Opaque

An Oblivious and Encrypted Distributed Analytics Platform

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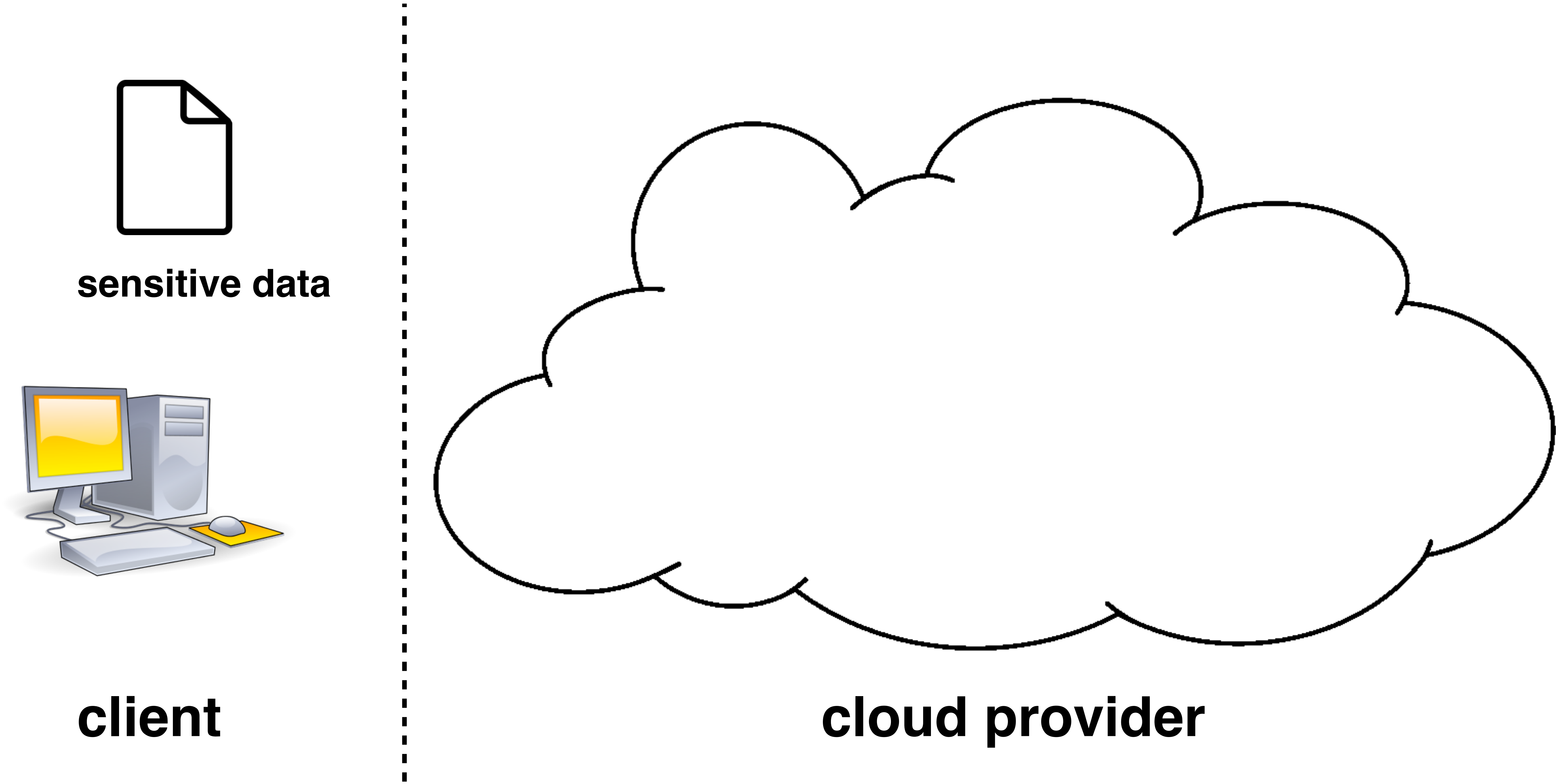
Raluca Ada Popa, Joseph E. Gonzalez, Ion Stoica

UC Berkeley

Complex analytics run on sensitive data



sensitive data

client

cloud provider

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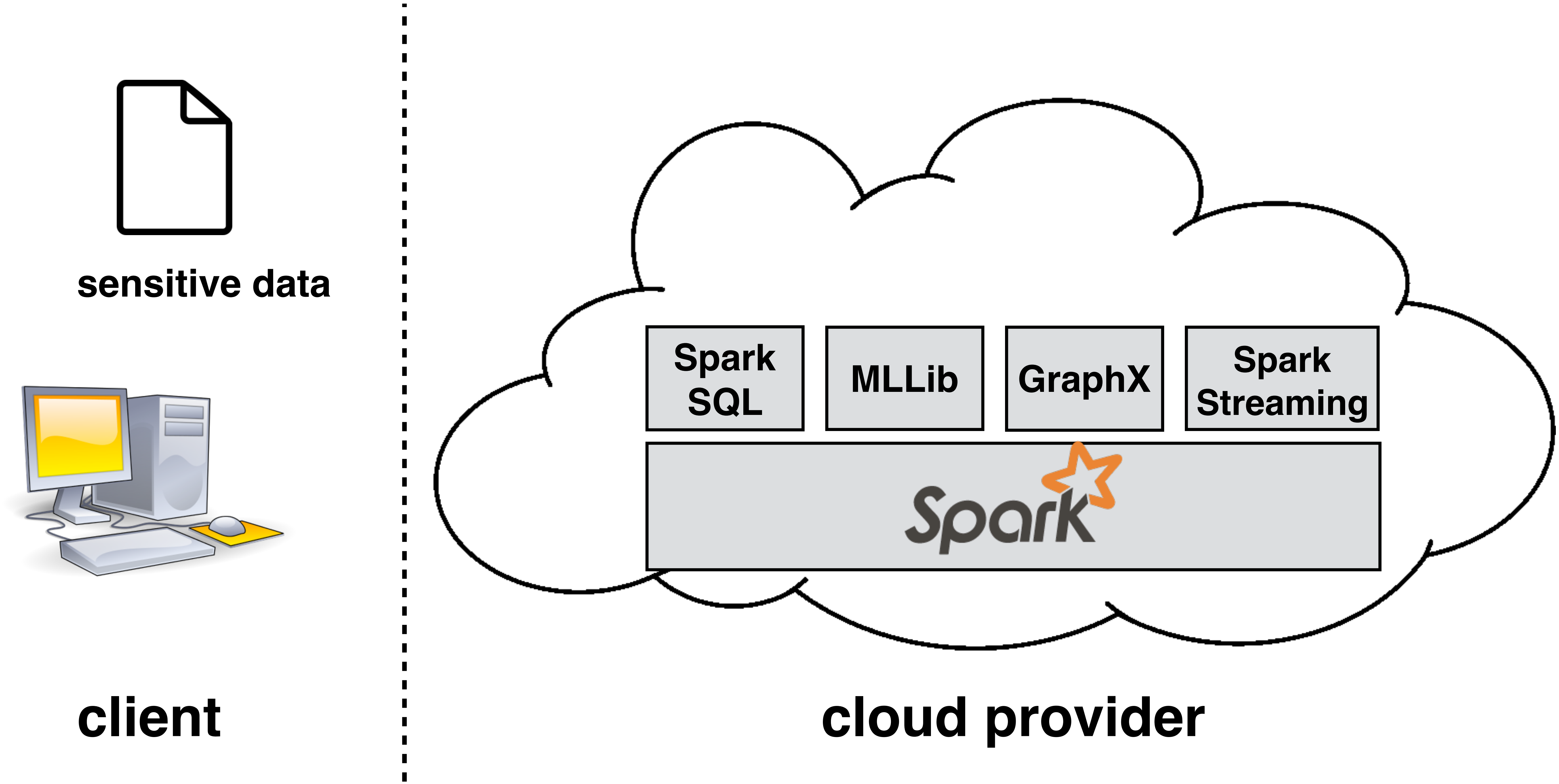

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Spark SQL

MLLib

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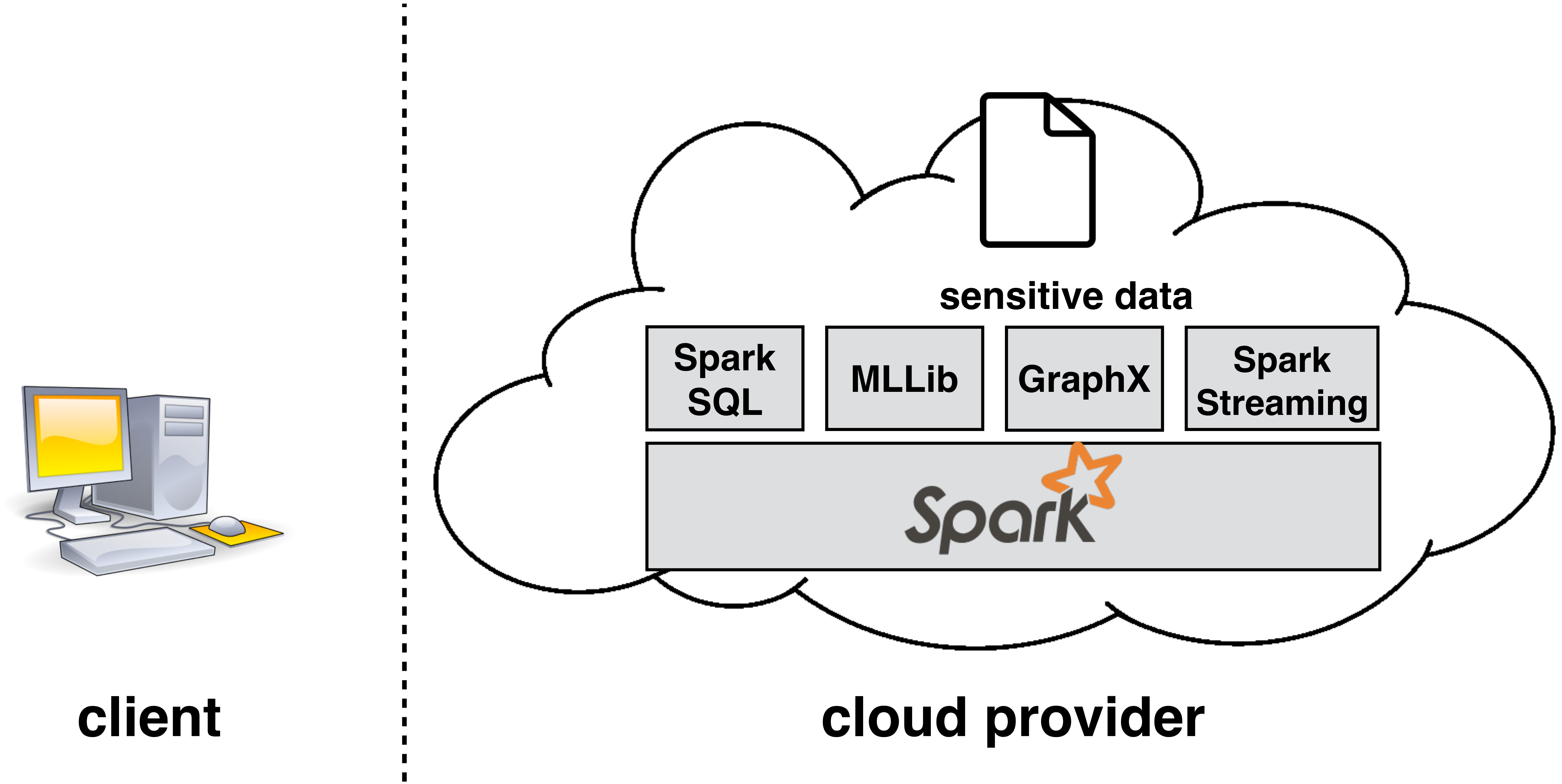

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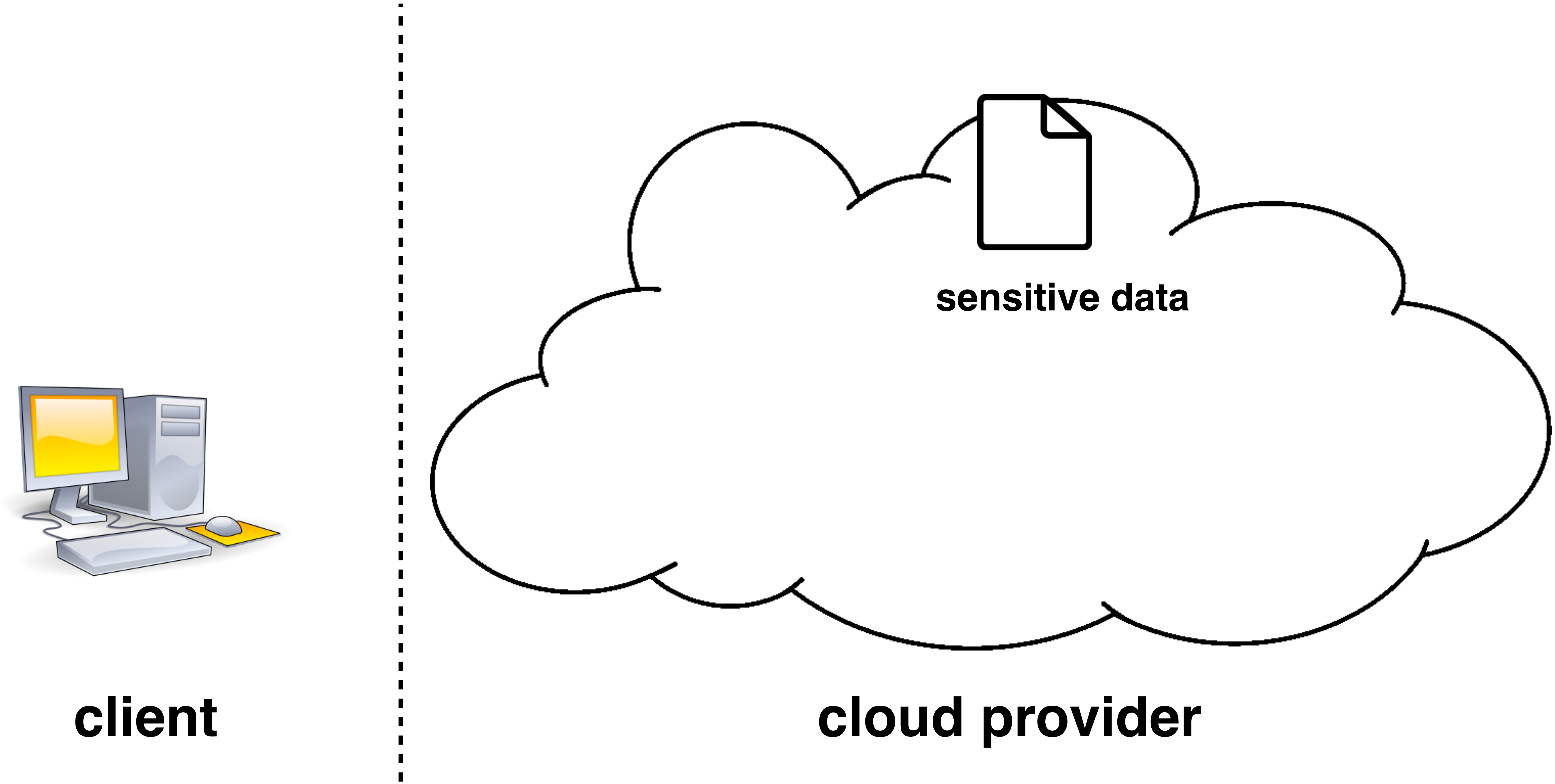

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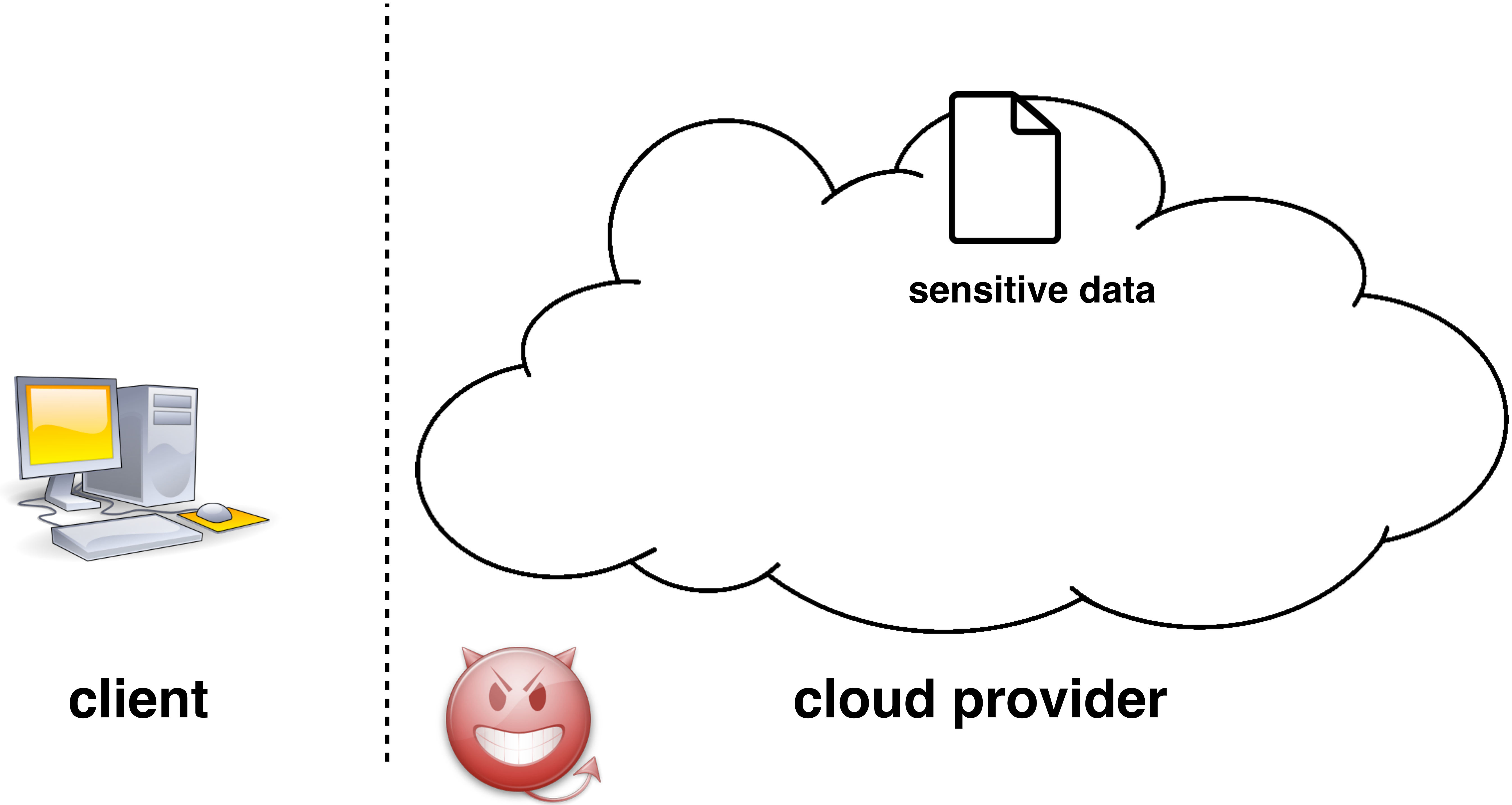

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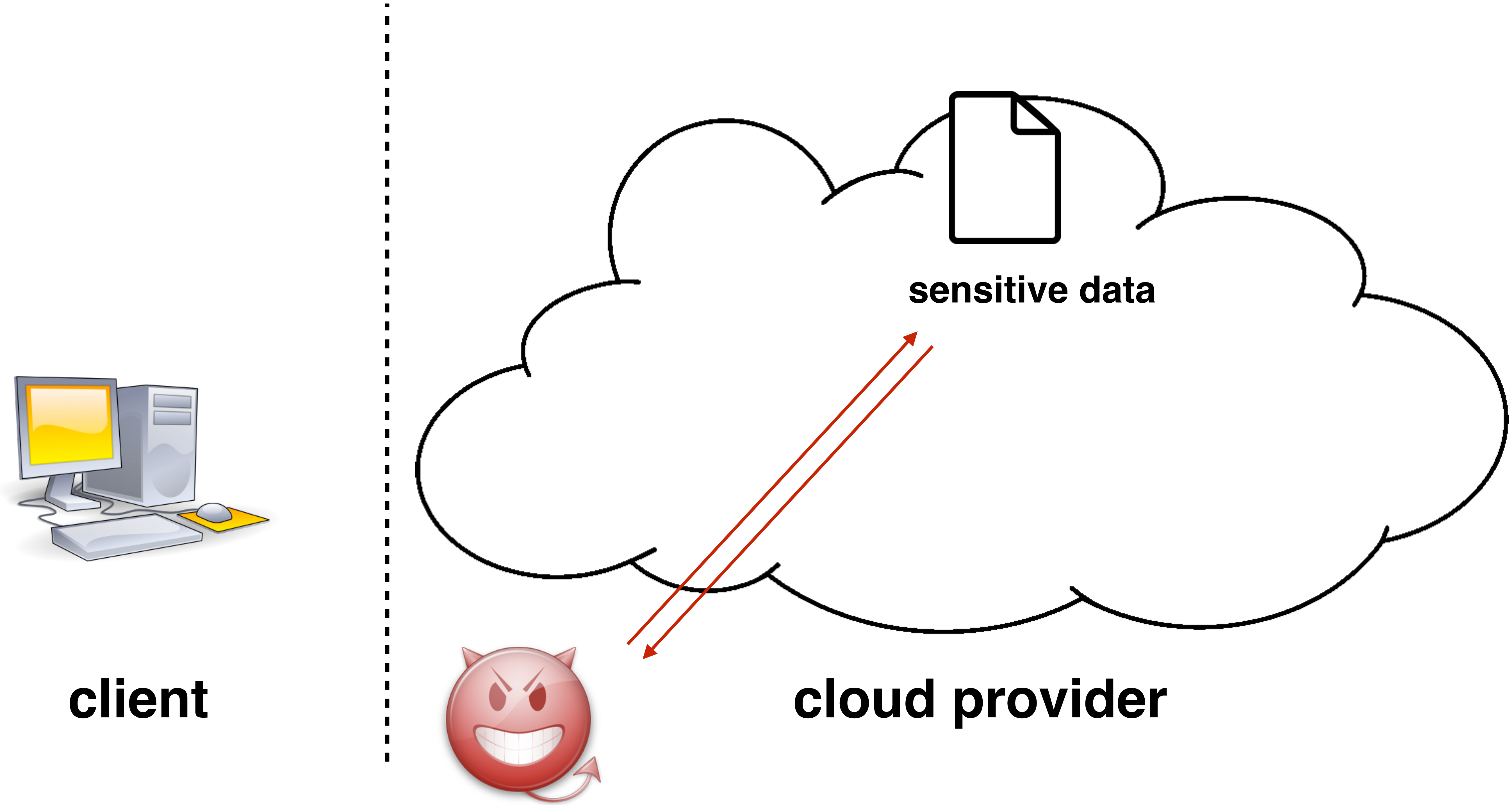

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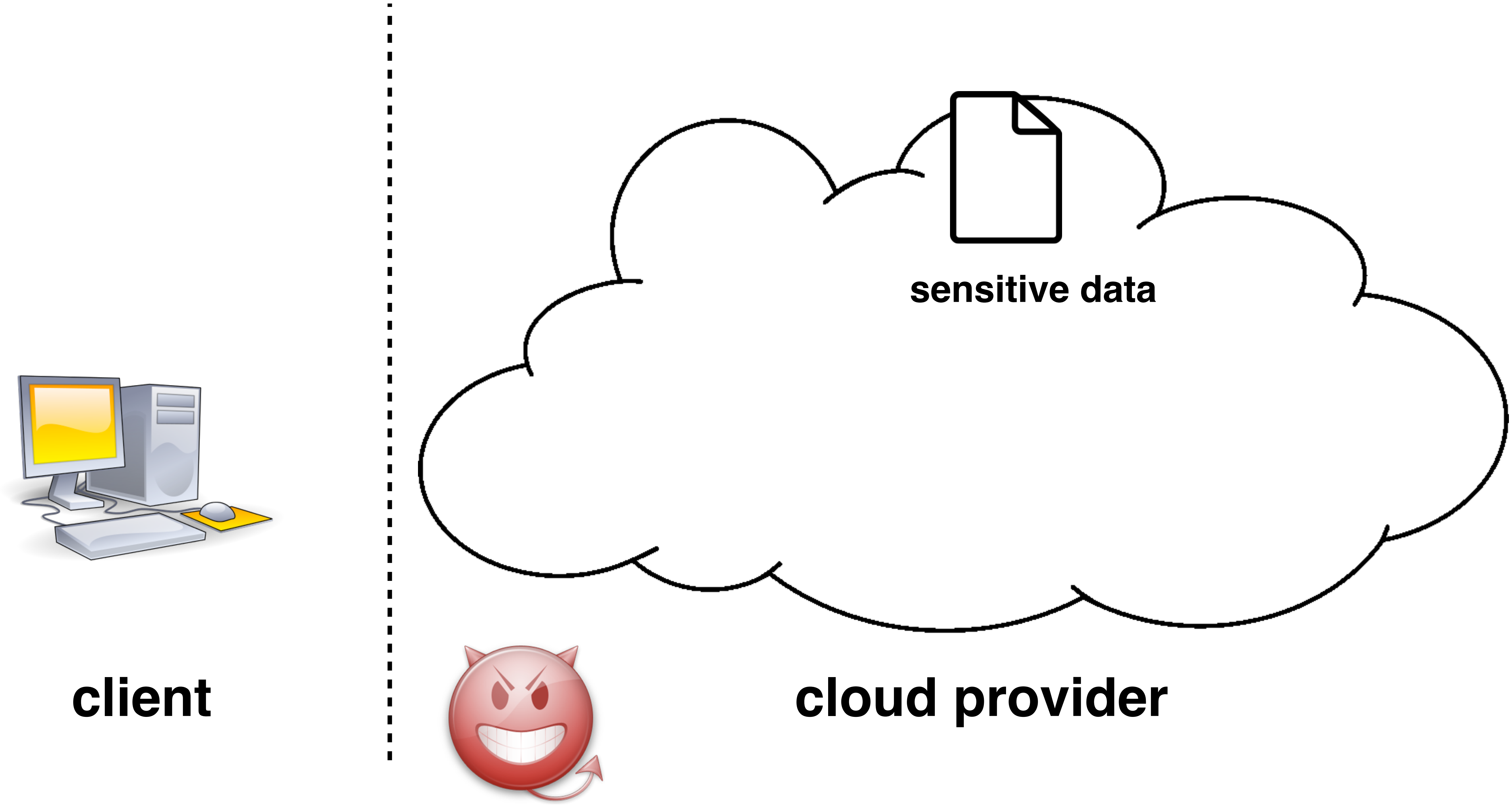

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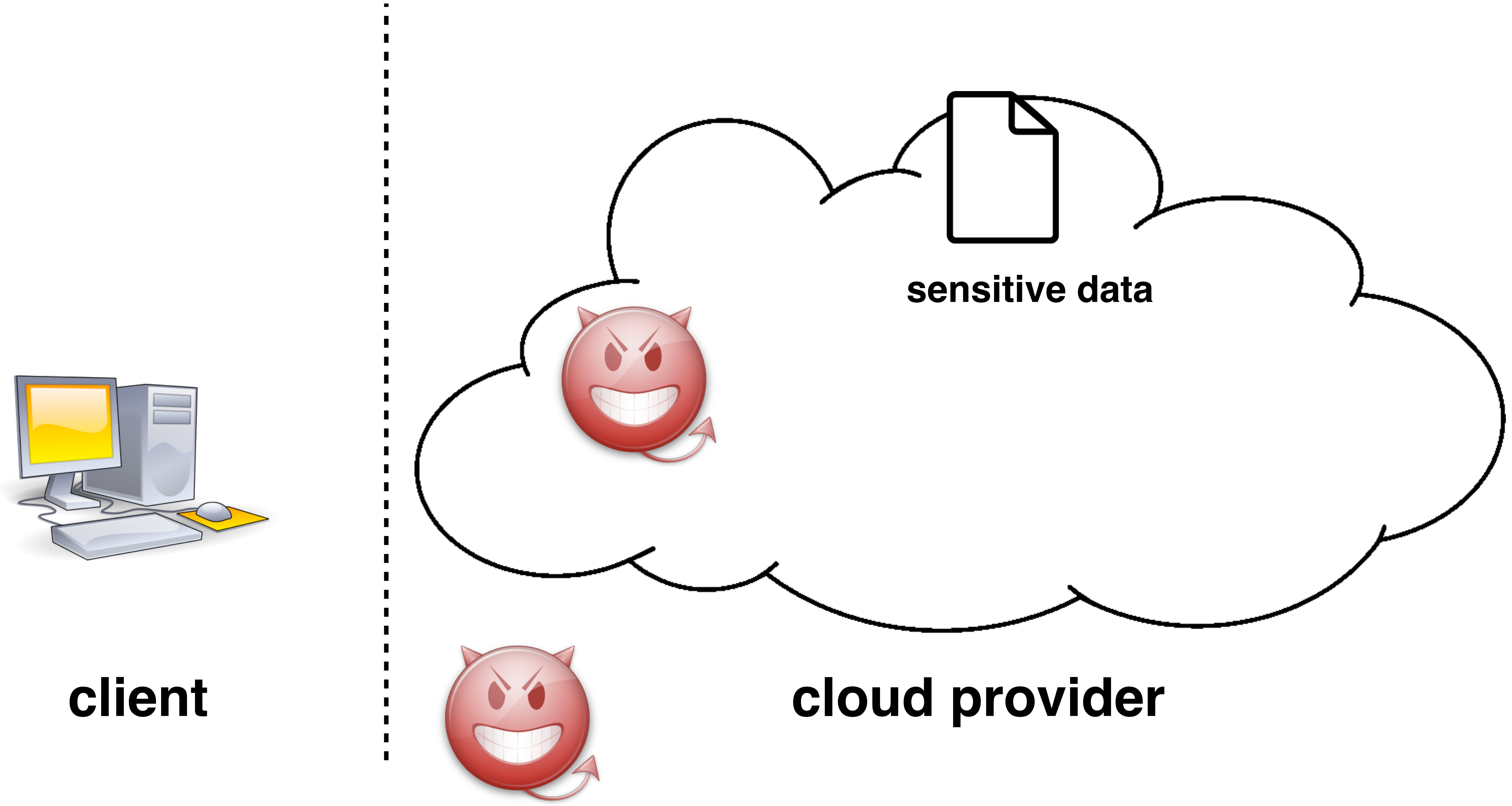

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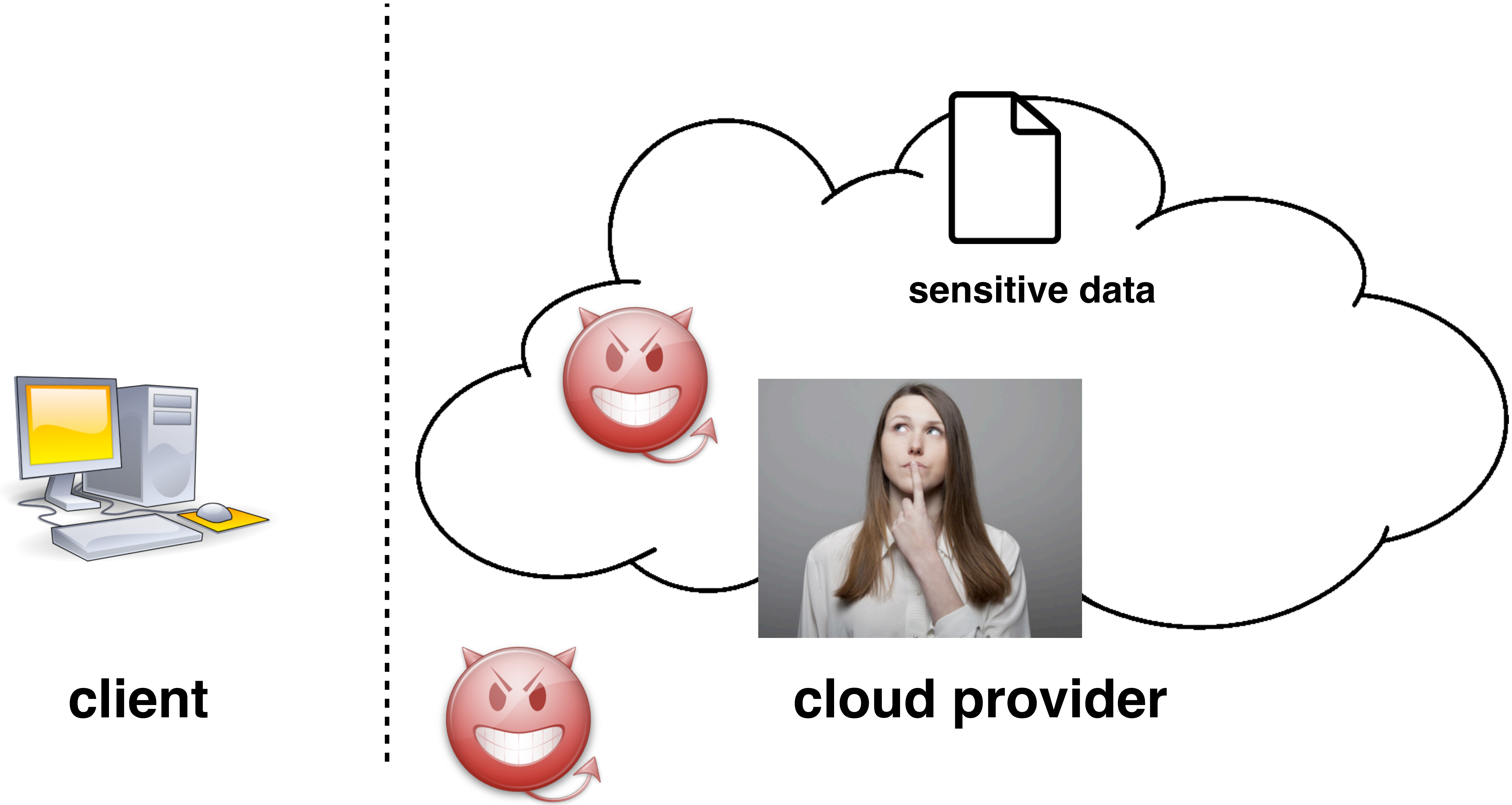

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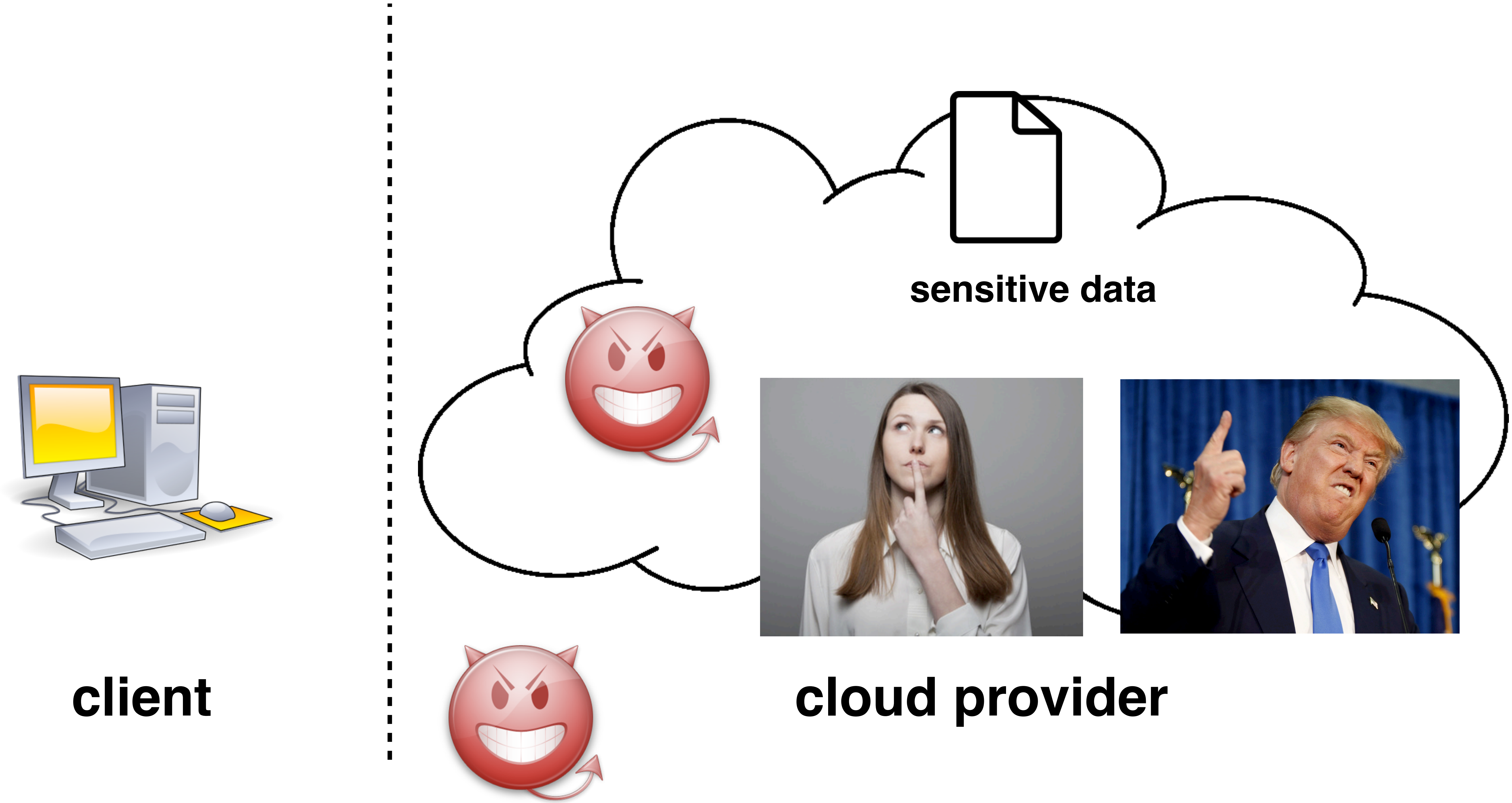

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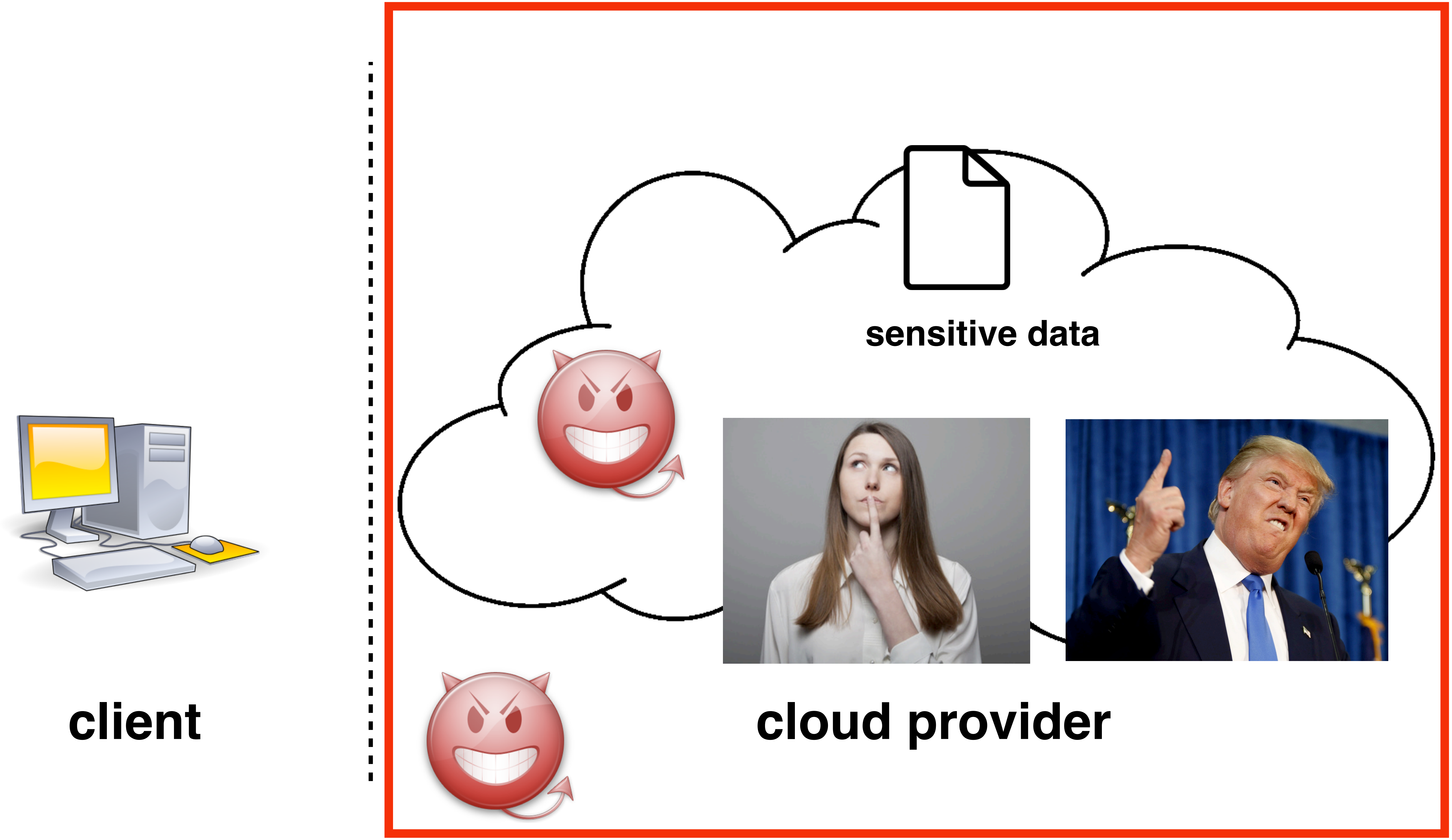

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How to protect data
while preserving functionality?

Cryptographic approach?

