A Survey of Deductive Databases

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CS 848, Fall 2016
University of Waterloo
Presented by: Siddhartha Sahu

Overview

- Relational Databases
- Deductive Databases
- Datalog
- Example Queries
- Query Execution
- Conclusion and Discussion

Relational Databases

Relational Databases

Predominant model for data storage and processing

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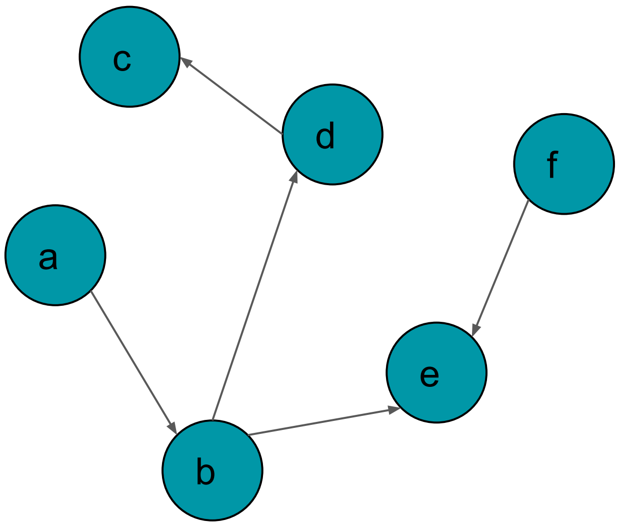
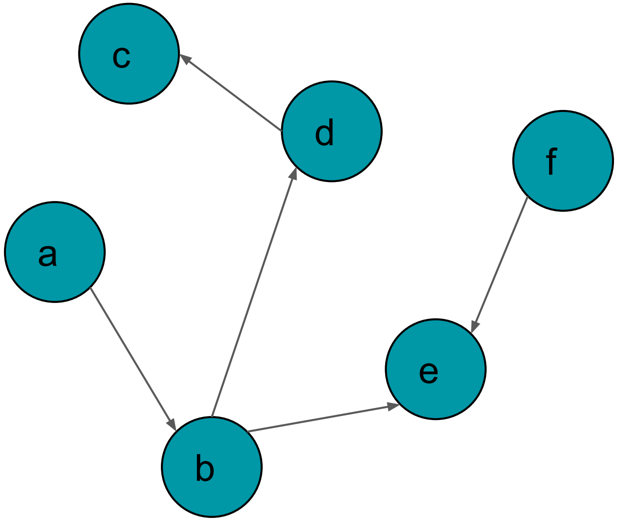
Predominant model for data storage and processing

Declarative language: focus on what rather than how

Relational Databases



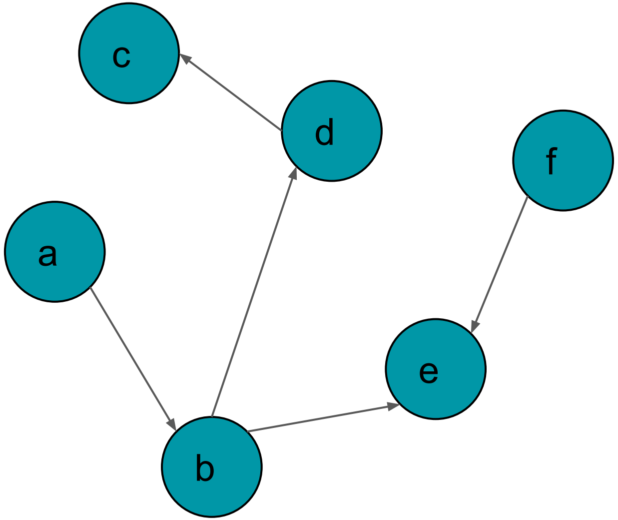
Relational Databases



INSERT INTO edges (...)

edges	
id_from	**id_to**
a	b
b	d
b	e
d	c
f	e

Relational Databases



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Q: List vertices that vertex ‘b’ have an outgoing edge to.

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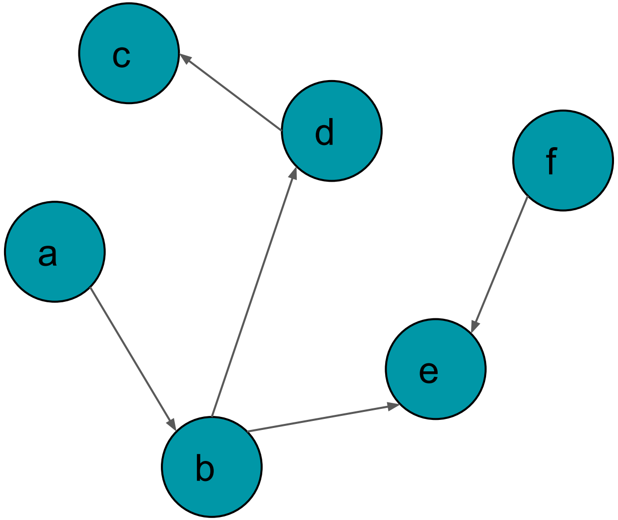

INSERT INTO edges (...)

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id_from	**id_to**
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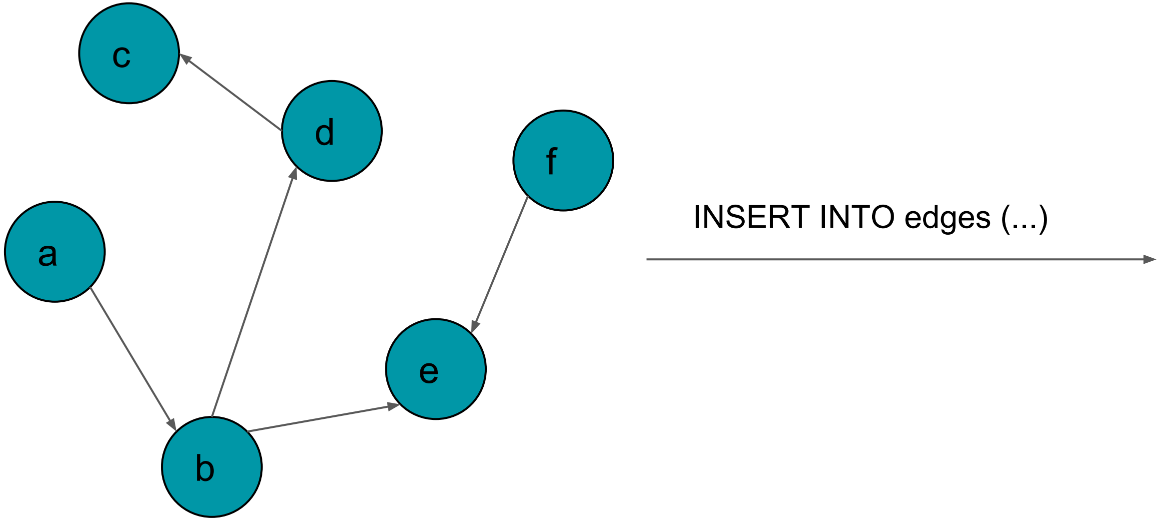
Q: List vertices that vertex ‘b’ have an outgoing edge to.

