Incremental Materialisation in Datalog and its Relationship to Stream Reasoning

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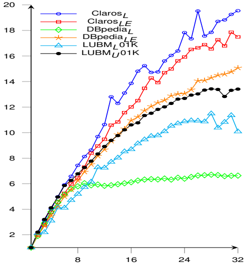
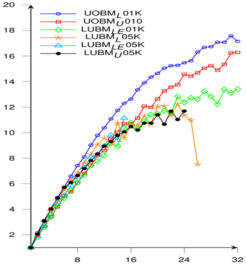
RDFox: A Scalable RDF/Datalog Main-Memory Reasoner

- http://www.cs.ox.ac.uk/isg/tools/RDFox/
- RAM-based; currently centralised, but a distributed system is in the works
- Datalog reasoning via materialisation
  - Arbitrary (recursive) datalog rules, not just OWL 2 RL
  - Materialisation ⇒ precompute all facts in a preprocessing stage
  - Very effective parallelisation on multi-core architectures
- Efficient reasoning with *owl:sameAs* via rewriting
  - Known and widely-used technique, but correctness not trivial
- SPARQL query answering
  - Most of SPARQL 1.0 and some of SPARQL 1.1

Evaluation (I): Parallelisation Overhead and Speedup





- Speedup of up to 13x with 16 physical cores
- Increases to 19x with 32 virtual cores

Evaluation (II): Oracle's SPARC T5 (128/1024 cores, 4 TB)

	LUBM-50K		Claros		DBpedia	
Threads	sec	speedup	sec	speedup	sec	speedup
import	6.8k	—	168	—	952	—
1	27.0k	1.0x	10.0k	1.0x	31.2k	1.0x
16	1.7k	15.7x	906.0	11.0x	3.0k	10.4x
32	1.1k	24.0x	583.3	17.1x	1.8k	17.5x
48	920.7	29.3x	450.8	22.2x	2.0k	16.0x
64	721.2	37.4x	374.9	26.7x	1.2k	25.8x
80	523.6	51.5x	384.1	26.0x	1.2k	26.7x
96	442.4	60.9x	364.3	27.4x	825	37.8x
112	400.6	67.3x	331.4	30.2x	1.3k	24.3x
128	387.4	69.6x	225.7	44.3x	697.9	44.7x
256	—	—	226.1	44.2x	684.0	45.7x
384	—	—	189.1	52.9x	546.2	57.2x
512	—	—	153.5	65.1x	431.8	72.3x
640	—	—	140.5	71.2x	393.4	79.4x
768	—	—	130.4	76.7x	366.2	85.3x
896	—	—	127.0	78.8x	364.9	86.6x
1024	—	—	124.9	80.1x	358.8	87.0x
size	B/trp	Triples	B/trp	Triples	B/trp	Triples
aft imp	124.1	6.7G	80.5	18.8M	58.4	112.7M
aft mat	101.0	9.2G	36.9	539.2M	39.0	1.5G
import rate	1.0M		112k		120k	
mat. rate	6.1M		4.2M		4.0M	

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Why Incremental Reasoning?

- Common application scenario: continuous small changes in input data
  - Similar to stream reasoning!
- Materialisation can be expensive ⇒ starting from scratch is unacceptable!
- Incremental maintenance: minimise work needed to update materialisation
- State of the art (from the 90s):
  - the Counting algorithm
    - Basic variant applicable only to nonrecursive programs!
    - Extension to recursive programs rather complex
  - the Delete/Rederive (DRed) algorithm
    - Works for nonrecursive rules too

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x)$ $\quad$ $C_0(x) \leftarrow B(x)$ $\quad$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad$ $C_0(x) \leftarrow C_n(x)$

$A(a)$	1
$B(a)$	1

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x) \quad C_0(x) \leftarrow B(x) \quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1
$B(a)$	1
$C_0(a)$	1

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1
$B(a)$	1
$C_0(a)$	2

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation

$A(a)$	1
$B(a)$	1
$C_0(a)$	2
$C_1(a)$	1

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x)$ $\quad$ $C_0(x) \leftarrow B(x)$ $\quad$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad$ $C_0(x) \leftarrow C_n(x)$

$A(a)$	1
$B(a)$	1
$C_0(a)$	2
$C_1(a)$	1
...	