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Alternative: hardware enclaves

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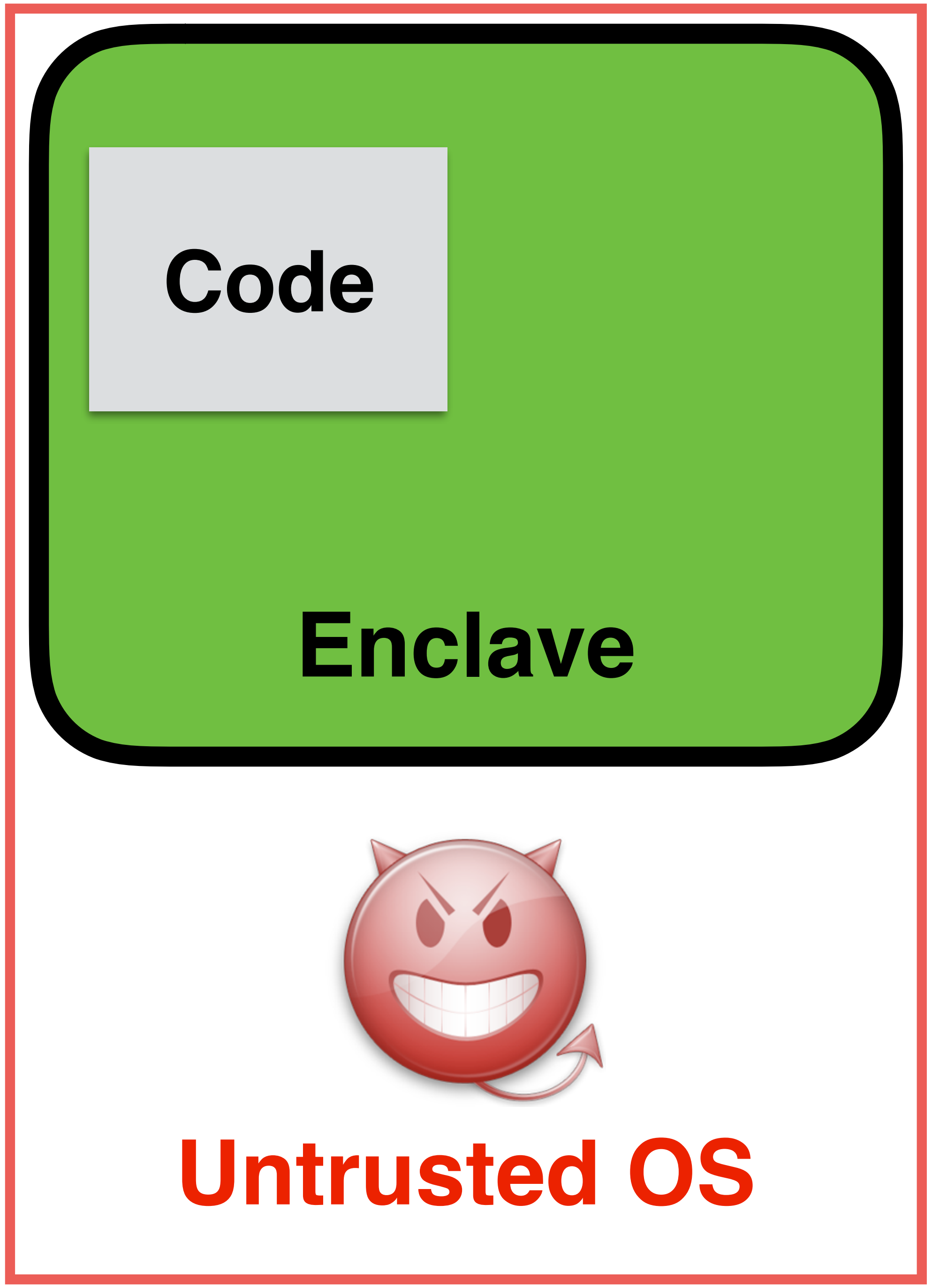

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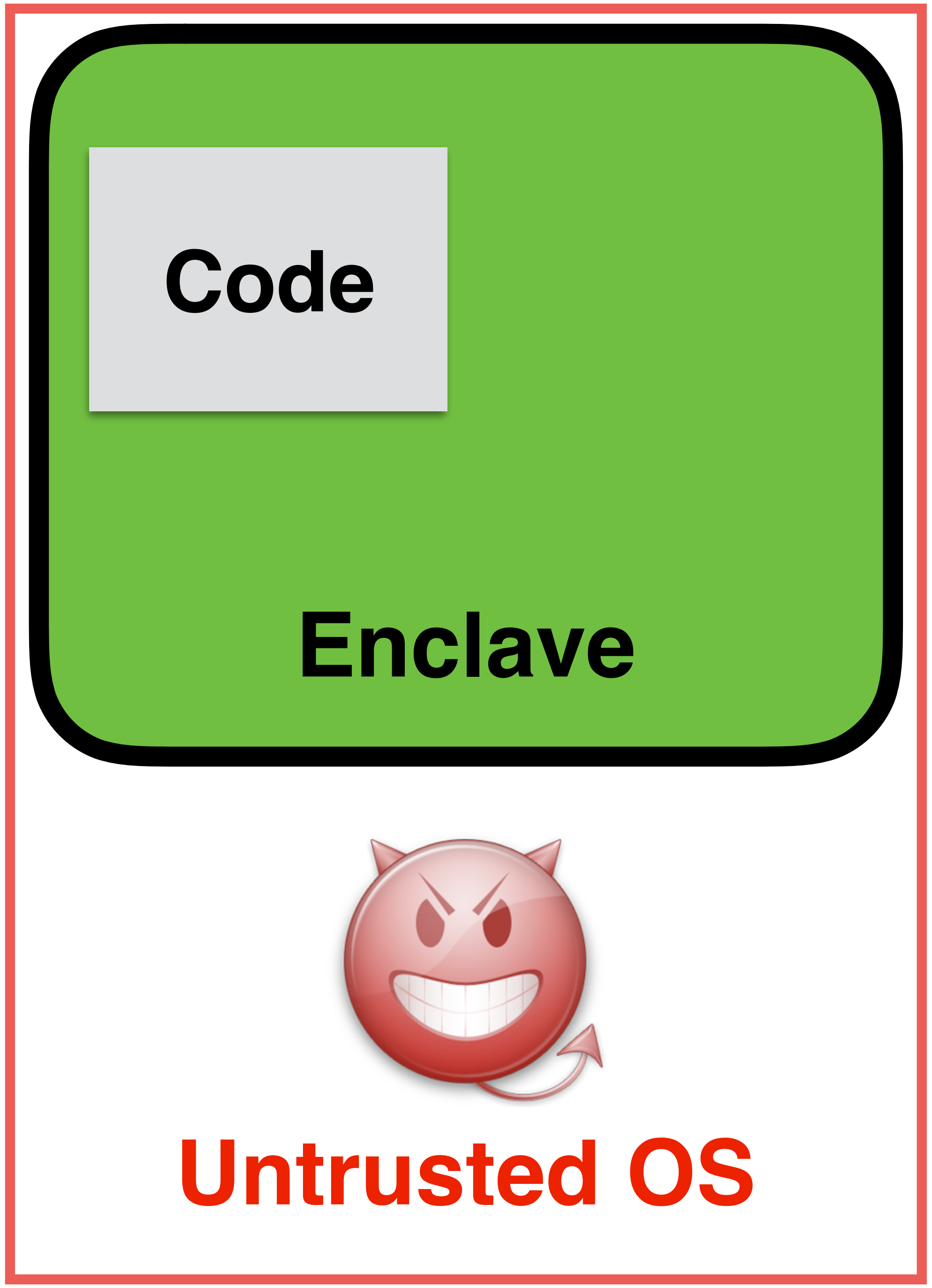

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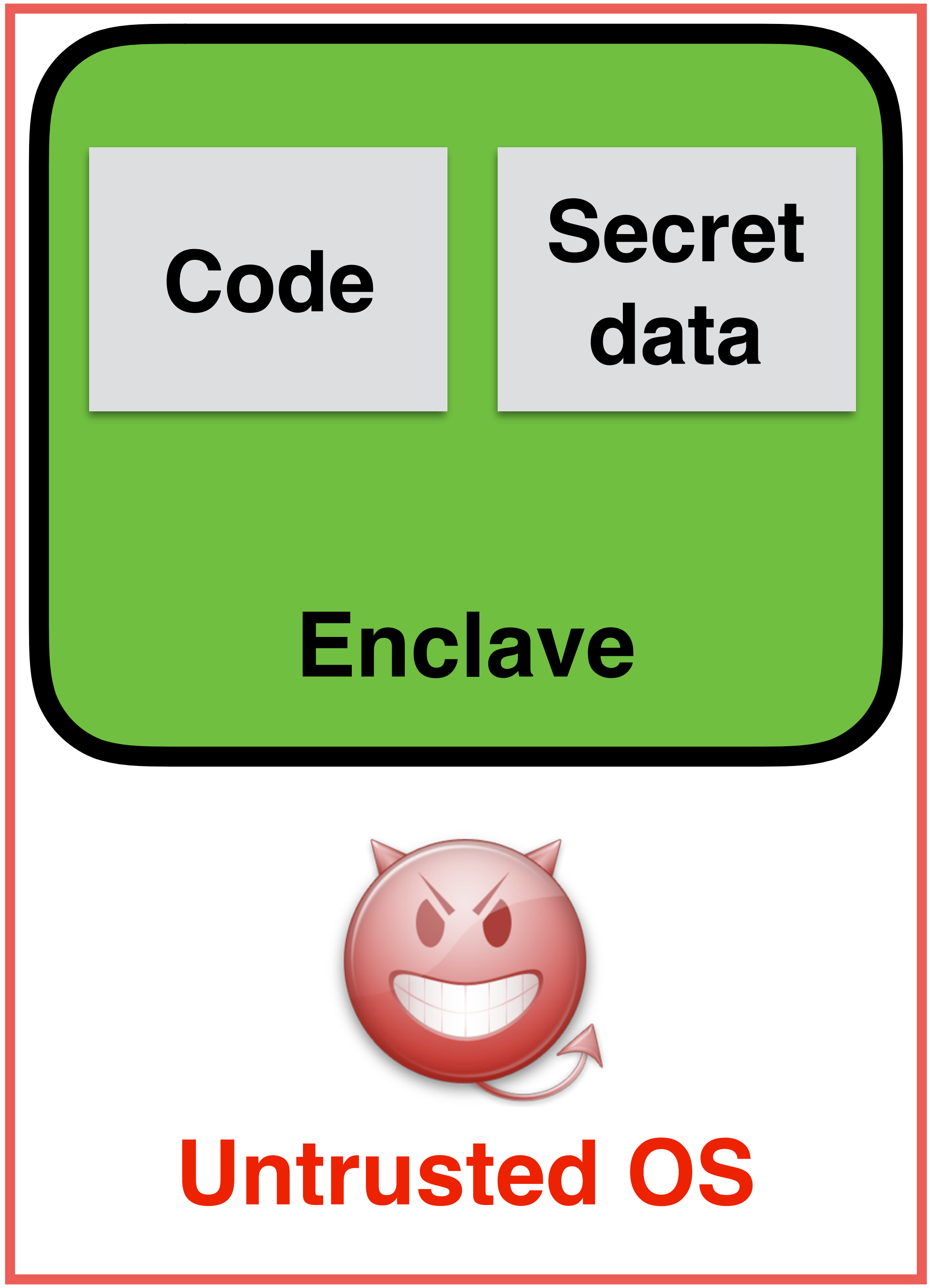

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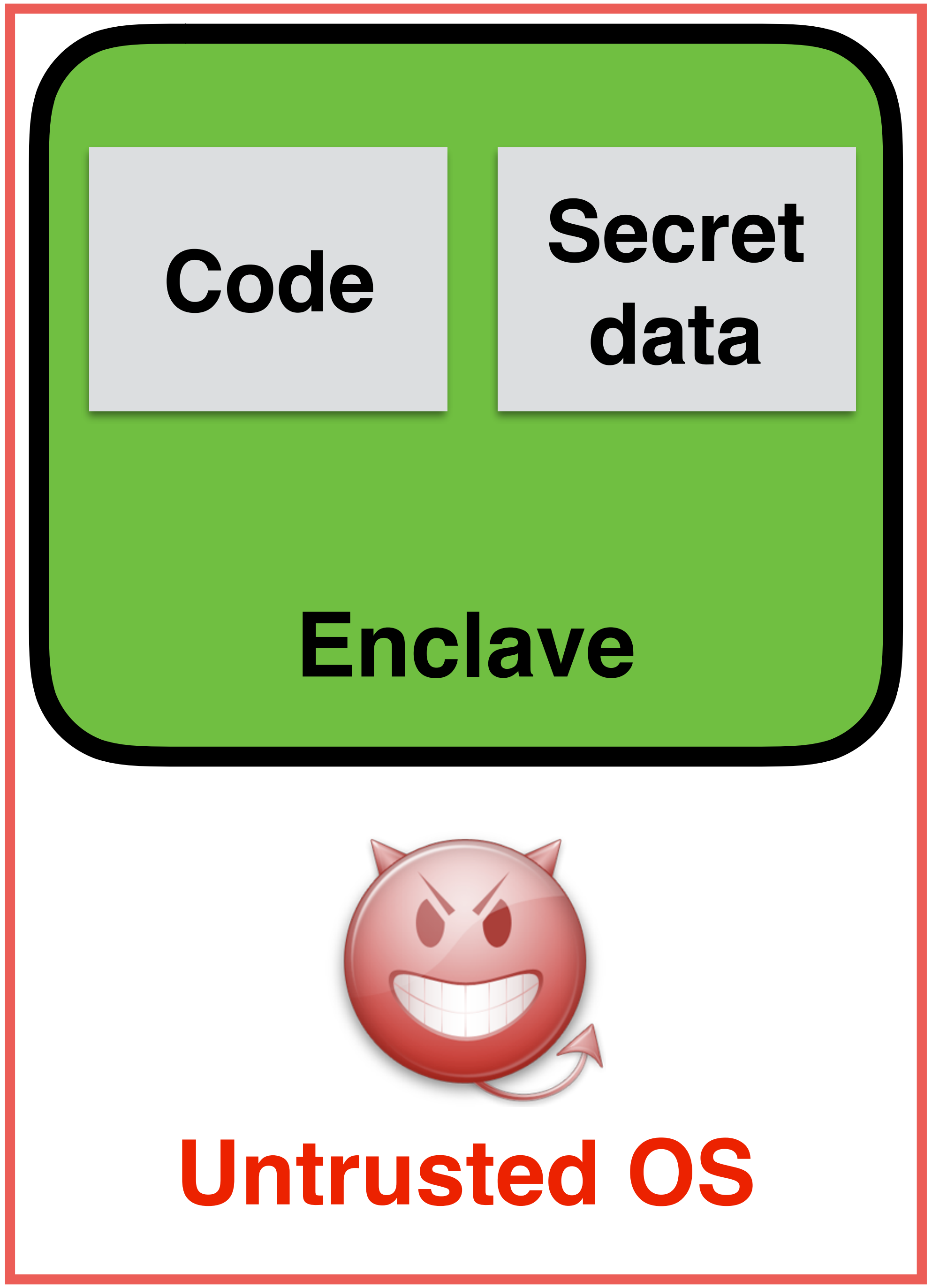
- Protect against an attacker who has root access



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  - **data access pattern leakage [XCP '15, OCFGKS '15]**

Problem: access pattern leakage [XCP ‘15, OCFGKS ‘15]