A: SELECT id_to from edges WHERE id_from = ‘b’

Relational Databases



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Q: List all vertex pairs (x,y), such that y is reachable from x.

A: ?

Deductive Databases

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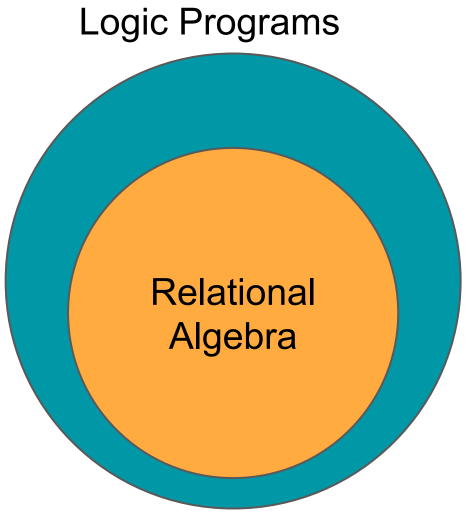
Support a superset of relational algebra.

- Supports all queries from relational algebra.
- Supports recursions.



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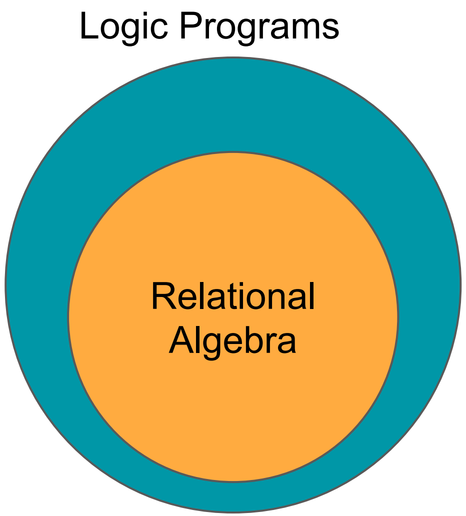
Datalog: subset of Prolog, a logic programming language

- Database centric requirements
- Emphasis on completeness and termination
- Queries on data stored on secondary storage



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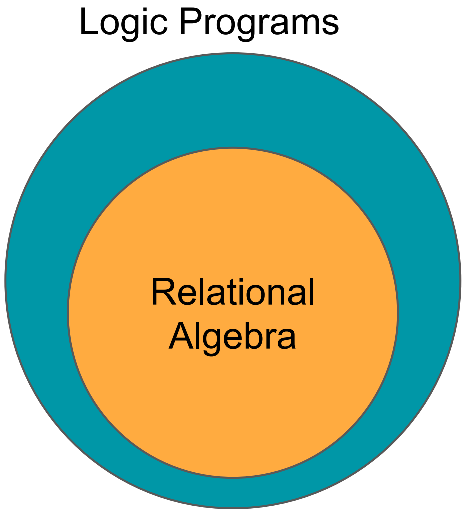
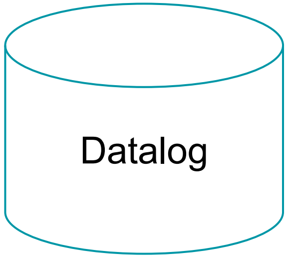
A database of facts.
A set of rules for deriving new facts from existing facts.



Datalog: Terminology



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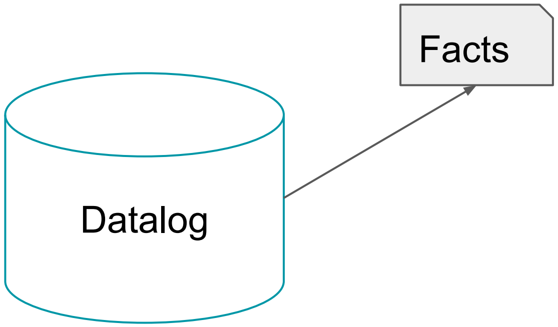

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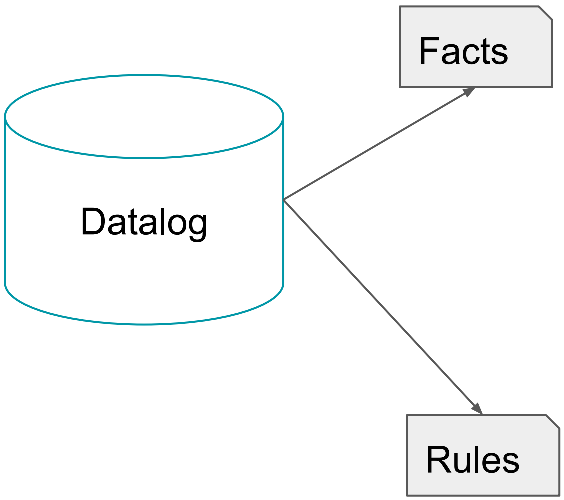


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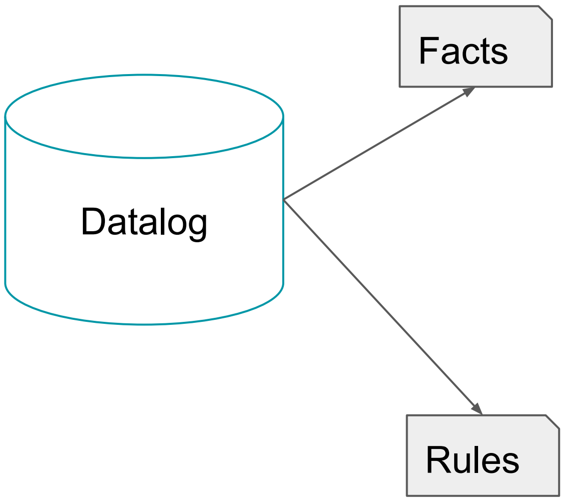

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Implication/Clause: A_0 :- A_1, A_2, ..., A_k where A_0 is **true** if A_1 and A_2 … and A_k are **true.**