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x)$ $\quad$ $C_0(x) \leftarrow B(x)$ $\quad$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad$ $C_0(x) \leftarrow C_n(x)$

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation

$A(a)$	1
$B(a)$	1
$C_0(a)$	2
$C_1(a)$	1
...	
$C_n(a)$	1

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1
$B(a)$	1
$C_0(a)$	3
$C_1(a)$	1
...	
$C_n(a)$	1

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0
$B(a)$	1
$C_0(a)$	3
$C_1(a)$	1
...	
$C_n(a)$	1

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation
- Delete $A(a)$:
  - Decrease its counter

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0
$B(a)$	1
$C_0(a)$	2
$C_1(a)$	1
...	
$C_n(a)$	1

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation
- Delete $A(a)$:
  - Decrease its counter
  - The counter of $A(a)$ reaches zero, so propagate deletion

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x)$ $\quad$ $C_0(x) \leftarrow B(x)$ $\quad$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad$ $C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0
~~$B(a)$~~	0
$C_0(a)$	2
$C_1(a)$	1
...	
$C_n(a)$	1

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation
- Delete $A(a)$:
  - Decrease its counter
  - The counter of $A(a)$ reaches zero, so propagate deletion
- Problem of this variant: delete $B(a)$
  - Decrease its counter

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0
~~$B(a)$~~	0
$C_0(a)$	1
$C_1(a)$	1
$\dots$	
$C_n(a)$	1

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation
- Delete $A(a)$:
  - Decrease its counter
  - The counter of $A(a)$ reaches zero, so propagate deletion
- Problem of this variant: delete $B(a)$
  - Decrease its counter
  - The counter of $B(a)$ reaches zero, so propagate deletion

Basic Counting (Nonrecursive Variant)

Example

$C_0(x) \leftarrow A(x)$ $C_0(x) \leftarrow B(x)$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0
~~$B(a)$~~	0
$C_0(a)$	1
$C_1(a)$	1
...	
$C_n(a)$	1

- Associate with each fact a counter initialised to zero
- Increment the counter after each derivation
- Delete $A(a)$:
  - Decrease its counter
  - The counter of $A(a)$ reaches zero, so propagate deletion
- Problem of this variant: delete $B(a)$
  - Decrease its counter
  - The counter of $B(a)$ reaches zero, so propagate deletion
  - However, $C_0(a)$ still has a cyclic derivation from $C_n(a)$
  - $\Rightarrow$ The algorithm does not delete $C_0(a), \ldots, C_n(a)$!
  - Reference counting is not a general garbage collection method

Counting and Recursion

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1
$B(a)$	1

Counting and Recursion

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1	
$B(a)$	1	
$C_0(a)$		1

- Associate with each fact an array of counters, one per iteration

Counting and Recursion

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1	
$B(a)$	1	
$C_0(a)$		2

- Associate with each fact an array of counters, one per iteration

Counting and Recursion

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1		
$B(a)$	1		
$C_0(a)$		2	
$C_1(a)$			1

- Associate with each fact an array of counters, one per iteration

Counting and Recursion

Example

$C_0(x) \leftarrow A(x)$ $\quad$ $C_0(x) \leftarrow B(x)$ $\quad$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad$ $C_0(x) \leftarrow C_n(x)$

$A(a)$	1		
$B(a)$	1		
$C_0(a)$		2	
$C_1(a)$			1
...			

- Associate with each fact an array of counters, one per iteration

Counting and Recursion

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1				
$B(a)$	1				
$C_0(a)$		2			
$C_1(a)$			1		
...					
$C_n(a)$					1

- Associate with each fact an array of counters, one per iteration

Counting and Recursion

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

$A(a)$	1				
$B(a)$	1				
$C_0(a)$		2			1
$C_1(a)$			1		
...					
$C_n(a)$				1	

- Associate with each fact an array of counters, one per iteration

Counting and Recursion

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0				
~~$B(a)$~~	0				
$C_0(a)$		2			1
$C_1(a)$			1		
...					
$C_n(a)$				1	

- Associate with each fact an array of counters, one per iteration
- Delete $A(a)$ and $B(a)$ by undoing derivations