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ID	Name	Age	Disease
12809	Amanda D. Edwards	40	Diabetes
29489	Robert R. McGowan	56	Diabetes
13744	Kimberly R. Seay	51	Cancer
18740	Dennis G. Bates	32	Diabetes
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```
SELECT count(*) FROM medical
GROUP BY disease
```

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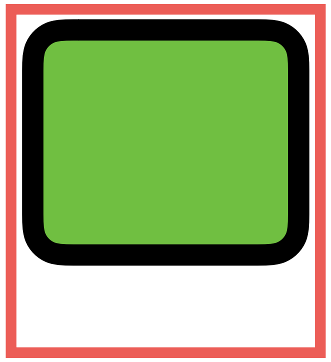

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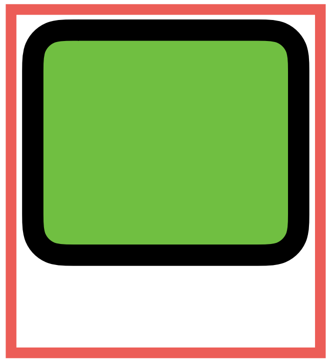

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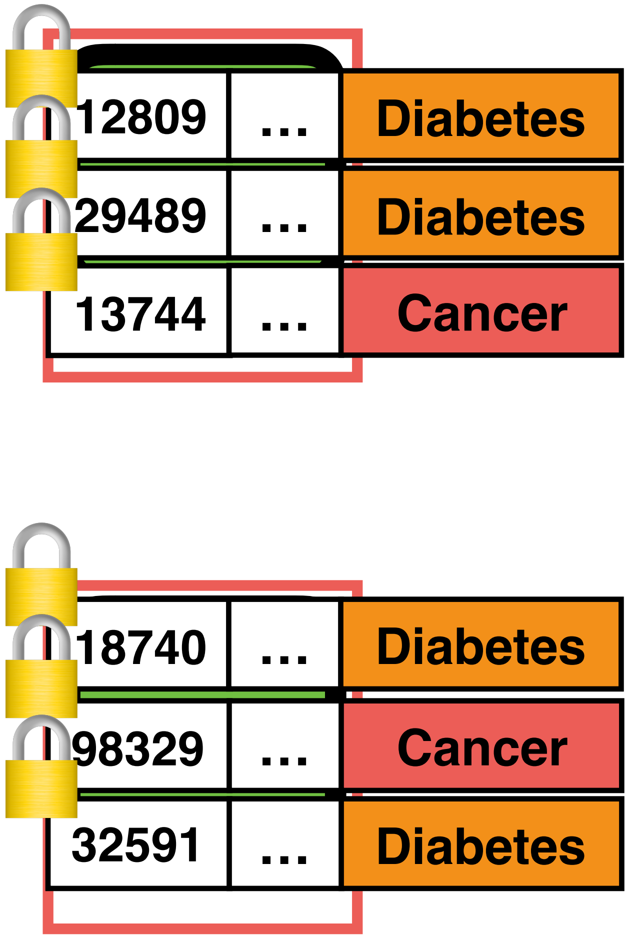

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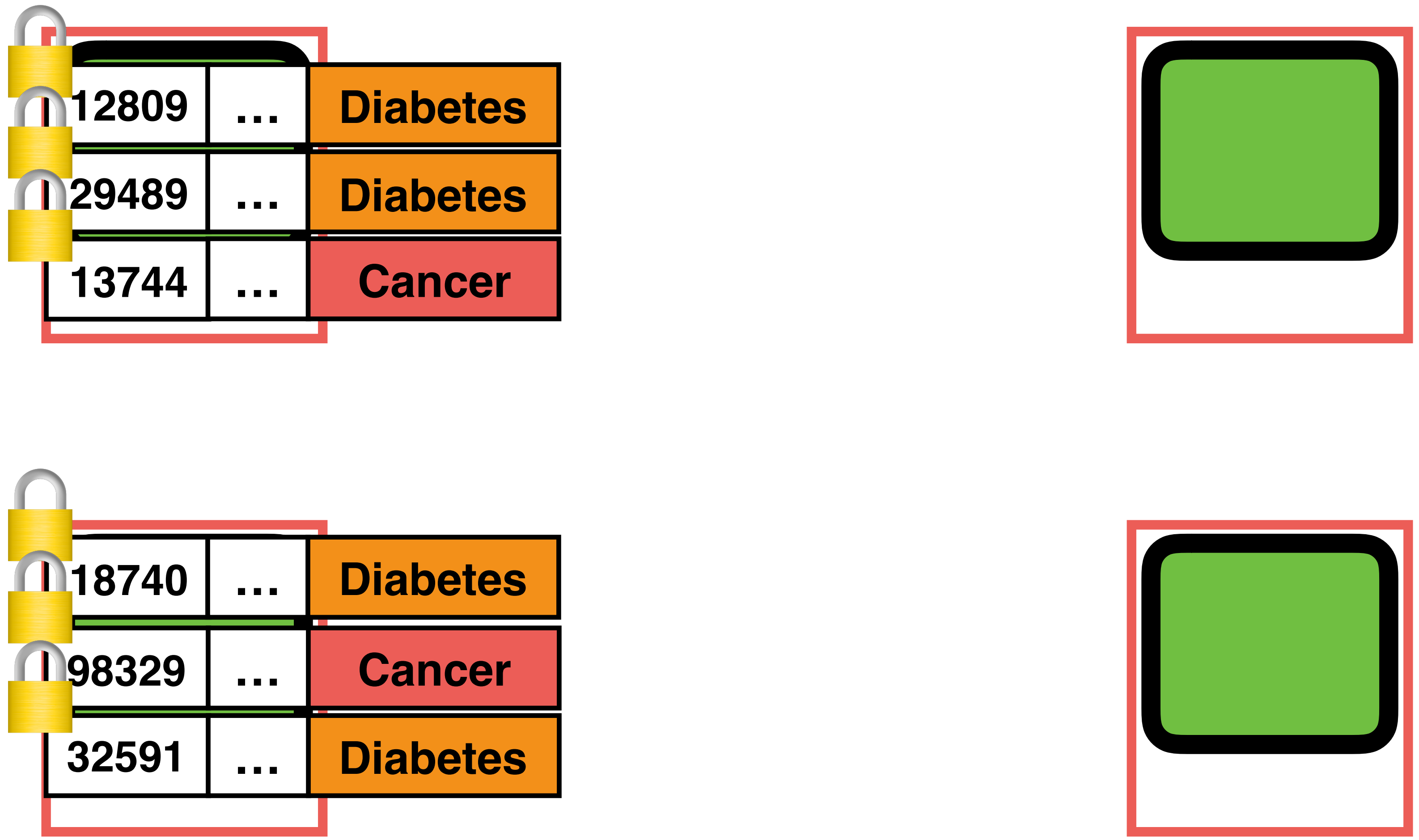

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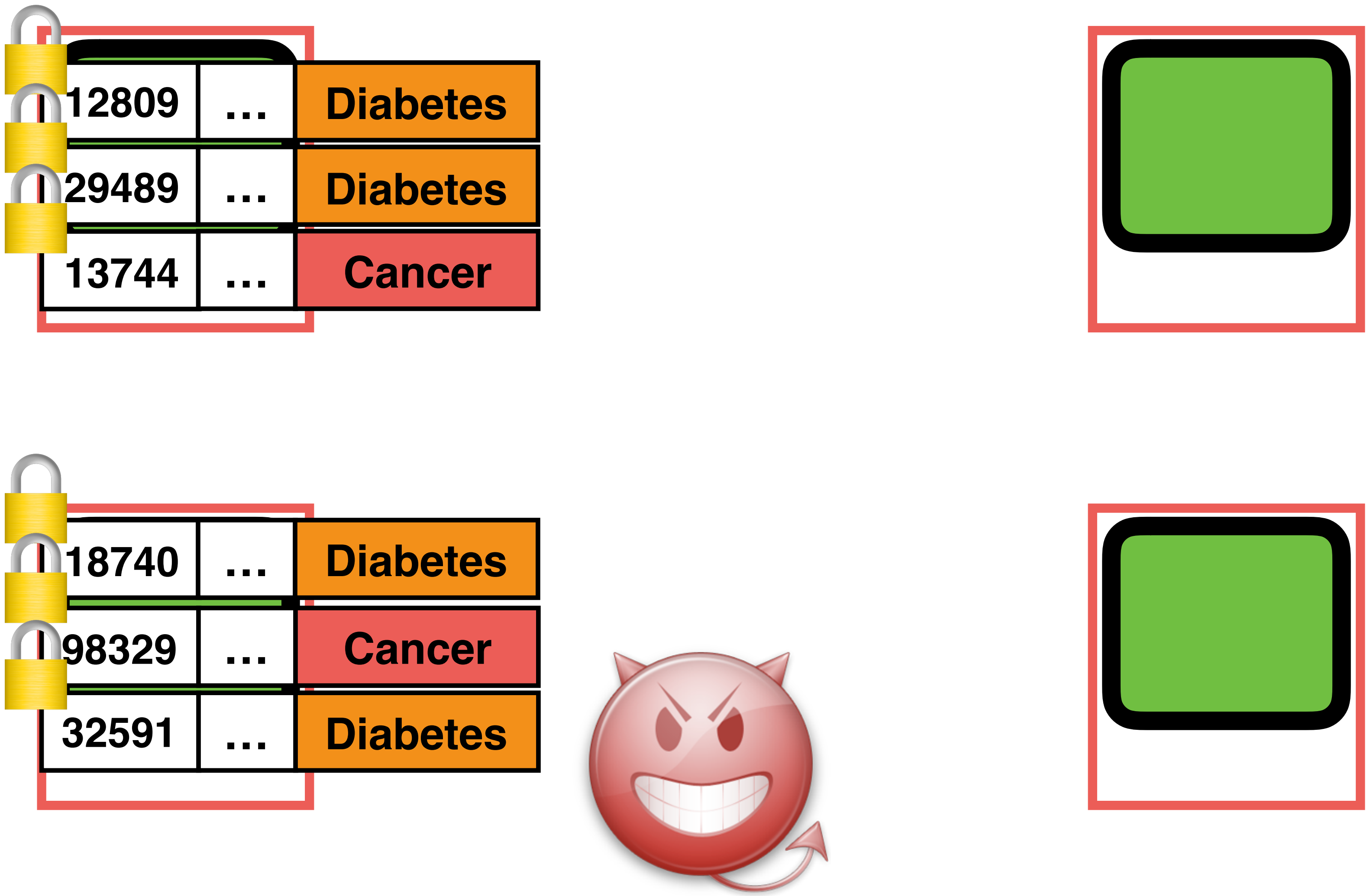

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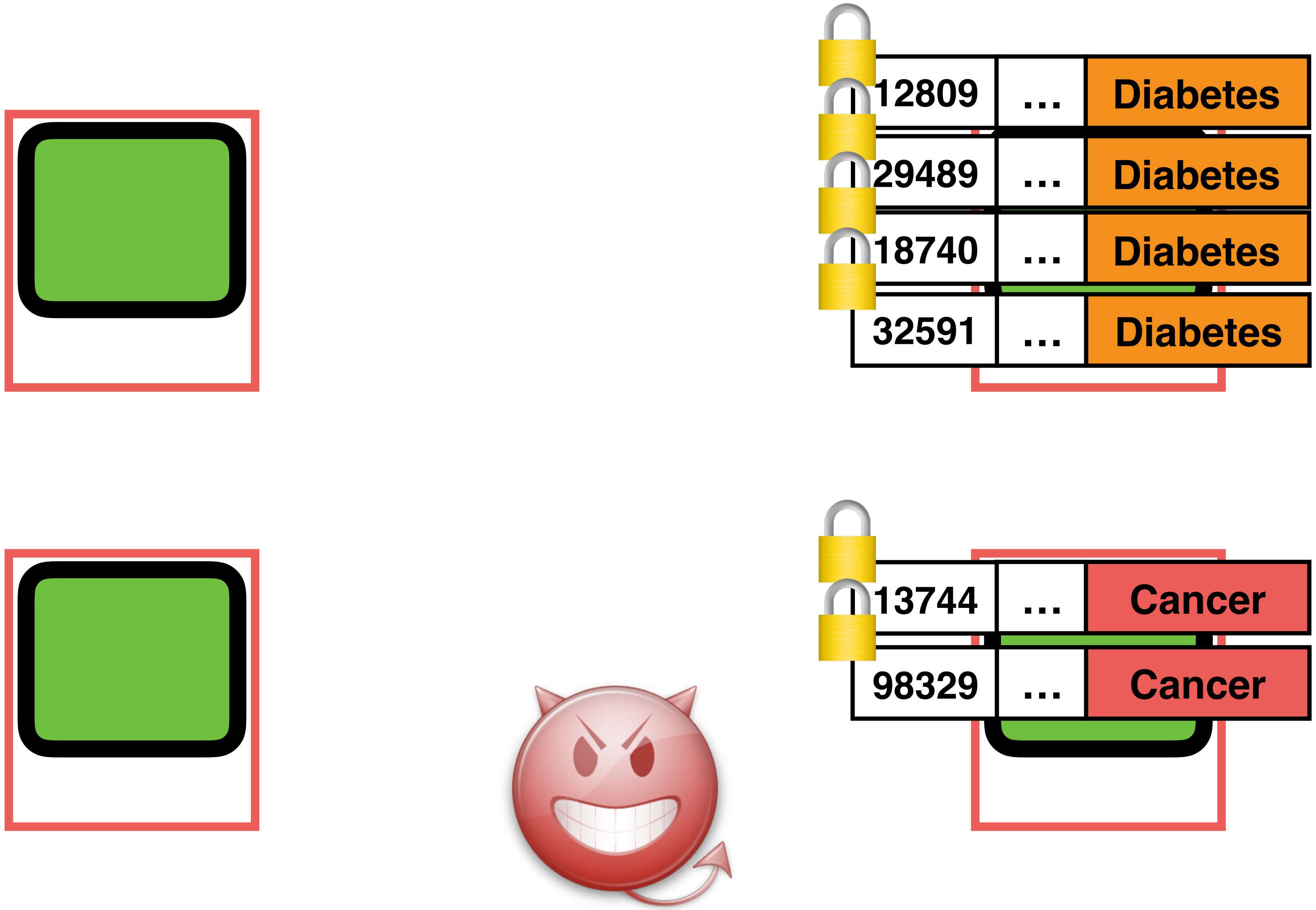

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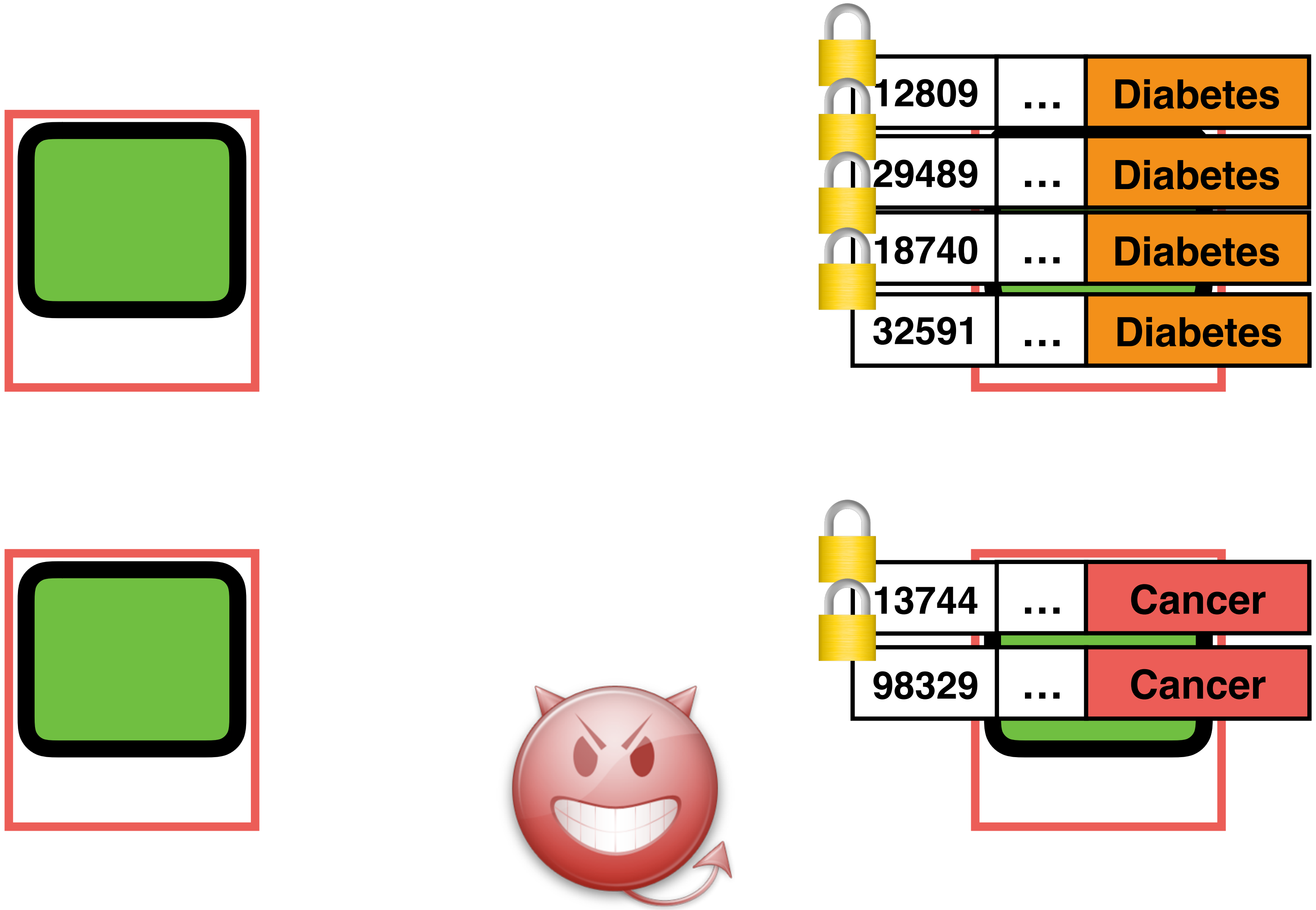

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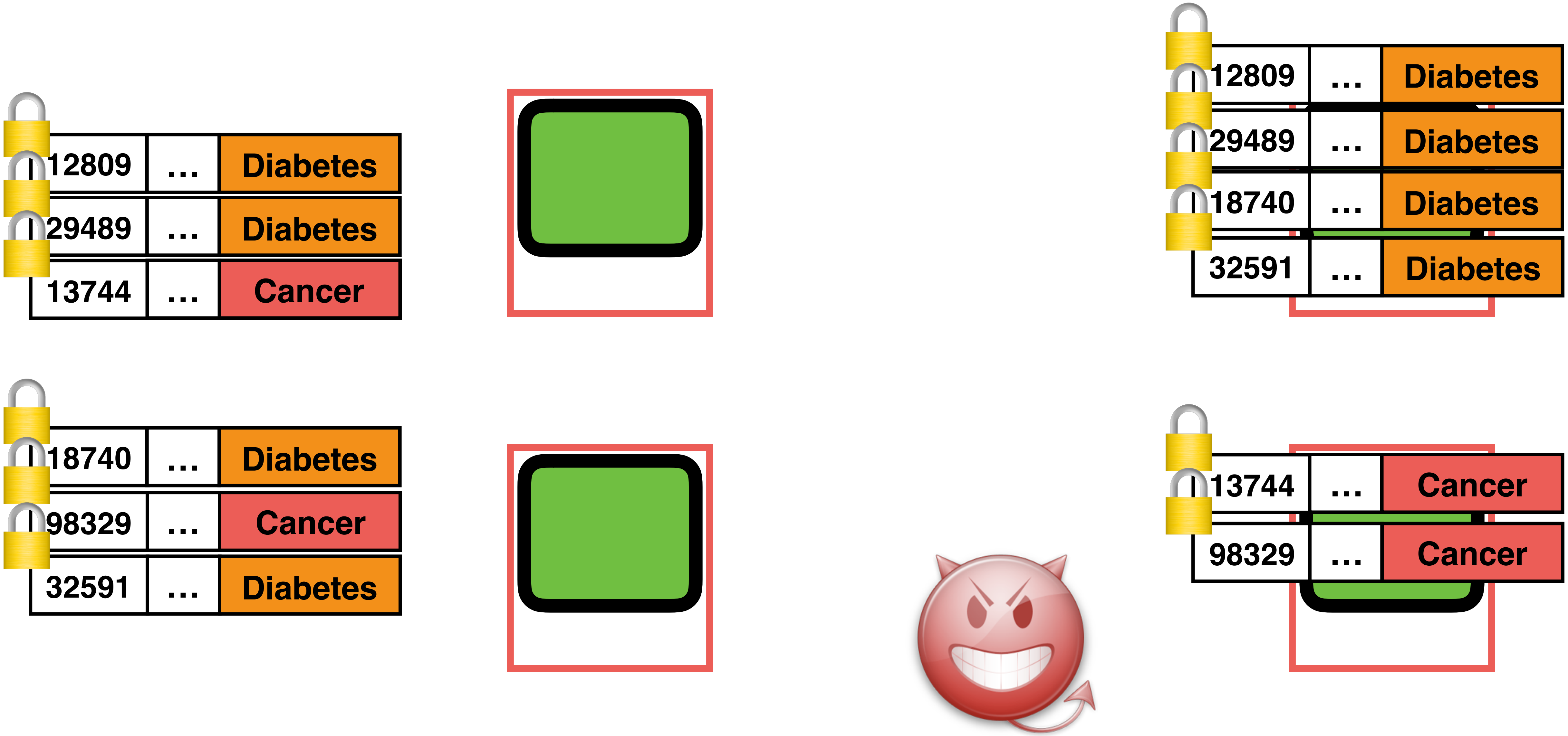

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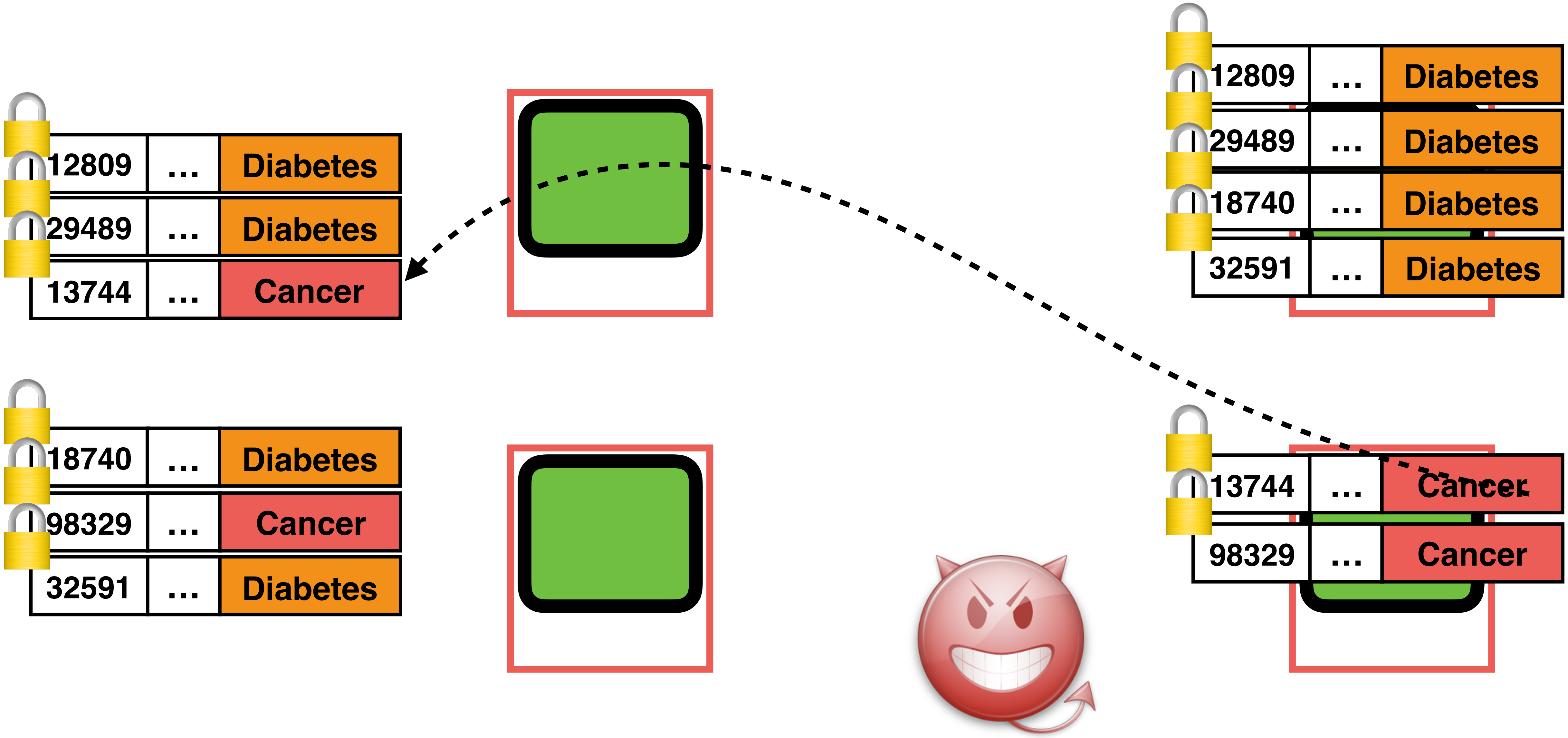

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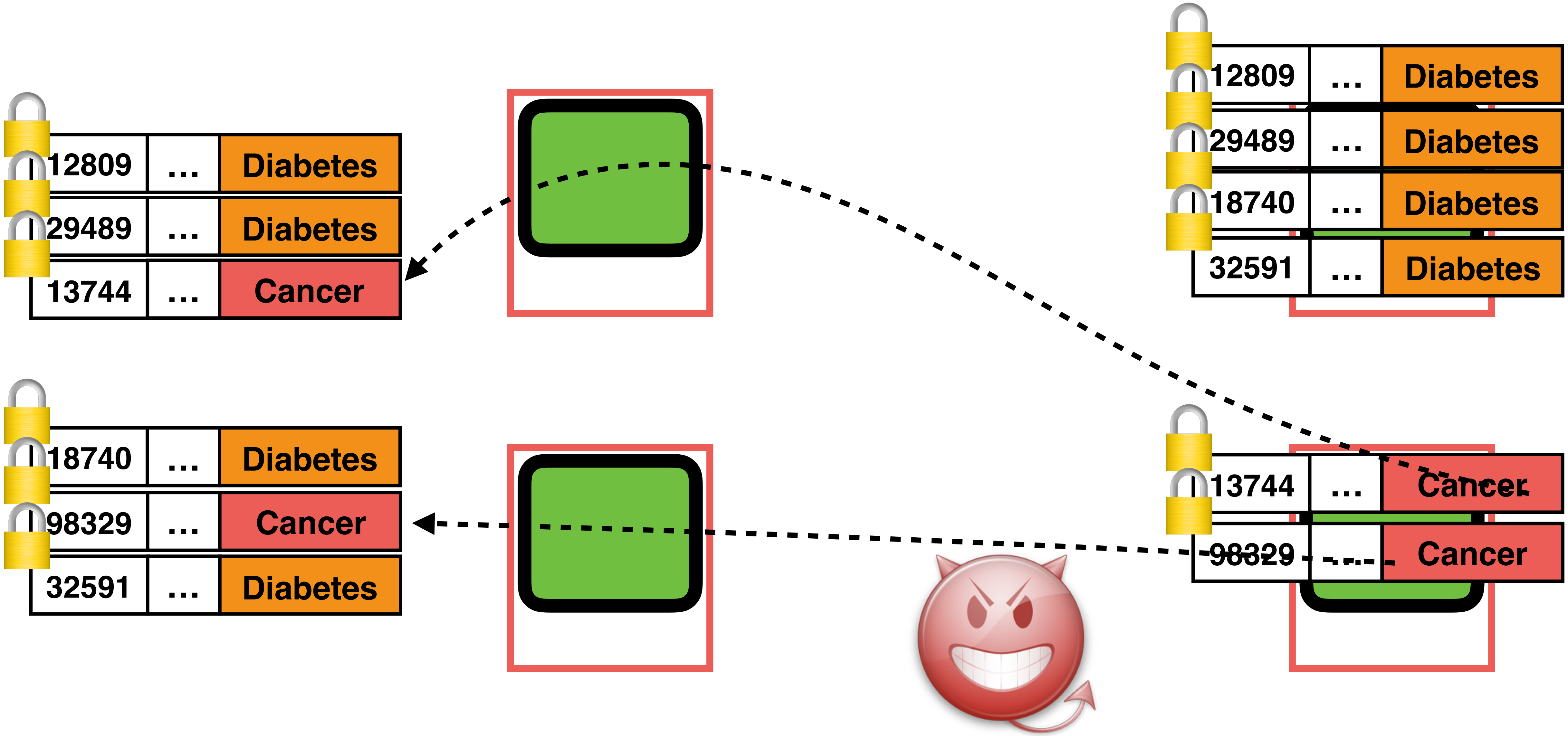

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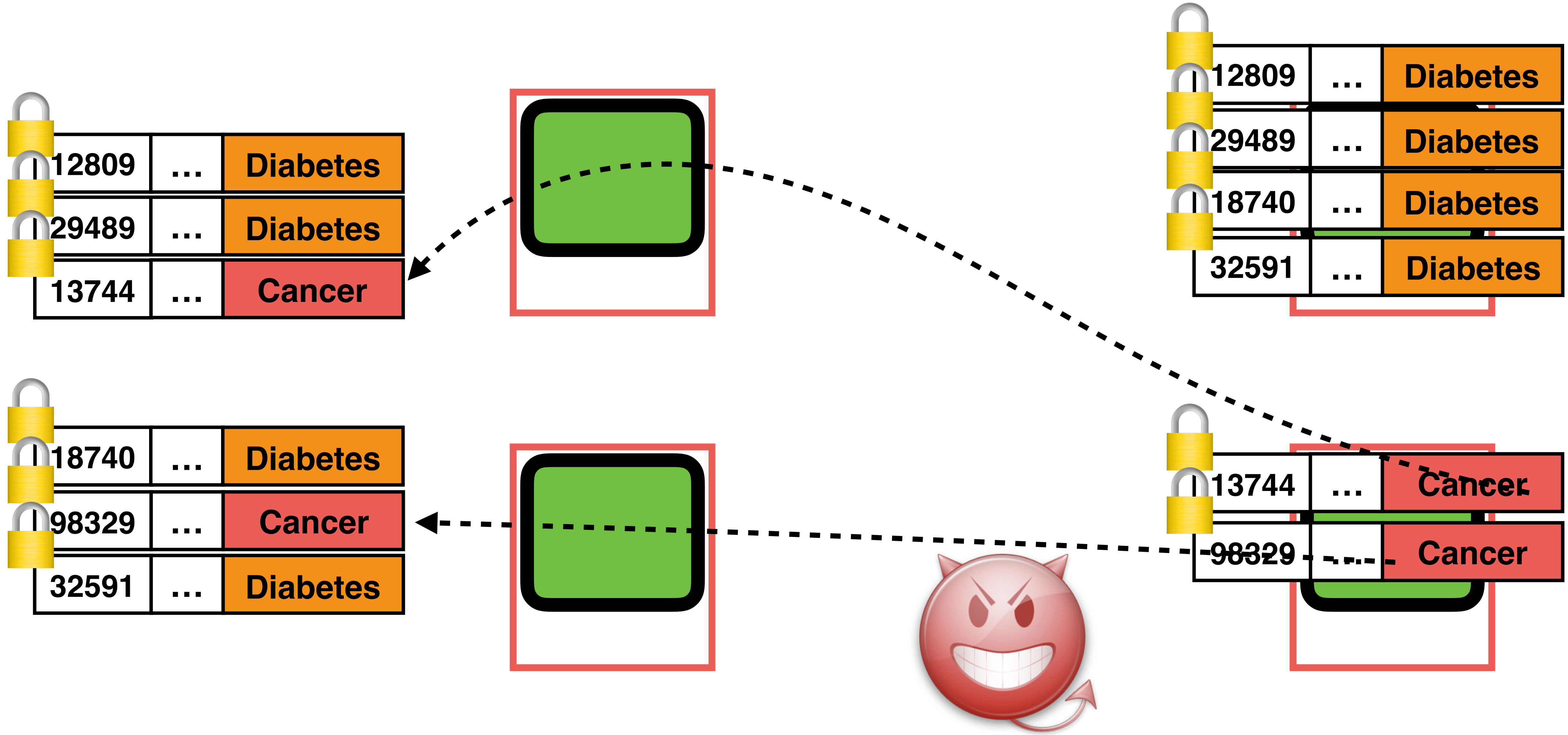

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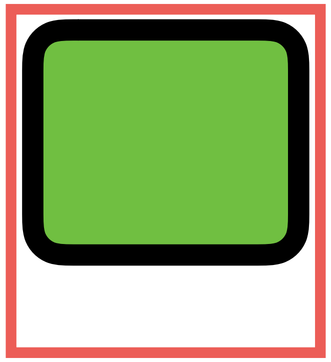

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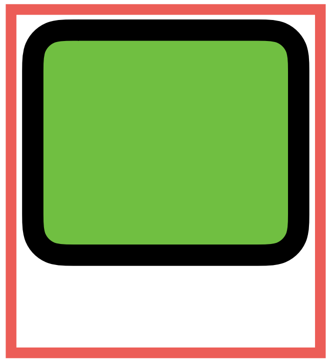

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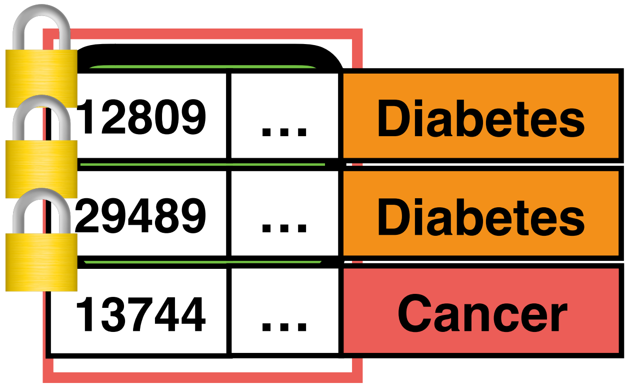

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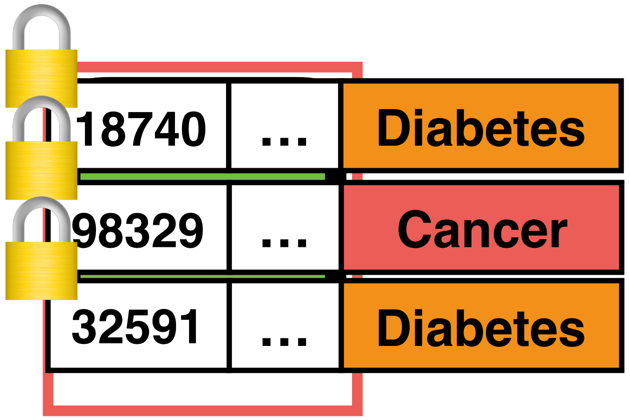

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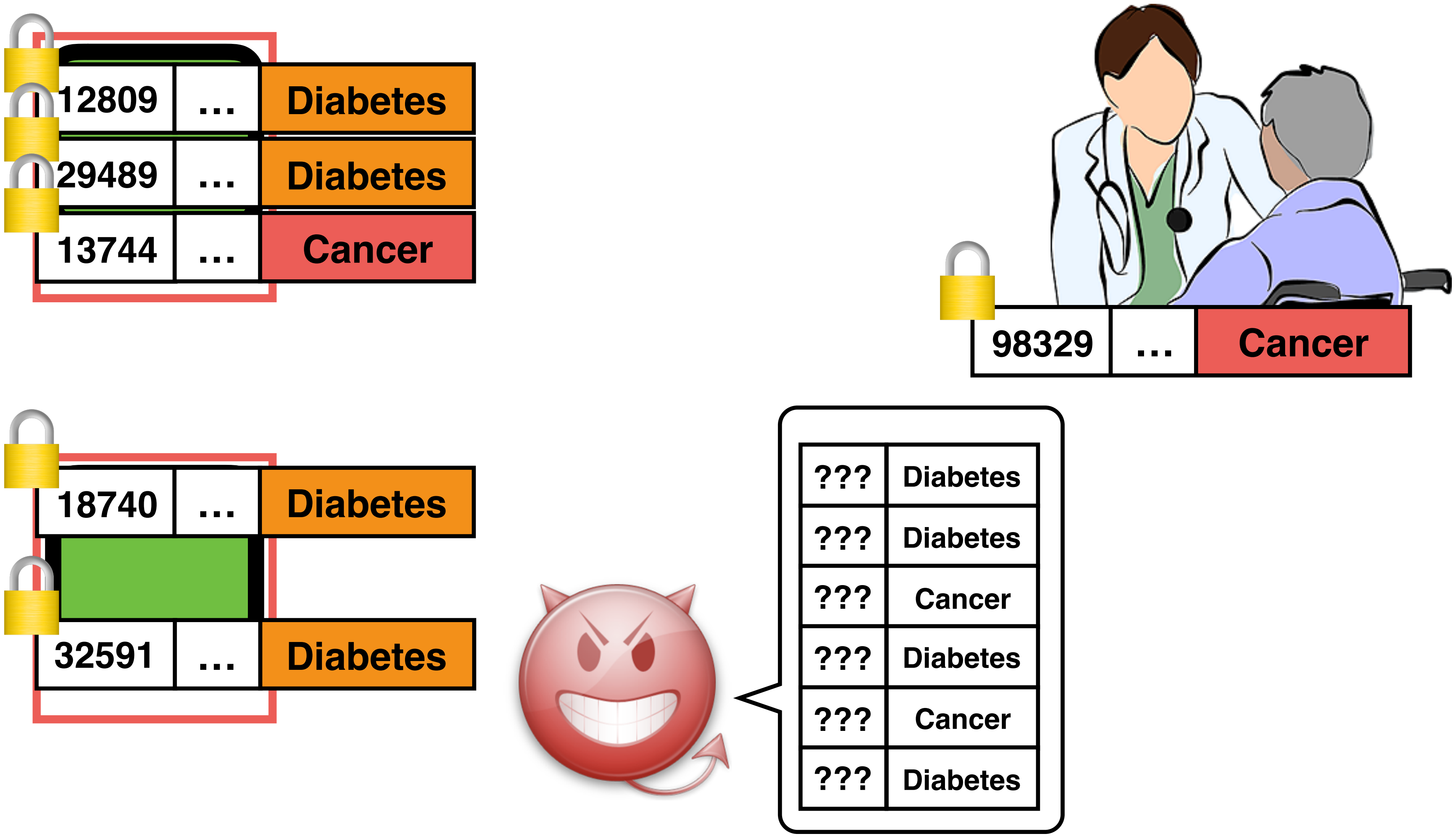

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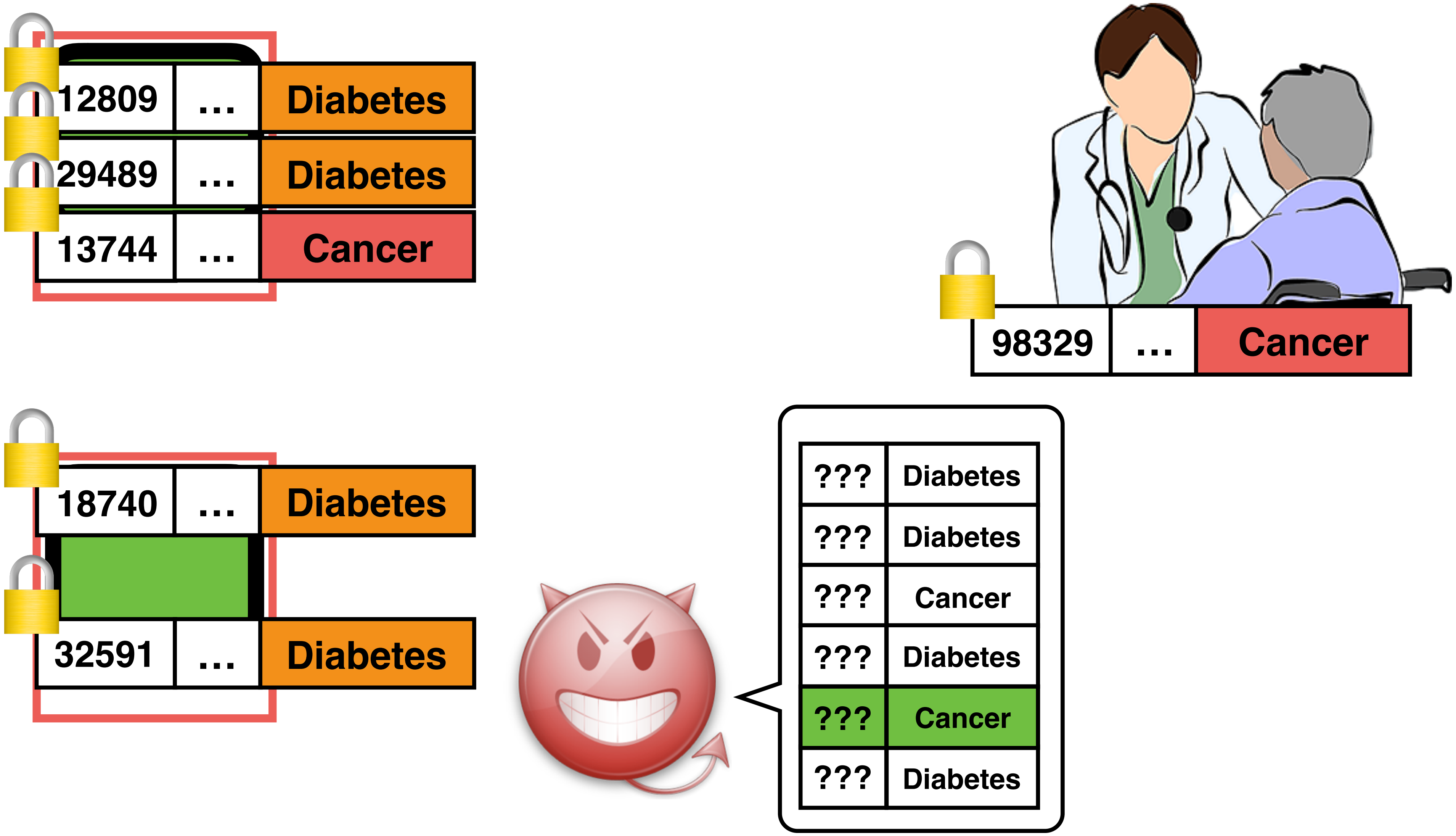

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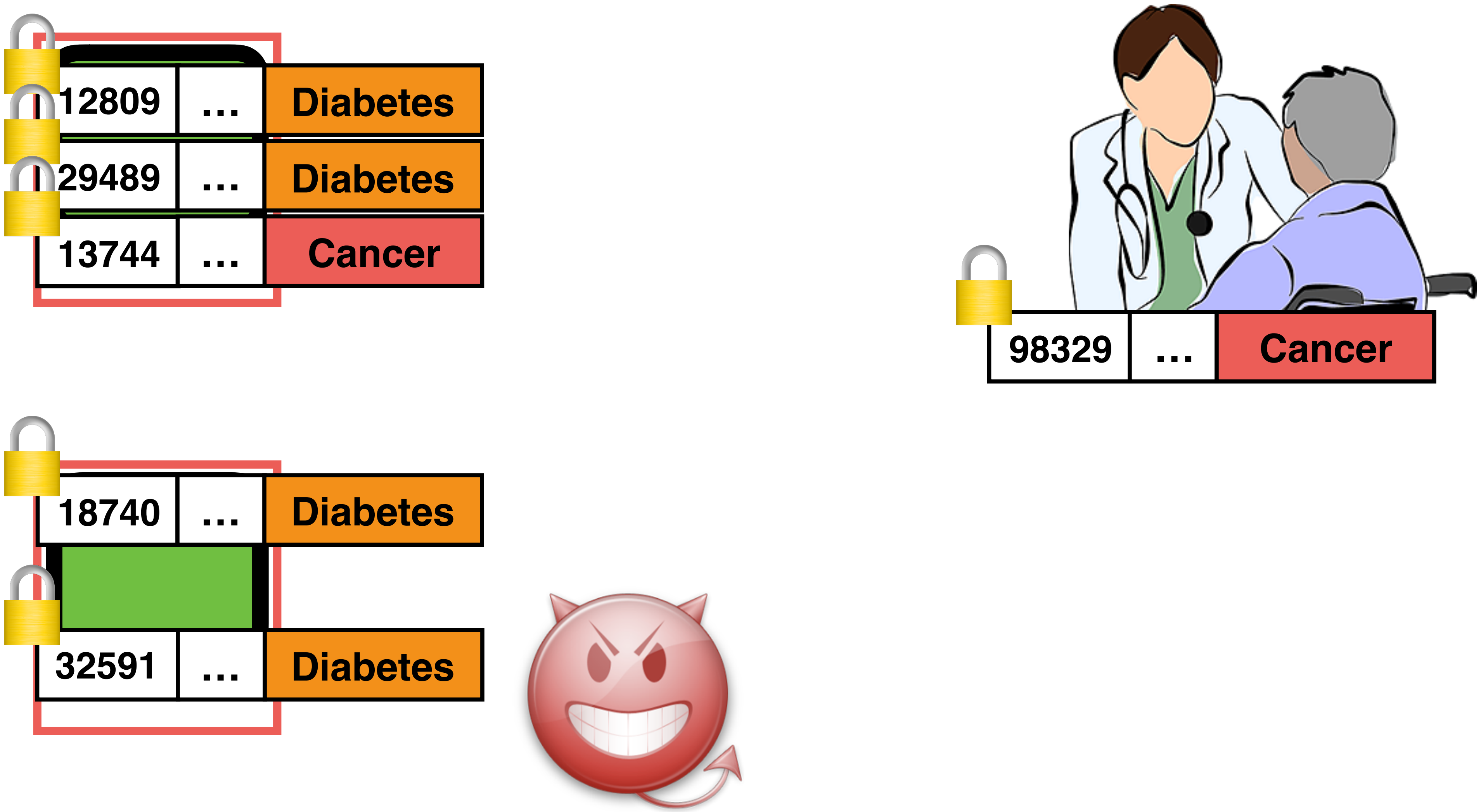

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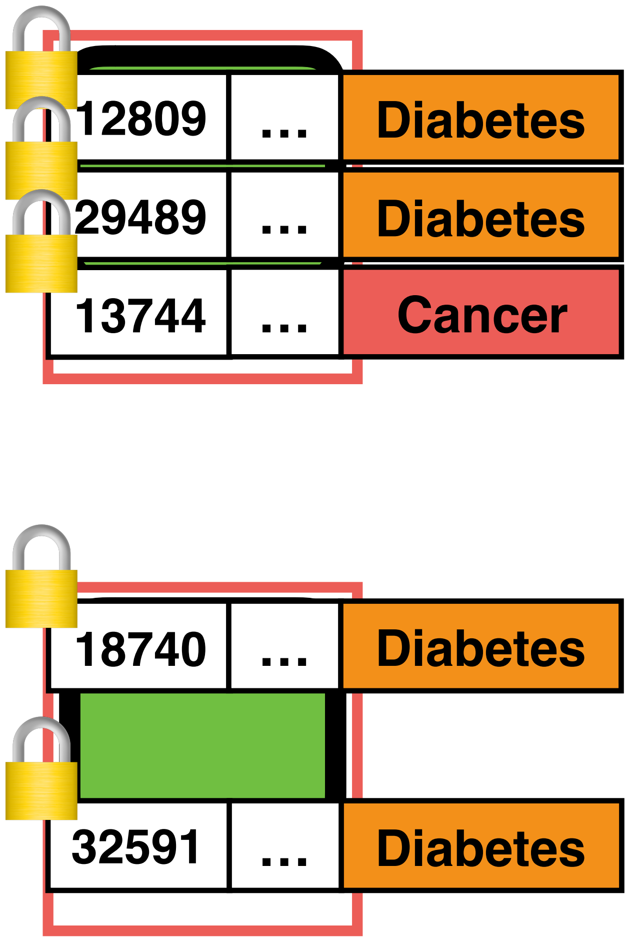

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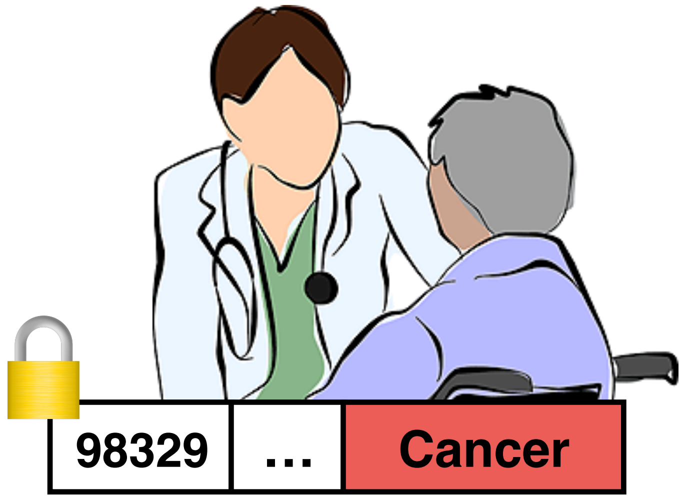

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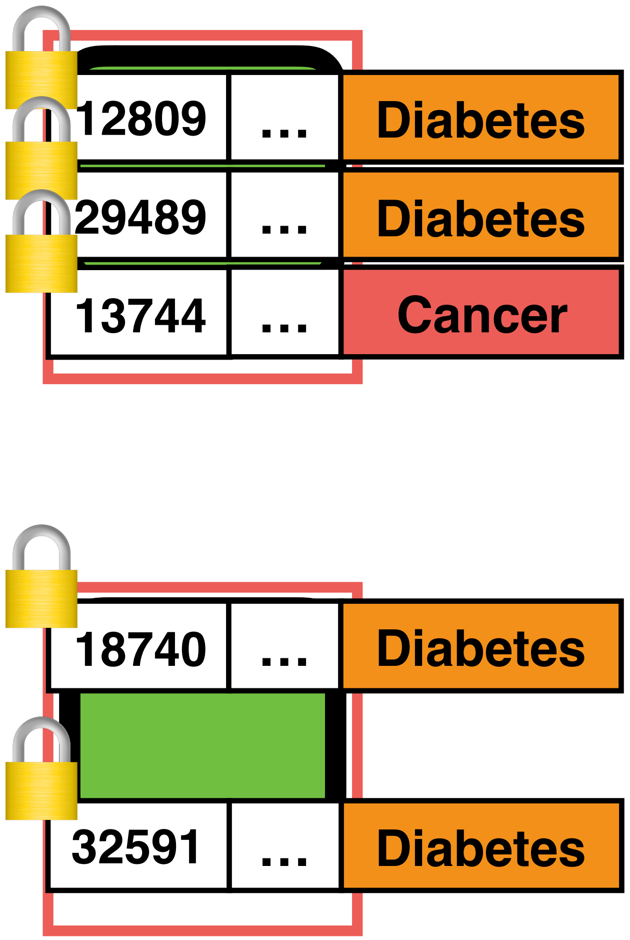