k = 0: fact; k > 0: rule

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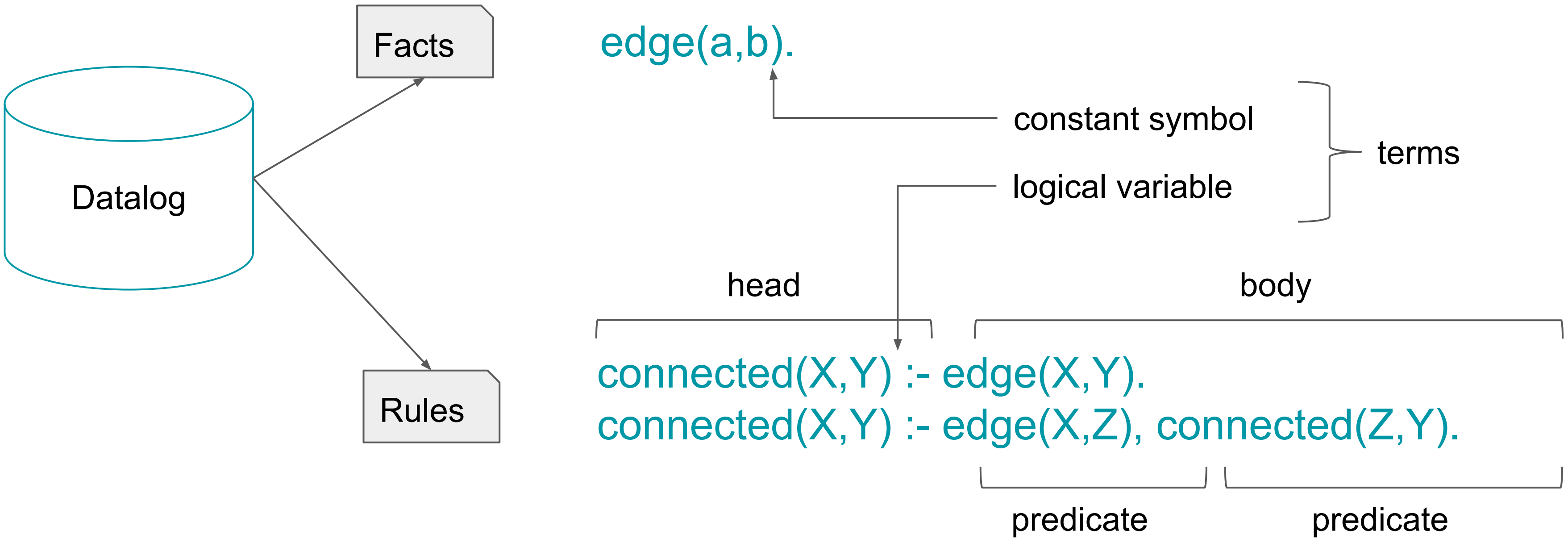

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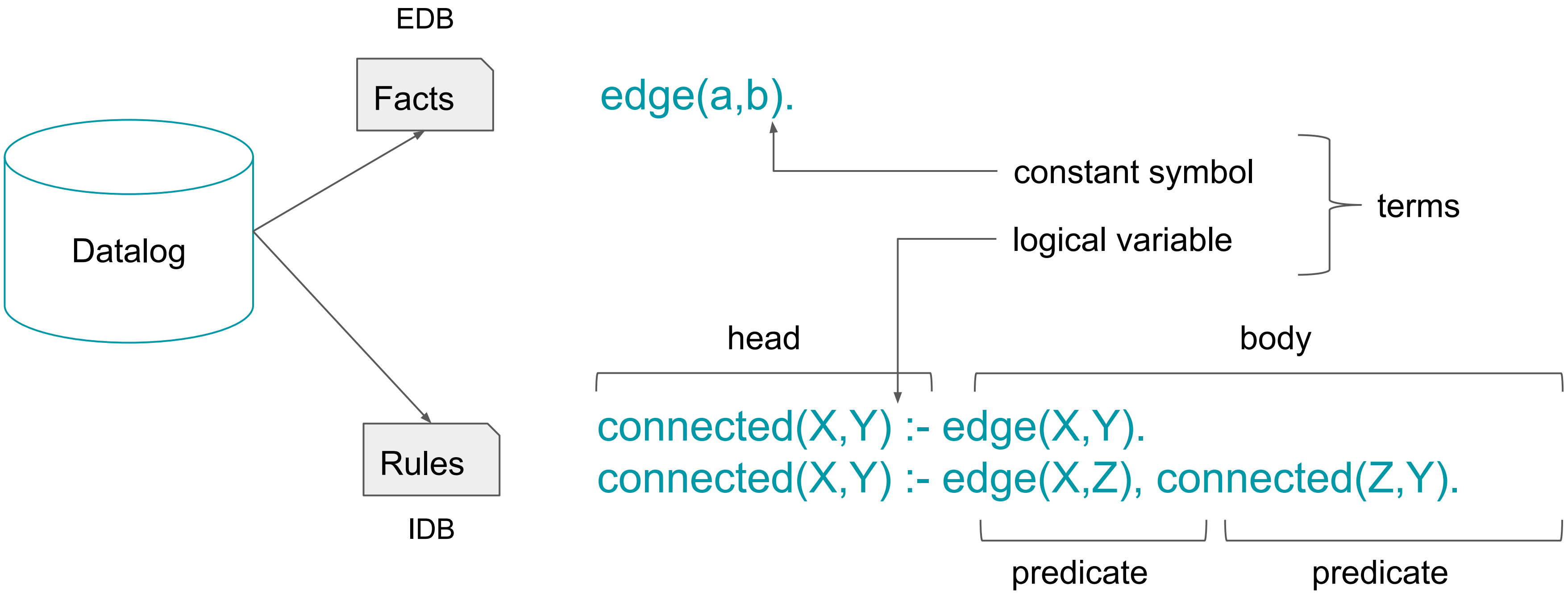

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Datalog: Examples

users
uid
name
age

accounts
uid
account_type
amount

Datalog: Examples

users
uid
name
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users(42, ‘Jane Doe’, 26).

accounts(42, ‘savings’, 5692.23)

Datalog: Examples

Selection

Q: List all users with **age** > 23.

users
uid
name
age

accounts
uid
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Relational Algebra: $\sigma_{\textbf{age} > 23}(\text{users})$

SQL: SELECT * FROM users WHERE **age** > 23;

Datalog: Examples

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SQL: SELECT * FROM users WHERE **age** > 23;

Datalog: S(Uid, Name, Age) :- users(Uid, Name, Age), **Age** > 23.

Datalog: Examples

Projection

Q: List **name** of users with age > 23.

users
uid
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accounts
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Datalog: Examples

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Datalog: Examples

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Projection

Q: List **name** of users with age > 23.

Relational Algebra: $\pi_{\textbf{name}}(\sigma_{age > 23}(users))$

SQL: SELECT **name** FROM users WHERE age > 23;

Datalog: P(**Name**) :- users(Uid, Name, Age), Age > 23.

Datalog: Examples

Join

Q: List **name, amount** of users with age > 23.

users
uid
name
age

accounts
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account_type
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Datalog: Examples

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Join

Q: List **name, amount** of users with age > 23.

Relational Algebra: $\pi_{\textbf{name,amount}}(\sigma_{age > 23}(users \bowtie_{uid} accounts))$

SQL:

SELECT **name,amount** FROM users,accounts

WHERE users.uid = accounts.uid AND age > 23;

Datalog: Examples

users
uid
name
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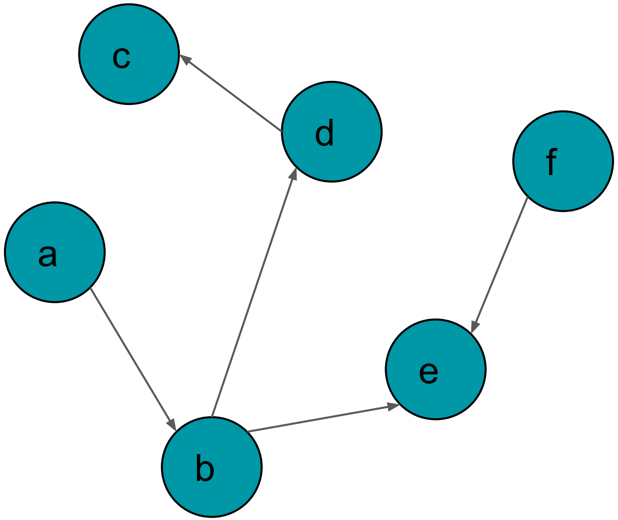
Datalog:

J(**Name,Amount**) :- users(Uid, Name, Age), accounts(Uid,

Account_type, Amount), Age > 23.