Counting and Recursion

Example

$C_0(x) \leftarrow A(x)$ $\quad$ $C_0(x) \leftarrow B(x)$ $\quad$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad$ $C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0				
~~$B(a)$~~	0				
$C_0(a)$		0			1
$C_1(a)$			1		
...					
$C_n(a)$				1	

- Associate with each fact an array of counters, one per iteration
- Delete $A(a)$ and $B(a)$ by undoing derivations

Counting and Recursion

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0				
~~$B(a)$~~	0				
$C_0(a)$		0			1
$C_1(a)$			0		
...					
$C_n(a)$				1	

- Associate with each fact an array of counters, one per iteration
- Delete $A(a)$ and $B(a)$ by undoing derivations

Counting and Recursion

Example

$C_0(x) \leftarrow A(x)$ $\quad$ $C_0(x) \leftarrow B(x)$ $\quad$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad$ $C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0				
~~$B(a)$~~	0				
$C_0(a)$		0			1
$C_1(a)$			0		
. . .					
$C_n(a)$				0	

- Associate with each fact an array of counters, one per iteration
- Delete $A(a)$ and $B(a)$ by undoing derivations

Counting and Recursion

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~	0				
~~$B(a)$~~	0				
$C_0(a)$		0			0
$C_1(a)$			0		
...					
$C_n(a)$				0	

- Associate with each fact an array of counters, one per iteration
- Delete $A(a)$ and $B(a)$ by undoing derivations

Inefficiency of Recursive Counting

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

$A(a)$	1				
$B(a)$	1				
$C_0(a)$		2			1
$C_1(a)$			1		
...					
$C_n(a)$				1	

Inefficiency of Recursive Counting

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

$A(a)$	1				
$B(a)$	1				
$C_0(a)$	1	2			1
$C_1(a)$			1		
...					
$C_n(a)$				1	

- Add $C_0(a)$ explicitly

Inefficiency of Recursive Counting

Example

$C_0(x) \leftarrow A(x)$ $C_0(x) \leftarrow B(x)$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $C_0(x) \leftarrow C_n(x)$

$A(a)$	1				
$B(a)$	1				
$C_0(a)$	1	2			1
$C_1(a)$		1			
...					
$C_n(a)$				1	

- Add $C_0(a)$ explicitly
- We must update all counts to reflect the new state although there is no change in the available facts!

The DRed Algorithm at a Glance

Delete/Rederive (DRed): state of the art incremental maintenance algorithm

Example

$C_0(x) \leftarrow A(x) \qquad C_0(x) \leftarrow B(x) \qquad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n \qquad C_0(x) \leftarrow C_n(x)$

$A(a)$ $B(a)$

The DRed Algorithm at a Glance

Delete/Rederive (DRed): state of the art incremental maintenance algorithm

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

- Materialise initial facts

$A(a)$
$B(a)$
$C_0(a)$
$C_1(a)$
$\ldots$
$C_n(a)$

The DRed Algorithm at a Glance

Delete/Rederive (DRed): state of the art incremental maintenance algorithm

Example

$C_0(x) \leftarrow A(x)$ $C_0(x) \leftarrow B(x)$ $C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $C_0(x) \leftarrow C_n(x)$

- Materialise initial facts
- Delete $A(a)$ using DRed:

~~$A(a)$~~
$B(a)$
$C_0(a)$
$C_1(a)$
$\ldots$
$C_n(a)$

The DRed Algorithm at a Glance

Delete/Rederive (DRed): state of the art incremental maintenance algorithm

Example

$C_0(x) \leftarrow A(x) \quad C_0(x) \leftarrow B(x) \quad C_i(x) \leftarrow C_{i-1}(x) \text{ for } 1 \leq i \leq n \quad C_0(x) \leftarrow C_n(x)$

- Materialise initial facts
- Delete $A(a)$ using DRed:
  1. Delete all facts with a derivation from $A(a)$

$$
\begin{aligned}
C_0(x)^D &\leftarrow A(x)^D \\
C_0(x)^D &\leftarrow B(x)^D \\
C_i(x)^D &\leftarrow C_{i-1}(x)^D \text{ for } 1 \leq i \leq n \\
C_0(x)^D &\leftarrow C_n(x)^D
\end{aligned}
$$