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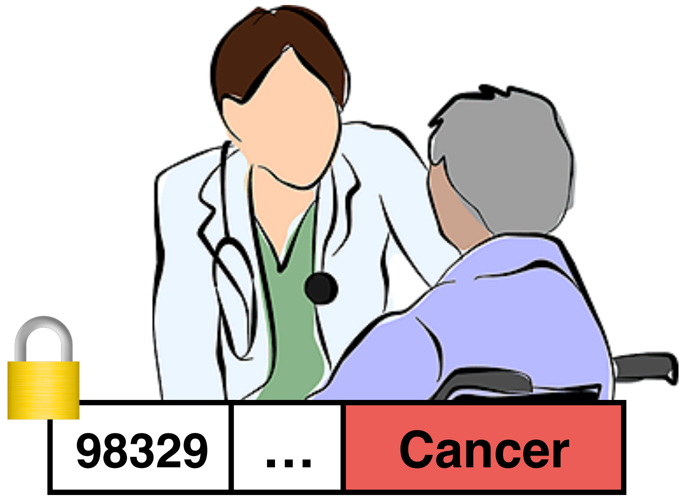

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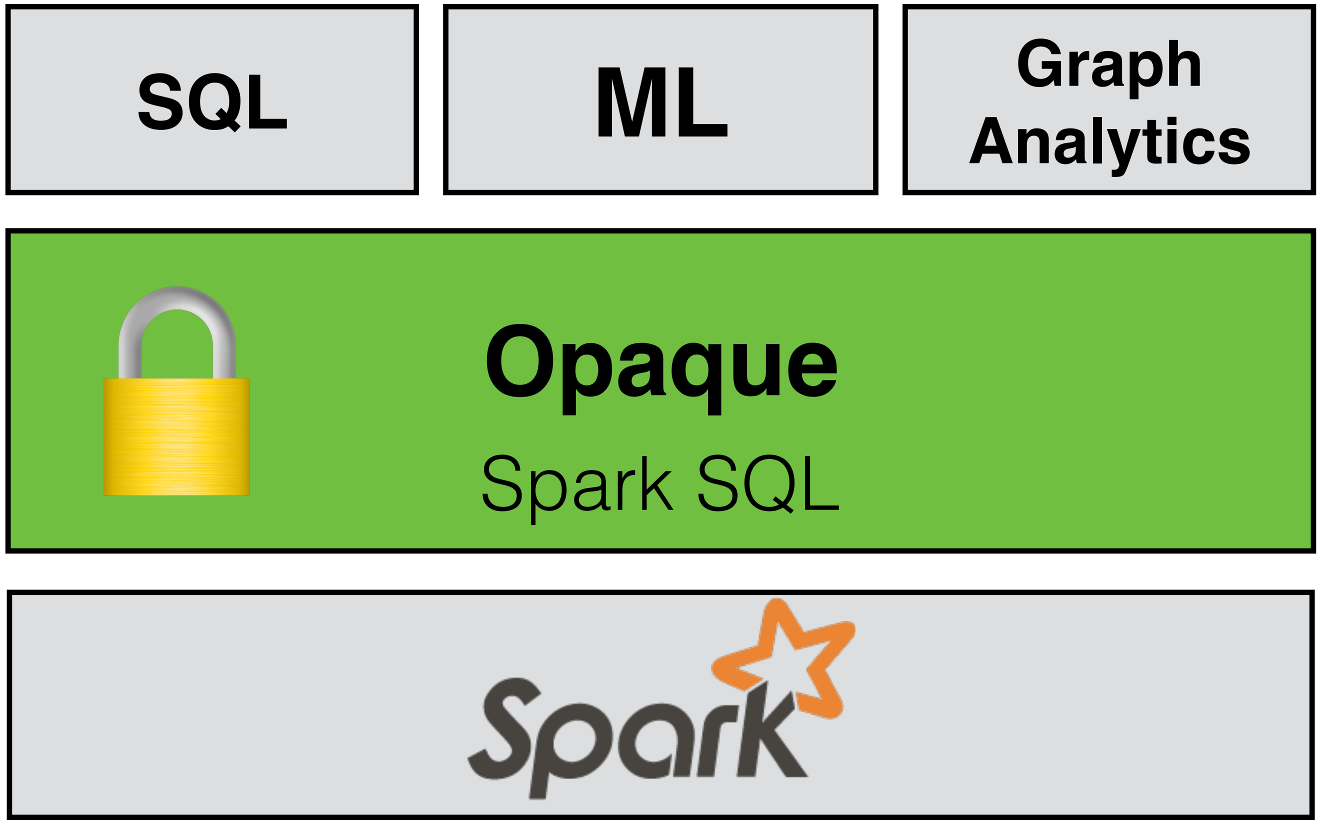
Attack viable by observing both memory and network accesses!

Opaque*: secure distributed analytics



* Oblivious Platform for Analytic QUEries

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- **Obliviousness = hiding access patterns**
    - *Informal statement*
        - *The memory and network accesses of the computation is the same for any input of the same size*

Challenge: obliviousness is expensive

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Two-part solution:

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Distributed oblivious SQL operators

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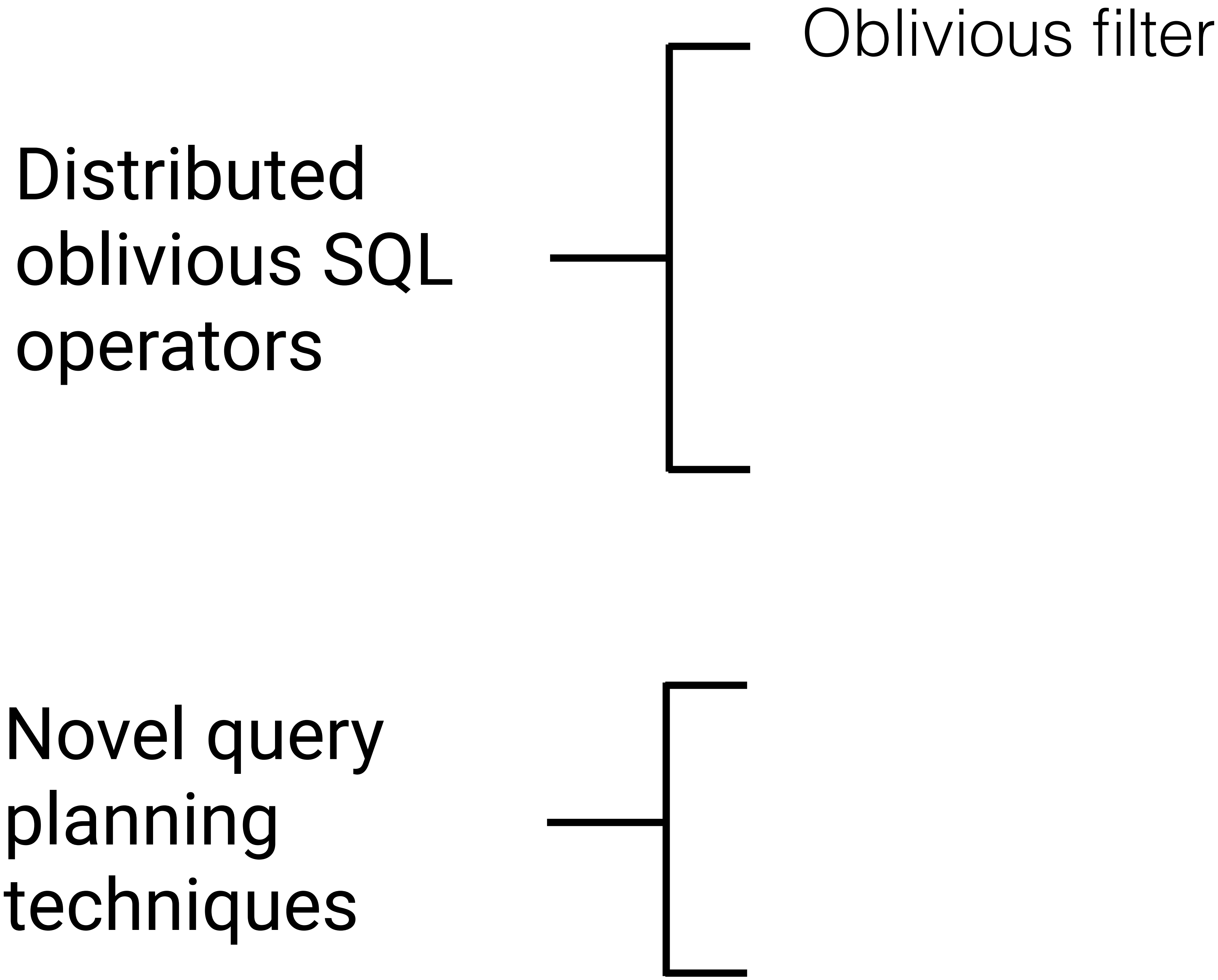

Distributed oblivious SQL operators

Oblivious filter

Novel query planning techniques

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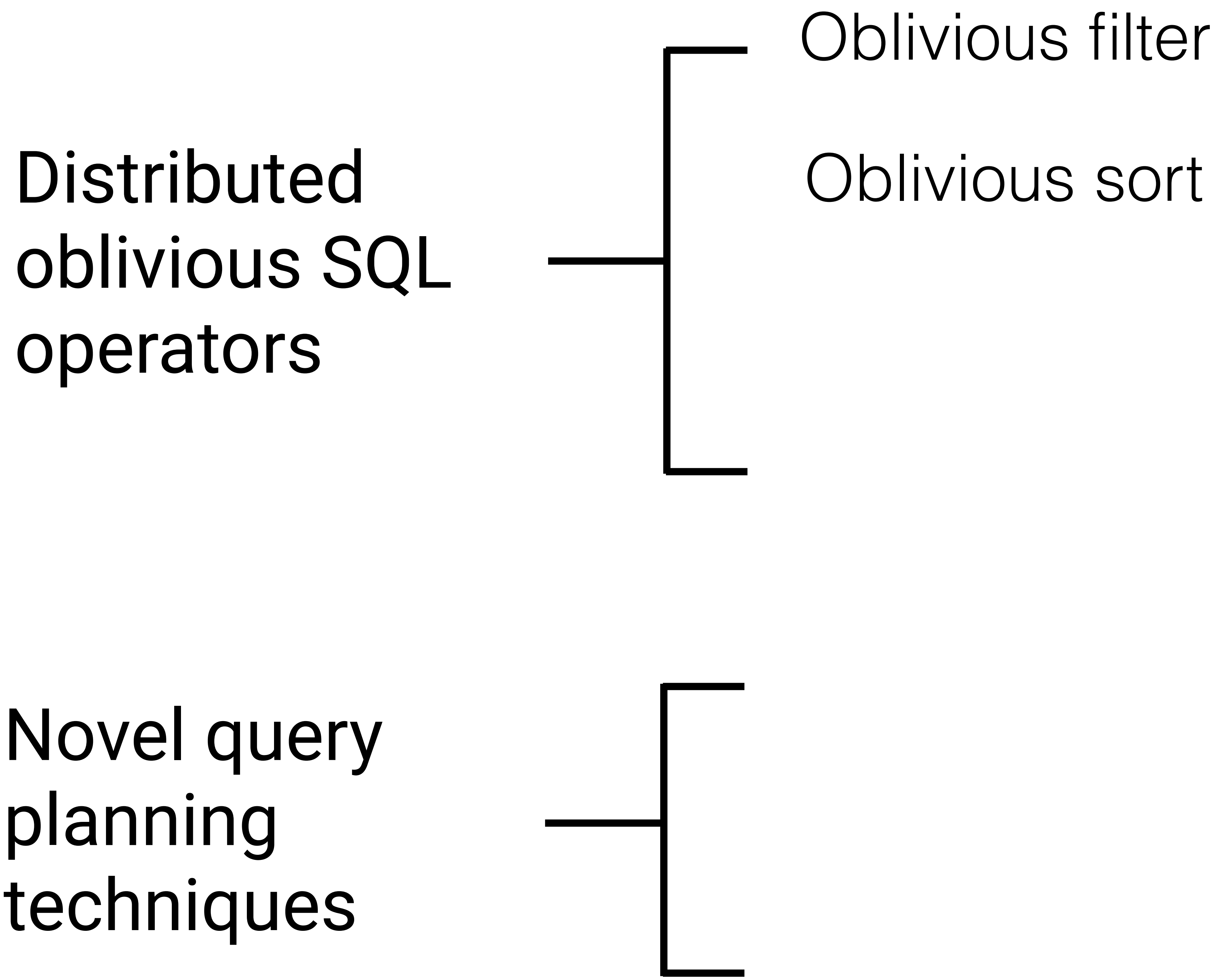

Distributed oblivious SQL operators

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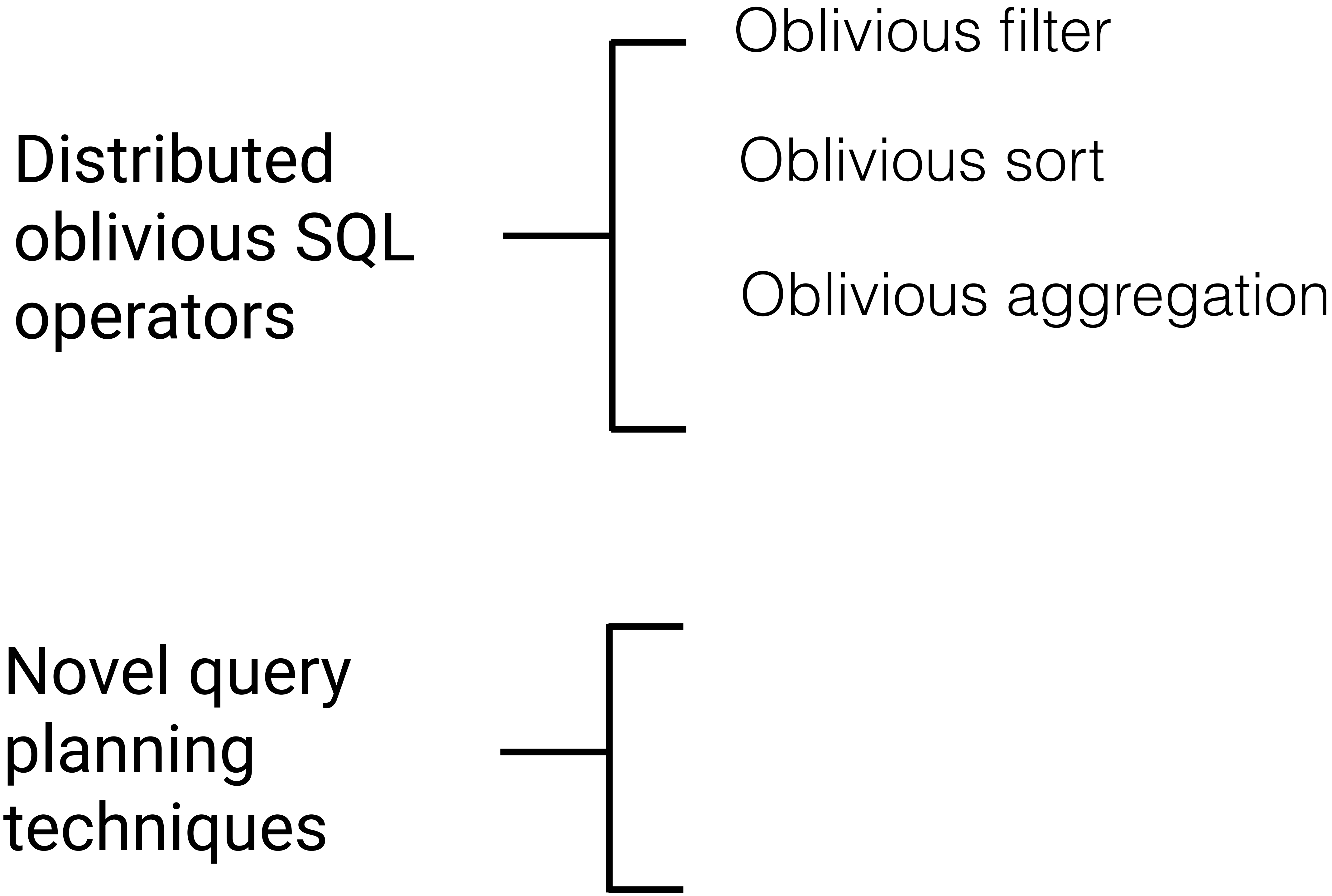

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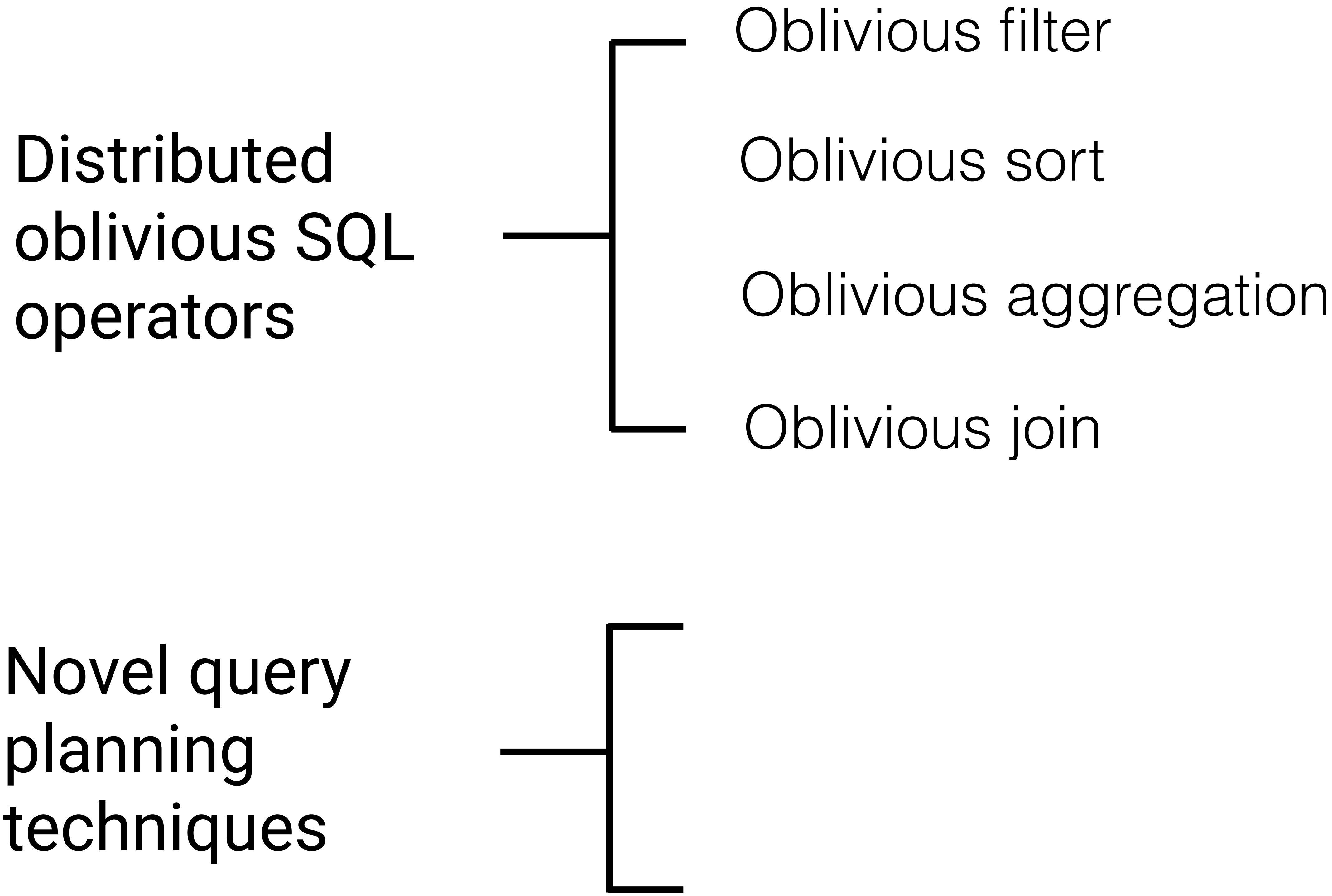

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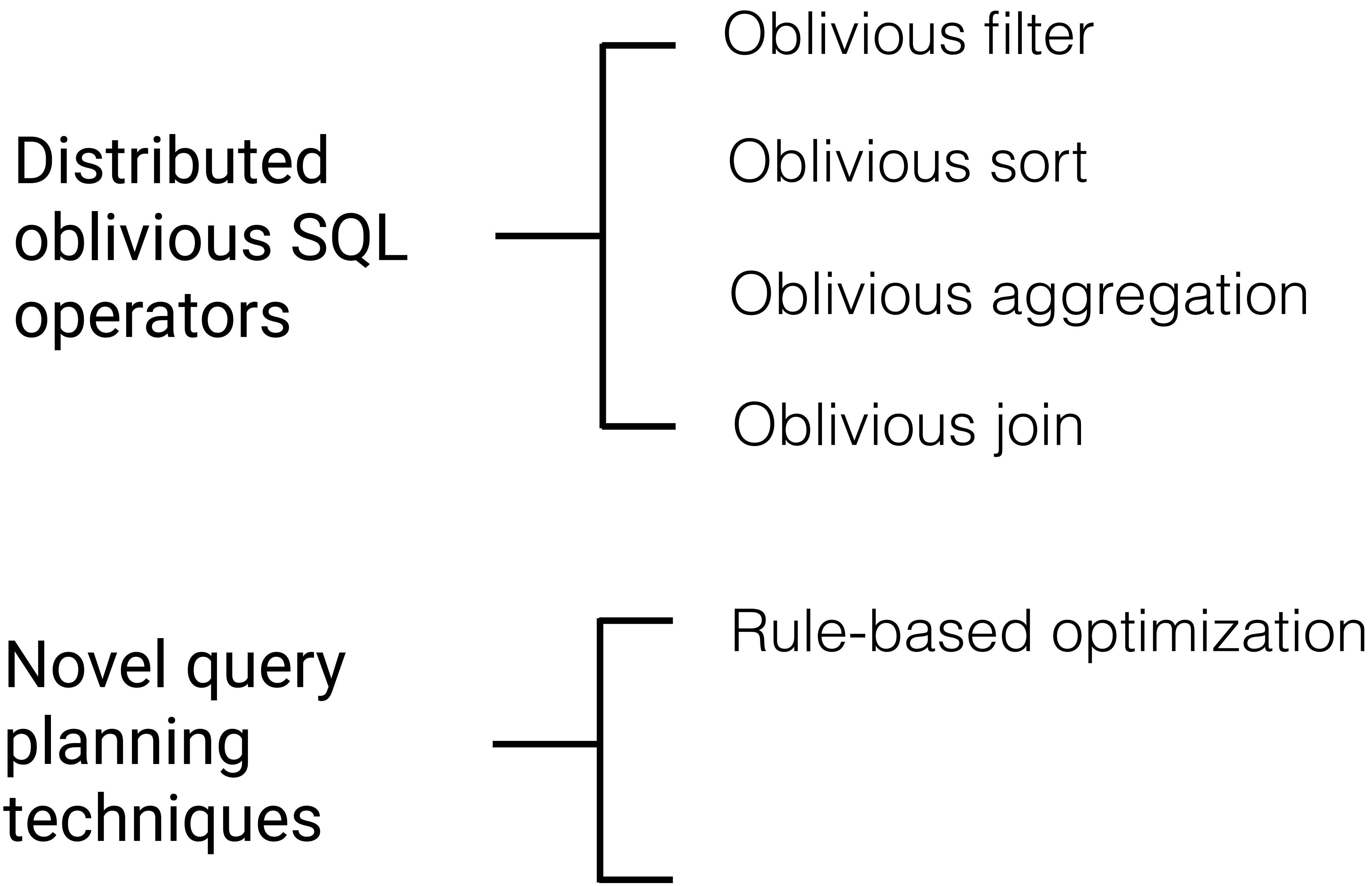

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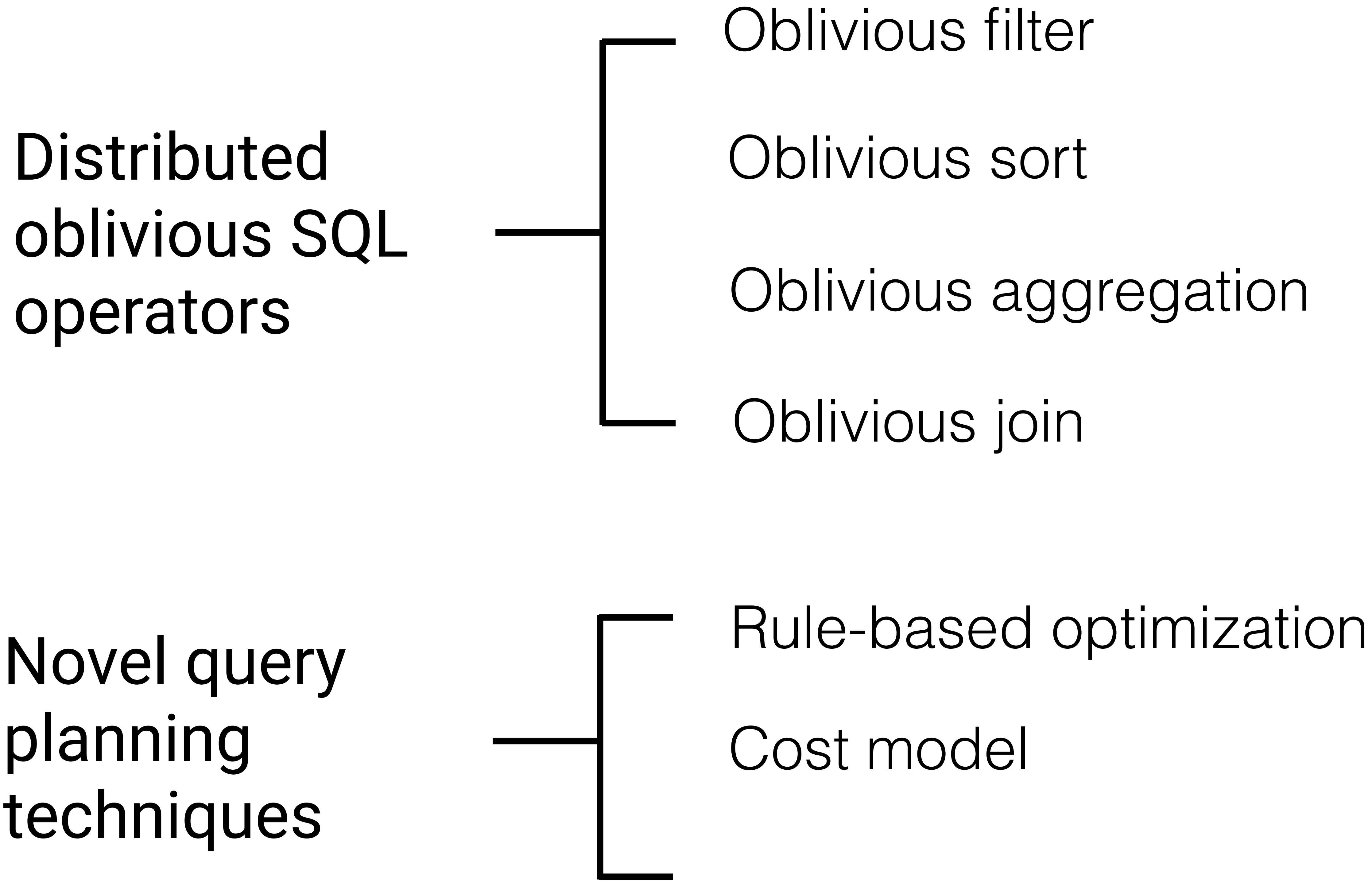
- Oblivious filter
- Oblivious sort
- Oblivious aggregation
- Oblivious join

Novel query planning techniques

- Rule-based optimization

Two-part solution:



Distributed oblivious SQL operators

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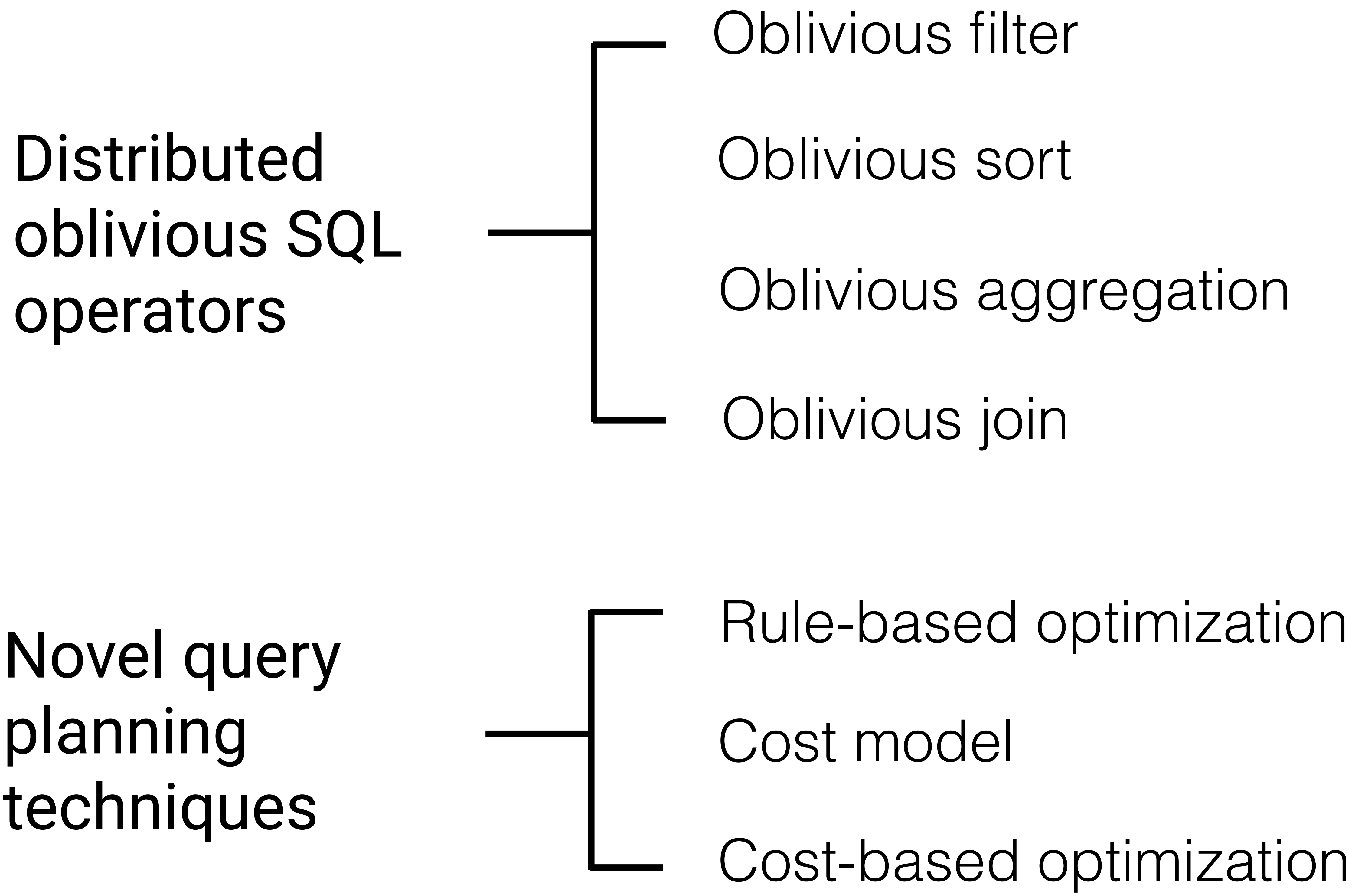

Distributed oblivious SQL operators

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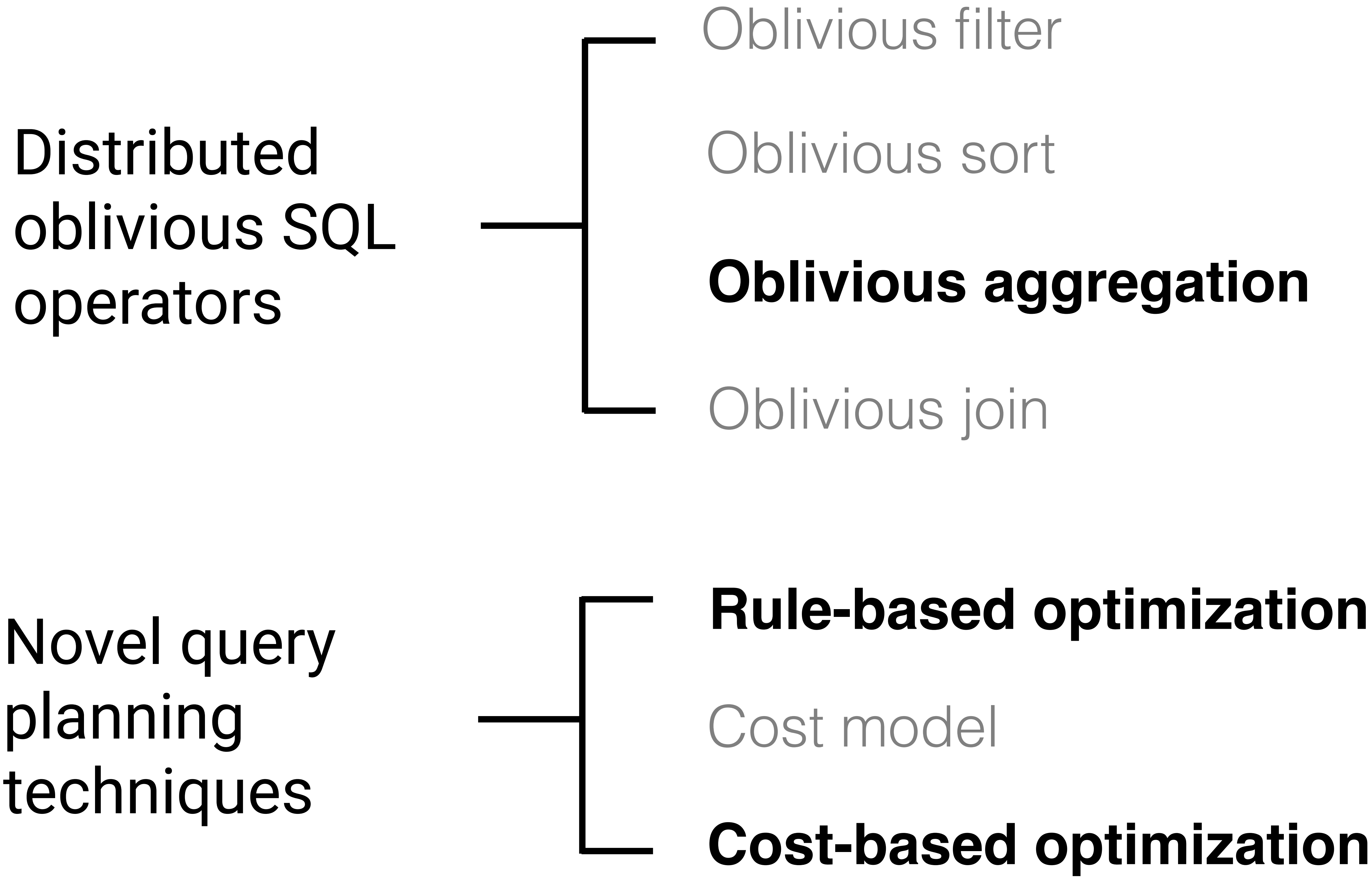


Distributed oblivious SQL operators

- Oblivious filter
- Oblivious sort
- **Oblivious aggregation**
- Oblivious join

Novel query planning techniques

- **Rule-based optimization**
- Cost model
- **Cost-based optimization**

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

🔒	12809	…	Diabetes
🔒	29489	…	Diabetes
🔒	13744	…	Cancer

🔒	18740	…	Diabetes
🔒	98329	…	Cancer
🔒	32591	…	Diabetes

Oblivious aggregation