Datalog: Examples



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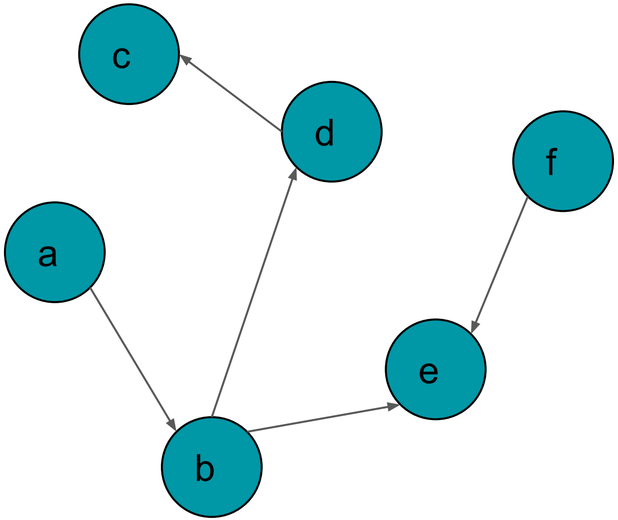


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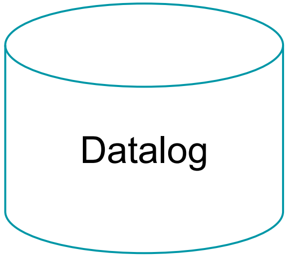

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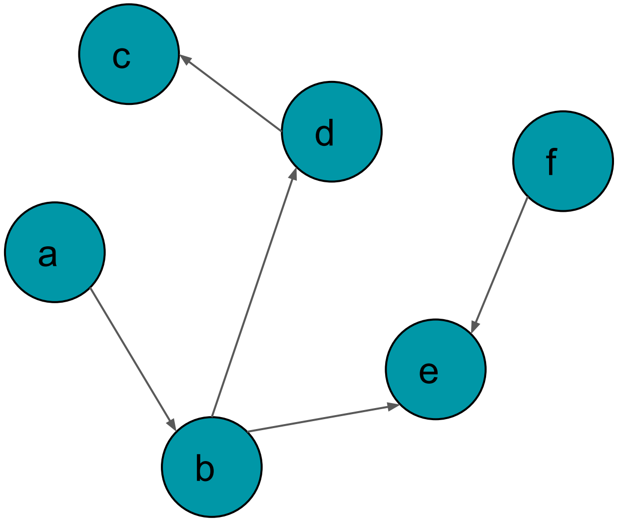

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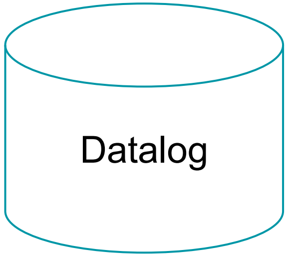

Q: List vertices that vertex ‘b’ have an outgoing edge to.

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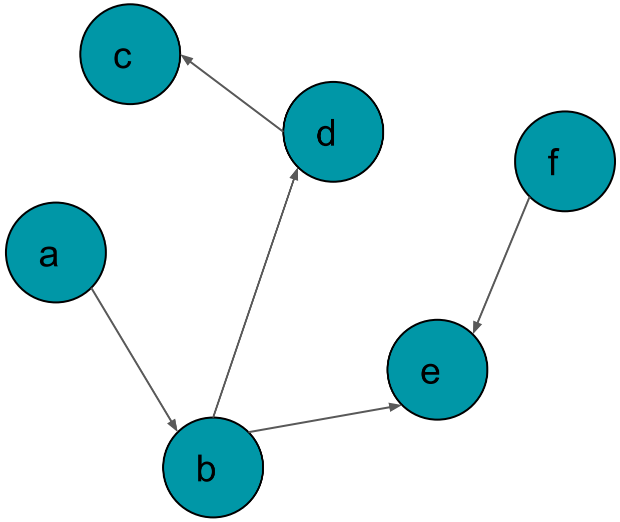

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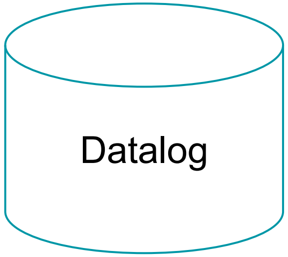
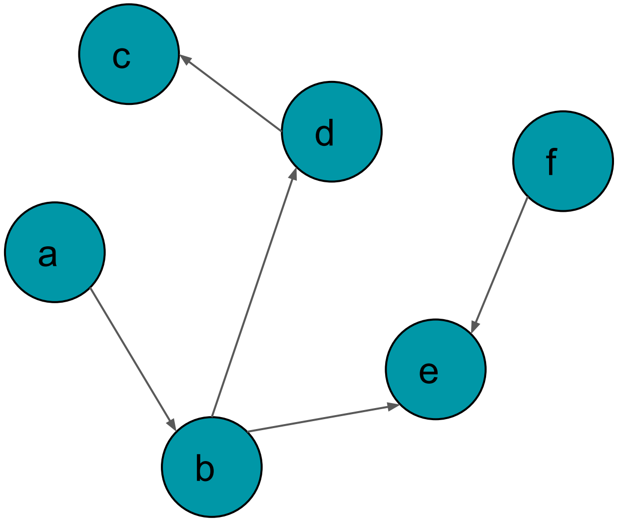


Q: List vertices that vertex ‘b’ have an outgoing edge to.

A: query(X) :- edge(b,X).

Datalog: Examples



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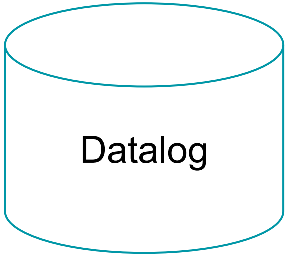

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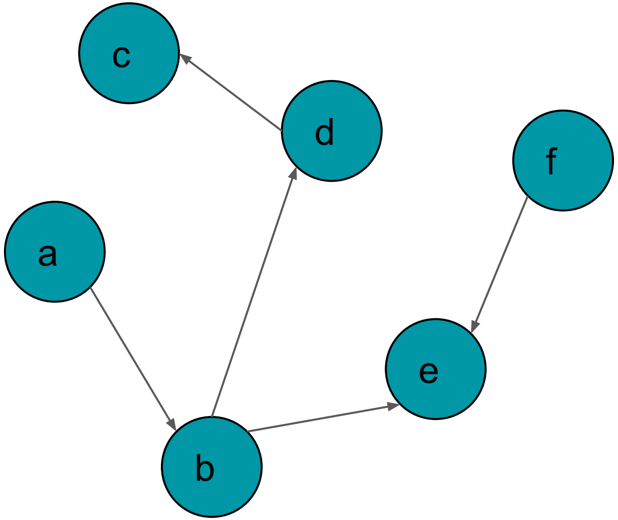

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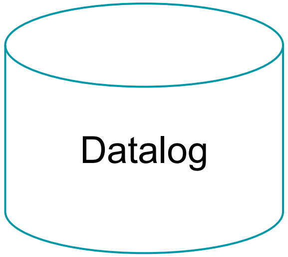

Q: List all vertex pairs (x,y), such that y is reachable from x.