~~$A(a)$~~
$B(a)$
~~$C_0(a)$~~
~~$C_1(a)$~~
~~...~~
~~$C_n(a)$~~

The DRed Algorithm at a Glance

Delete/Rederive (DRed): state of the art incremental maintenance algorithm

Example

$C_0(x) \leftarrow A(x)$ $\quad C_0(x) \leftarrow B(x)$ $\quad C_i(x) \leftarrow C_{i-1}(x)$ for $1 \leq i \leq n$ $\quad C_0(x) \leftarrow C_n(x)$

~~$A(a)$~~
$B(a)$
$C_0(a)$
$C_1(a)$
$\ldots$
$C_n(a)$

- Materialise initial facts
- Delete $A(a)$ using DRed:
  1. Delete all facts with a derivation from $A(a)$

$$
\begin{aligned}
C_0(x)^D &\leftarrow A(x)^D \\
C_0(x)^D &\leftarrow B(x)^D \\
C_i(x)^D &\leftarrow C_{i-1}(x)^D \text{ for } 1 \leq i \leq n \\
C_0(x)^D &\leftarrow C_n(x)^D
\end{aligned}
$$

  2. Rederive facts that have an alternative derivation

$$
\begin{aligned}
C_0(x) &\leftarrow C_0(x)^D \wedge A(x) \\
C_0(x) &\leftarrow C_0(x)^D \wedge B(x) \\
C_i(x) &\leftarrow C_i(x)^D \wedge C_{i-1}(x) \text{ for } 1 \leq i \leq n \\
C_0(x) &\leftarrow C_0(x)^D \wedge C_n(x)
\end{aligned}
$$

Improvement: the Forward/Backward/Forward Algorithm

- Facts often have many derivations, so many facts get deleted in the first step
- The Forward/Backward/Forward algorithm looks for alternatives immediately

$A(a)$
$B(a)$
$C_0(a)$
$C_1(a)$
$\ldots$
$C_n(a)$

B. Motik, Y. Nenov, R. Piro, and I. Horrocks.:

- Incremental Update of Datalog Materialisation: the Backward/Forward Algorithm. AAAI 2015
- Combining Rewriting and Incremental Materialisation Maintenance for Datalog Programs with Equality. IJCAI 2015

Improvement: the Forward/Backward/Forward Algorithm

- Facts often have many derivations, so many facts get deleted in the first step
- The Forward/Backward/Forward algorithm looks for alternatives immediately

$A(a)$
$B(a)$
$C_0(a)$
$C_1(a)$
...
$C_n(a)$

- Delete $A(a)$ using FBF:

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IMPROVEMENT: THE FORWARD/BACKWARD/FORWARD ALGORITHM

- Facts often have many derivations, so many facts get deleted in the first step
- The Forward/Backward/Forward algorithm looks for alternatives immediately

$A(a)$
$B(a)$
$C_0(a)$
$C_1(a)$
$\dots$
$C_n(a)$

?

- Delete $A(a)$ using FBF:
  1. Is $A(a)$ derivable in any other way?

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Improvement: the Forward/Backward/Forward Algorithm

- Facts often have many derivations, so many facts get deleted in the first step
- The Forward/Backward/Forward algorithm looks for alternatives immediately

~~$A(a)$~~ ×
$B(a)$
$C_0(a)$
$C_1(a)$
...
$C_n(a)$

- Delete $A(a)$ using FBF:
  1. Is $A(a)$ derivable in any other way?
  2. No ⇒ delete

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Improvement: the Forward/Backward/Forward Algorithm

- Facts often have many derivations, so many facts get deleted in the first step
- The Forward/Backward/Forward algorithm looks for alternatives immediately

~~$A(a)$~~ ×
$B(a)$
$C_0(a)$?
$C_1(a)$
...
$C_n(a)$

- Delete $A(a)$ using FBF:
  1. Is $A(a)$ derivable in any other way?
  2. No $\Rightarrow$ delete
  3. As in DRed, identify $C_0(a)$ as derivable from $A(a)$

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IMPROVEMENT: THE FORWARD/BACKWARD/FORWARD ALGORITHM

- Facts often have many derivations, so many facts get deleted in the first step
- The Forward/Backward/Forward algorithm looks for alternatives immediately