```
SELECT count(*) FROM medical GROUP BY disease
```

1

12809	...	Diabetes
29489	...	Diabetes
13744	...	Cancer

2

18740	...	Diabetes
98329	...	Cancer
32591	...	Diabetes

Oblivious aggregation

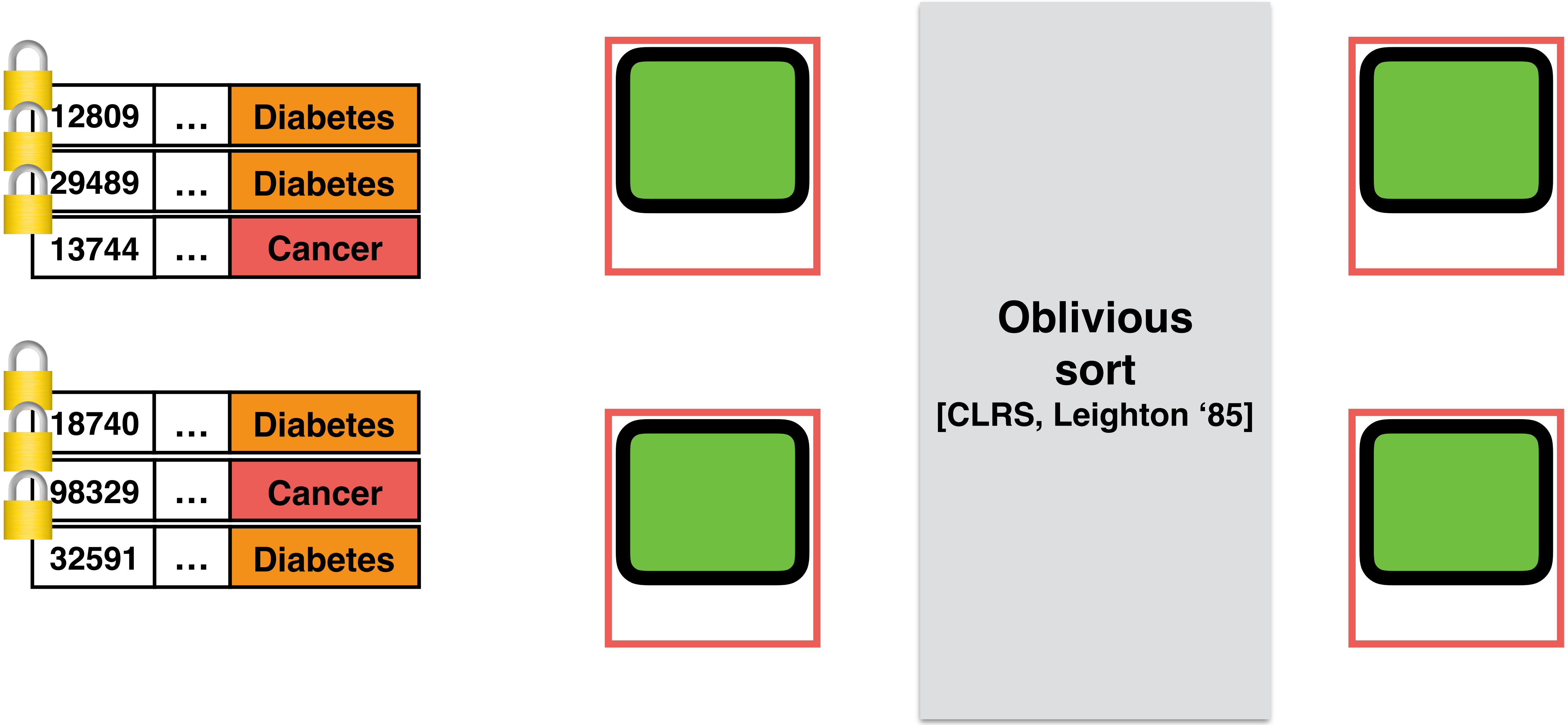
SELECT count(*) FROM medical GROUP BY disease

🔒 12809	…	Diabetes
🔒 29489	…	Diabetes
🔒 13744	…	Cancer

🔒 18740	…	Diabetes
🔒 98329	…	Cancer
🔒 32591	…	Diabetes

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



12809	…	Diabetes
29489	…	Diabetes
13744	…	Cancer

18740	…	Diabetes
98329	…	Cancer
32591	…	Diabetes

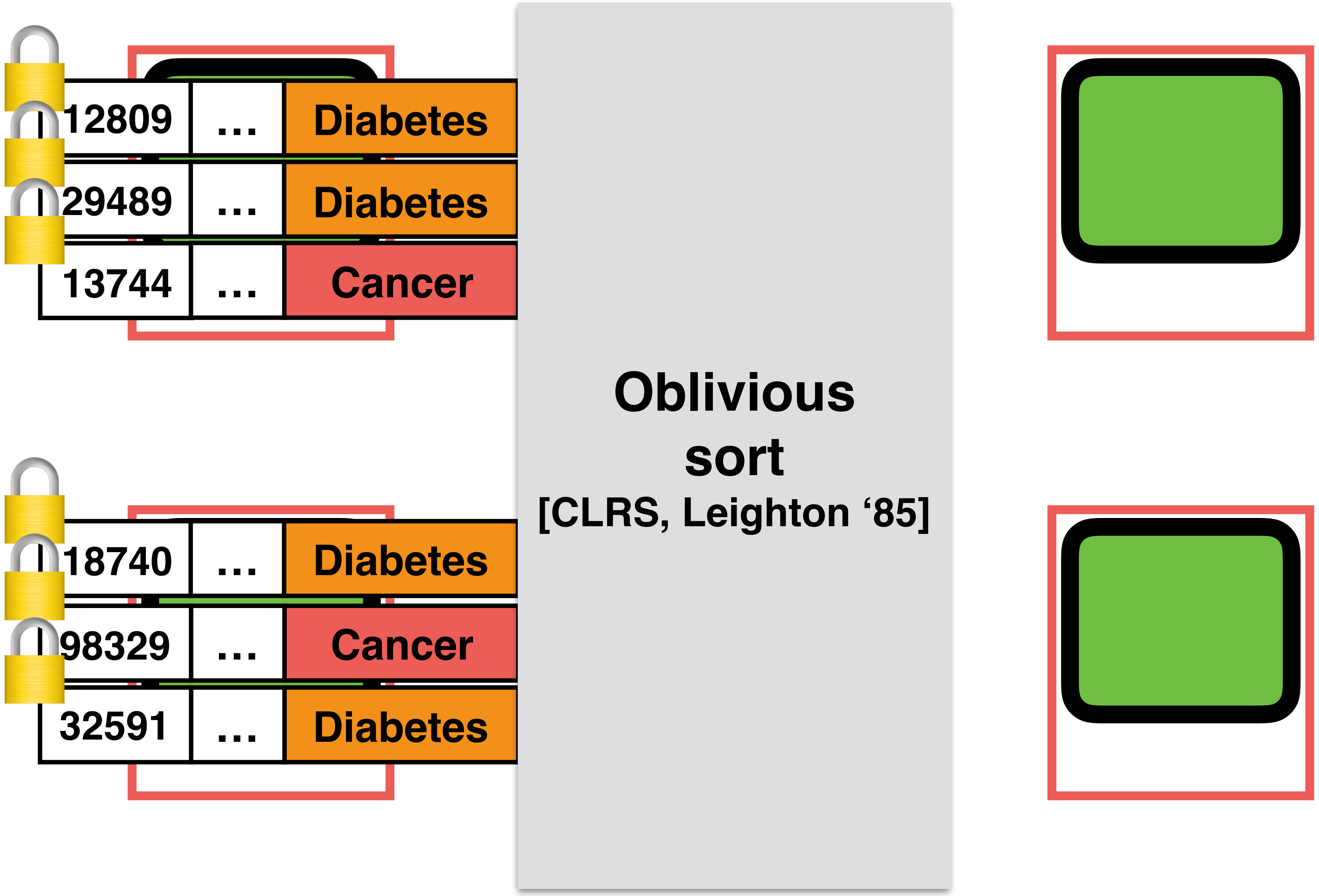
Oblivious sort
[CLRS, Leighton '85]

Map

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

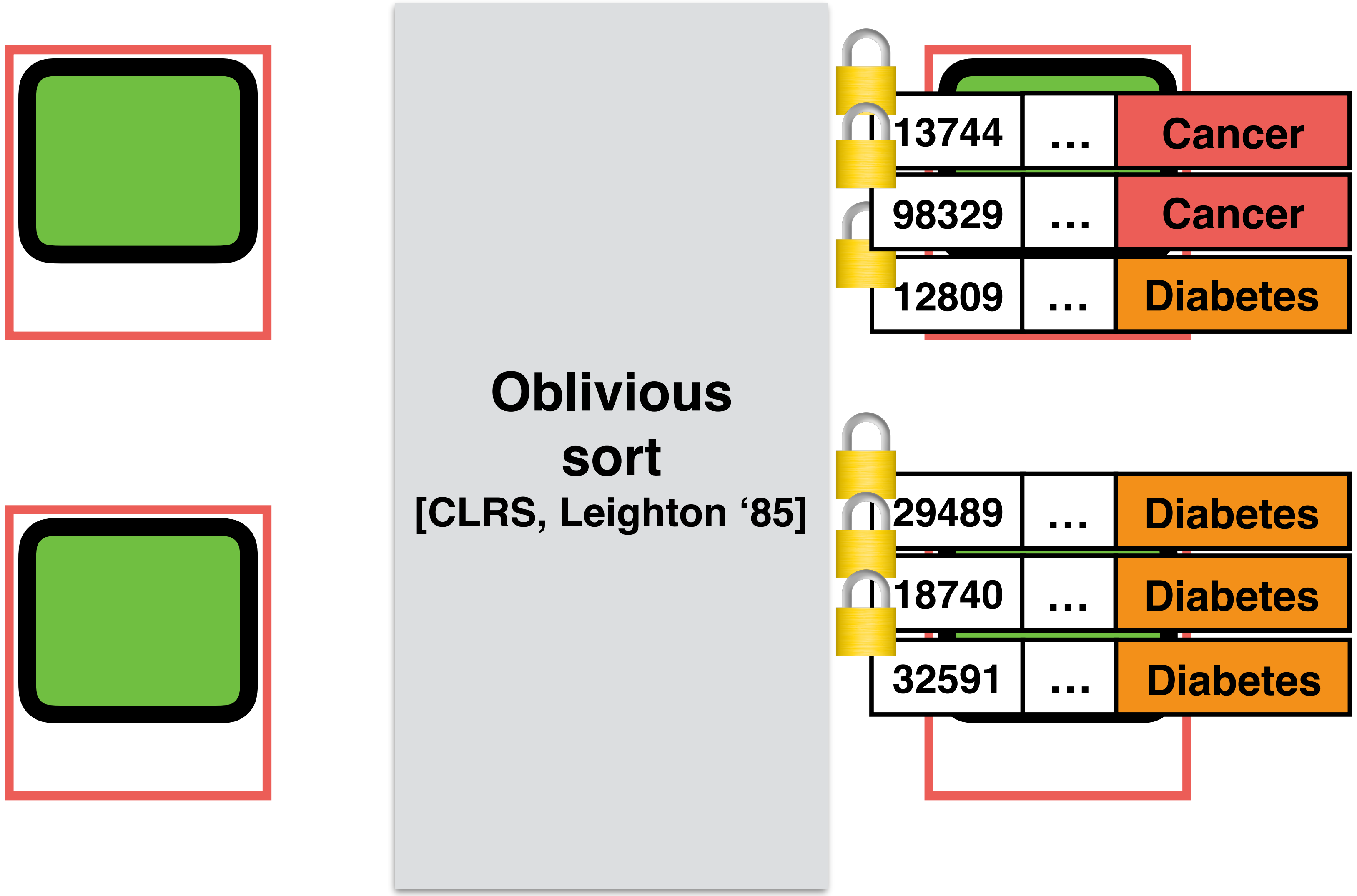


Map

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious sort
[CLRS, Leighton ‘85]

13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

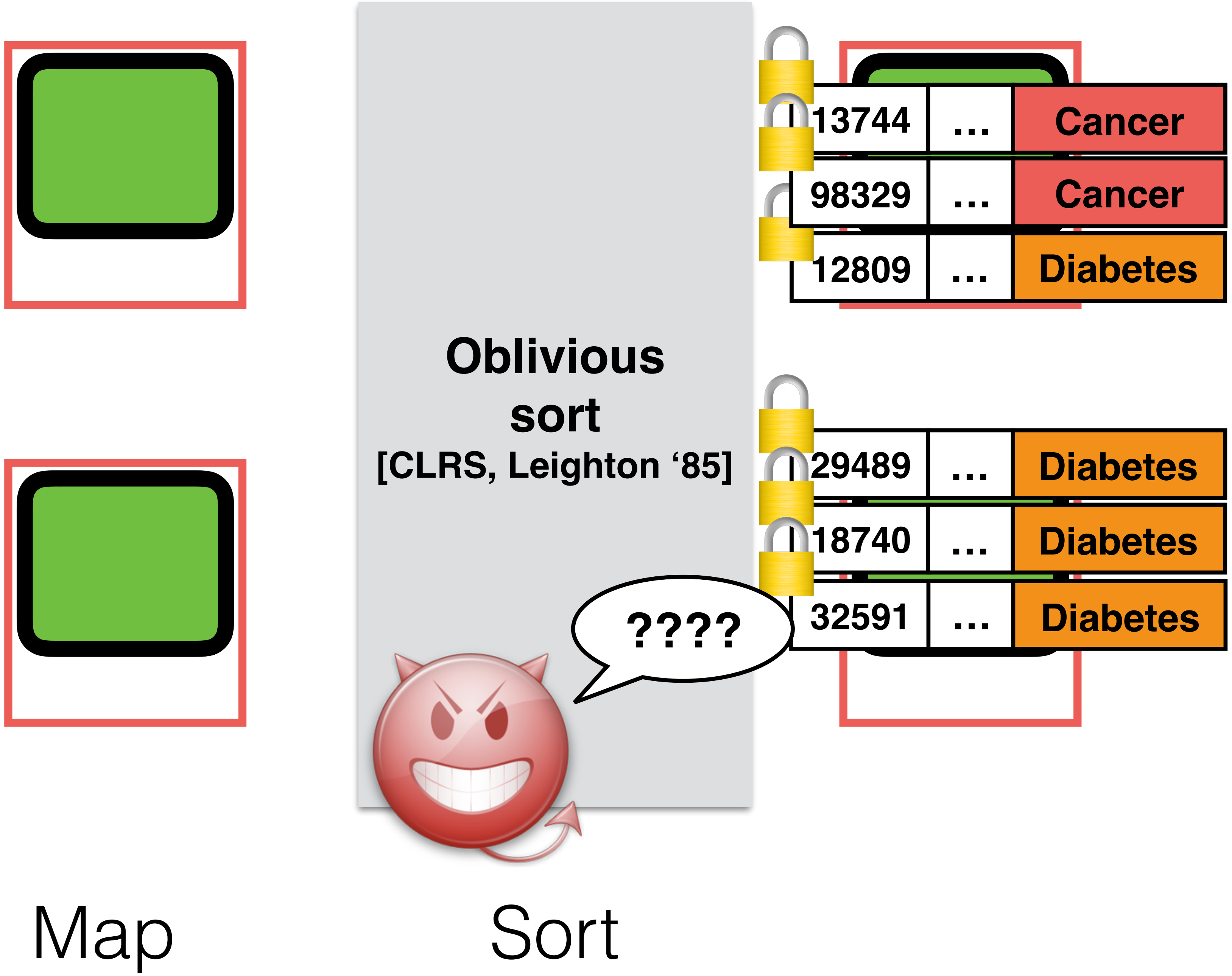
29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Map

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

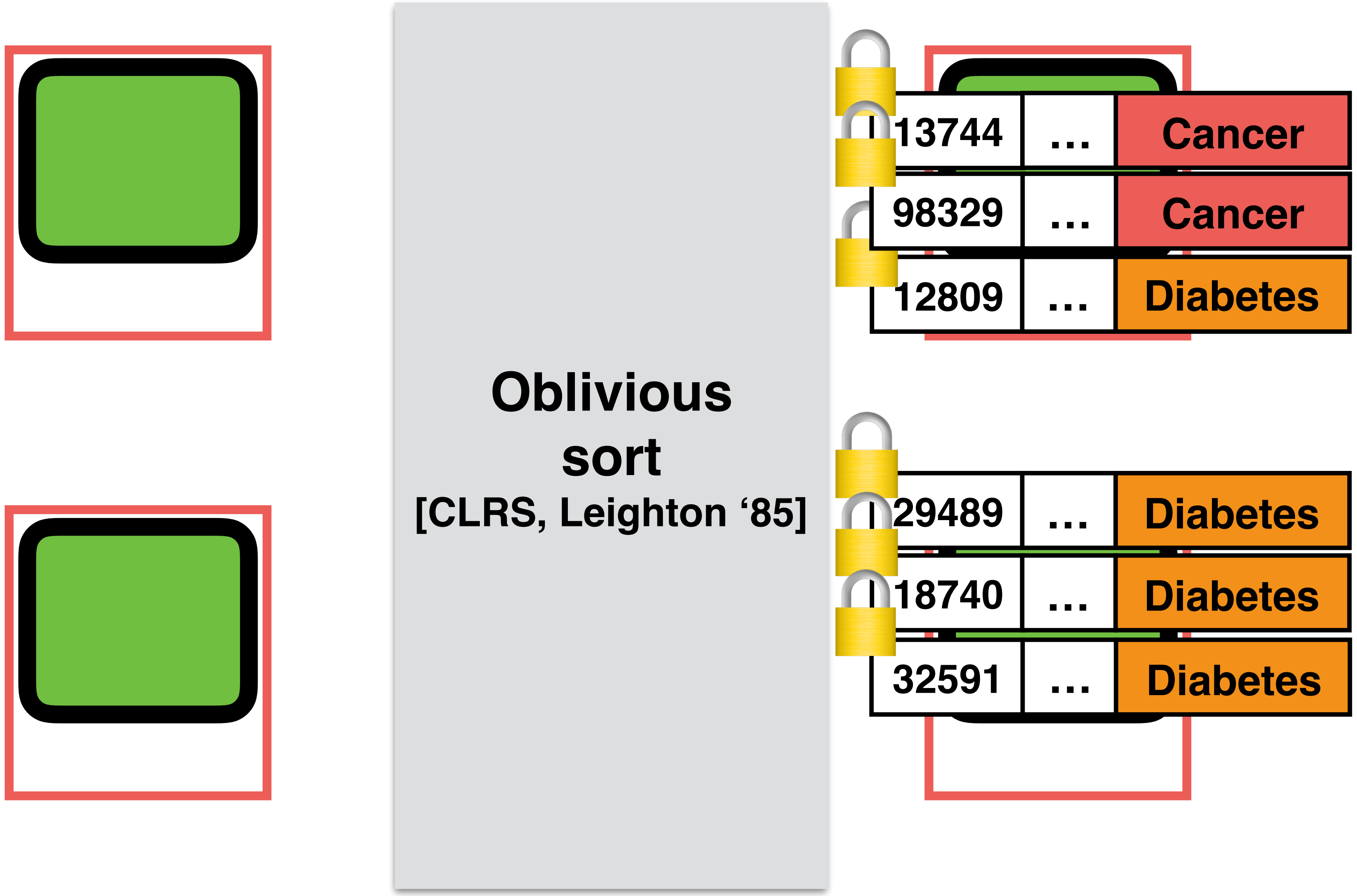


13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious sort
[CLRS, Leighton '85]

13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

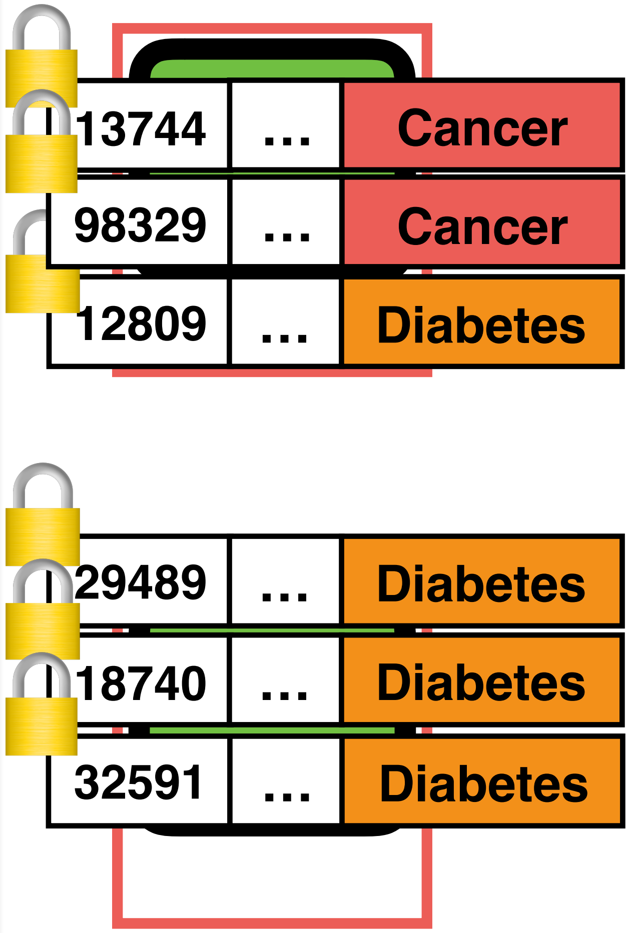
Map Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

s

n ‘85]

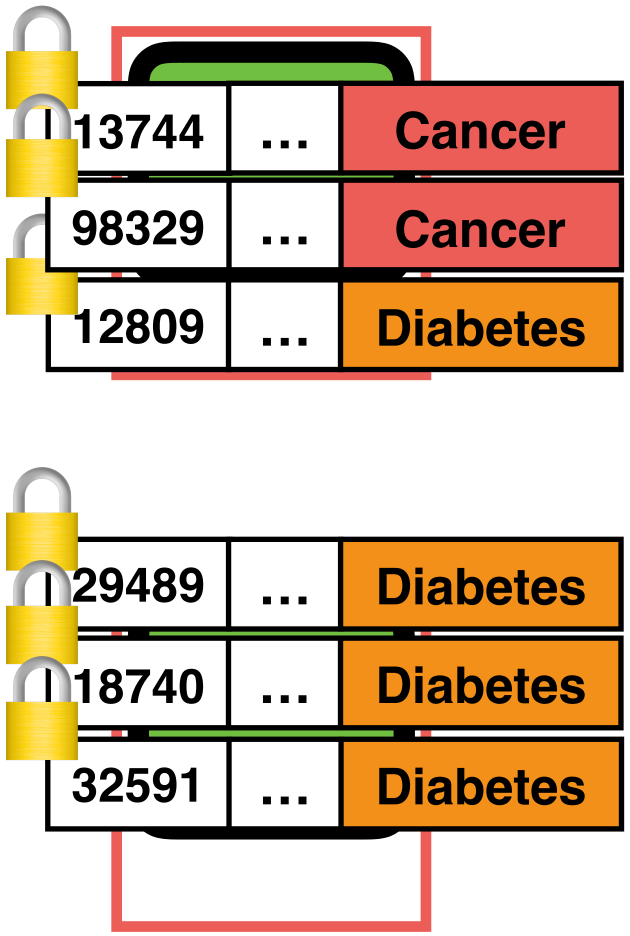


13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

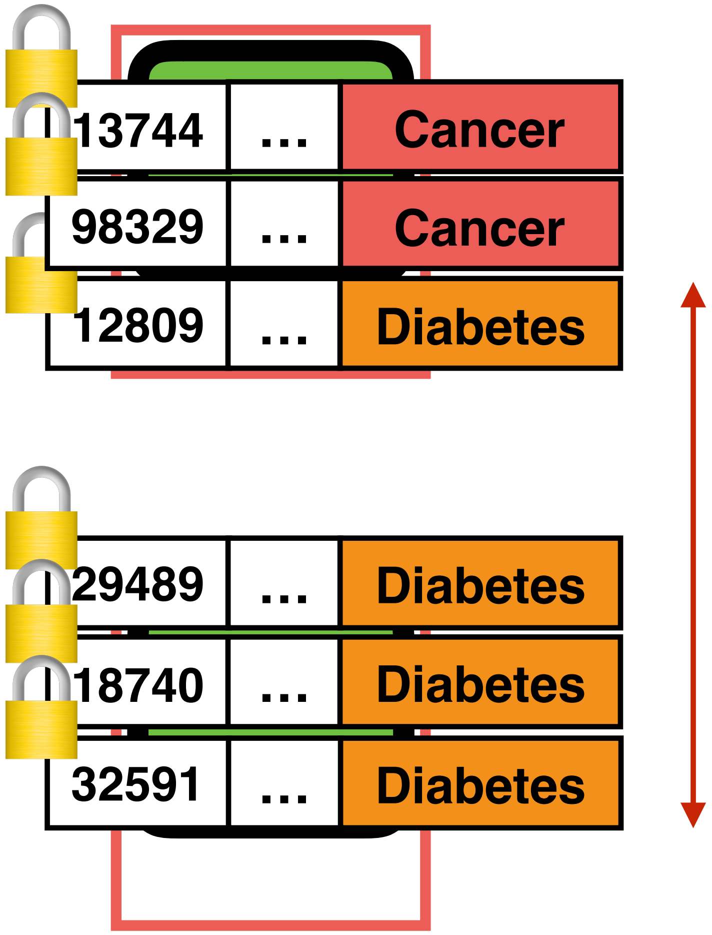


13744	...	Cancer
98329	...	Cancer
12809	...	Diabetes

29489	...	Diabetes
18740	...	Diabetes
32591	...	Diabetes

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



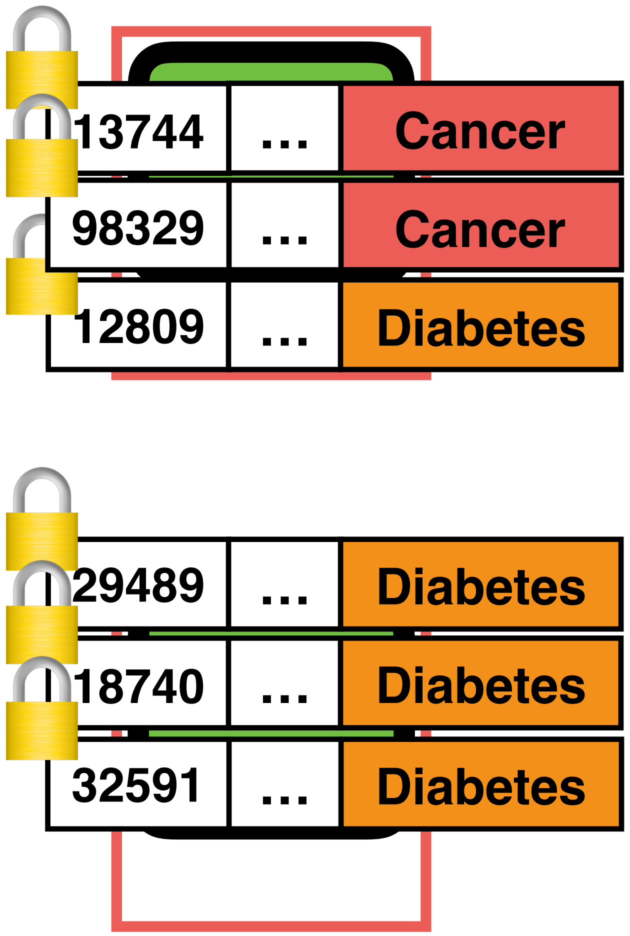
13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

The “Diabetes” group
is split!

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
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12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
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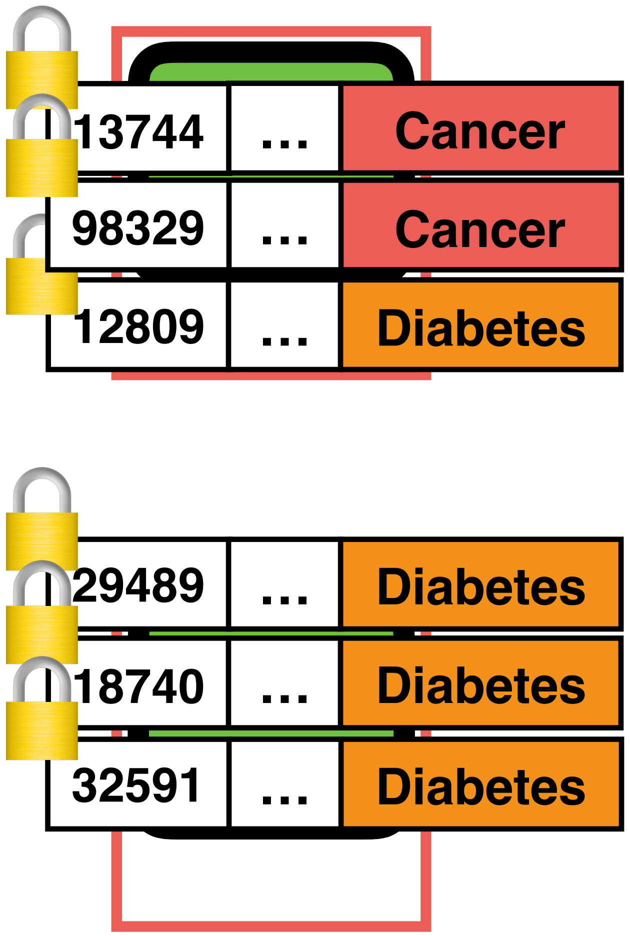
Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



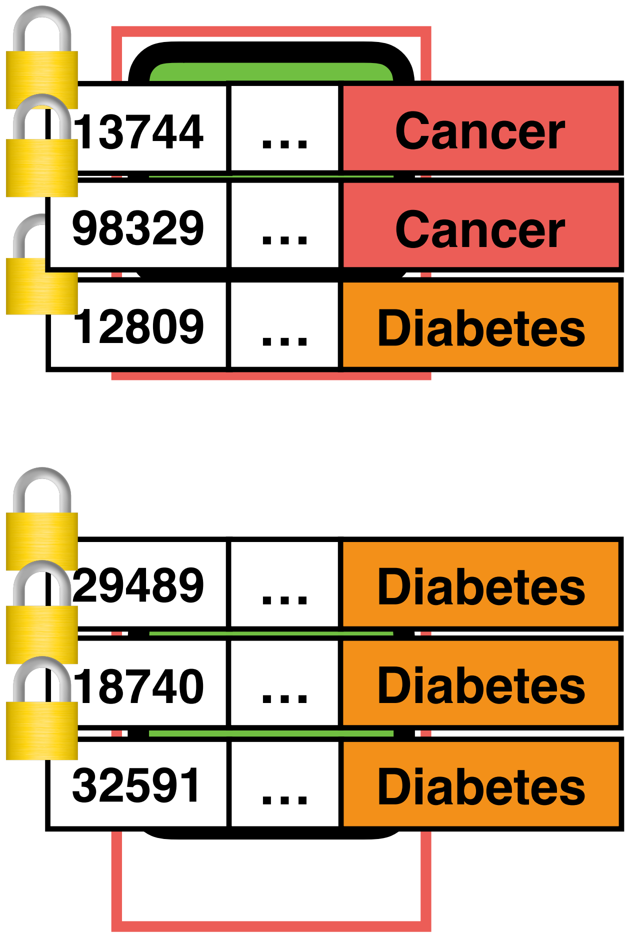
13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

How to aggregate *obliviously* and in *parallel*?

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	...	Cancer
98329	...	Cancer
12809	...	Diabetes

29489	...	Diabetes
18740	...	Diabetes
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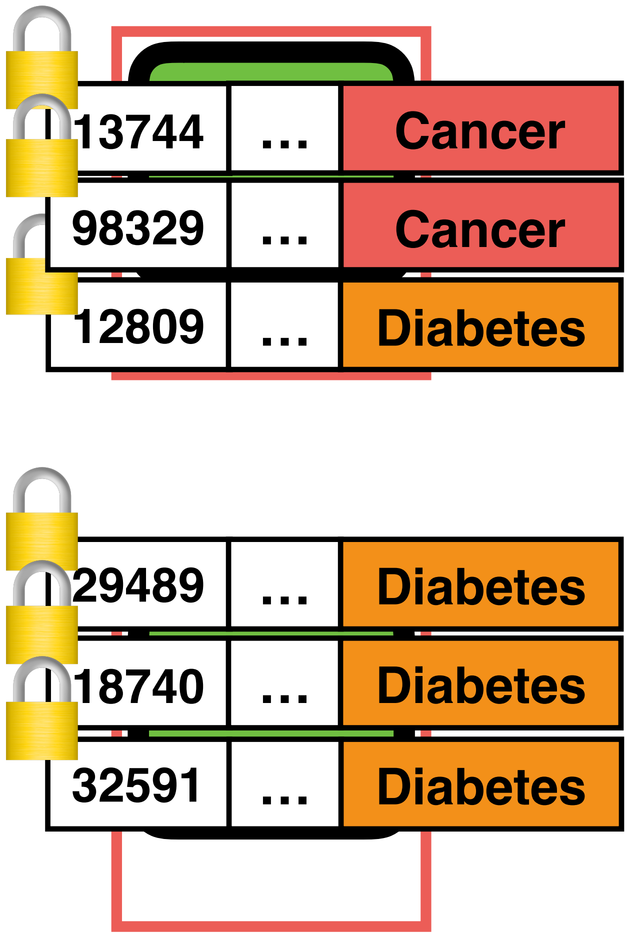
Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



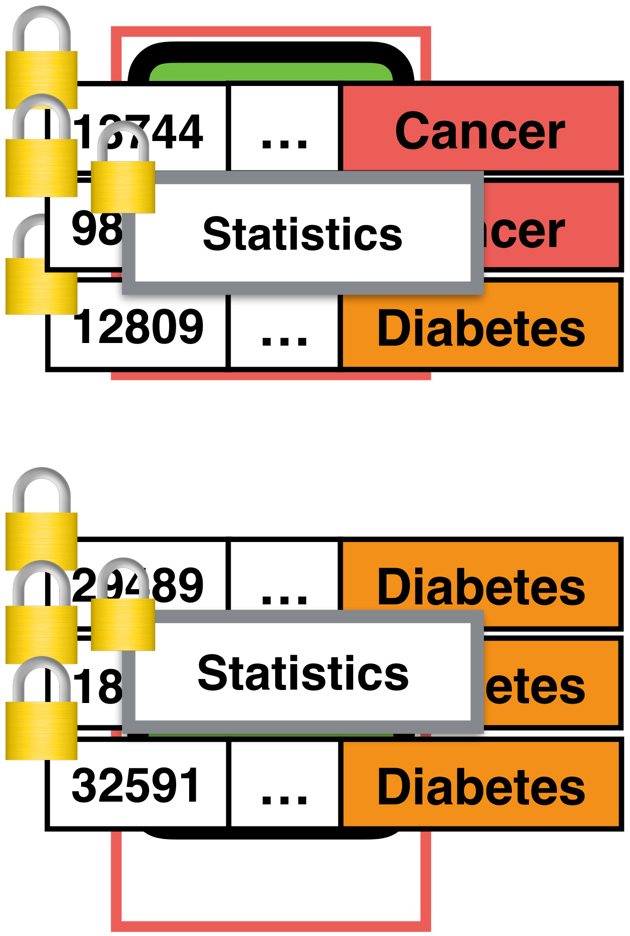
13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Scan

Oblivious aggregation

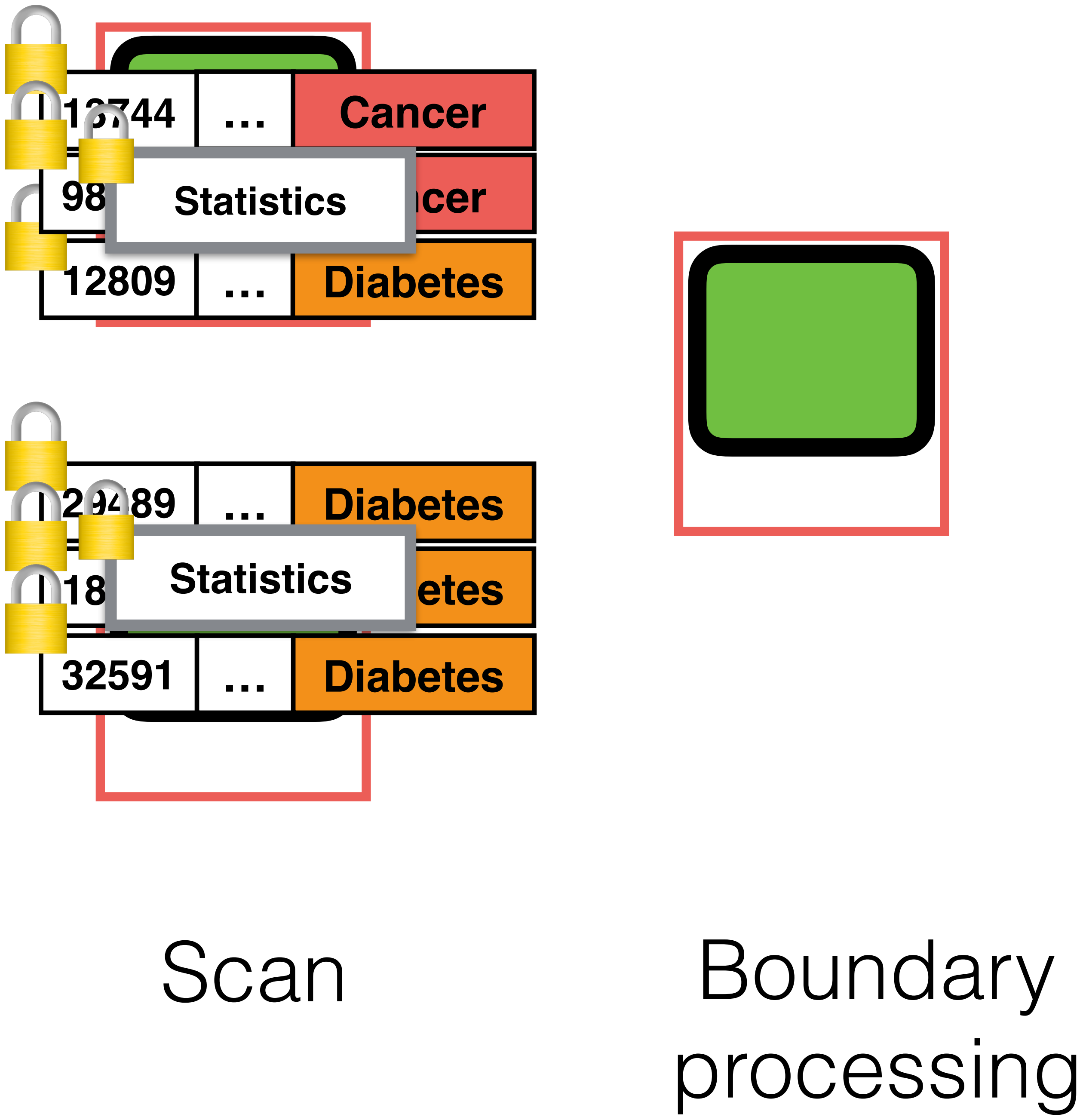
SELECT count(*) FROM medical GROUP BY disease



Scan

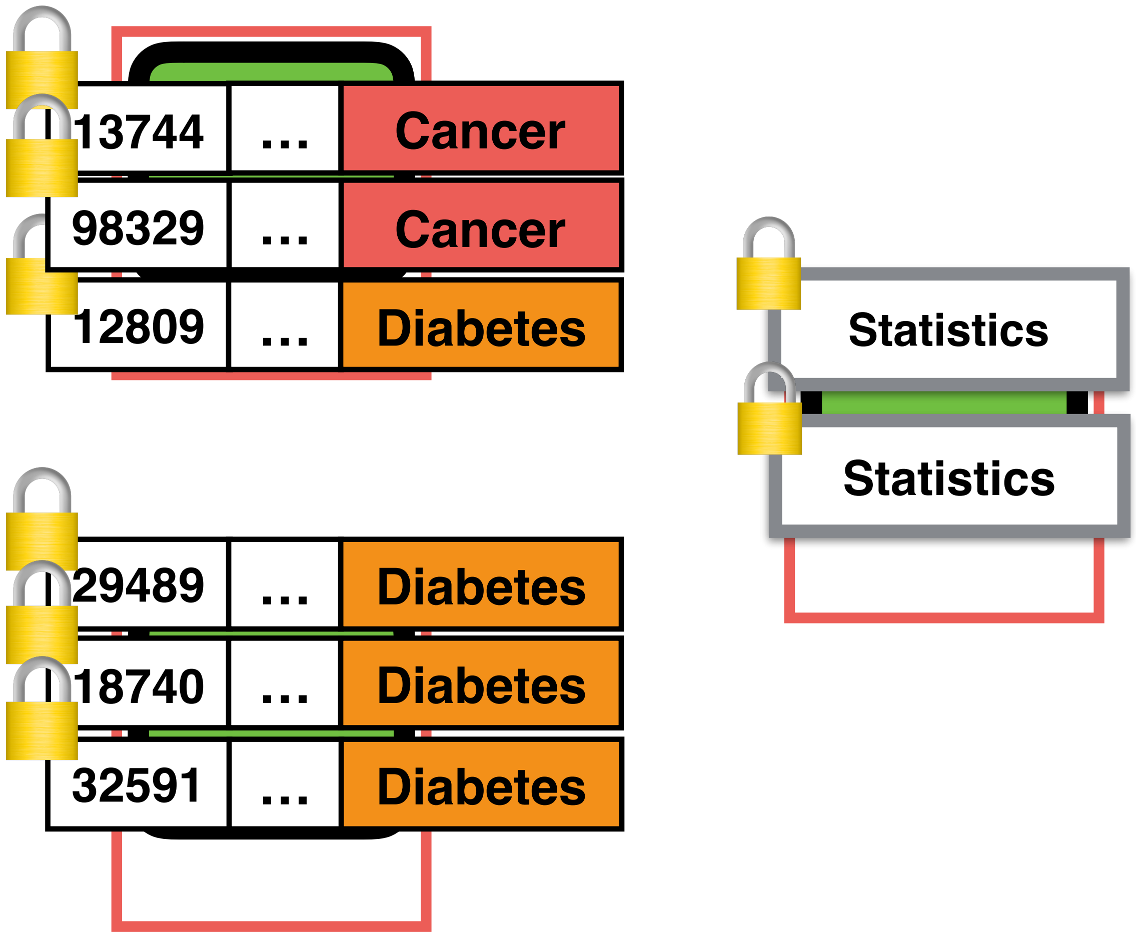
Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Statistics

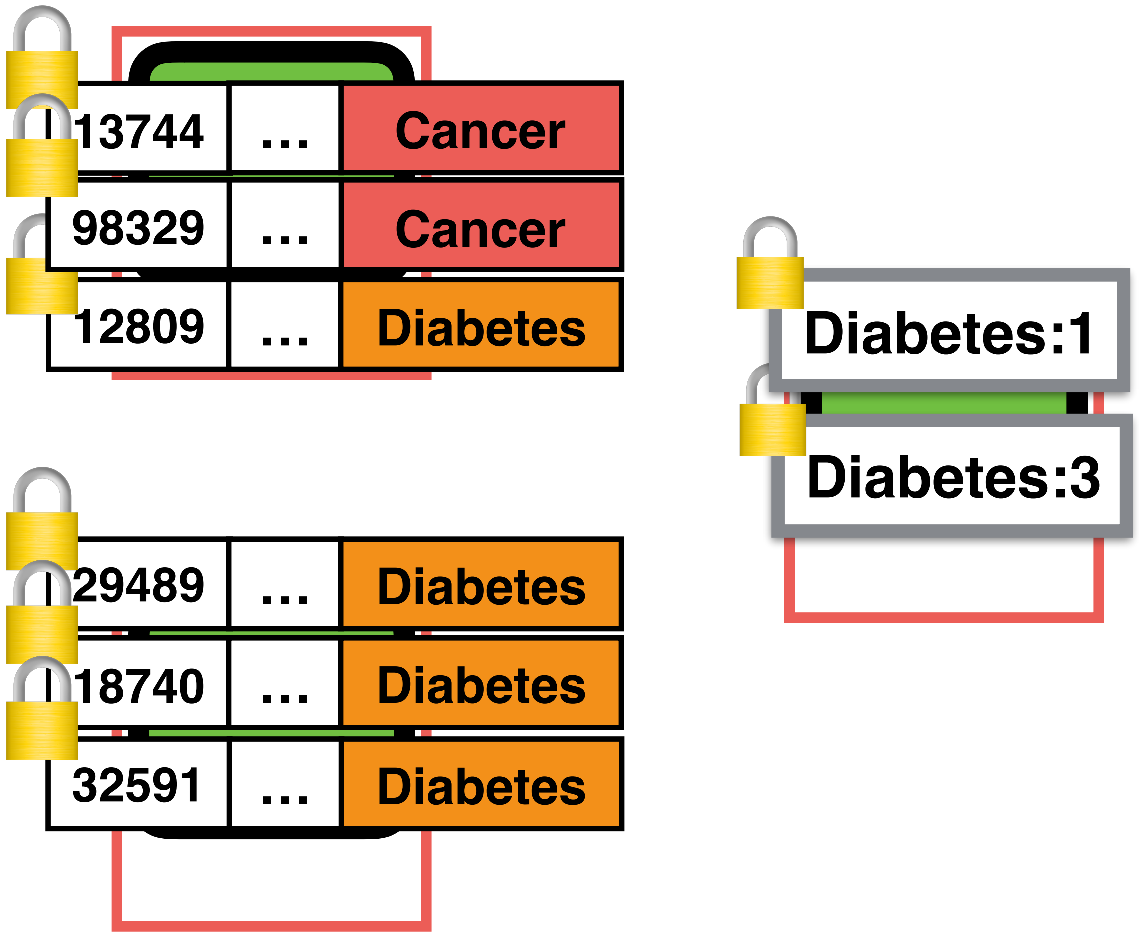
Statistics

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Diabetes:1

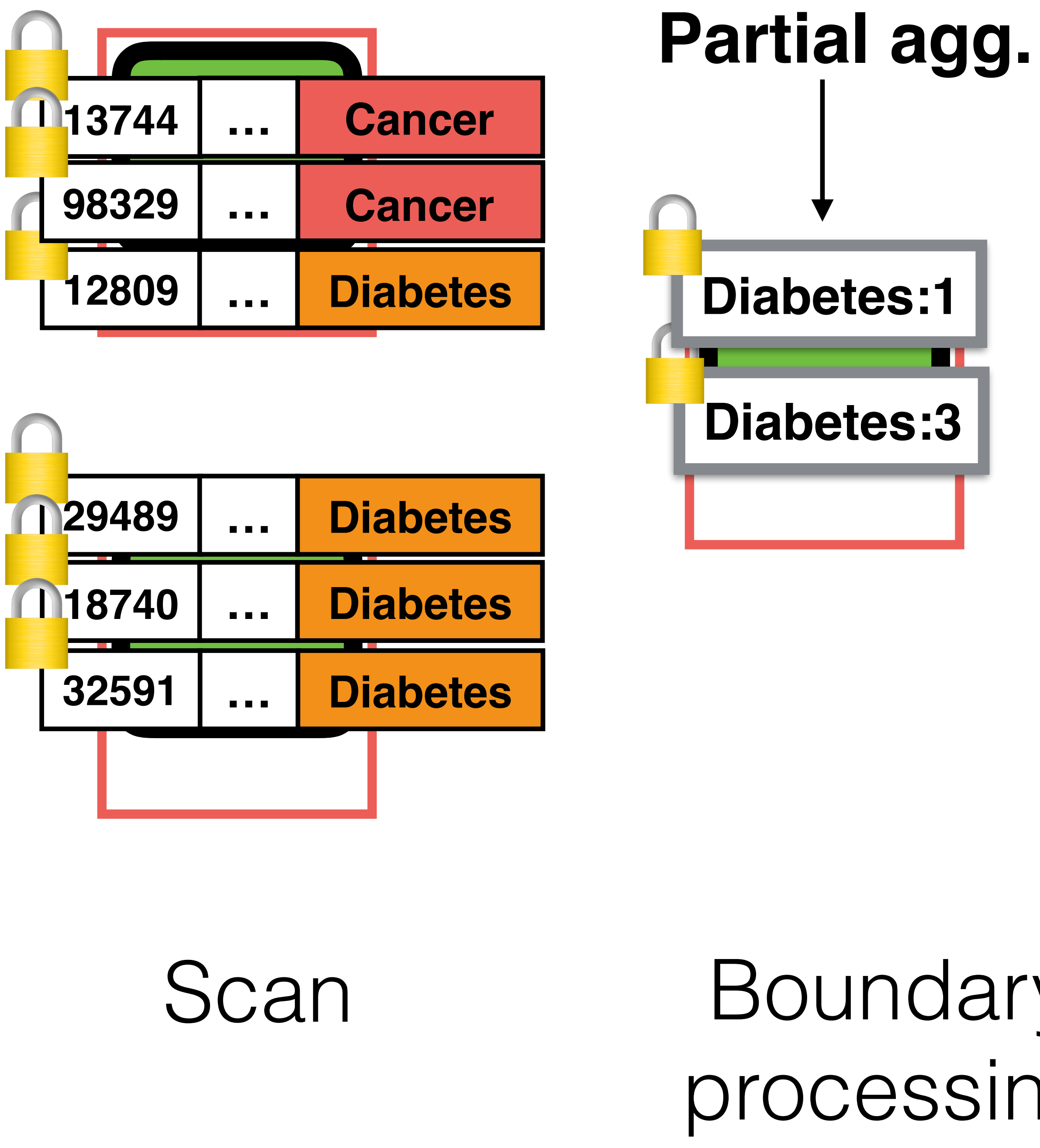
Diabetes:3

Scan

Boundary processing

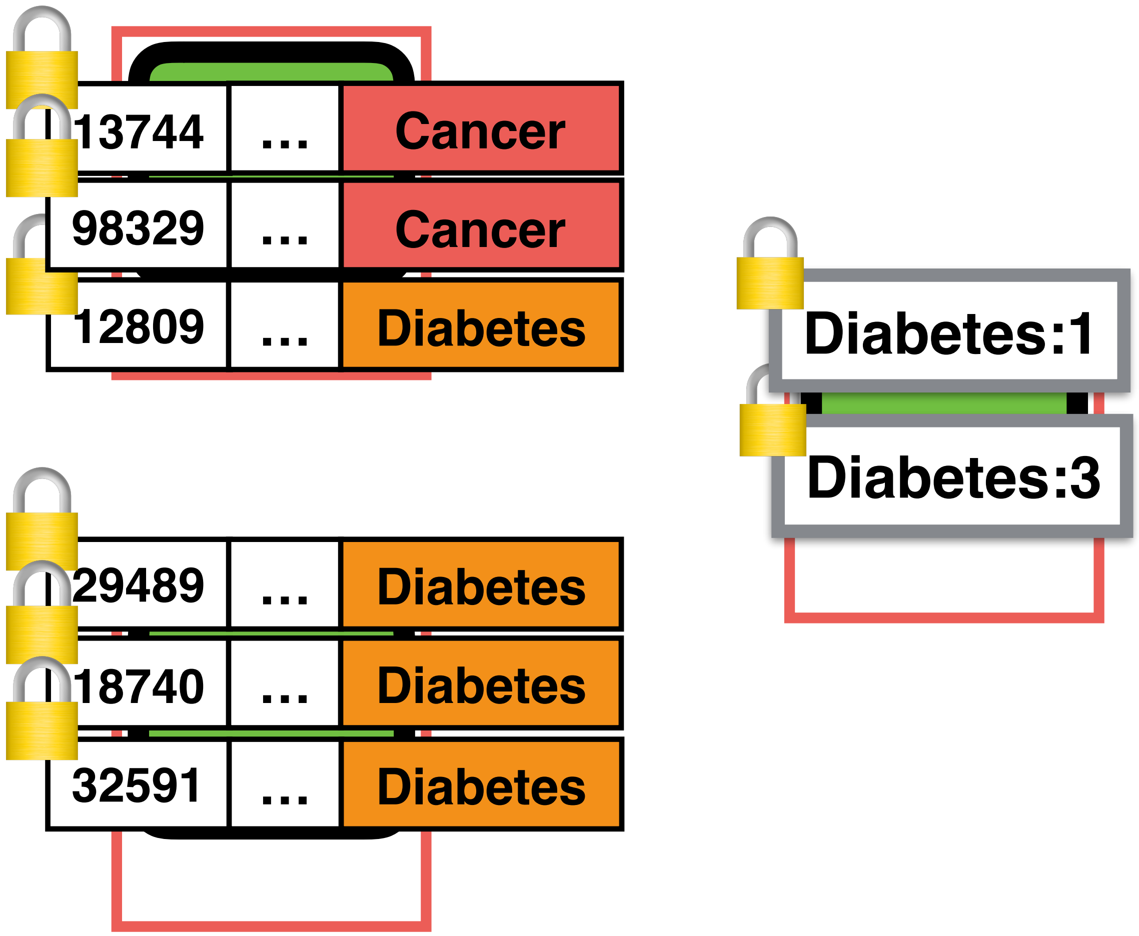
Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
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29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Diabetes:1

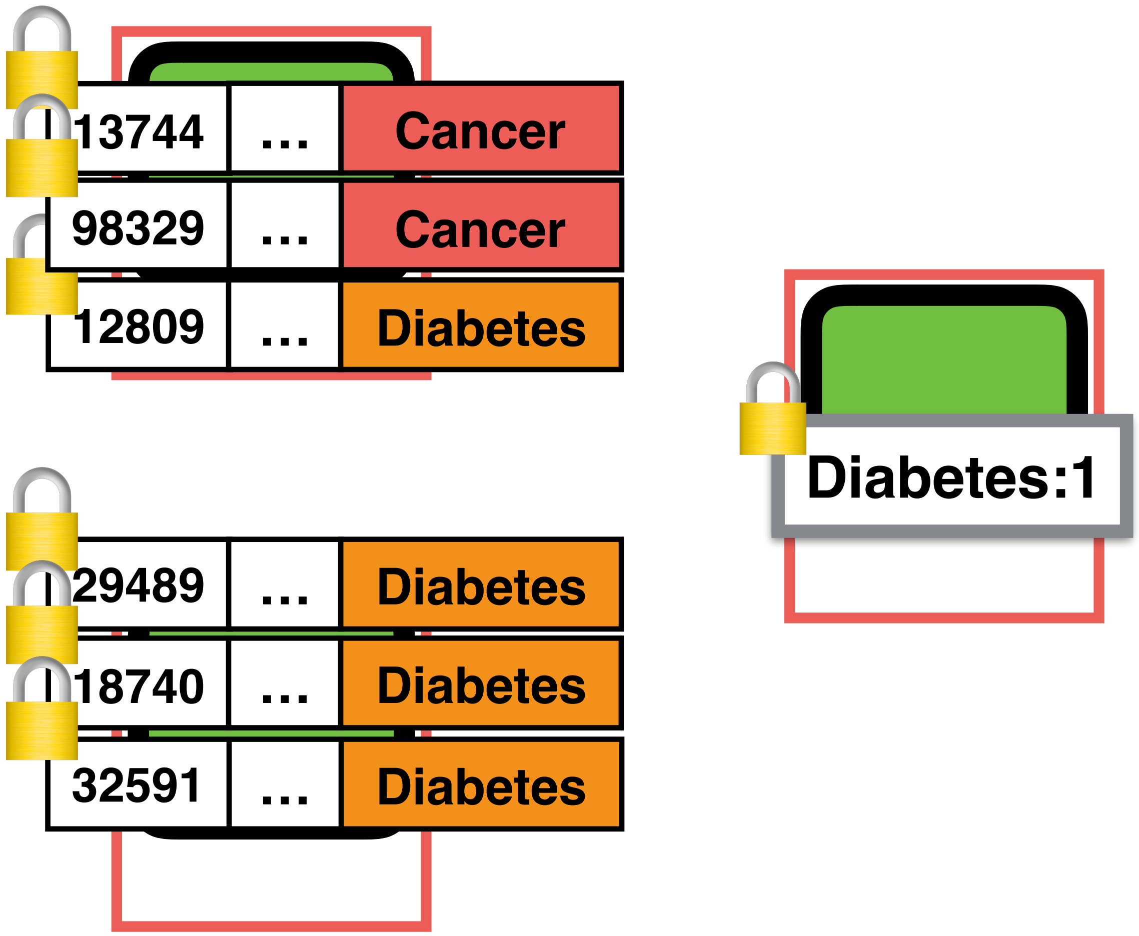
Diabetes:3

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	...	Cancer
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29489	...	Diabetes
18740	...	Diabetes
32591	...	Diabetes

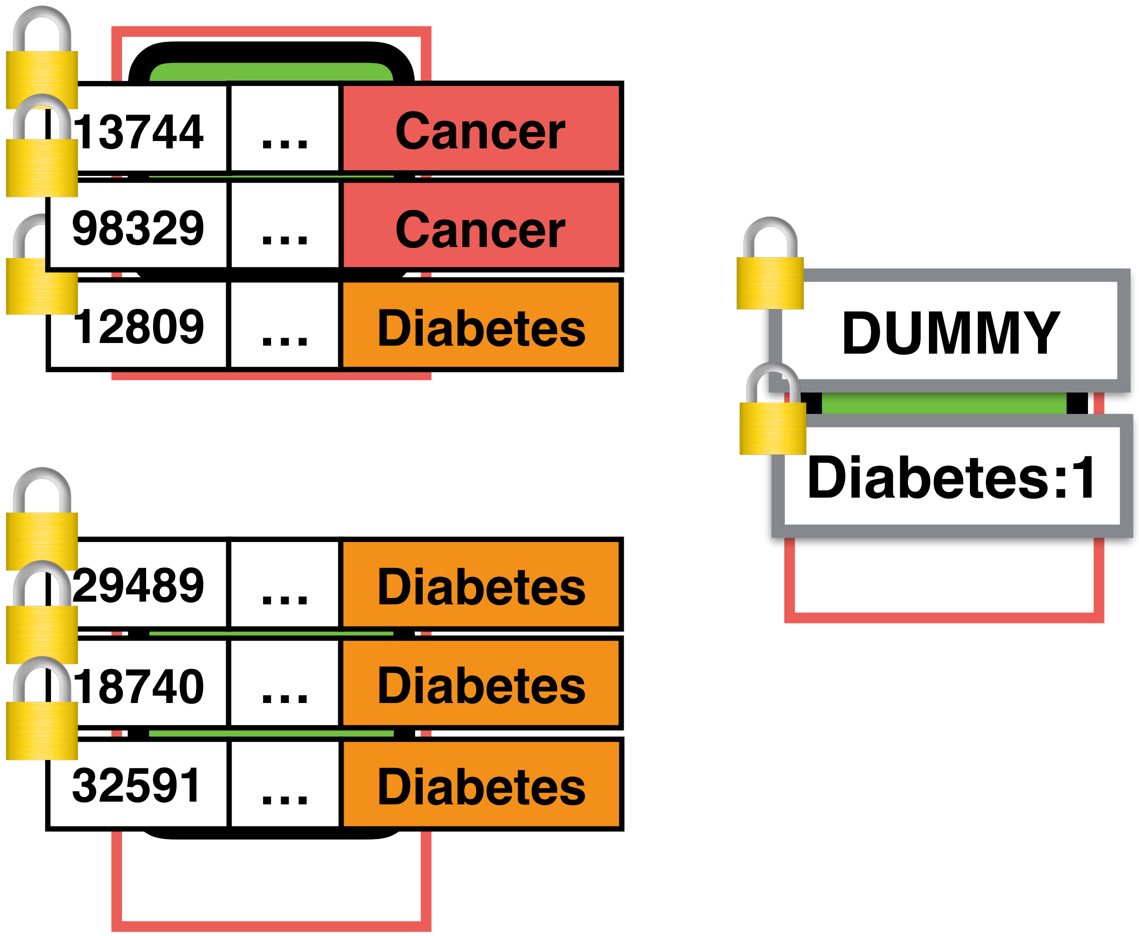
Diabetes:1

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

DUMMY

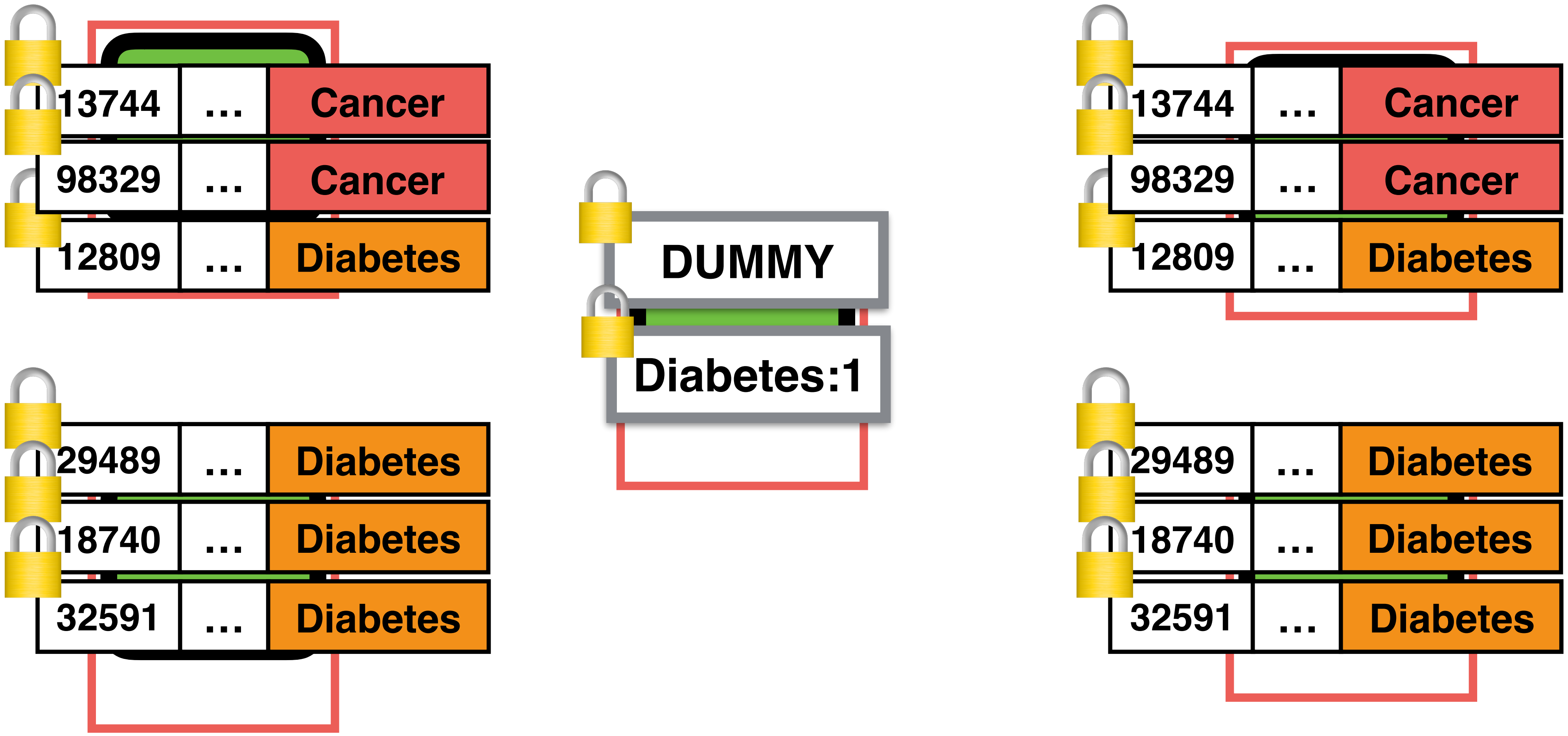
Diabetes:1

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

DUMMY
Diabetes:1

13744	…	Cancer
98329	…	Cancer
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29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Scan

Boundary processing

Oblivious aggregation

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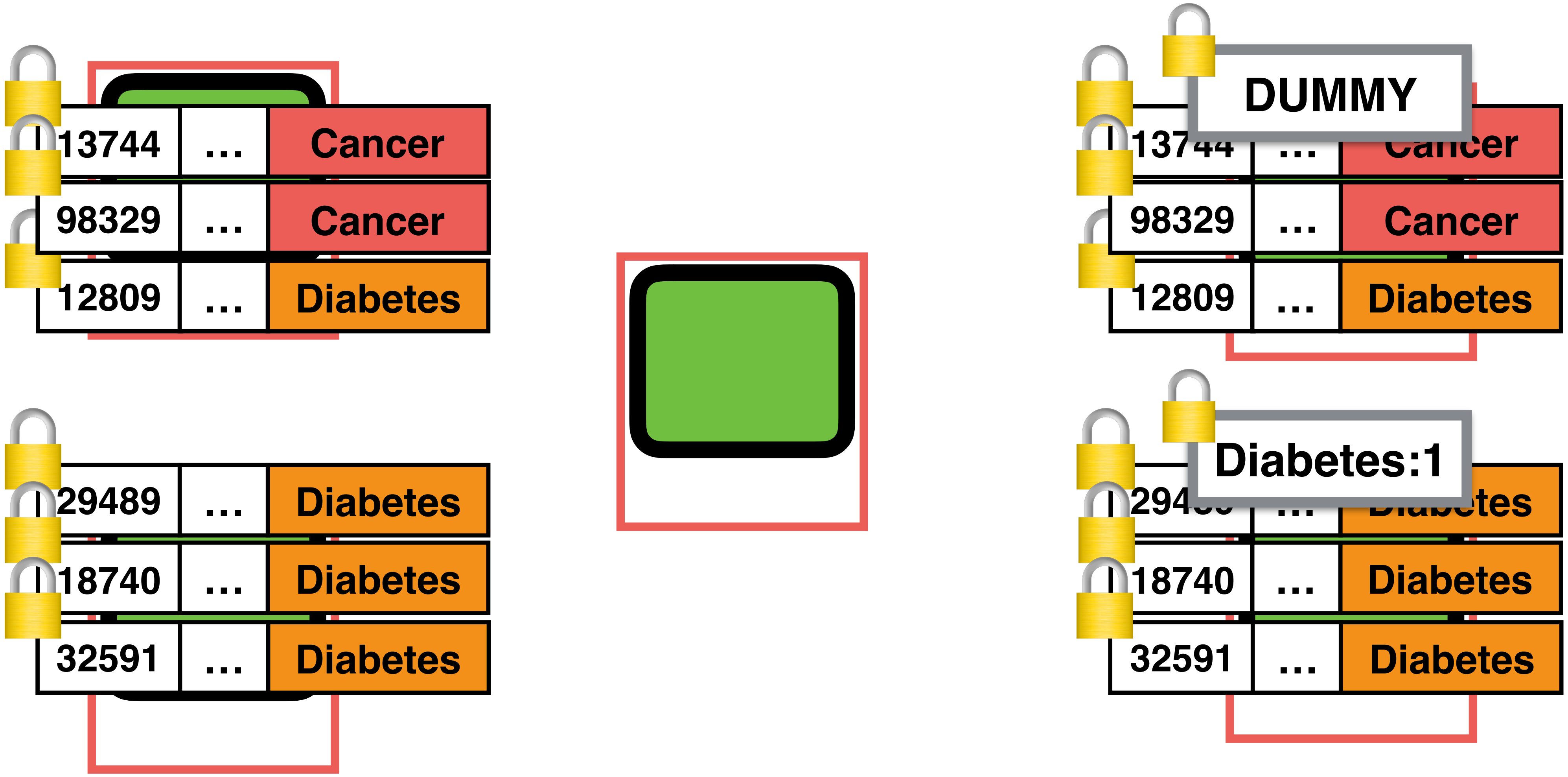

13744	…	Cancer
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12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

DUMMY

13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

Diabetes:1

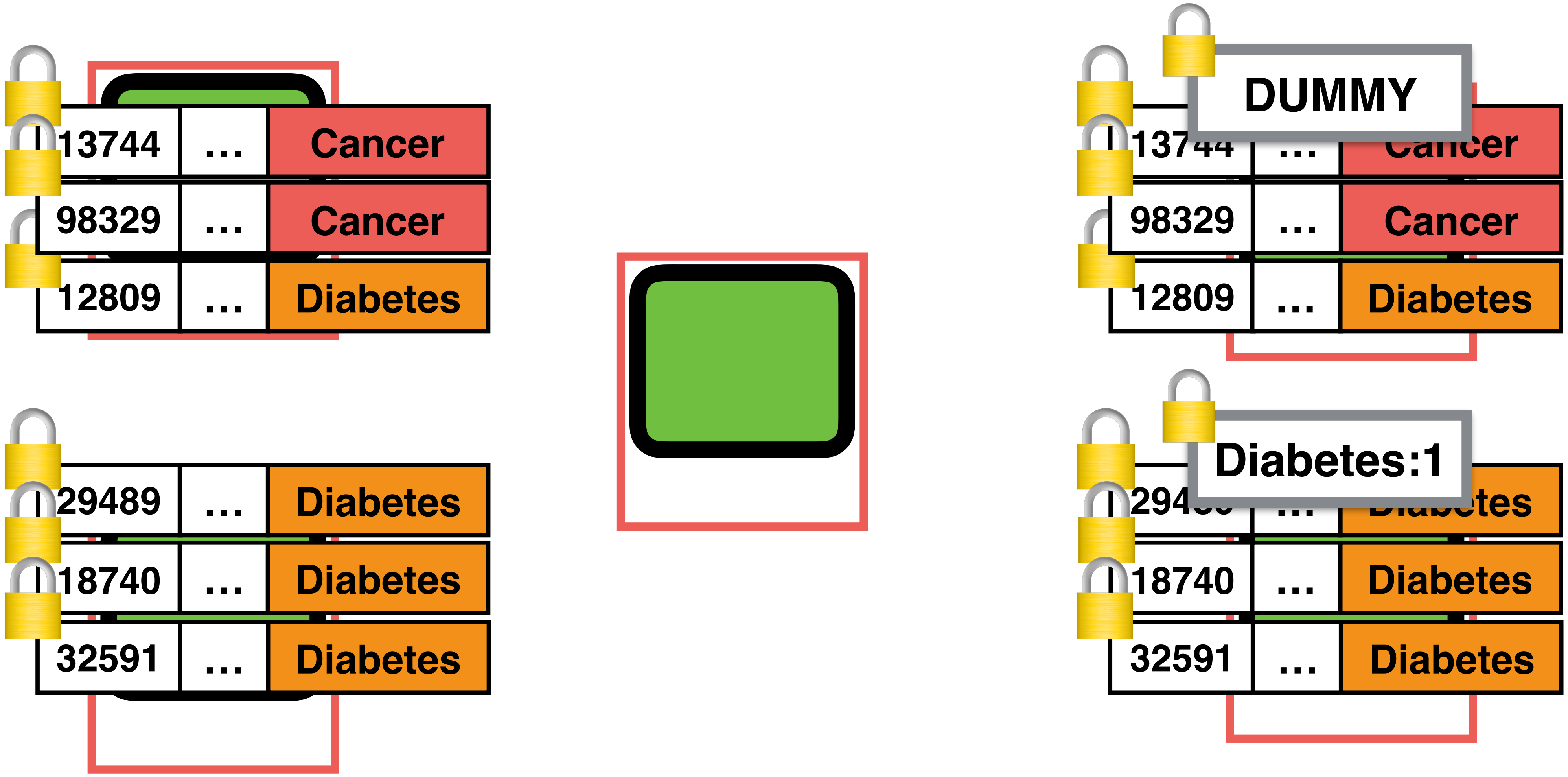
294	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

294	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

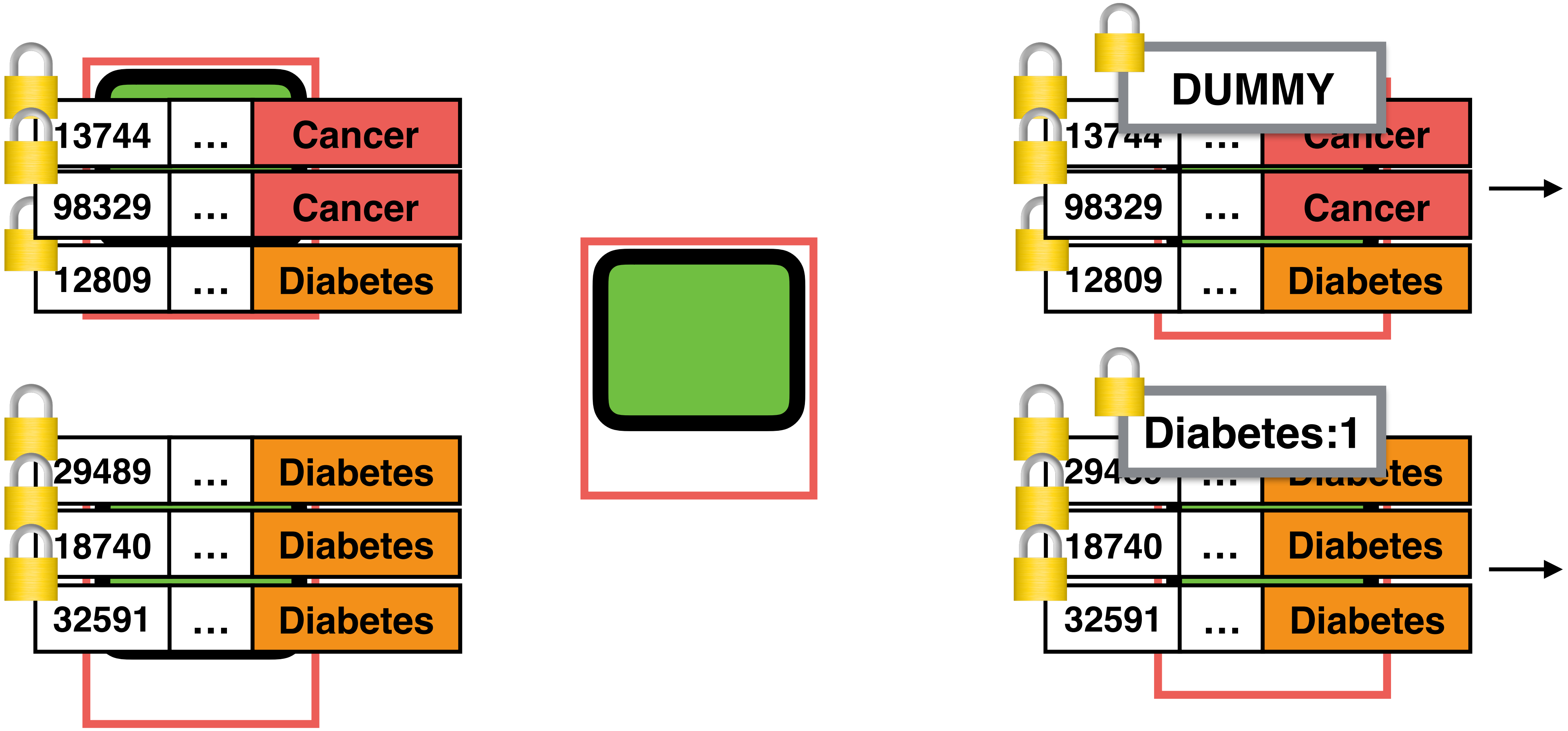
Scan

Boundary processing

Scan

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



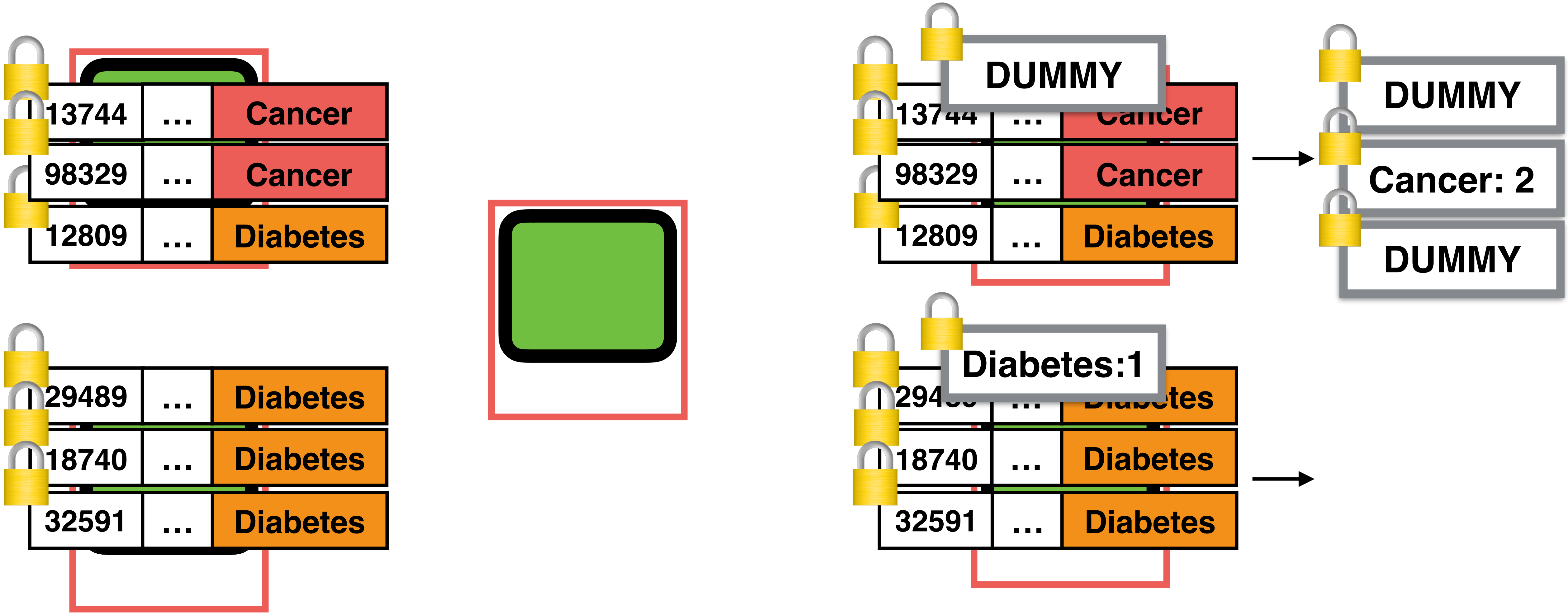
Scan

Boundary processing

Scan

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744 … Cancer
98329 … Cancer
12809 … Diabetes

29489 … Diabetes
18740 … Diabetes
32591 … Diabetes

DUMMY
13744 … Cancer
98329 … Cancer
12809 … Diabetes

Diabetes:1
294… … Diabetes
18740 … Diabetes
32591 … Diabetes

DUMMY
Cancer: 2
DUMMY

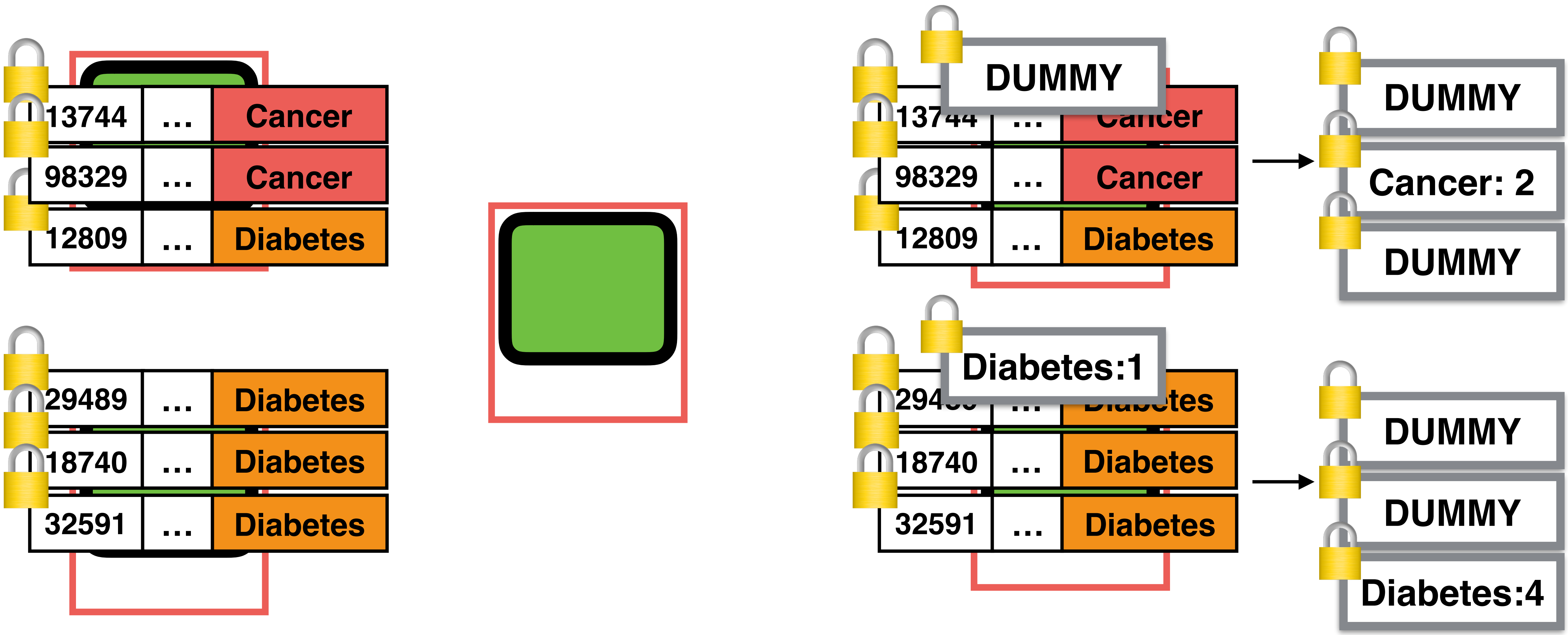
Scan

Boundary processing

Scan

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



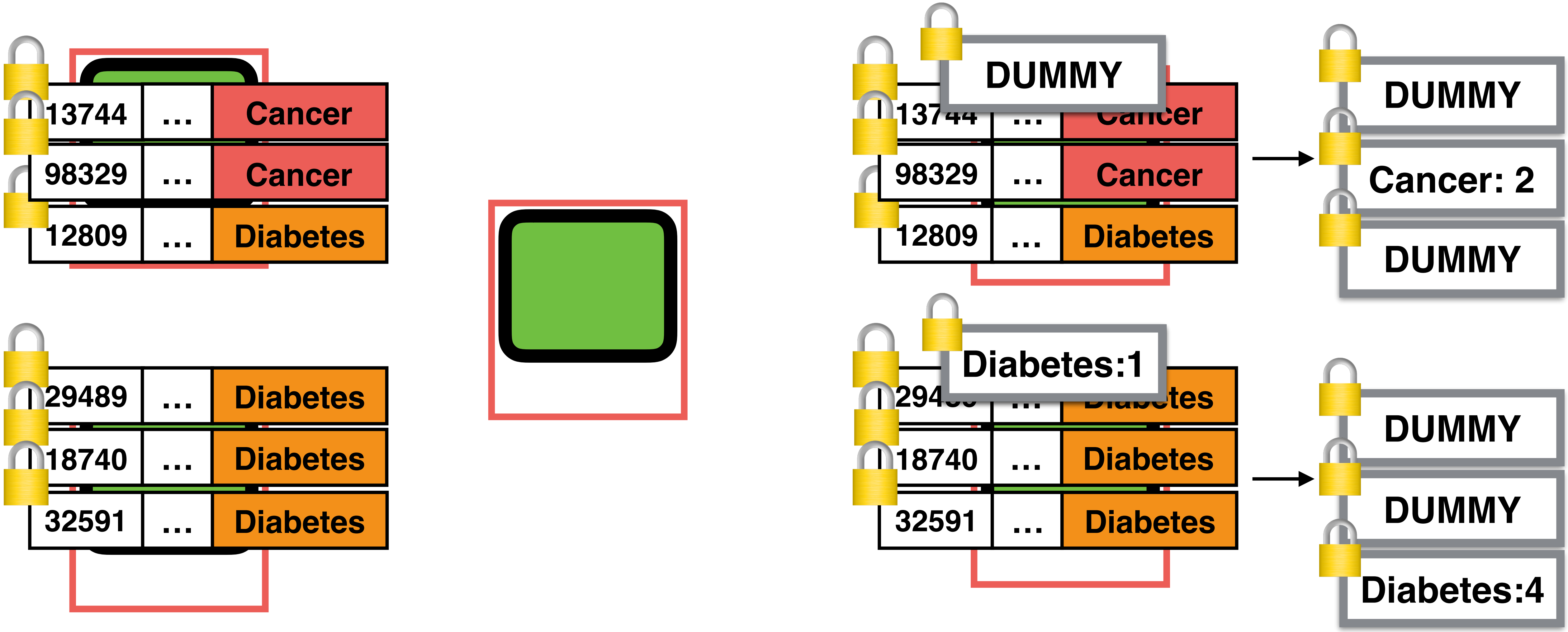
Scan

Boundary processing

Scan

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

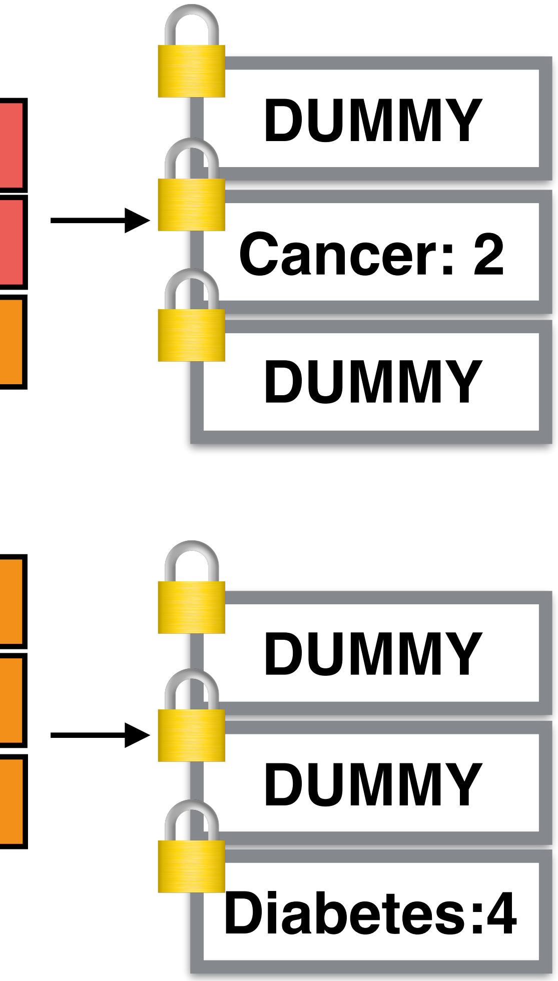
Scan

Boundary processing

Scan

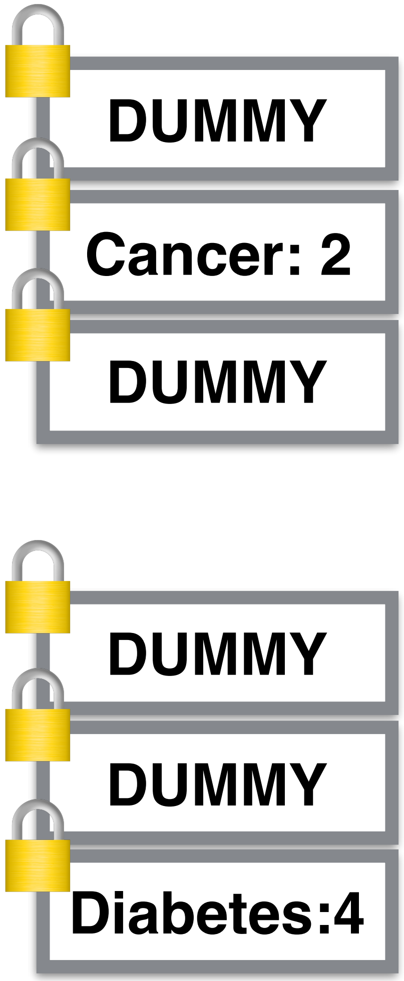
Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



DUMMY

Cancer: 2

DUMMY

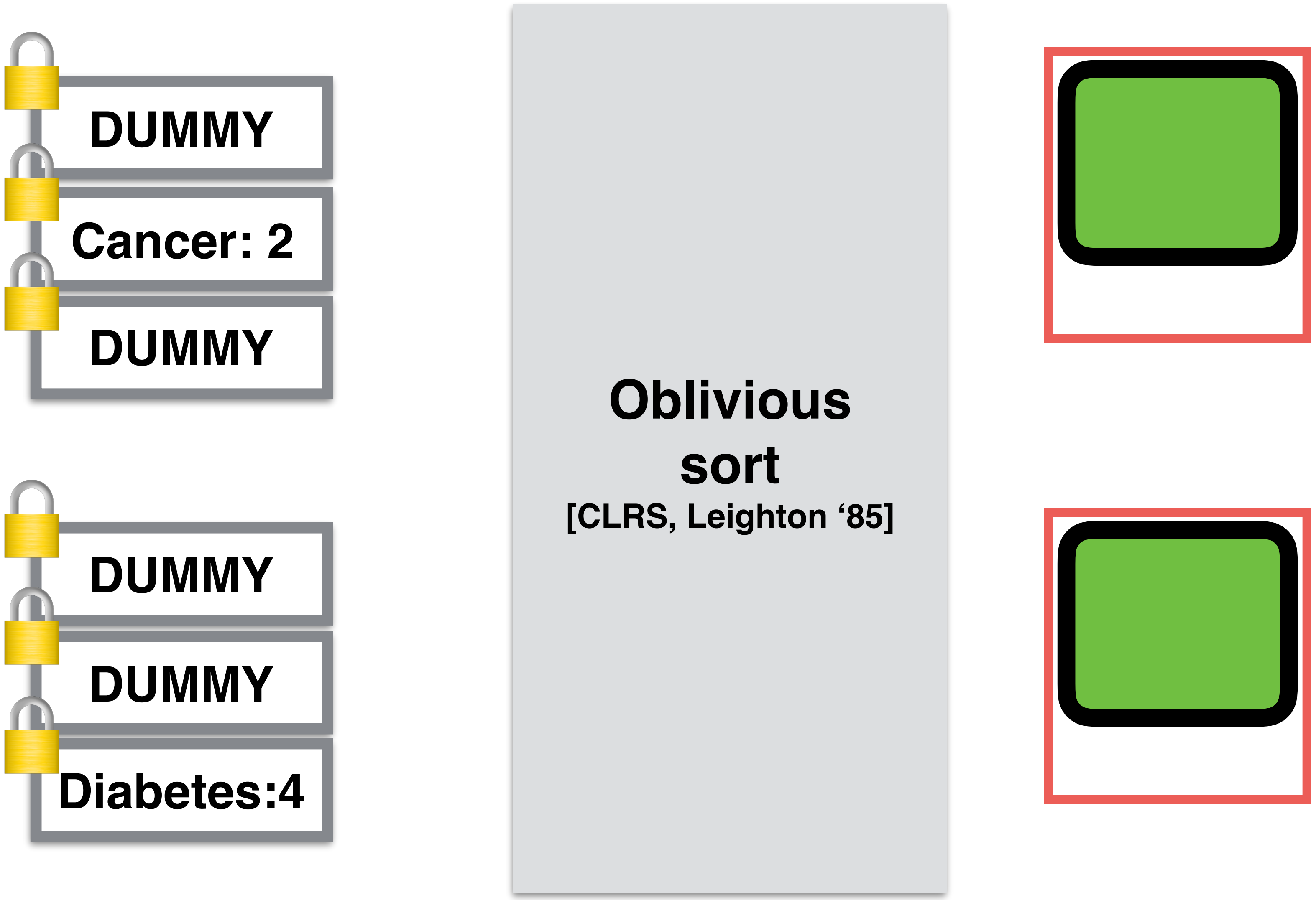
DUMMY

DUMMY

Diabetes:4

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



DUMMY

Cancer: 2

DUMMY

DUMMY

DUMMY

Diabetes:4

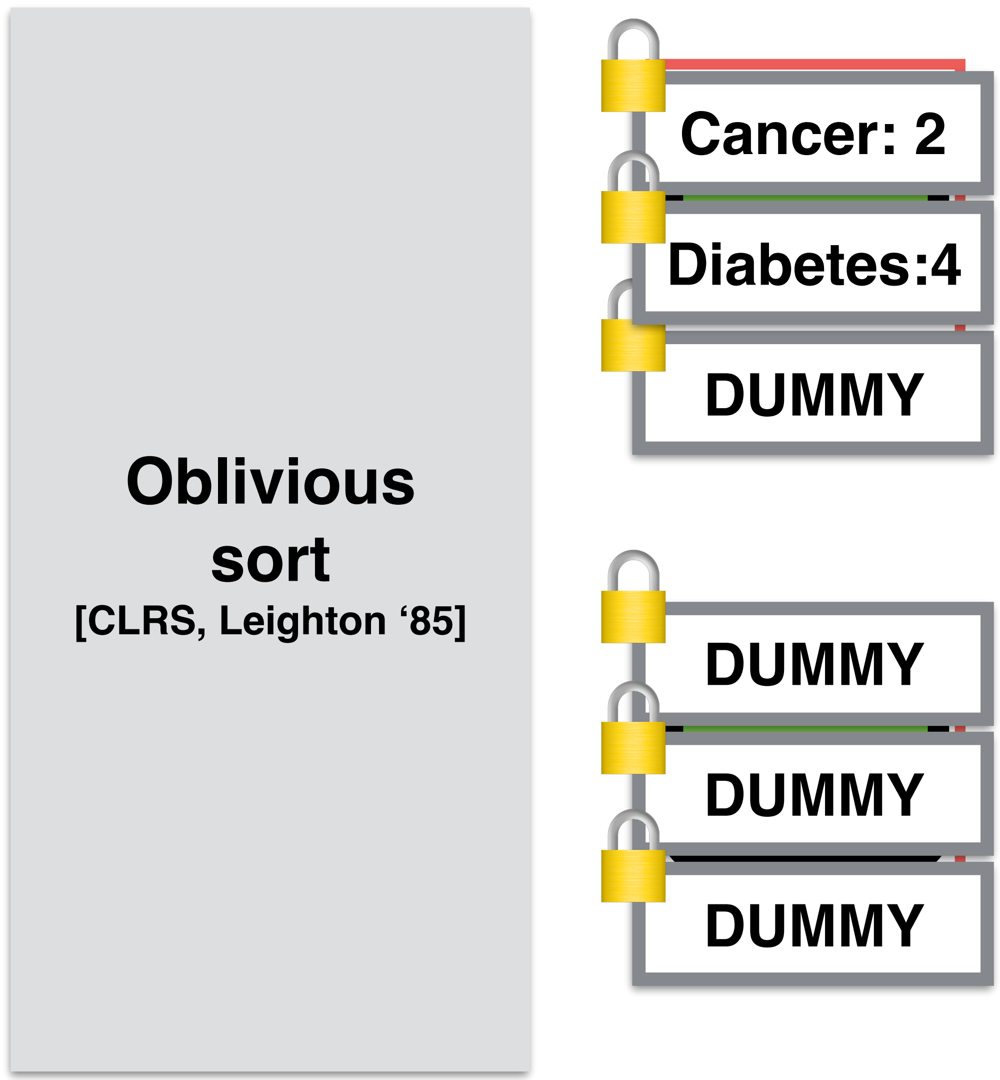
Oblivious sort

[CLRS, Leighton ‘85]

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious sort

[CLRS, Leighton '85]

Cancer: 2

Diabetes:4

DUMMY

DUMMY

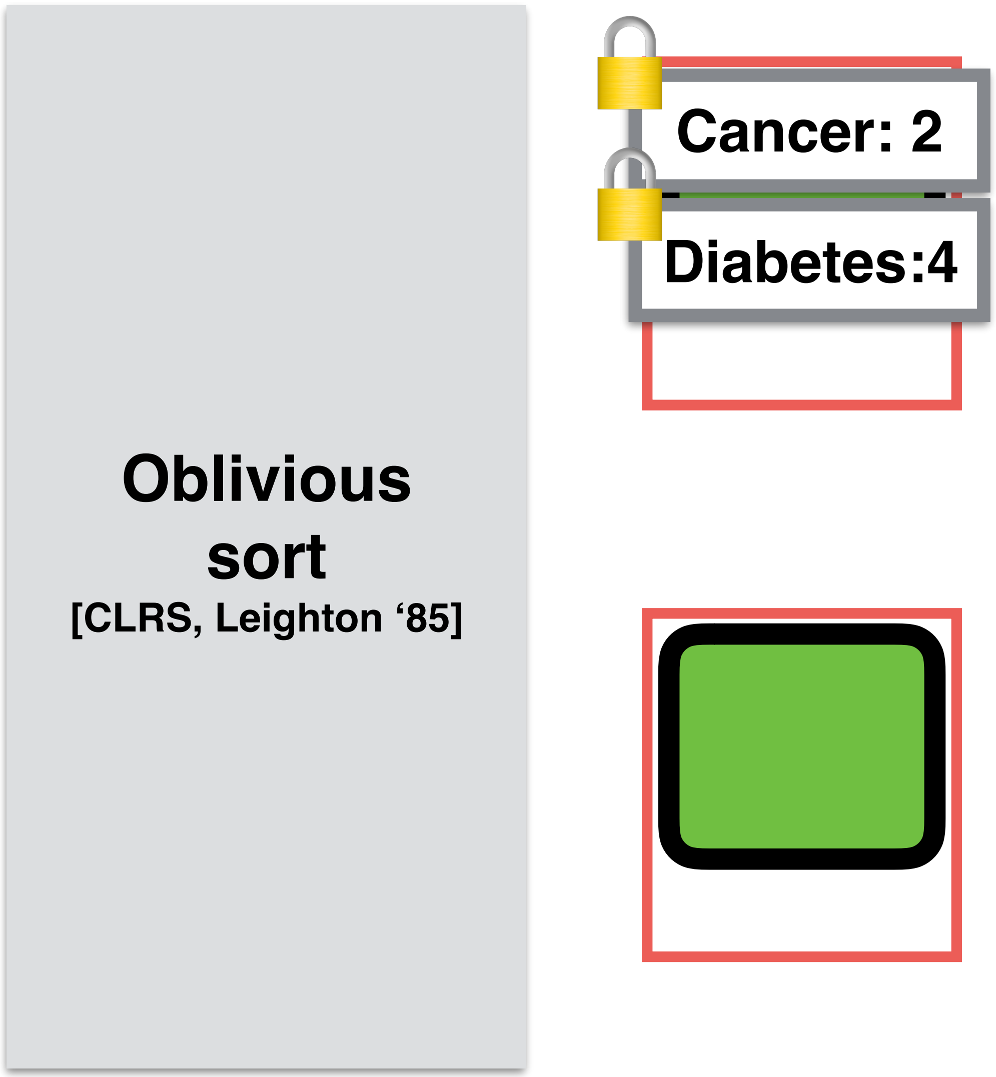
DUMMY

DUMMY

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious sort

[CLRS, Leighton ‘85]

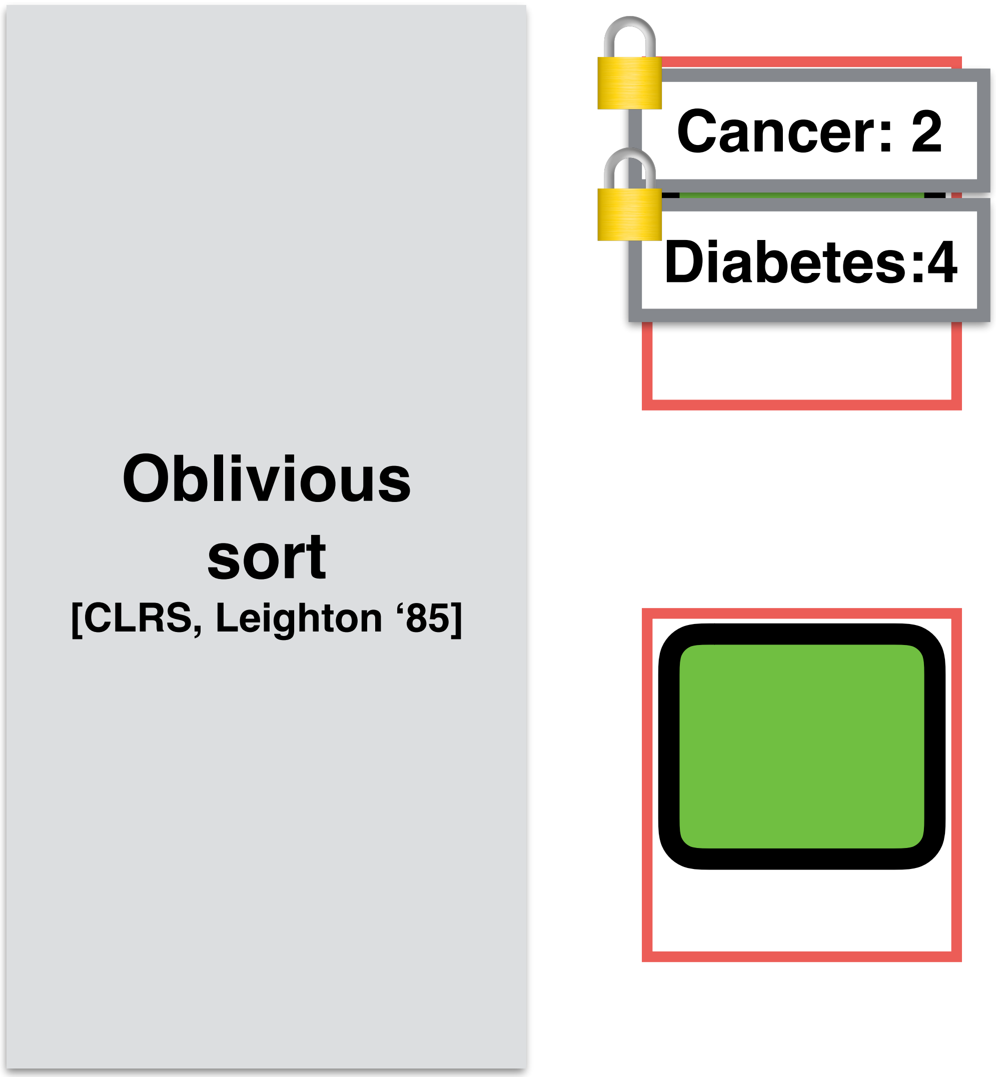
Cancer: 2

Diabetes:4

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

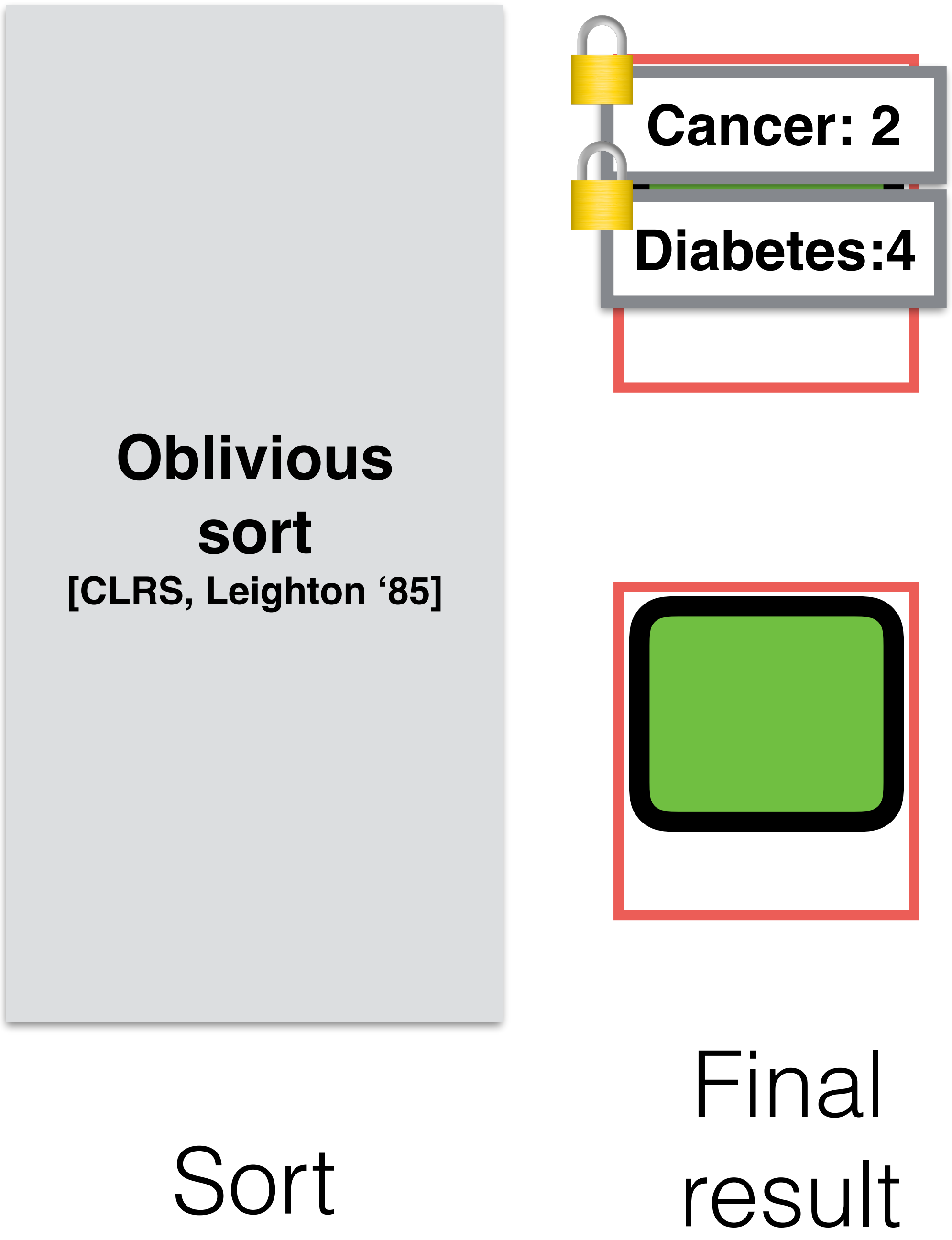


Sort

Final result

Oblivious aggregation

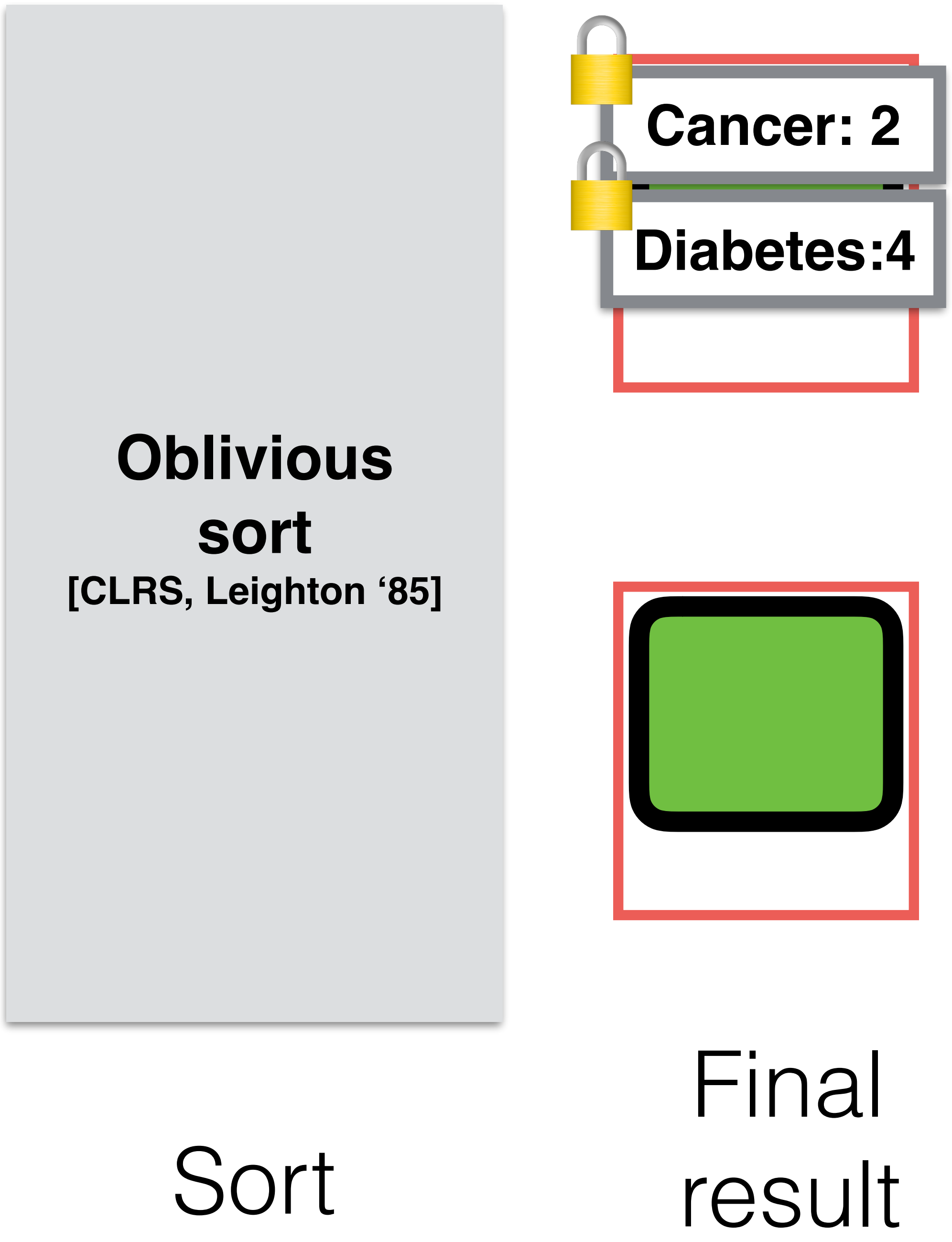
SELECT count(*) FROM medical GROUP BY disease



Aggregation has <u>two </u>sorts…

Oblivious aggregation

