX index_Helpline FOR (h:Helpline)
ON (h.name, h.phone)
```

- query optimizer will take advantage of the index
- a NodeUniqueIndexSeek search is very efficient

Use Case 3: Logical query optimization

```
MATCH (s:Helpline:Complaints)
RETURN DISTINCT s.no, s.email
```

- Removal of duplicates expensive
- *Helpline*:{*no*} can avoid DISTINCT
- {*Helpline*,*Complaints*}:{*no*,*email*} may use multi-label index

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No support of multi-label keys by Neo4j (yet)

Axiomatic Characterization

$$\frac{\mathfrak{L} : \mathfrak{K}}{\mathfrak{L} \cup \mathfrak{L}' : \mathfrak{K}}\ \text{(label-extension)} \qquad \frac{\mathfrak{L} : \mathfrak{K}_1 \quad \mathfrak{L} : \mathfrak{K}_2 \cup \mathfrak{K}_3}{\mathfrak{L} : \mathfrak{K}_1 \cup \mathfrak{K}_2}\ \text{(attribute-extension)}$$

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Theorem

Label-extension and attribute-extension form a sound and complete set of inference rules for the implication of Neo4j keys

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Example ($\Sigma = \{$*Helpline:*$\{$*no*$\}$, *Helpline:*$\{$*name,phone*$\}$, *Complaints:*$\{$*name,email*$\}\}$)

Helpline:$\{$*name,phone*$\}$ *Complaints:*$\{$*name,email*$\}$

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Deciding Implication

1: **procedure** IMPLY($\Sigma, \mathfrak{L} : \mathfrak{K}$) **return** *TRUE*, if $\Sigma \models \mathfrak{L} : \mathfrak{K}$, and *FALSE*, otherwise
2: `Unique` $\leftarrow$ *FALSE*
3: `Exists` $\leftarrow$ *FALSE*
4: $\mathfrak{K}_{\mathfrak{L},\Sigma} \leftarrow \emptyset$
5: **for all** $\mathfrak{L}' : \mathfrak{K}' \in \Sigma$ **do**
6: **if** $\mathfrak{L}' \subseteq \mathfrak{L}$ **then** ▷ Properties of such keys must exist
7: $\mathfrak{K}_{\mathfrak{L},\Sigma} \leftarrow \mathfrak{K}_{\mathfrak{L},\Sigma} \cup \mathfrak{K}'$ ▷ Include properties of the key
8: **if** (NOT(`Unique`) AND $\mathfrak{K}' \subseteq \mathfrak{K}$) **then**
9: `Unique` $\leftarrow$ *TRUE* ▷ Found input key that makes $\mathfrak{L} : \mathfrak{K}$ unique
10: **if** $\mathfrak{K} \subseteq \mathfrak{K}_{\mathfrak{L},\Sigma}$ **then return** `Exists` $\leftarrow$ *TRUE* ▷ All required properties exist
11: **if** (`Exists` AND `Unique`) **then return** *TRUE* ▷ Properties exist and are unique
12: **else return** *FALSE*

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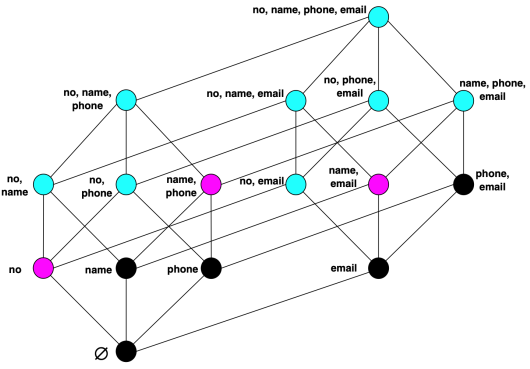
12: **else return** *FALSE*

Theorem

Let $\Sigma \cup \{\mathfrak{L} : \mathfrak{K}\}$ denote a set of Neo4j keys over $\mathcal{L}$ and $\mathcal{K}$. Then $\Sigma \models \mathfrak{L} : \mathfrak{K}$ if and only if $\mathfrak{K} \subseteq \mathfrak{K}_{\mathfrak{L},\Sigma}$ and there is some $\mathfrak{L}' : \mathfrak{K}' \in \Sigma$ where $\mathfrak{L}' \subseteq \mathfrak{L}$ and $\mathfrak{K}' \subseteq \mathfrak{K}$. The algorithm IMPLY$(\Sigma, \mathfrak{L} : \mathfrak{K})$ *decides the implication problem for the class of Neo4j keys in $\mathcal{O}(||\Sigma \cup \{\mathfrak{L} : \mathfrak{K}\}||)$ time.*

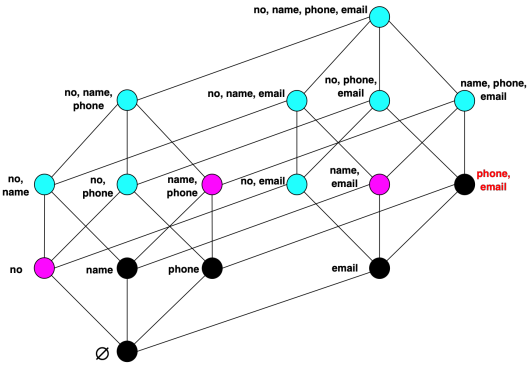
Example for Implication



:Helpline, :Complaints

Powerset lattice of Neo4j keys Implied by the keys marked in magenta: implied non-given keys marked in cyan, and non-implied keys marked in black

Example for Implication



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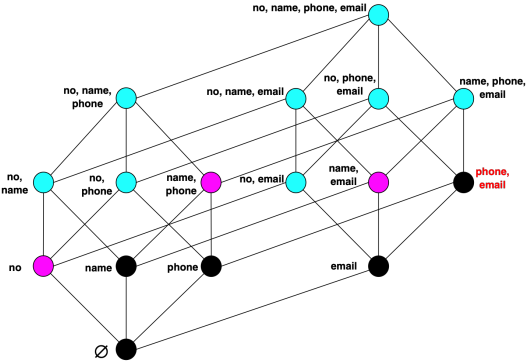
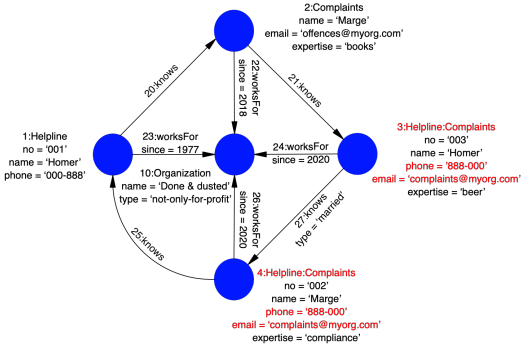
Example for Implication



:Helpline, :Complaints



Powerset lattice of Neo4j keys Implied by the keys marked in magenta: implied non-given keys marked in cyan, and non-implied keys marked in black

Summary

- Keys in Neo4j require completeness and uniqueness, as do candidate keys in SQL
- Neo4j is a multi-label graph model but only supports single-label keys
- Introduced a notion of Neo4j keys that
  - subsumes the single-label keys currently supported by Neo4j
  - permits the specification of multi-label keys
- Illustrated the importance of Neo4j keys through several use cases, including
  - updates
  - indexing
  - physical and logical query optimization
- Characterized the implication problem
  - axiomatically
  - algorithmically
- Future work
  - Combinatorics, sampling, discovery
  - Smarter notions of keys
  - Other constraints

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