~~$A(a)$~~	$\times$
$B(a)$	?
$C_0(a)$	?
$C_1(a)$	
...	
$C_n(a)$	

- Delete $A(a)$ using FBF:
  1. Is $A(a)$ derivable in any other way?
  2. No $\Rightarrow$ delete
  3. As in DRed, identify $C_0(a)$ as derivable from $A(a)$
  4. Apply the rules to $C_0(a)$ 'backwards' $\Rightarrow$ by $C_0(x) \leftarrow B(x)$, we get $B(a)$

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Improvement: the Forward/Backward/Forward Algorithm

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- The Forward/Backward/Forward algorithm looks for alternatives immediately

~~$A(a)$~~	$\times$
$B(a)$	$\checkmark$
$C_0(a)$	?
$C_1(a)$	
$\cdots$	
$C_n(a)$	

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  5. $B(a)$ is explicit so it is derivable

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IMPROVEMENT: THE FORWARD/BACKWARD/FORWARD ALGORITHM

- Facts often have many derivations, so many facts get deleted in the first step
- The Forward/Backward/Forward algorithm looks for alternatives immediately

~~$A(a)$~~	$\times$
$B(a)$	✓
$C_0(a)$	✓
$C_1(a)$	
$\dots$	
$C_n(a)$	

- Delete $A(a)$ using FBF:
  1. Is $A(a)$ derivable in any other way?
  2. No $\Rightarrow$ delete
  3. As in DRed, identify $C_0(a)$ as derivable from $A(a)$
  4. Apply the rules to $C_0(a)$ 'backwards' $\Rightarrow$ by $C_0(x) \leftarrow B(x)$, we get $B(a)$
  5. $B(a)$ is explicit so it is derivable
  6. So $C_0(a)$ is derivable too
  7. Stop propagation and terminate

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EVALUATION (III): INCREMENTAL REASONING