A: query(X,Y) :- connected(X,Y).

Query Evaluation: Naïve algorithm

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P_0 = InitialValue
Repeat
    $P_k = f(P_{k-1})$
Until *no-more-change*

http://www.cs.toronto.edu/~drosu/csc343-l7-handout6.pdf, http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/csep544_14wi_8/slide775.jpg

Query Evaluation: Naïve algorithm

1. Begin by assuming all IDB relations are empty.

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Query Evaluation: Naïve algorithm

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2. Repeatedly evaluate the rules using the EDB and the previous IDB to get a new IDB.

3. End when there is no change to the IDB.

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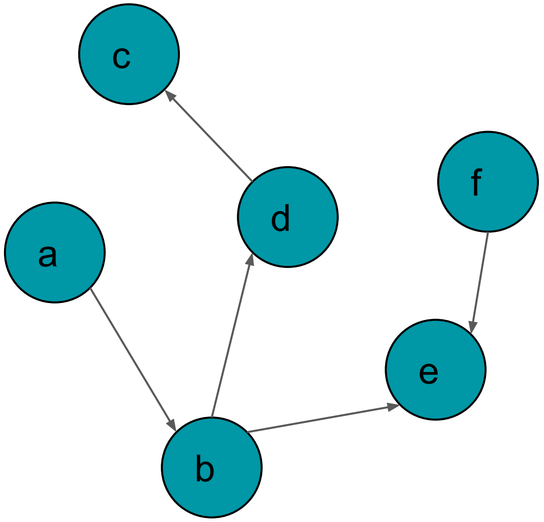

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connected(X,Y).
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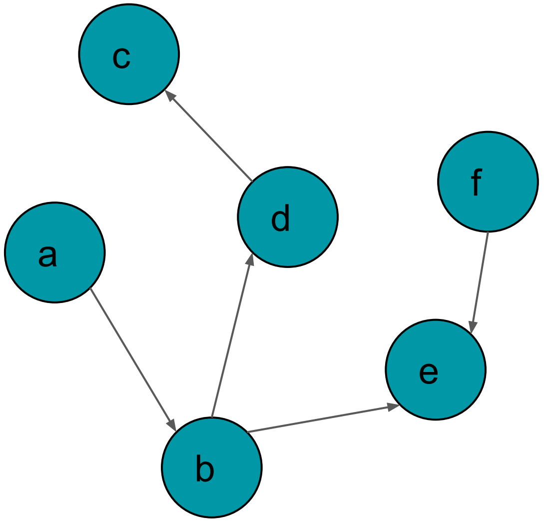

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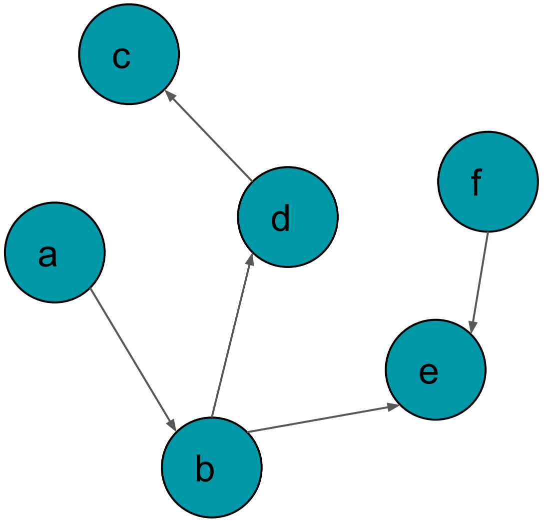

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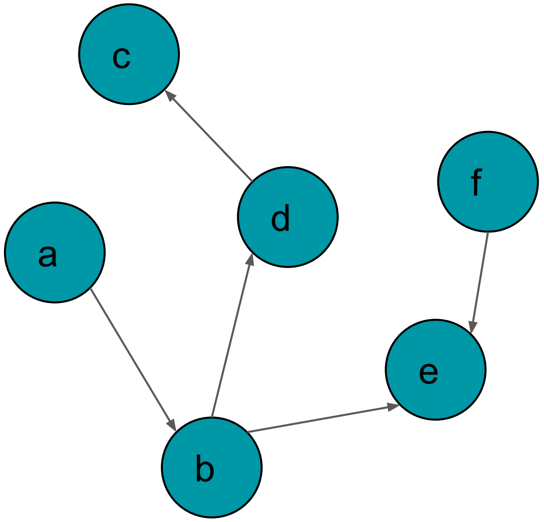
∅

I = 0

Query Evaluation: Naïve algorithm



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∅

I = 0

a	b
b	d
d	c
b	e
f	e

I = 1

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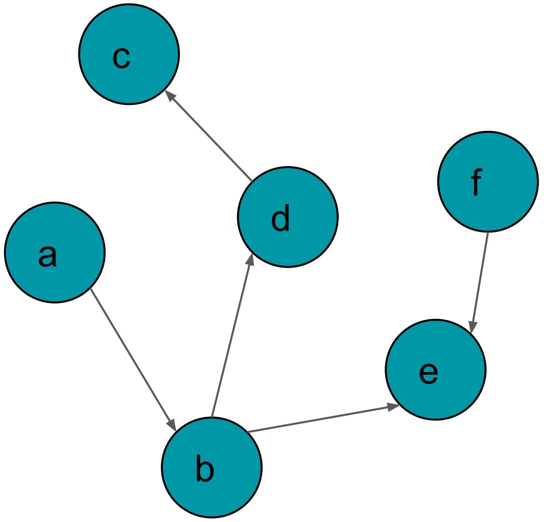

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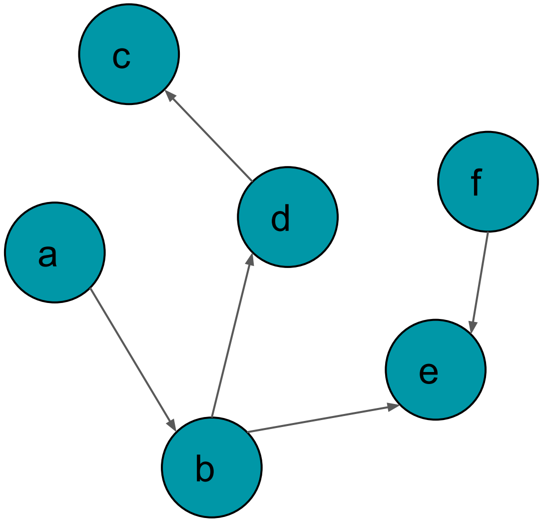

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I = 0 I = 1 I = 2

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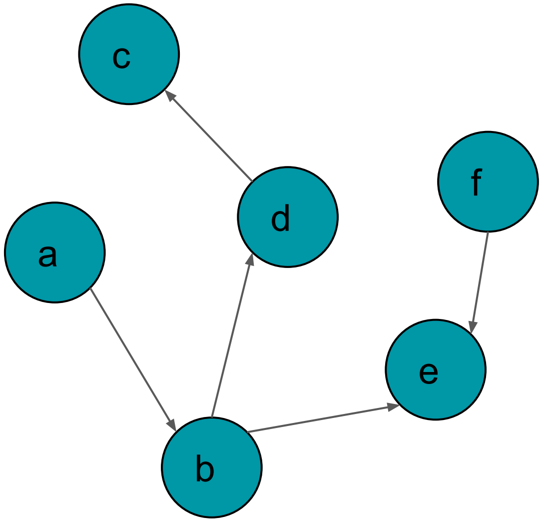