```
SELECT count(*) FROM medical GROUP BY disease
```



Oblivious sort

[CLRS, Leighton '85]

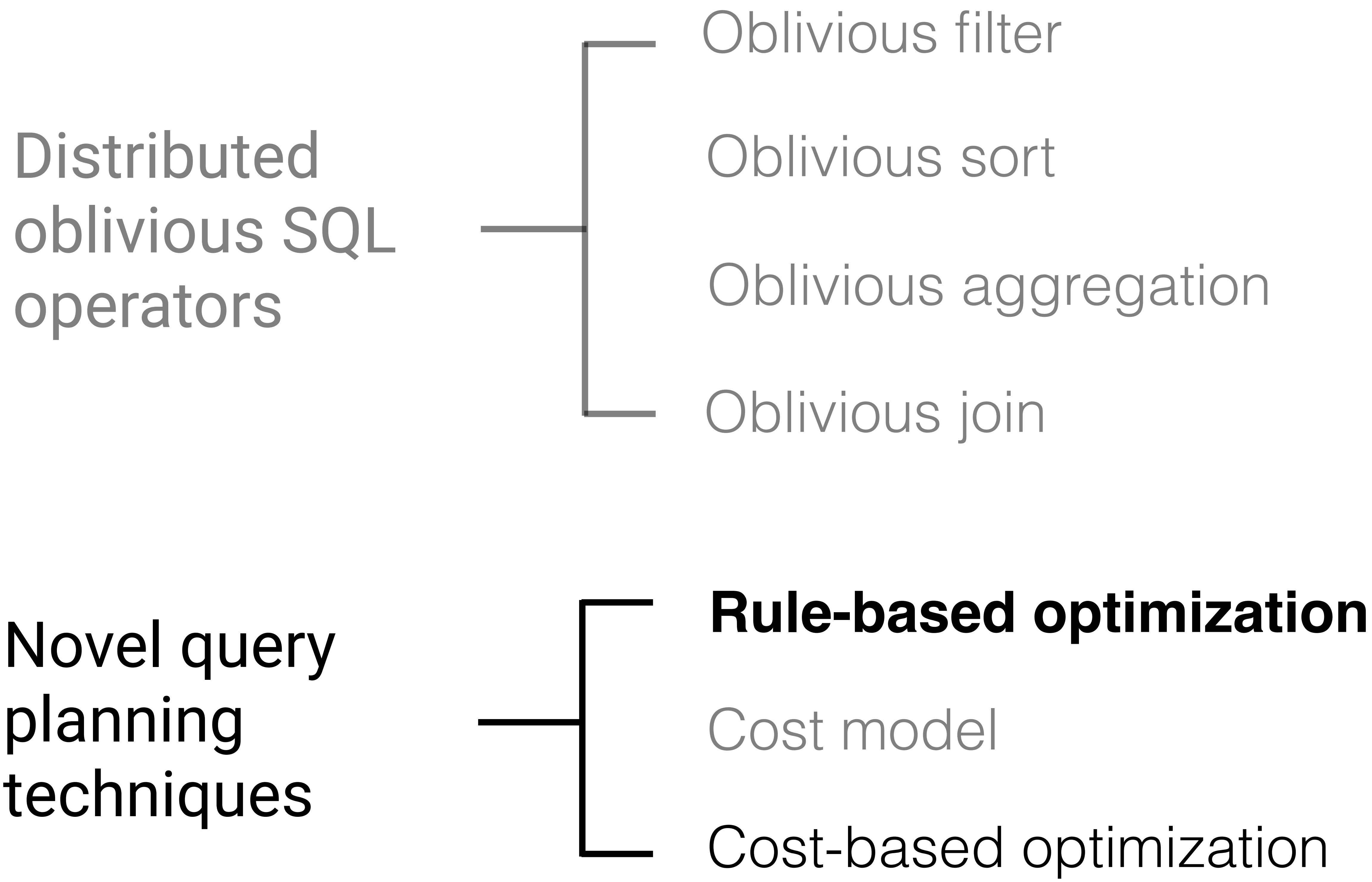
Aggregation has <u>two</u> sorts…

Can we do better?

Two-part solution:

- Distributed oblivious SQL operators
  - Oblivious filter
  - Oblivious sort
  - Oblivious aggregation
  - Oblivious join
- Novel query planning techniques
  - Rule-based optimization
  - Cost model
  - Cost-based optimization

Two-part solution:



Distributed oblivious SQL operators

- Oblivious filter
- Oblivious sort
- Oblivious aggregation
- Oblivious join

Novel query planning techniques

- **Rule-based optimization**
- Cost model
- Cost-based optimization

Rule-based optimization

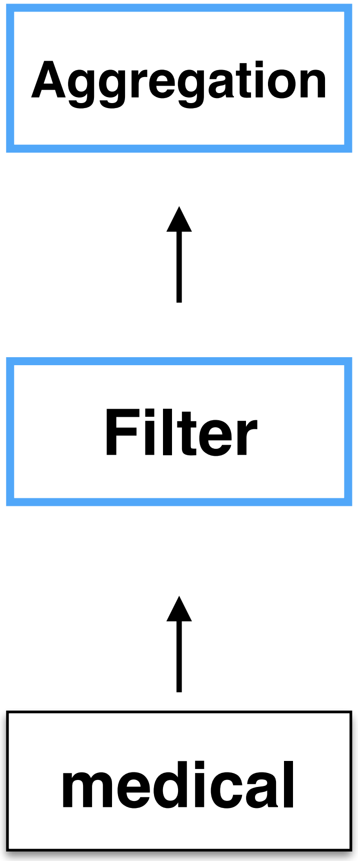
Rule-based optimization