Dataset		$\|E^-\|$	$\|I \setminus I'\|$	Rematerialise		DRed					B/F				
				Time	Derivations	Time		Derivations			Time		Derivations		
				(s)	Fwd	(s)	$\|D\|$	DR2	DR4	DR5	(s)	$\|C\|$	Bwd	Sat	Del Prop
	LUBM-1k-L	**100**	113	139.4	212.5M	0.0	1.0k	1.1k	0.8k	1.0k	0.0	0.5k	0.2k	0.3k	0.2k
$\|E\| = 133.6$M		**5.0k**	5.5k	101.8	212.5M	0.2	55.5k	67.2k	46.9k	59.8k	0.2	23.0k	9.3k	13.7k	7.4k
$\|I\| = 182.4$M		**2.5M**	2.7M	138.5	208.8M	39.4	10.3M	15.2M	6.6M	11.5M	32.8	10.0M	4.1M	5.6M	3.7M
$M_t = 121.5$s		**5.0M**	5.5M	91.8	205.0M	54.8	17.8M	26.3M	10.5M	18.9M	62.3	18.8M	7.8M	10.1M	7.5M
$M_d = 212.5$M		**7.5M**	8.3M	89.2	201.3M	71.5	24.3M	35.5M	13.6M	24.3M	85.4	26.7M	11.0M	14.0M	11.2M
		10.0M	11.0M	99.5	197.5M	127.9	30.0M	43.1M	15.9M	28.1M	102.2	34.1M	14.0M	17.4M	15.0M
	UOBM-1k-Uo	**100**	160	3482.0	3.6G	8797.6	1.8G	2.6G	53.2M	2.6G	5.4	0.8k	0.5k	1.3k	0.5k
$\|E\| = 254.8$M		**5.0k**	85.2k	3417.8	3.6G	9539.3	1.8G	2.6G	53.2M	2.6G	28.2	105.9k	17.9k	42.1k	104.1k
$\|I\| = 2.2$G		**17.0M**	130.9M	3903.1	3.4G	8934.3	1.8G	2.7G	63.7M	2.5G	988.8	175.8M	47.6M	104.0M	196.7M
$M_t = 5034.0$s		**34.0M**	269.0M	4084.1	3.2G	9492.5	1.9G	2.8G	68.4M	2.4G	1877.2	340.7M	87.5M	182.3M	401.1M
$M_d = 3.6$G		**51.0M**	422.8M	4010.0	3.0G	10659.3	1.9G	2.9G	71.5M	2.2G	2772.7	513.7M	125.2M	246.8M	622.0M
		68.0M	581.4M	3981.9	2.8G	11351.6	1.9G	2.9G	73.3M	2.1G	3737.3	687.0M	162.5M	289.5M	848.6M
	Claros-L	**100**	212	62.9	128.6M	0.0	0.8k	1.0k	0.2k	0.5k	0.0	0.6k	0.3k	0.7k	0.5k
$\|E\| = 18.8$M		**5.0k**	11.3k	62.8	128.6M	0.4	37.8k	50.7k	10.9k	23.9k	0.4	29.1k	18.8k	35.3k	26.8k
$\|I\| = 74.2$M		**0.6M**	1.3M	62.3	125.6M	32.3	4.1M	5.5M	1.1M	2.5M	14.9	3.1M	2.0M	3.6M	3.0M
$M_t = 78.9$s		**1.2M**	2.6M	61.2	122.6M	53.2	7.8M	10.8M	2.0M	4.8M	33.6	6.1M	3.8M	6.7M	6.0M
$M_d = 128.6$M		**1.7M**	4.0M	60.5	119.5M	73.6	11.4M	15.9M	2.8M	6.8M	47.8	8.9M	5.6M	9.5M	9.1M
		2.3M	5.5M	60.0	116.3M	91.0	14.8M	20.9M	3.6M	8.6M	60.6	11.7M	7.3M	12.0M	12.3M
	Claros-LE	**100**	0.5k	3992.8	12.6G	0.0	1.3k	2.0k	0.3k	0.9k	0.0	1.0k	0.7k	1.0k	1.1k
$\|E\| = 18.8$M		**2.5k**	178.9k	5235.1	12.6G	8077.4	5.5M	11.7G	176.6k	11.7G	10.3	216.4k	161.2k	8.8M	320.0k
$\|I\| = 533.7$M		**5.0k**	427.5k	4985.1	12.6G	7628.2	6.0M	11.7G	186.0k	11.7G	16.5	485.6k	369.0k	8.9M	769.3k
$M_t = 4024.5$s		**7.5k**	609.6k	4855.0	12.6G	7419.1	6.5M	11.7G	193.9k	11.7G	19.5	683.4k	516.8k	9.0M	1.1M
$M_d = 12.9$G		**10.0k**	780.8k	5621.3	12.6G	7557.9	6.8M	11.7G	207.6k	11.7G	3907.2	6.0M	723.0M	11.7G	16.9M

Table of Contents

APPLICATION: CONTEXT-AWARE MOBILE SERVICES (SAMSUNG)

- Use sensors (WiFi, GPS, . . .) to identify the context
  - E.g., 'at home', 'in a shop', 'with a friend' . . .
- Adapt behaviour depending on the context
  - 'If with a friend who has birthday, remind to congratulate'
- Declaratively describe contexts and adaptations
  - Use a bunch of rules
  - E.g., 'If can see home WiFi, then context is "at home"'
- Interpret rules in real-time via incremental reasoning
  - We used DRed
- User detect events by registering continuous queries
- The streaming aspect was lightweight:
  - The database always reflects the 'current' state of the world
  - Continuous queries just monitor this 'current' state
  - Queries cannot refer to states at different time points

Querying/Reasoning Across Time-Points

Querying a Stream of Events

- The database is an ever-filling set of events with time-points
- E.g., 'Quote for AAPL at 9am is $121'
- Queries must explicitly refer to events
- E.g., 'The price of AAPL at 9.05am?' makes no sense $\Rightarrow$ no global world-view
- $\Rightarrow$ 'The quote for AAPL at time t with $t <$ 9.05am and no quote from t to 9.05am'

Querying an Evolving World View

- There is a complete database state ('world view') for each time-point t
- We can have inertia rules
- E.g., 'The price a stock at any point t is the price of the most recent quote'
- Now 'The price of AAPL at 9.05am?' is correct as we have a notion of 'Price at time t'

- Windowing could be viewed as an implementation detail
  - Prevents memory from filling, but does not play part in the definition of a model
- Can we use incremental materialisation algorithms for stream reasoning?