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∅

I = 0

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b	d
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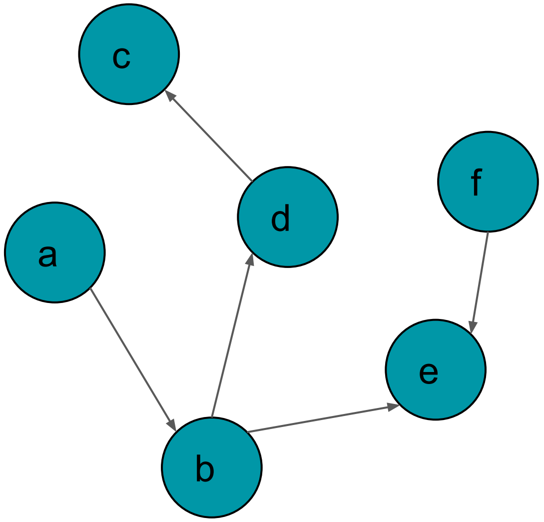

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a	b
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f	e

I = 2

a	d
a	e
a	b
b	d
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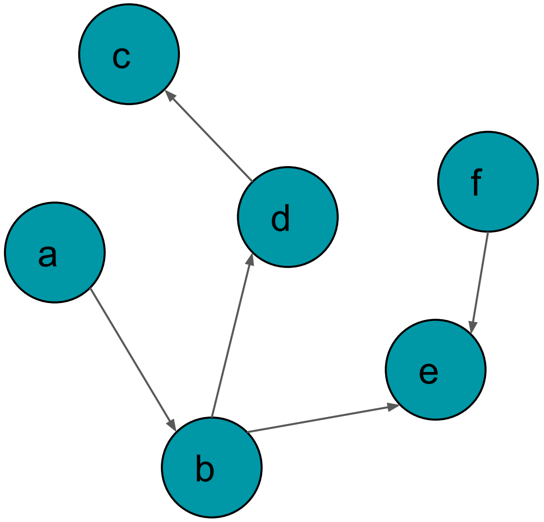

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```
connected(X,Y).
```

∅

I = 0

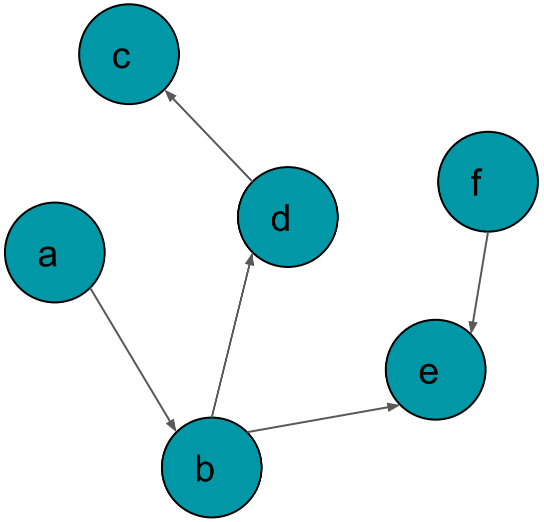
a	b
b	d
d	**c**
b	e
f	e

I = 1

b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 2

Query Evaluation: Naïve algorithm



edges	
a	b
b	d
d	c
b	e
f	e

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

connected(X,Y).

I = 0

∅

I = 1

a	b
b	d
d	c
b	e
f	e

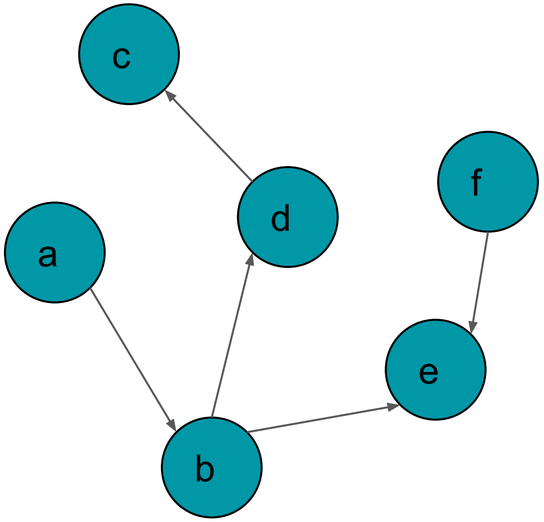
I = 2

b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 3

Query Evaluation: Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).



edges	
a	b
b	d
d	c
b	e
f	e

connected(X,Y).

I = 0

∅

I = 1

a	b
b	d
d	c
b	e
f	e

I = 2

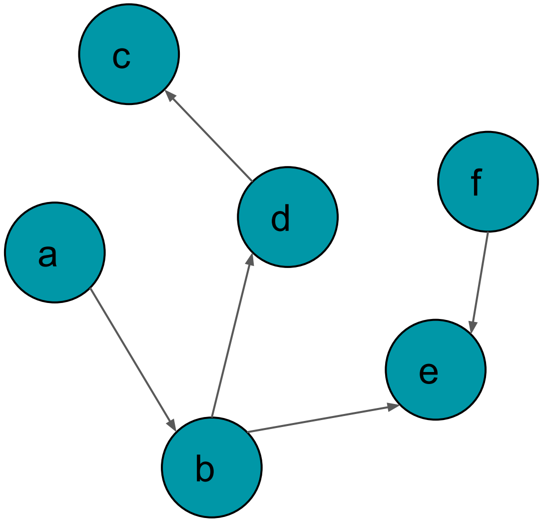
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 3

b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/video.html?id=csep544_14wi_8

Query Evaluation: Naïve algorithm



edges	
a	**b**
b	d
d	c
b	e
f	e

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

connected(X,Y).

I = 0

∅

I = 1

a	b
b	d
d	c
b	e
f	e

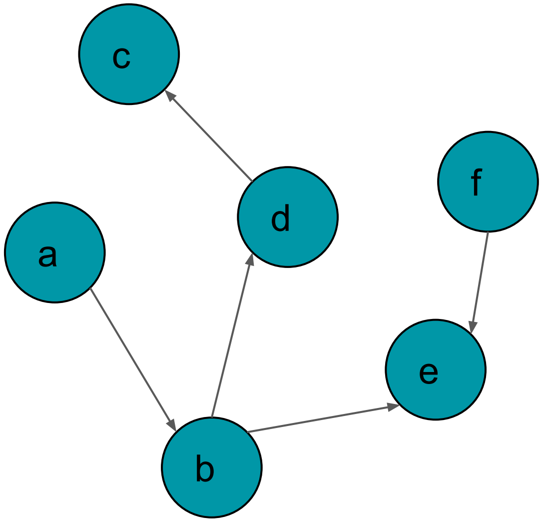
I = 2

b	**c**
a	d
a	e
a	b
b	**d**
d	c
b	**e**
f	e

I = 3

a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

Query Evaluation: Naïve algorithm



edges	
a	b
b	**d**
d	c
b	e
f	e

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

connected(X,Y).

I = 0

∅

I = 1

a	b
b	d
d	c
b	e
f	e

I = 2

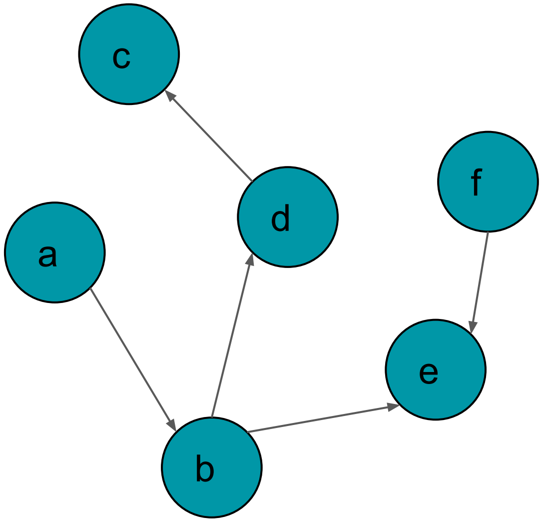
b	c
a	d
a	e
a	b
b	d
d	**c**
b	e
f	e

I = 3

a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/video.html?id=csep544_14wi_8

Query Evaluation: Naïve algorithm



edges	
a	b
b	d
d	c
b	e
f	e

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

I = 0

∅

I = 1

a	b
b	d
d	c
b	e
f	e

I = 2

b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 3

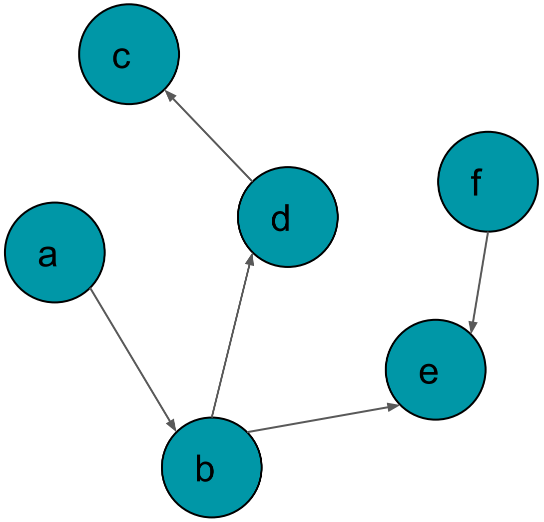
a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 4

```
connected(X,Y).
```

http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/video.html?id=csep544_14wi_8

Query Evaluation: Naïve algorithm



connected(X,Y).

edges	
a	b
b	d
d	c
b	e
f	e

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

∅

I = 0

a	b
b	d
d	c
b	e
f	e

I = 1

b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 2

a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

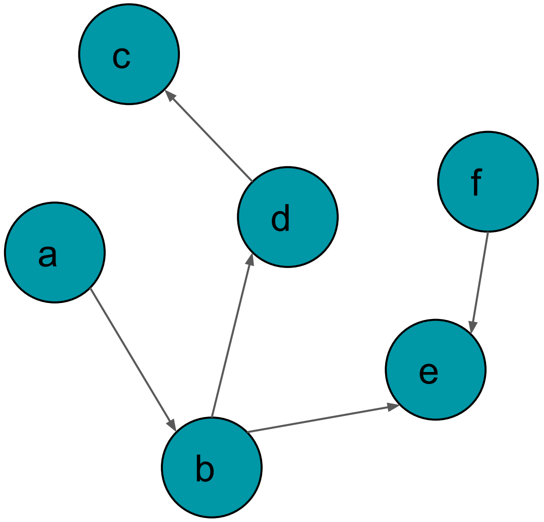
I = 3

a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 4

http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/video.html?id=csep544_14wi_8

Query Evaluation: Naïve algorithm



connected(X,Y).

edges	
a	b
b	d
d	c
b	e
f	e

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

I = 0

∅

I = 1

a	b
b	d
d	c
b	e
f	e

I = 2

b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 3

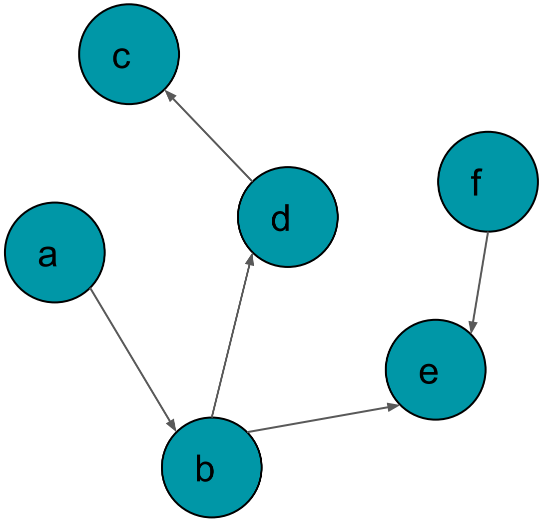
a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 4

a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/video.html?id=csep544_14wi_8

Query Evaluation: Naïve algorithm



edges	
a	b
b	d
d	c
b	e
f	e

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

connected(X,Y).

I = 0

∅

I = 1

a	b
b	d
d	c
b	e
f	e

I = 2

b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 3

a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

I = 4

a	c
b	c
a	d
a	e
a	b
b	d
d	c
b	e
f	e

http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/video.html?id=csep544_14wi_8

Query Evaluation: Semi-Naïve algorithm

* Avoid repeating computations already done in previous iterations.

* Focus on only the newly derived tuples (deltas) from previous iterations.

http://blogs.evergreen.edu/sosw/files/2014/04/Green-Vol5-DBS-017.pdf, http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/csep544_14wi_8/slide775.jpg

Query Evaluation: Semi-Naïve algorithm

* Avoid repeating computations already done in previous iterations.

* Focus on only the newly derived tuples (deltas) from previous iterations.

for each *IDB predicate* p

$$\textbf{do} \begin{cases} p^{[0]} := \emptyset \\ \delta(p)^{[0]} := \textit{tuples produced by rules using only EDB's} \end{cases}$$

$i := 1$

repeat

$p^{[i]} := p^{[i-1]} \cup \delta(p)^{[i-1]}$

evaluate $\Delta(p)^{[i]}$

$\delta(p)^{[i]} := \Delta(p)^{[i]} - p^{[i]}$

$i := i + 1$

until $\delta(p)^{[i]} = \emptyset$ *for each IDB predicate* p

http://blogs.evergreen.edu/sosw/files/2014/04/Green-Vol5-DBS-017.pdf, http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/csep544_14wi_8/slide775.jpg

Query Evaluation: Semi-Naïve algorithm

* Avoid repeating computations already done in previous iterations.

* Focus on only the newly derived tuples (deltas) from previous iterations.

for each *IDB predicate p*

$$\textbf{do} \begin{cases} p^{[0]} := \emptyset \\ \delta(p)^{[0]} := \textit{tuples produced by rules using only EDB's} \end{cases}$$

$i := 1$

repeat

$p^{[i]} := p^{[i-1]} \cup \delta(p)^{[i-1]}$

evaluate $\Delta(p)^{[i]}$

$\delta(p)^{[i]} := \Delta(p)^{[i]} - p^{[i]}$

$i := i + 1$

until $\delta(p)^{[i]} = \emptyset$ *for each IDB predicate p*

$$\Delta(p)^{[i]} \quad :- \quad \delta(p_1)^{[i-1]}, p_2^{[i-1]}, \ldots, p_n^{[i-1]}, q_1, \ldots, q_m .$$

$$\Delta(p)^{[i]} \quad :- \quad p_1^{[i]}, \delta(p_2)^{[i-1]}, p_3^{[i-1]} \ldots, p_n^{[i-1]}, q_1, \ldots, q_m .$$

$\ldots$

$$\Delta(p)^{[i]} \quad :- \quad p_1^{[i]}, \ldots, p_{n-1}^{[i]}, \delta(p_n)^{[i-1]}, q_1, \ldots, q_m .$$

http://blogs.evergreen.edu/sosw/files/2014/04/Green-Vol5-DBS-017.pdf, http://courses.cs.washington.edu/courses/csep544/14wi/video/archive/html5/csep544_14wi_8/slide775.jpg

Query Evaluation: Semi-Naïve algorithm

edges	
a	b
b	d
d	c
b	e
f	e

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

∅

$P_{I = 0}$

Query Evaluation: Semi-Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

edges	
a	b
b	d
d	c
b	e
f	e

∅

$P_{I=0}$

a	b
b	d
d	c
b	e
f	e

$\delta_{I=0}$

Query Evaluation: Semi-Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

edges	
a	b
b	d
d	c
b	e
f	e

∅

$P_{I=0}$

a	b
b	d
d	c
b	e
f	e

$\delta_{I=0}$

a	b
b	d
d	c
b	e
f	e

$P_{I=1}$

Query Evaluation: Semi-Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

edges	
a	b
b	d
d	c
b	e
f	e

∅

$P_{I = 0}$

a	b
b	d
d	c
b	e
f	e

$\delta_{I = 0}$

a	b
b	d
d	c
b	e
f	e

$P_{I = 1}$

a	d
a	e
b	c

$\Delta_{I = 1}$

Query Evaluation: Semi-Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

edges	
a	b
b	d
d	c
b	e
f	e

∅

$P_{I=0}$

a	b
b	d
d	c
b	e
f	e

$\delta_{I=0}$

a	b
b	d
d	c
b	e
f	e

$P_{I=1}$

a	d
a	e
b	c

$\Delta_{I=1}$

a	d
a	e
b	c

$\delta_{I=1}$

Query Evaluation: Semi-Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

edges	
a	b
b	d
d	c
b	e
f	e

∅

$P_{I=0}$

a	b
b	d
d	c
b	e
f	e

$\delta_{I=0}$

a	b
b	d
d	c
b	e
f	e

$P_{I=1}$

a	d
a	e
b	c

$\Delta_{I=1}$

a	d
a	e
b	c

$\delta_{I=1}$

a	d
a	e
b	c
a	b
b	d
d	c
b	e
f	e

$P_{I=2}$

Query Evaluation: Semi-Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

edges	
a	b
b	d
d	c
b	e
f	e

∅

$P_{I=0}$

a	b
b	d
d	c
b	e
f	e

$\delta_{I=0}$

a	b
b	d
d	c
b	e
f	e

$P_{I=1}$

a	d
a	e
b	c

$\Delta_{I=1}$

a	d
a	e
b	c

$\delta_{I=1}$

a	d
a	e
b	c
a	b
b	d
d	c
b	e
f	e

$P_{I=2}$

a	c

$\Delta_{I=2}$

Query Evaluation: Semi-Naïve algorithm

```
connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).
```

edges	
a	b
b	d
d	c
b	e
f	e

∅

$P_{I=0}$

a	b
b	d
d	c
b	e
f	e

$\delta_{I=0}$

a	b
b	d
d	c
b	e
f	e

$P_{I=1}$

a	d
a	e
b	c

$\Delta_{I=1}$

a	d
a	e
b	c

$\delta_{I=1}$

a	d
a	e
b	c
a	b
b	d
d	c
b	e
f	e

$P_{I=2}$

a	c

$\Delta_{I=2}$

a	c

$\delta_{I=2}$

Query Evaluation: Semi-Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

edges	
a	b
b	d
d	c
b	e
f	e

$P_{I=0}$: ∅

$\delta_{I=0}$

a	b
b	d
d	c
b	e
f	e

$P_{I=1}$

a	b
b	d
d	c
b	e
f	e

$\Delta_{I=1}$

a	d
a	e
b	c

$\delta_{I=1}$

a	d
a	e
b	c

$P_{I=2}$

a	d
a	e
b	c
a	b
b	d
d	c
b	e
f	e

$\Delta_{I=2}$

a	c

$\delta_{I=2}$

a	c

a	c
a	d
a	e
b	c
a	b
b	d
d	c
b	e
f	e

Query Evaluation: Semi-Naïve algorithm

connected(X,Y) :- edge(X,Y).
connected(X,Y) :- edge(X,Z), connected(Z,Y).

edges	
a	b
b	d
d	c
b e	
f	e

$P_{I=0}$: ∅

$\delta_{I=0}$

a	b
b	d
d	c
b	e
f	e

$P_{I=1}$

a	b
b	d
d	c
b	e
f	e

$\Delta_{I=1}$

a	d
a	e
b	c

$\delta_{I=1}$

a	d
a	e
b	c

$P_{I=2}$

a	d
a	e
b	c
a	b
b	d
d	c
b	e
f	e

$\Delta_{I=2}$

a	c

$\delta_{I=2}$

a	c

a	c
a	d
a	e
b	c
a	b
b	d
d	c
b	e
f	e

$\Delta_{I=3}$: ∅

$\delta_{I=3}$: ∅

Deductive Databases: Additional concepts

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Negation predicates

Deductive Databases: Additional concepts

Negation predicates

Safe rules

Deductive Databases: Additional concepts

Negation predicates

Safe rules

Query optimization
- Magic Sets
- Rule-Rewriting Techniques
- Iterative Fixpoint Evaluation

Deductive Databases: Additional concepts

Negation predicates

Safe rules

Query optimization
- Magic Sets
- Rule-Rewriting Techniques
- Iterative Fixpoint Evaluation

Aggregations

Conclusion

Conclusion

Deductive databases are more expressive than relational databases.

- Support for recursive queries

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- Support for recursive queries

Datalog: query language adapted from Prolog

Conclusion

Deductive databases are more expressive than relational databases.

Support for recursive queries

Datalog: query language adapted from Prolog

Focus on query optimization

Conclusion

Deductive databases are more expressive than relational databases.

- Support for recursive queries

Datalog: query language adapted from Prolog

Focus on query optimization

Naive vs Semi Naive query execution algorithms

- Avoid repeated computations

Discussion

SQL has recursion techniques like CTE
- How does that compare to Datalog in terms of expressiveness?

Application domains best suited for Datalog?
- Program analysis (recursion)
- Declarative networking (NDlog)
- Security (SeNDlog)

Applicability to general processing frameworks?
- Hive
- Spark SQL