```
SELECT count(*)
FROM medical
WHERE age > 30
GROUP BY disease
```

Rule-based optimization

```
SELECT count(*)
FROM medical
WHERE age > 30
GROUP BY disease
```

Logical op.



Insight 1

Insight 1

1. Split each logical operator into smaller Opaque operators

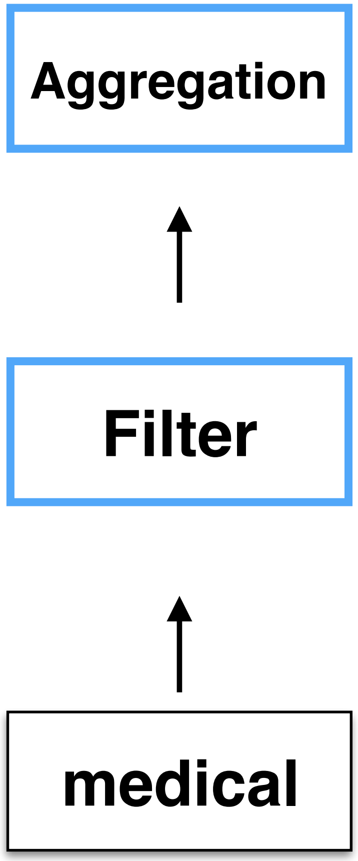
Insight 1

1. Split each logical operator into smaller Opaque operators

2. Take a global view across the plan to remove some Opaque operators

Rule-based optimization

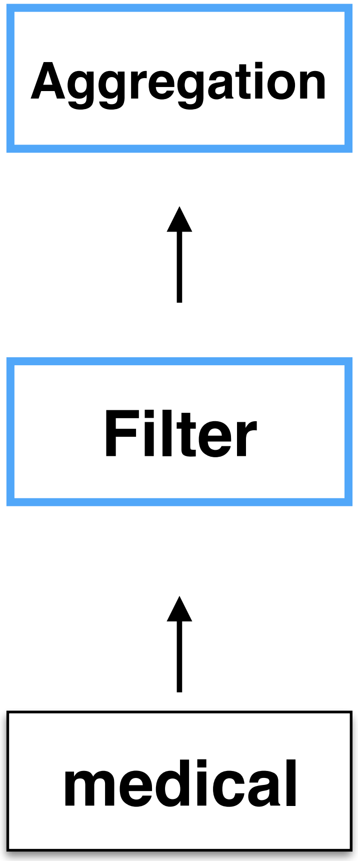
Logical op.



Rule-based optimization

Opaque op.

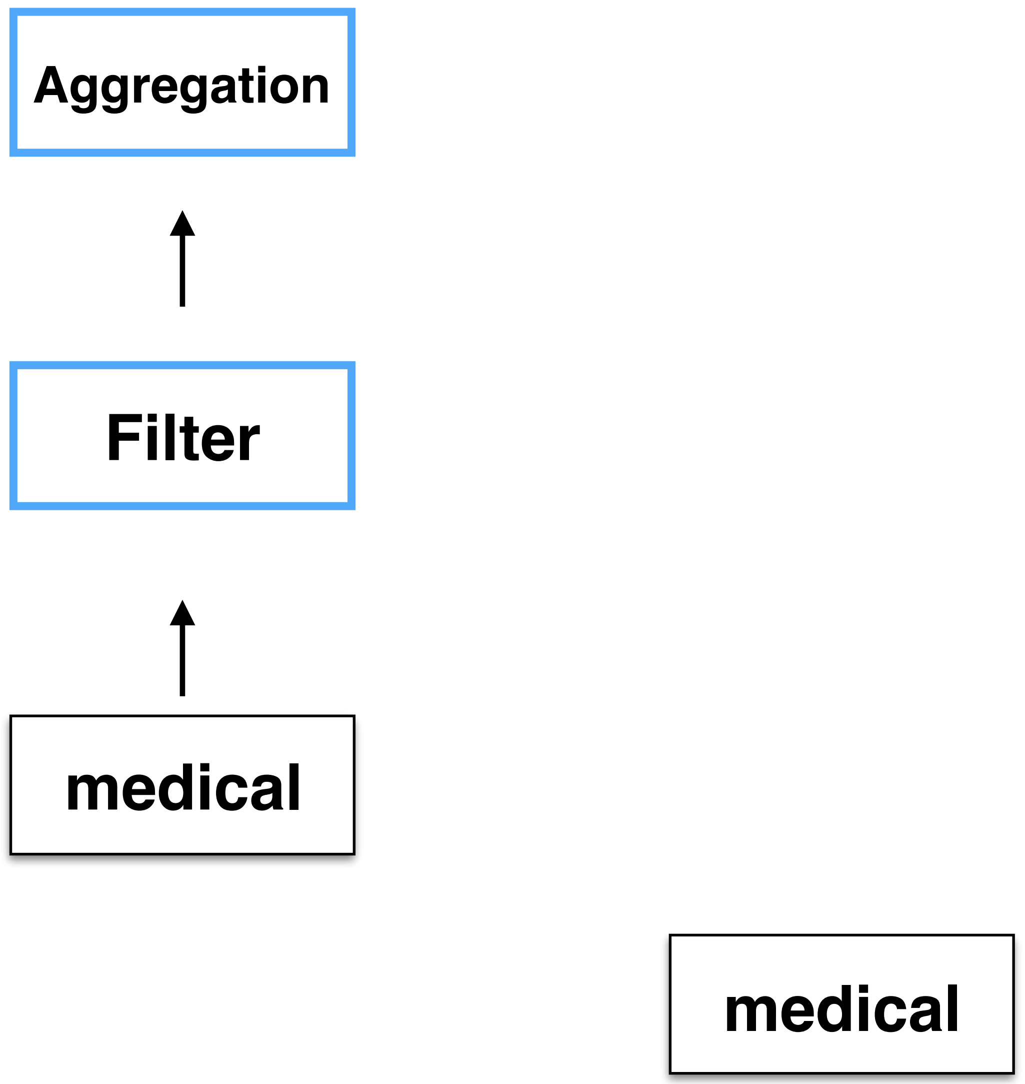
Logical op.



Rule-based optimization

Opaque op.

Logical op.



Aggregation

Filter

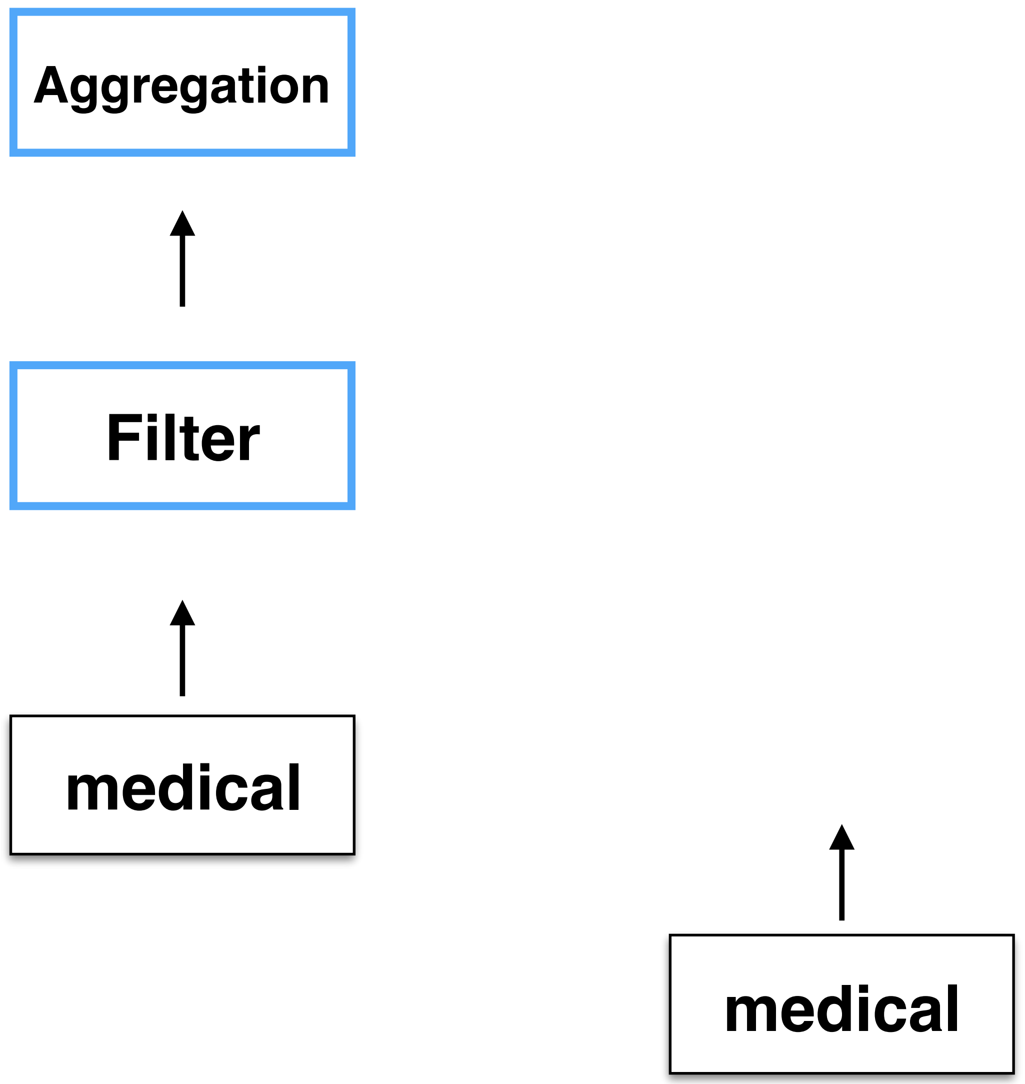
medical

medical

Rule-based optimization

Opaque op.

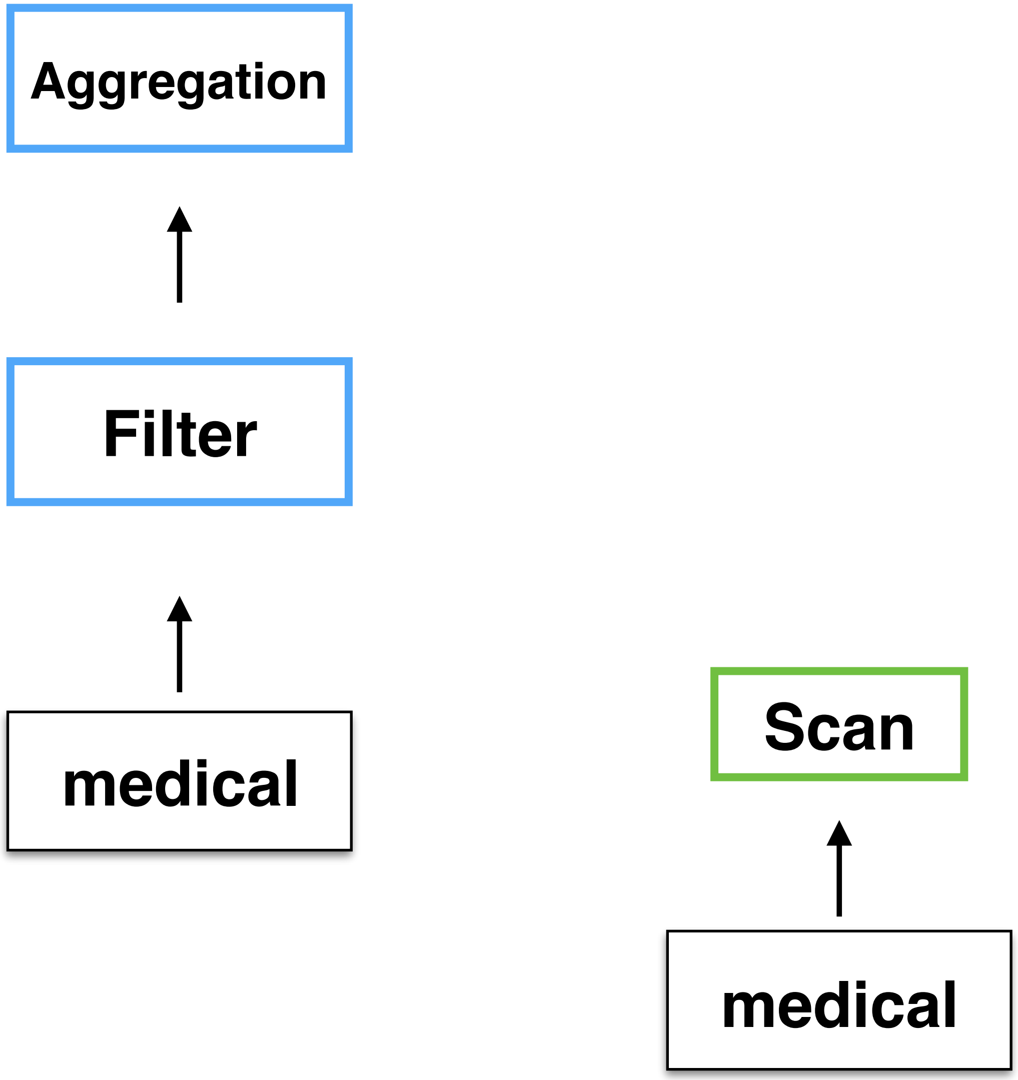
Logical op.



Rule-based optimization

Opaque op.

Logical op.



Aggregation

Filter

medical

Scan

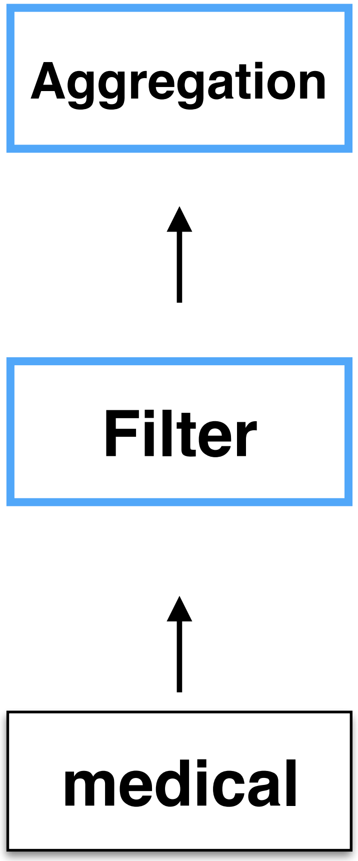
medical

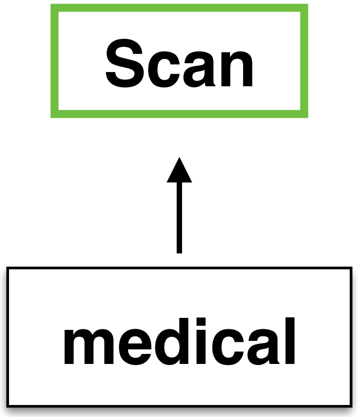
Rule-based optimization

Opaque op.

Logical op.

12809	Amanda D. Edwards	40	Diabetes
29489	Robert R. McGowan	56	Diabetes
13744	Kimberly R. Seay	51	Cancer
18740	Dennis G. Bates	32	Diabetes
32591	Donna R. Bridges	26	Diabetes
98329	Ronald S. Ogden	53	Cancer

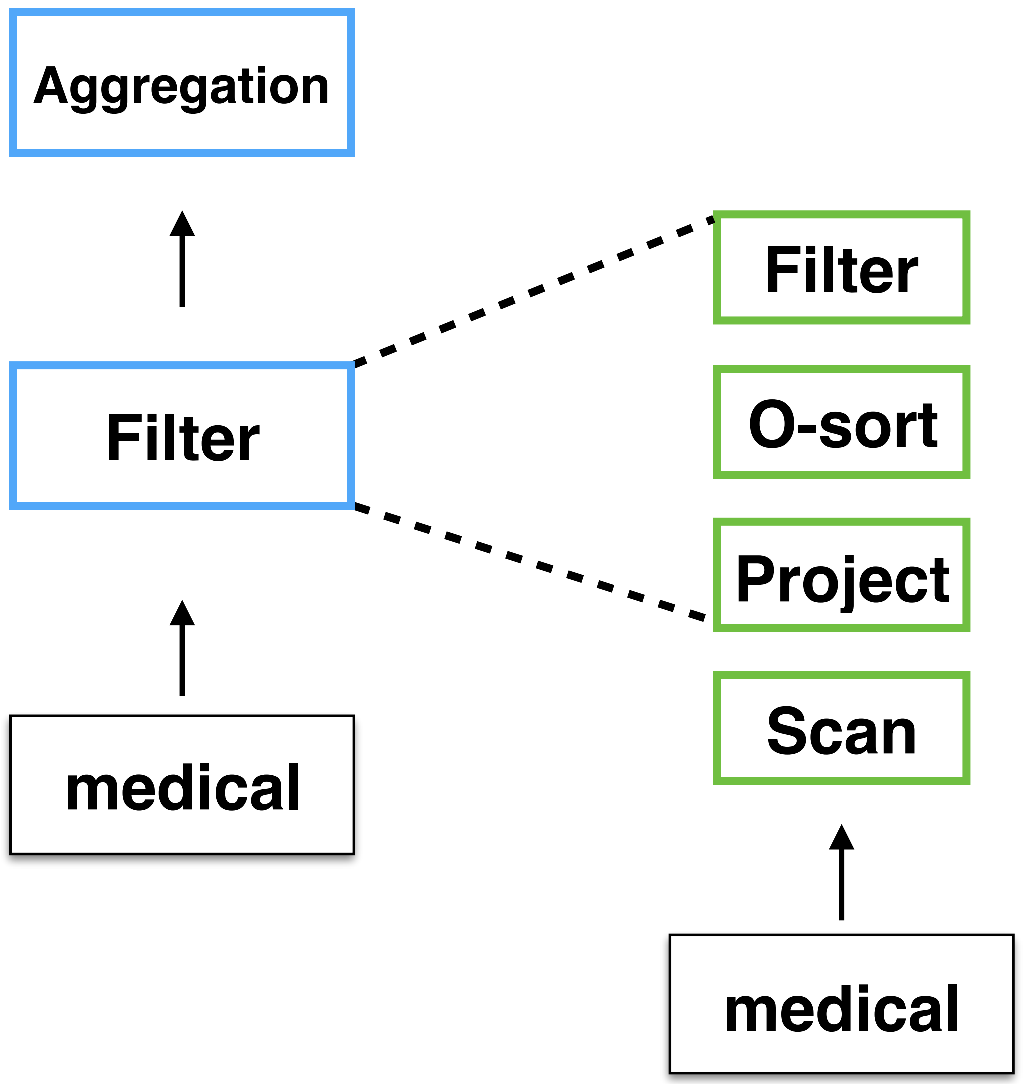




Rule-based optimization

Opaque op.

Logical op.



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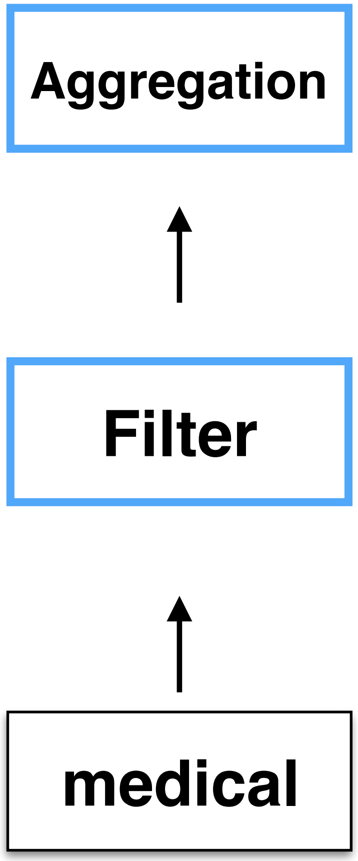
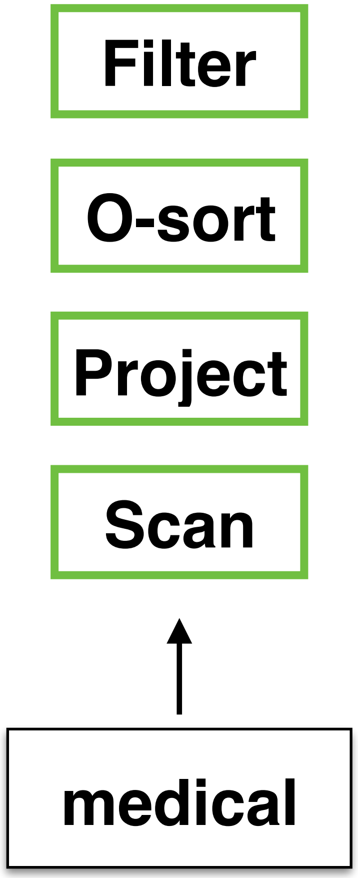
Rule-based optimization

Opaque op.

Logical op.





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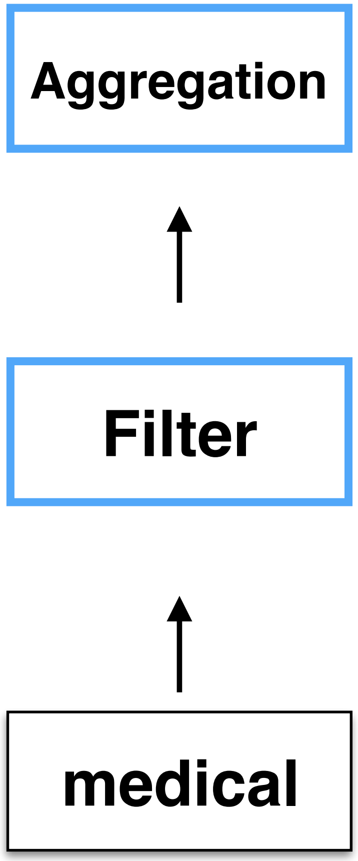
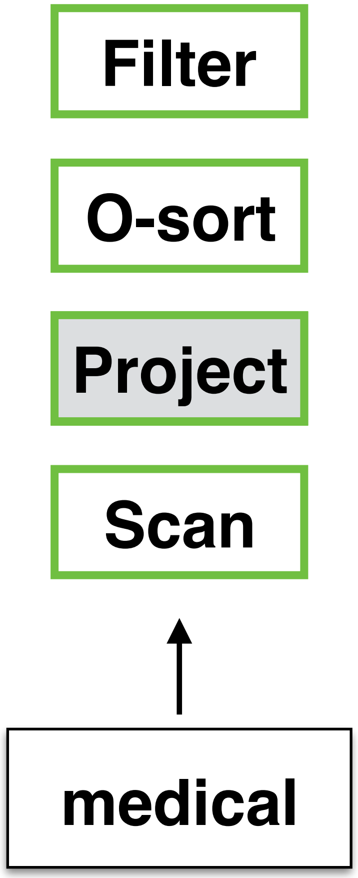
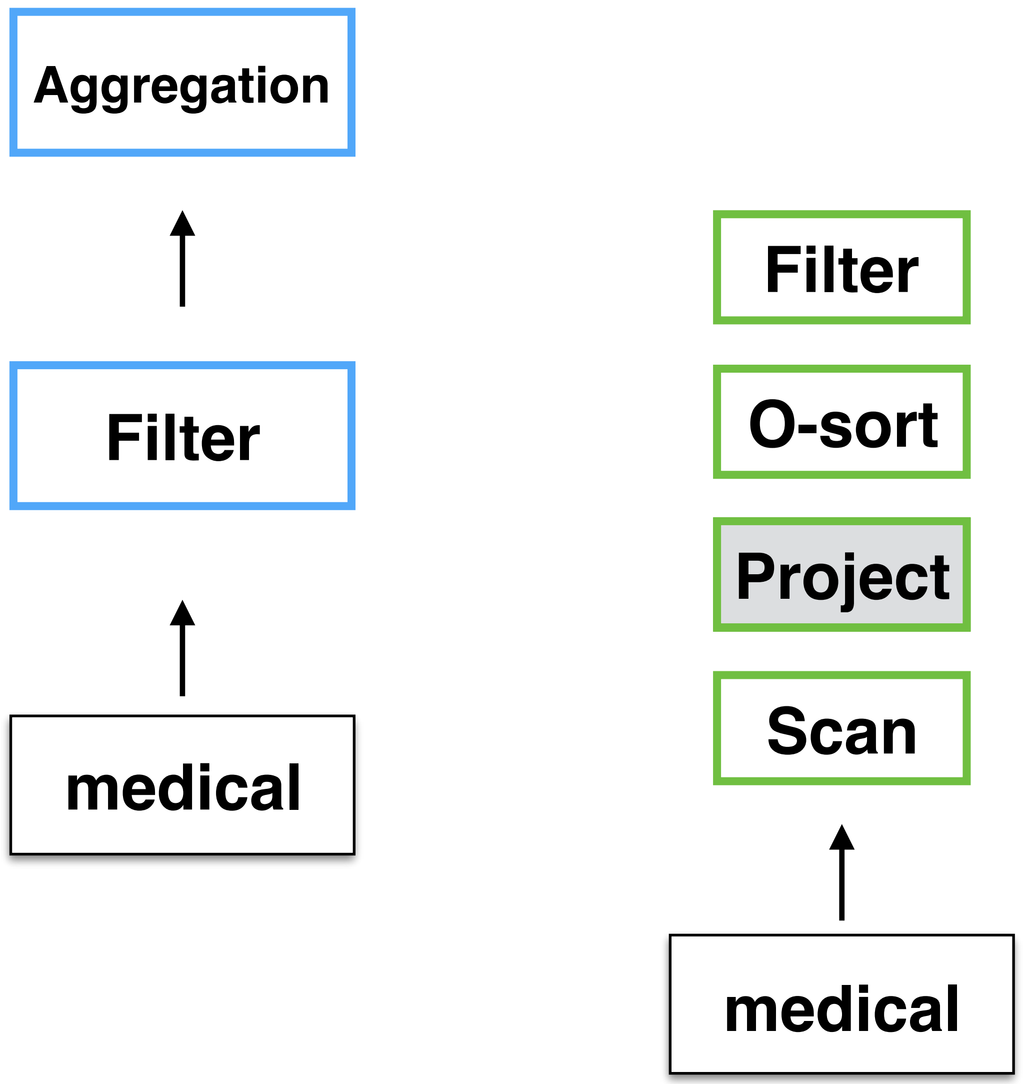




Rule-based optimization

Opaque op.

Logical op.



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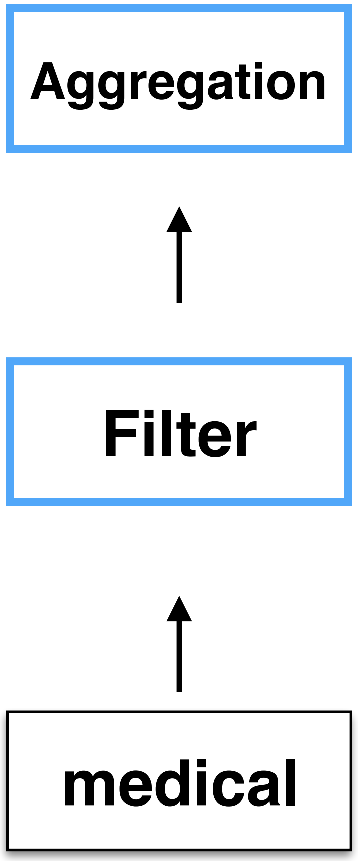

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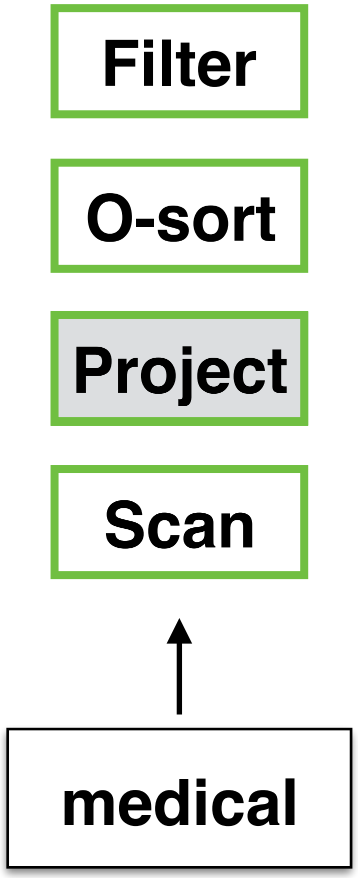

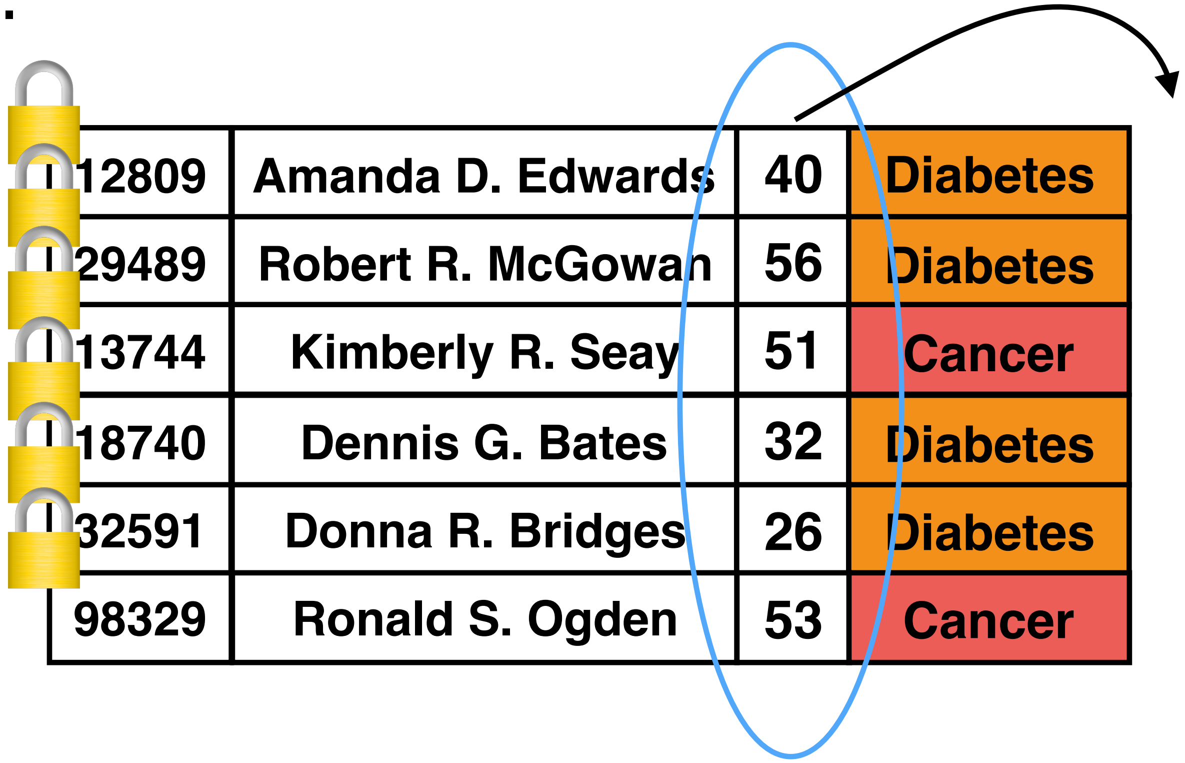

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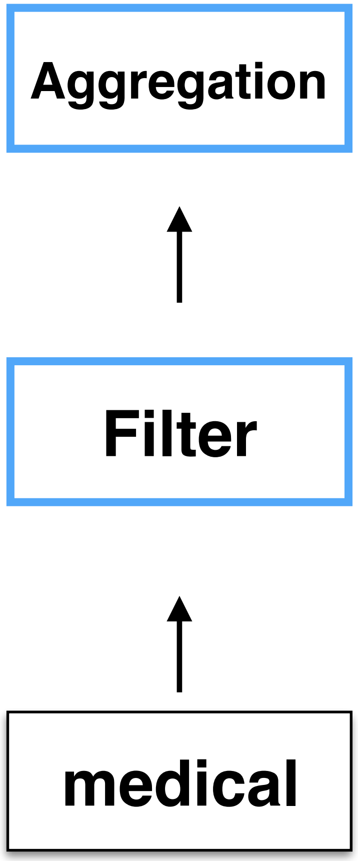
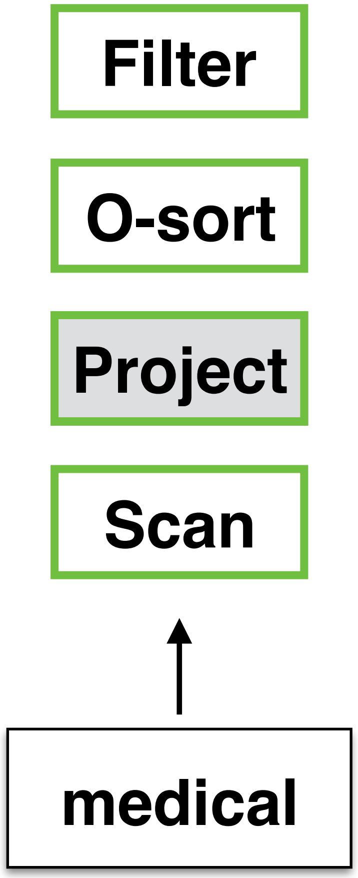
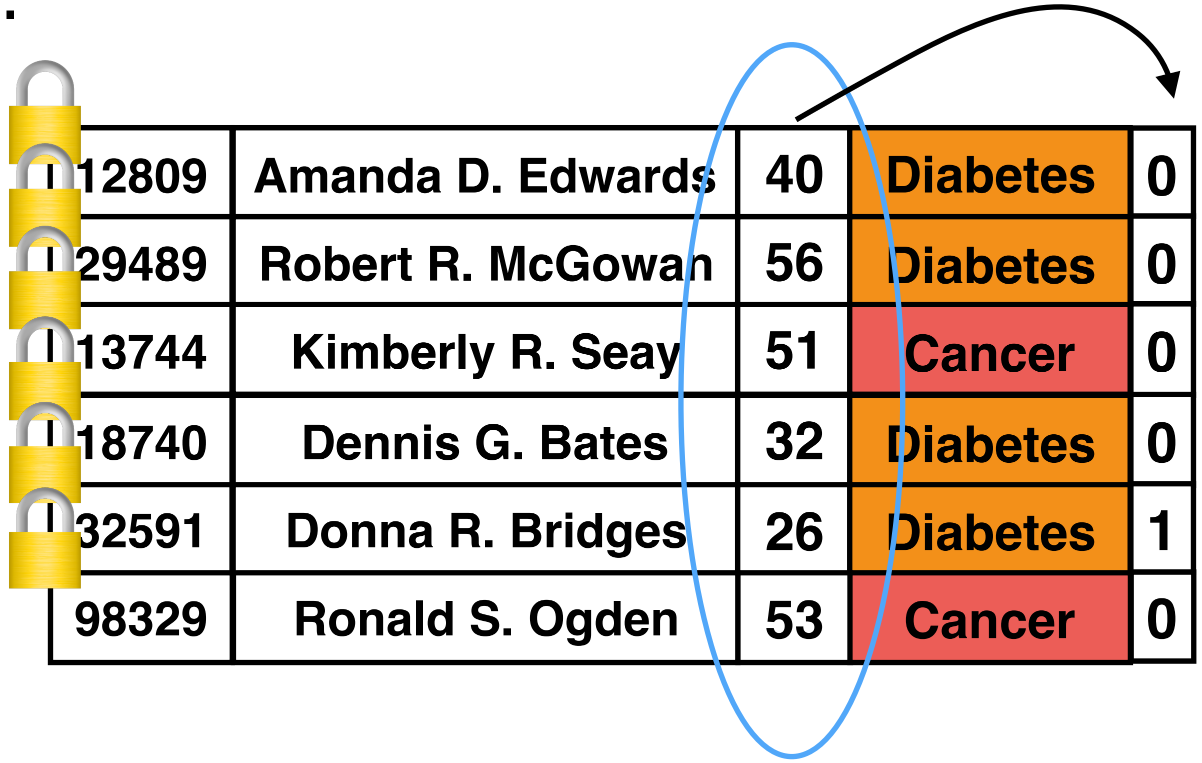
Rule-based optimization

Opaque op.

Logical op.







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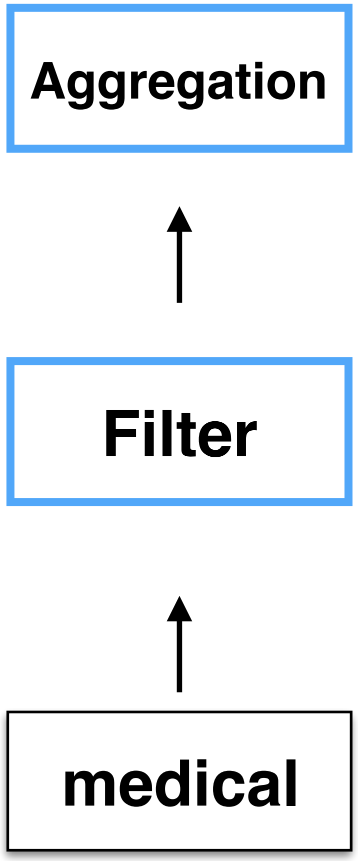
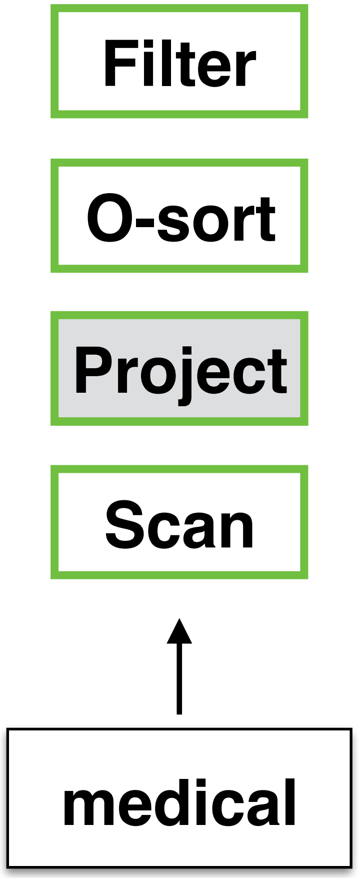
Rule-based optimization

Opaque op.

Logical op.





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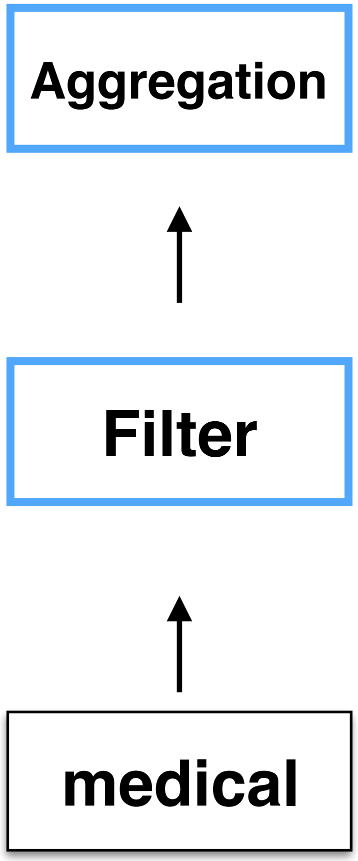
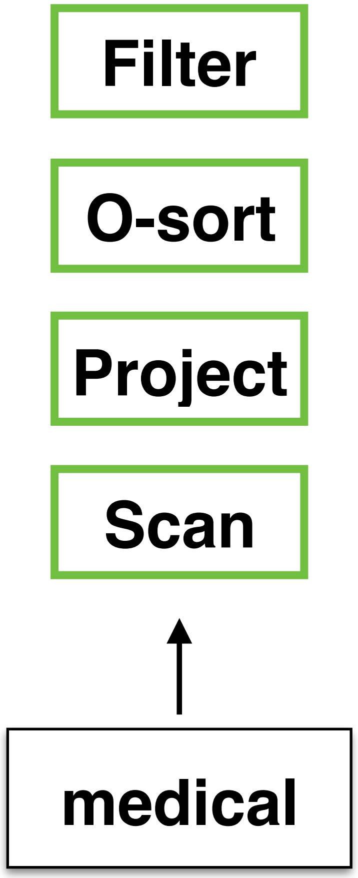
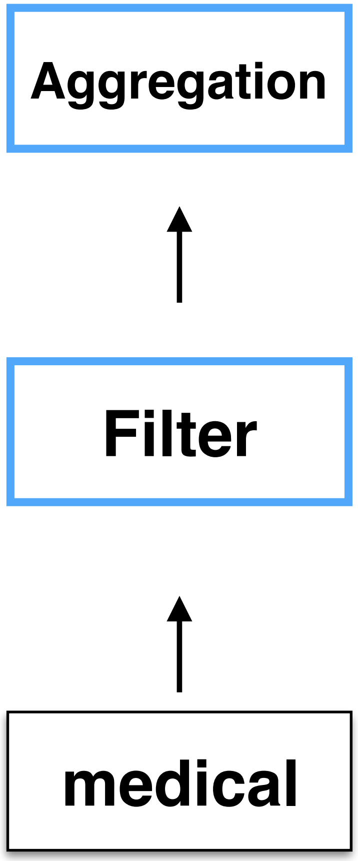


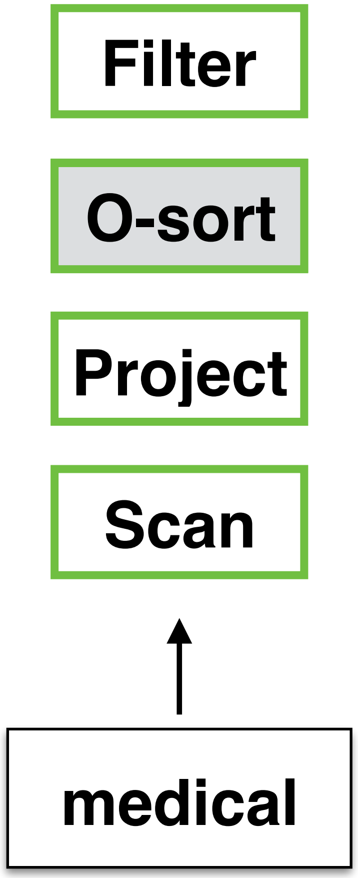


Rule-based optimization

Opaque op.

Logical op.





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Rule-based optimization

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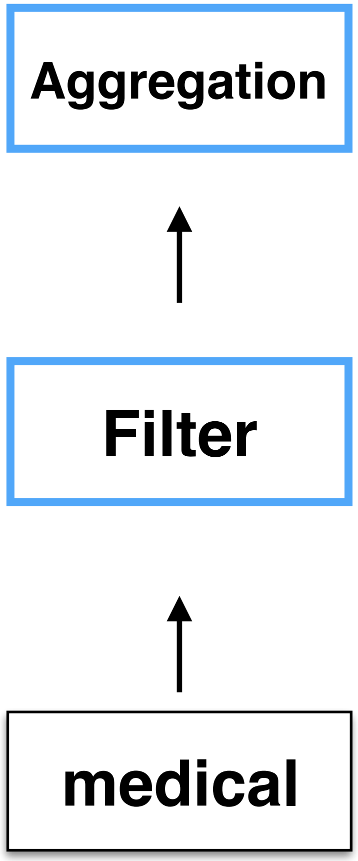

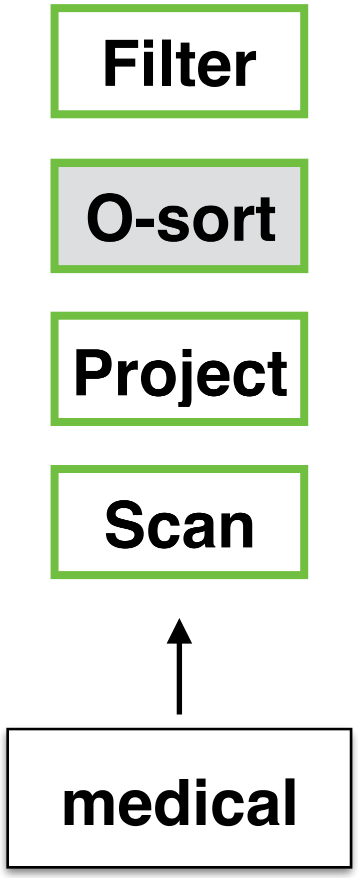

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Rule-based optimization

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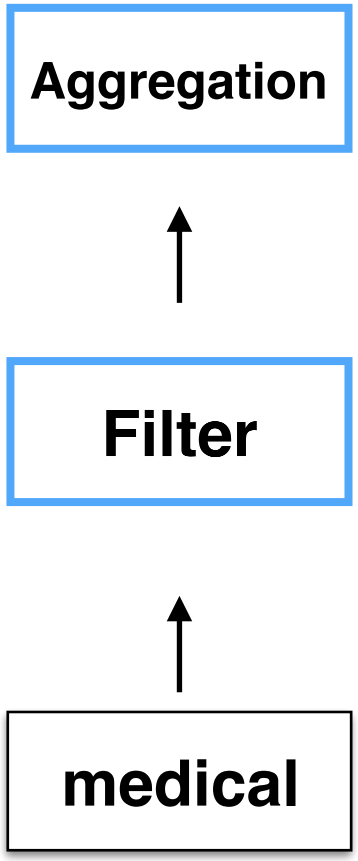

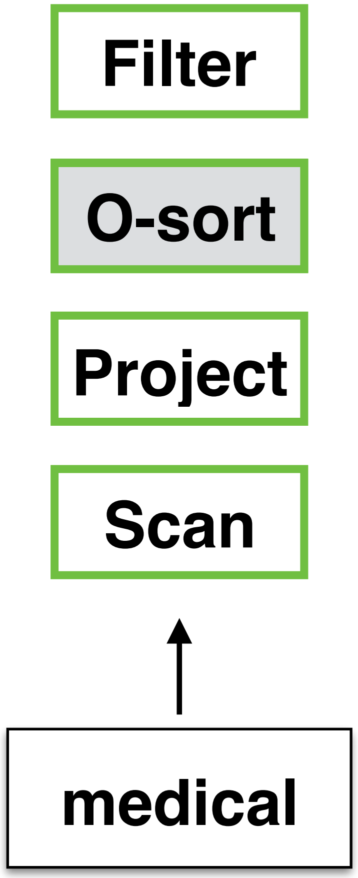

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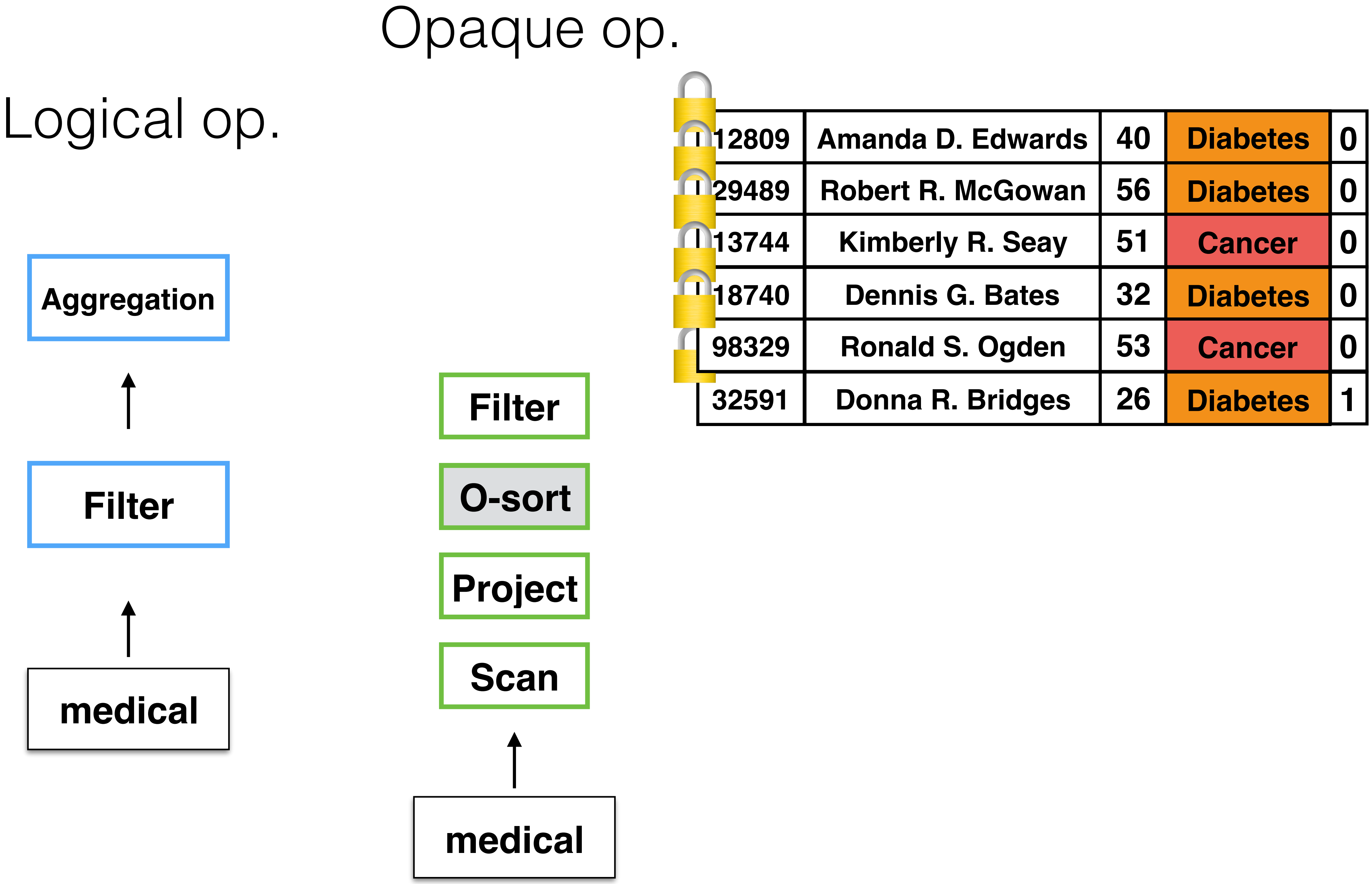
Rule-based optimization



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Rule-based optimization

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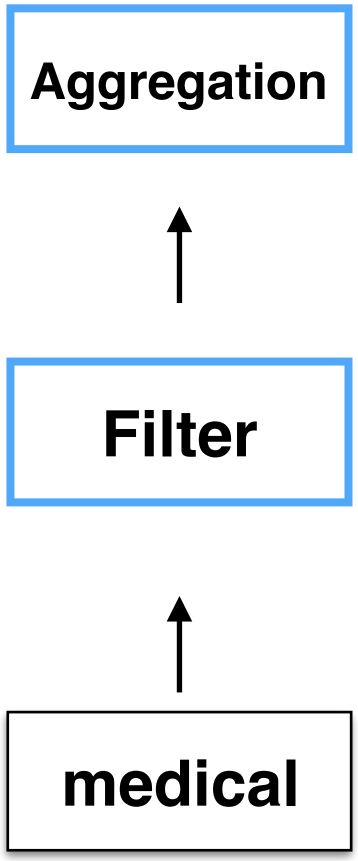

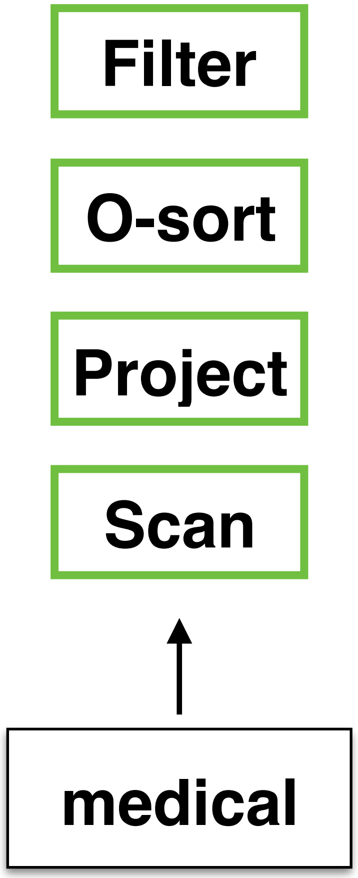

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Rule-based optimization

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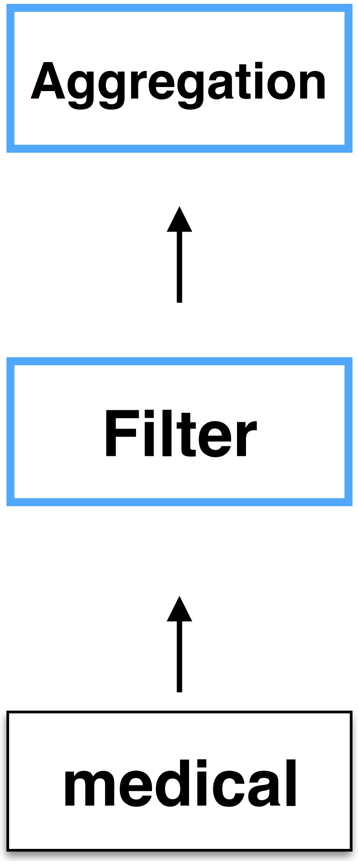

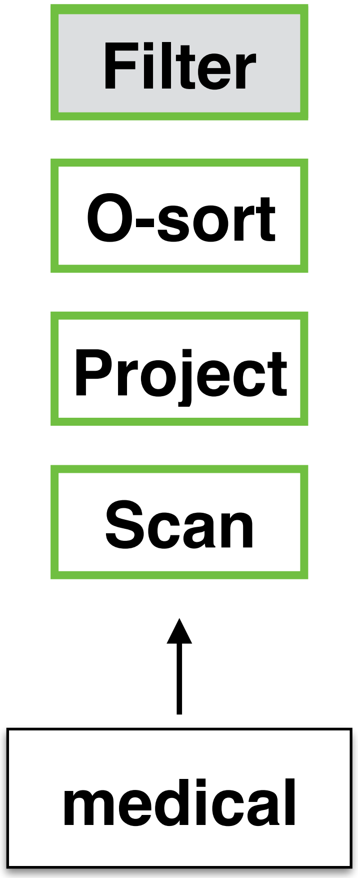

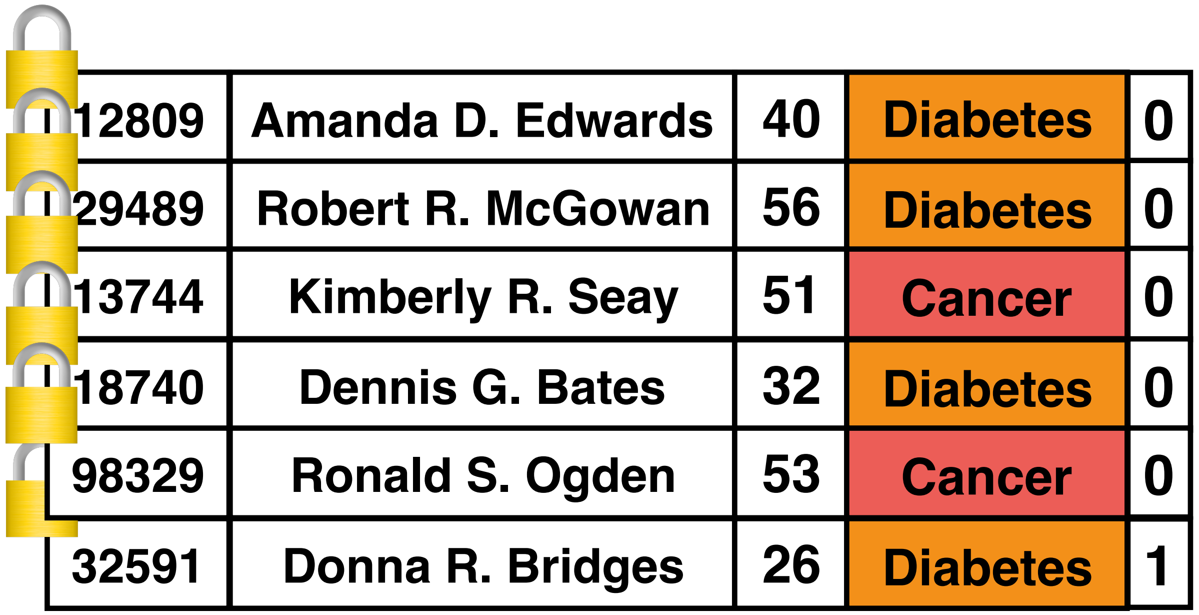

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Rule-based optimization

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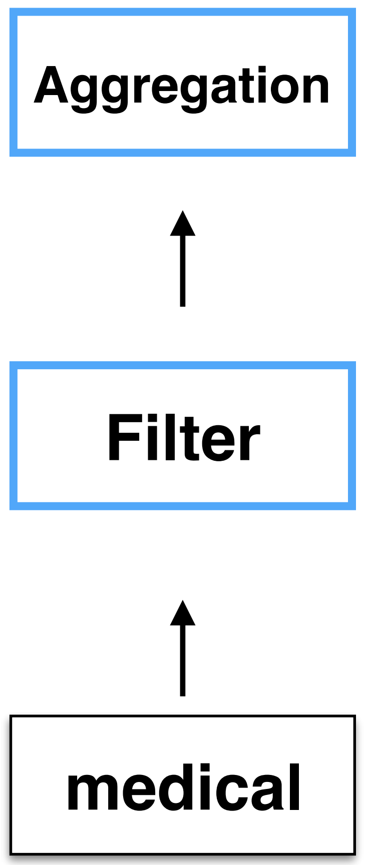

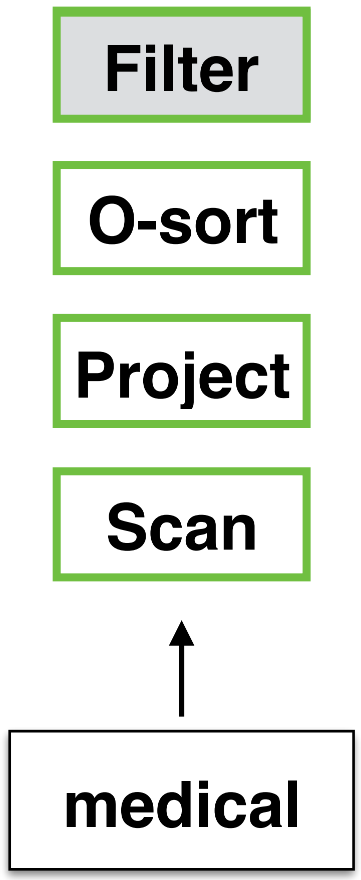

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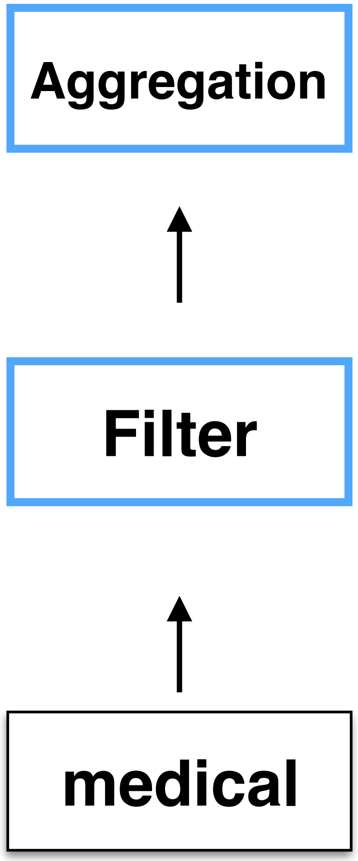

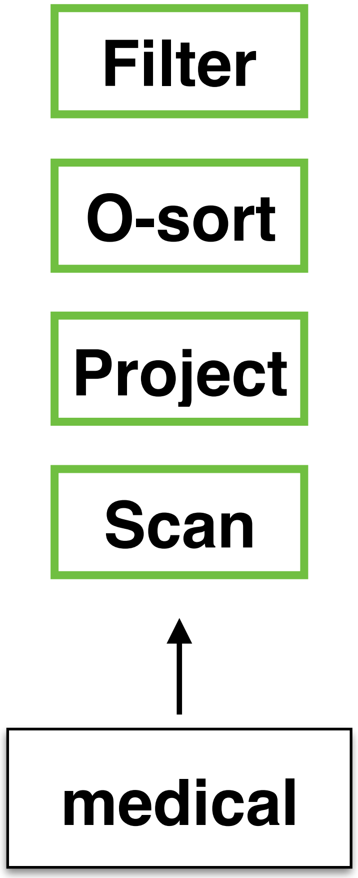

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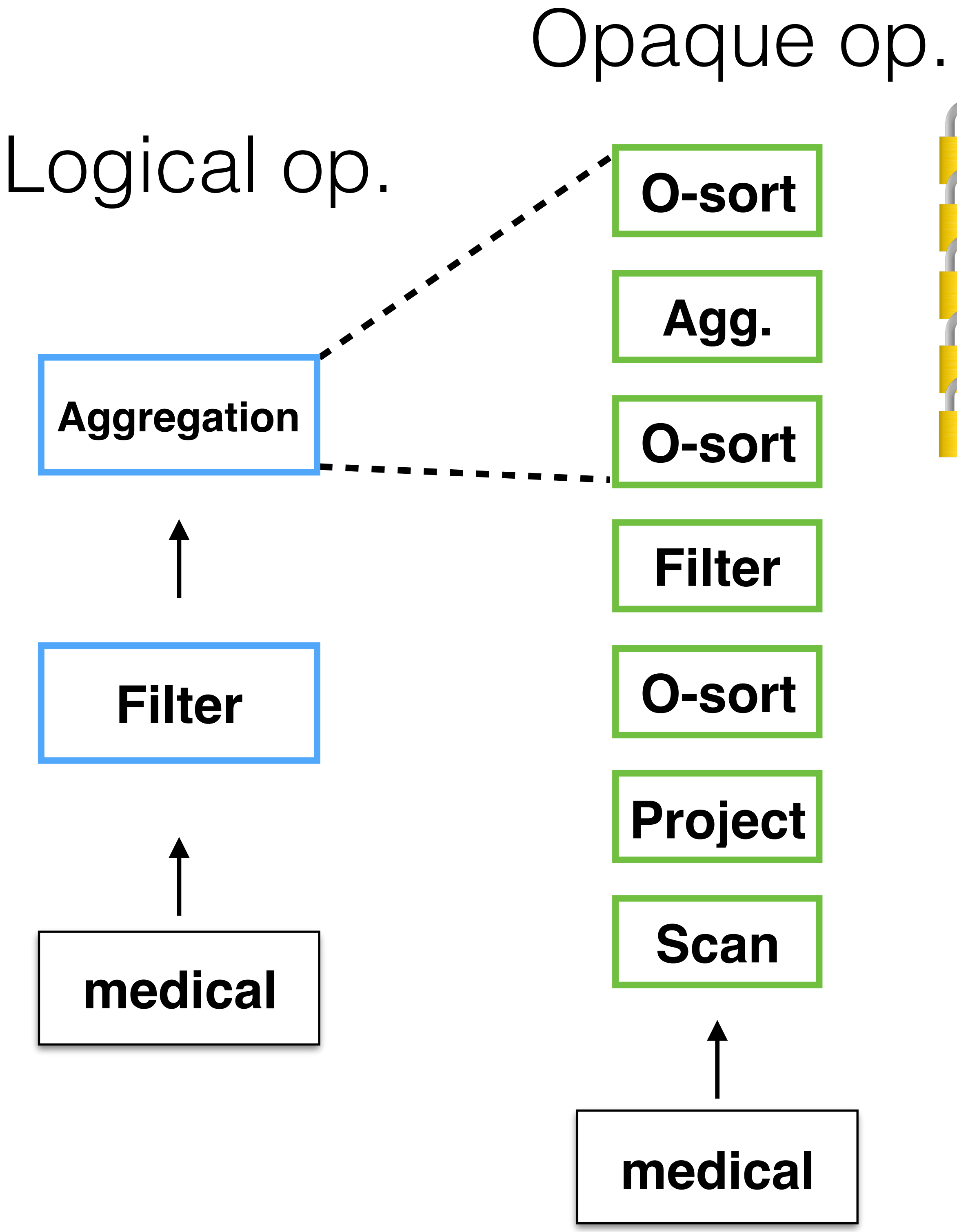

Opaque op.

Logical op.

Aggregation

Filter

medical

O-sort

Agg.

O-sort

Filter

O-sort

Project

Scan

medical

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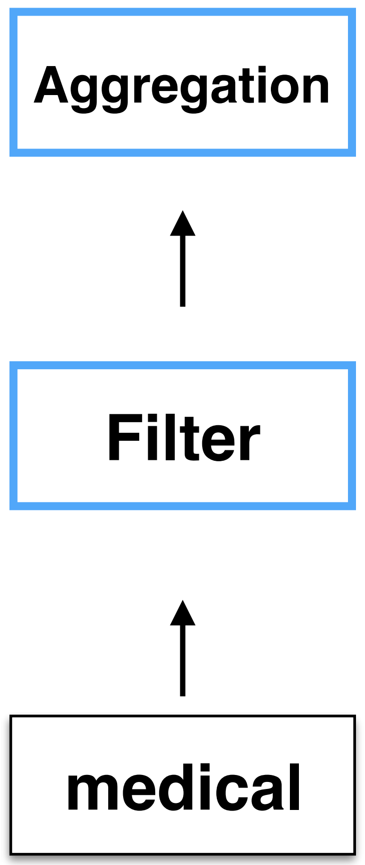

Aggregation

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medical

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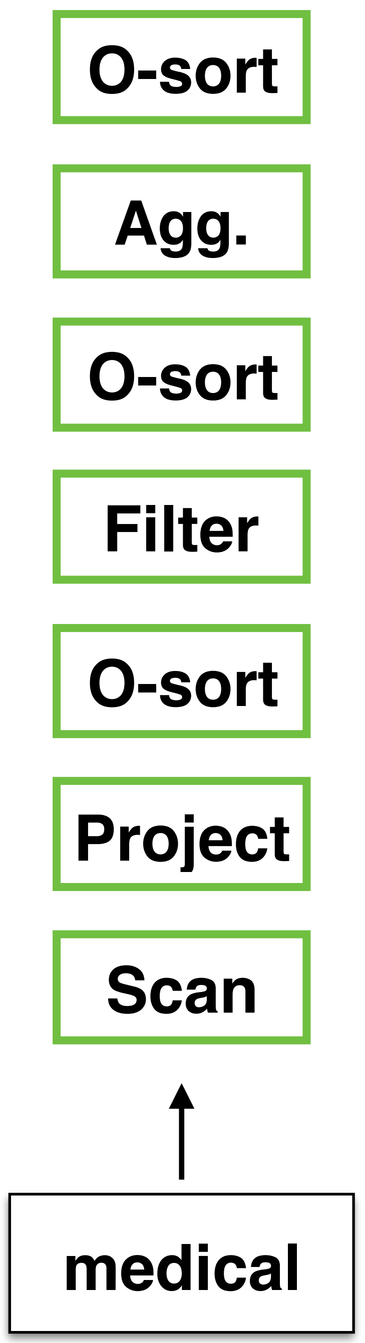

O-sort

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medical

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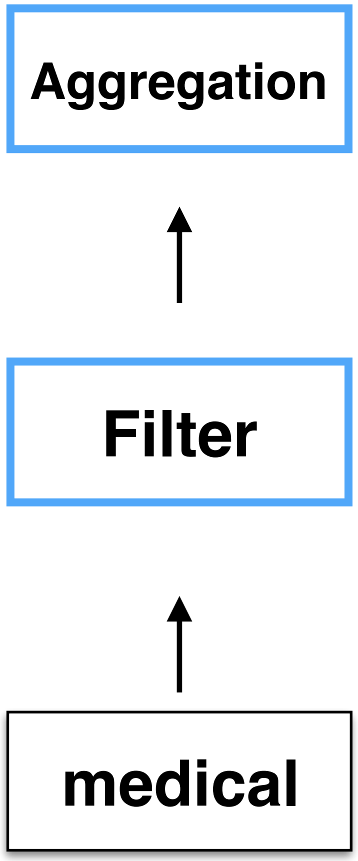

Aggregation

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medical

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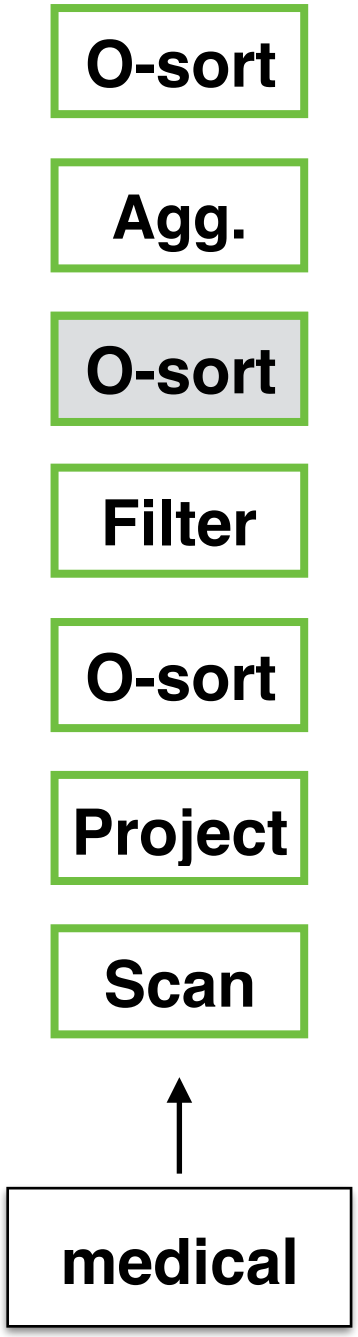

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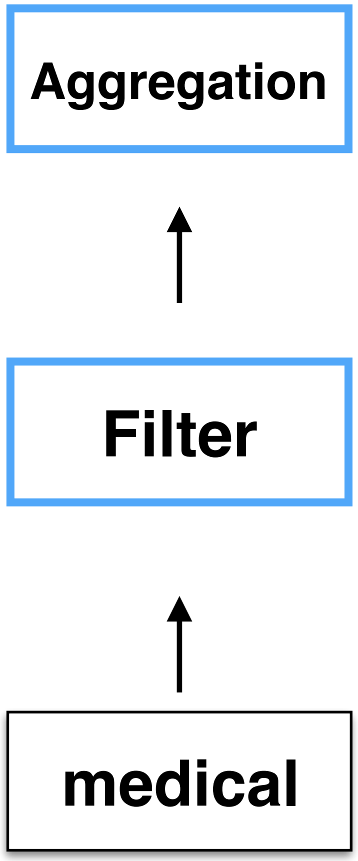

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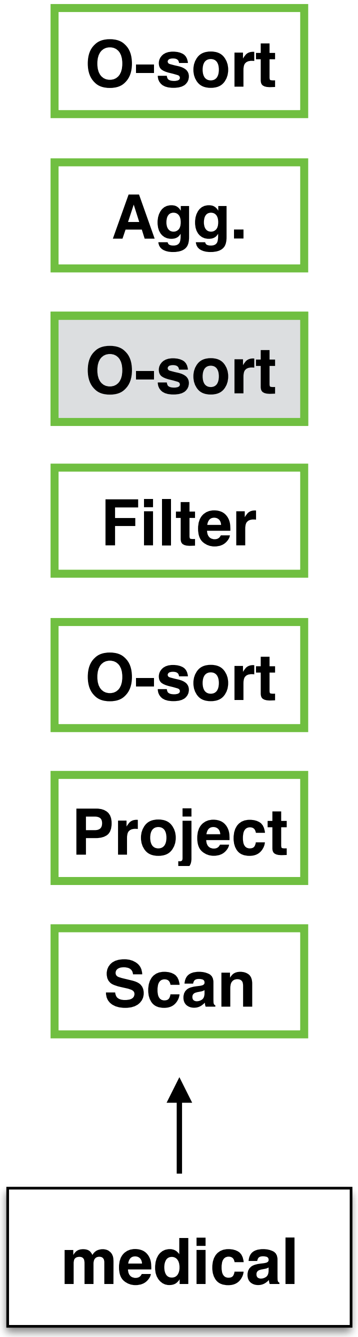

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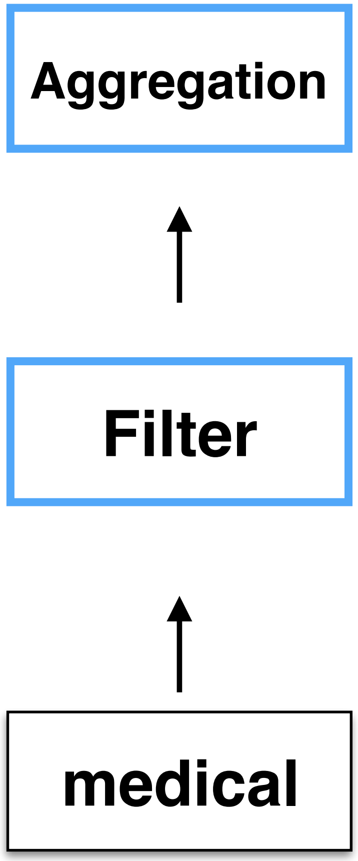
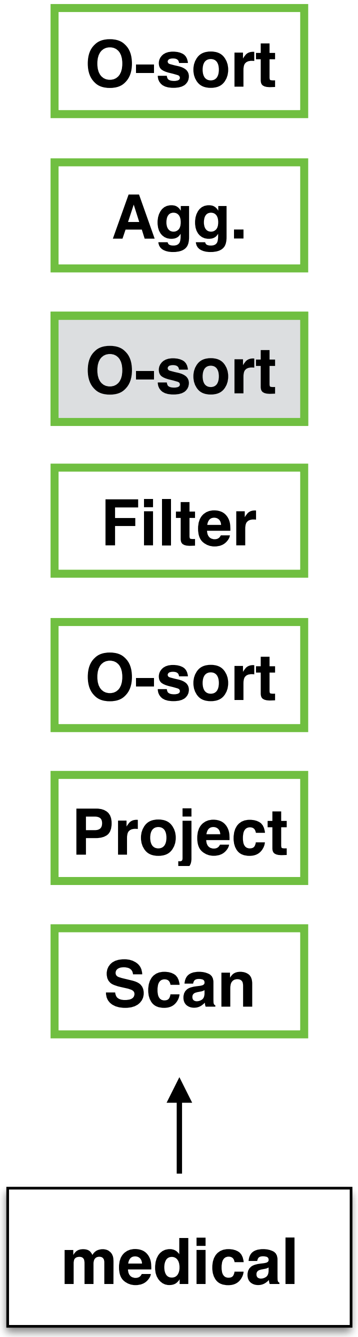


Aggregation

Filter

medical



O-sort

Agg.

O-sort

Filter

O-sort

Project

Scan

medical

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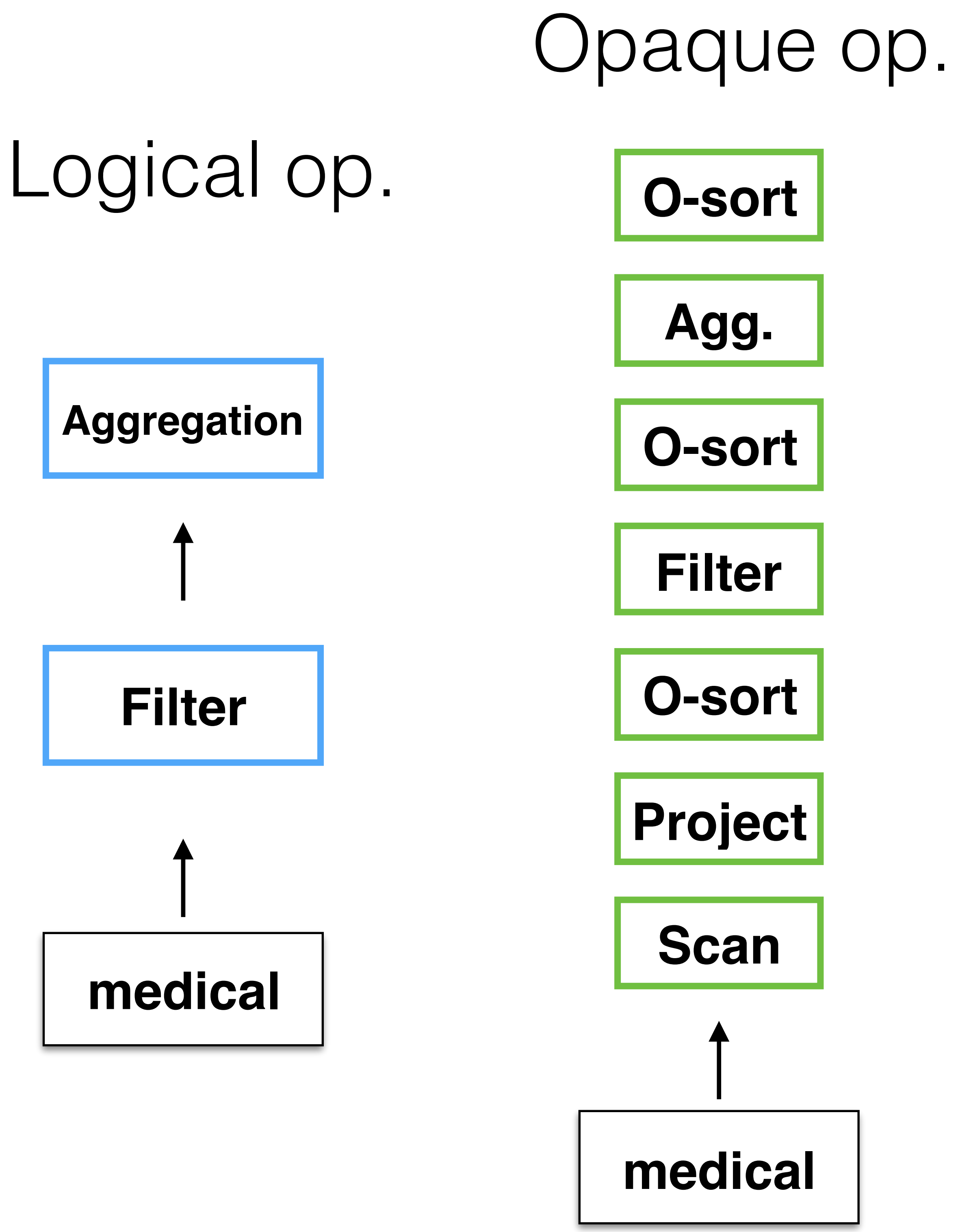
18740	Dennis G. Bates	32	Diabetes	0
12809	Amanda D. Edwards	40	Diabetes	0

Can we remove any sort?

Rule-based optimization



Opaque op.

Logical op.

O-sort

Agg.

Aggregation

O-sort

Filter

Filter

O-sort

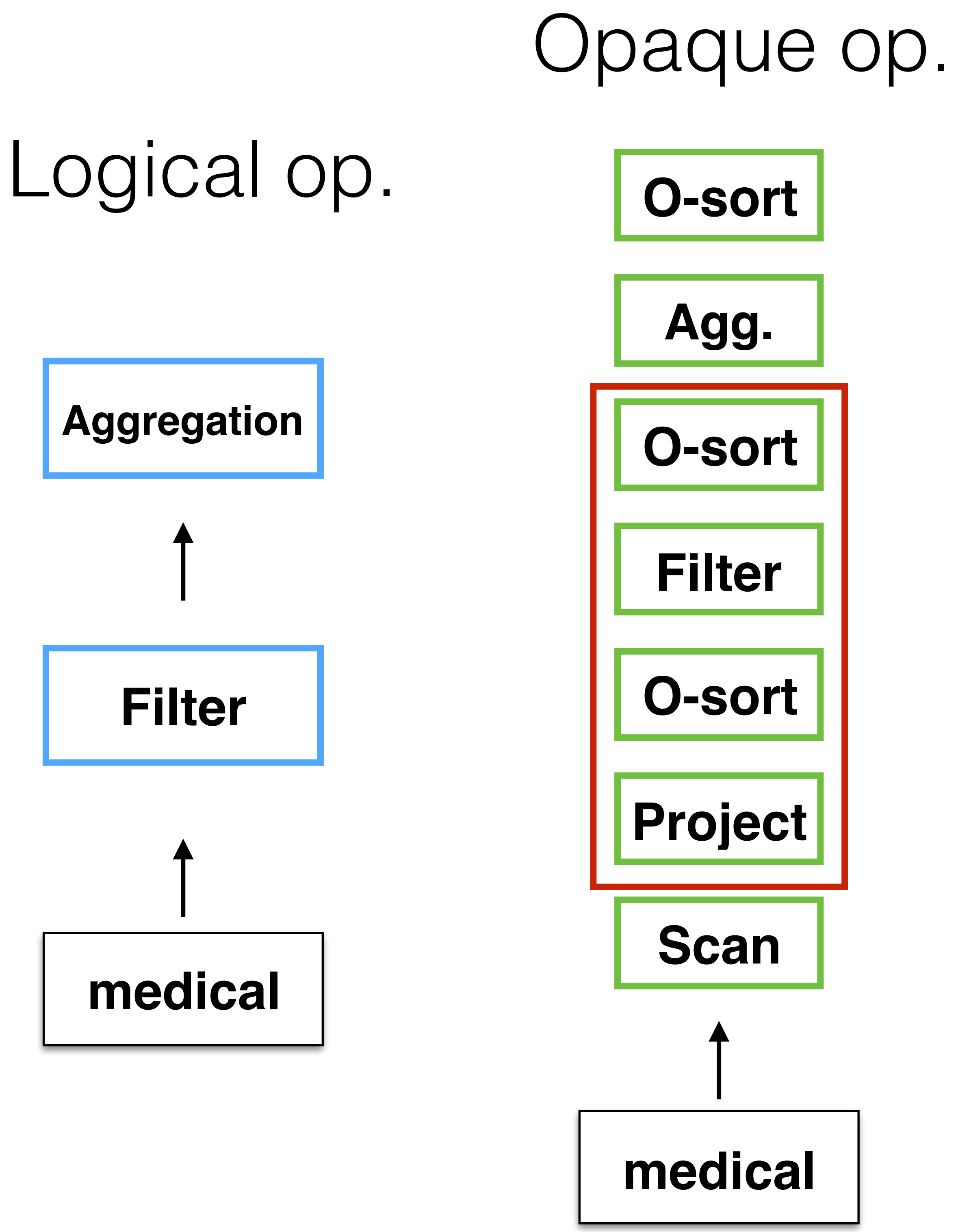
Project

medical

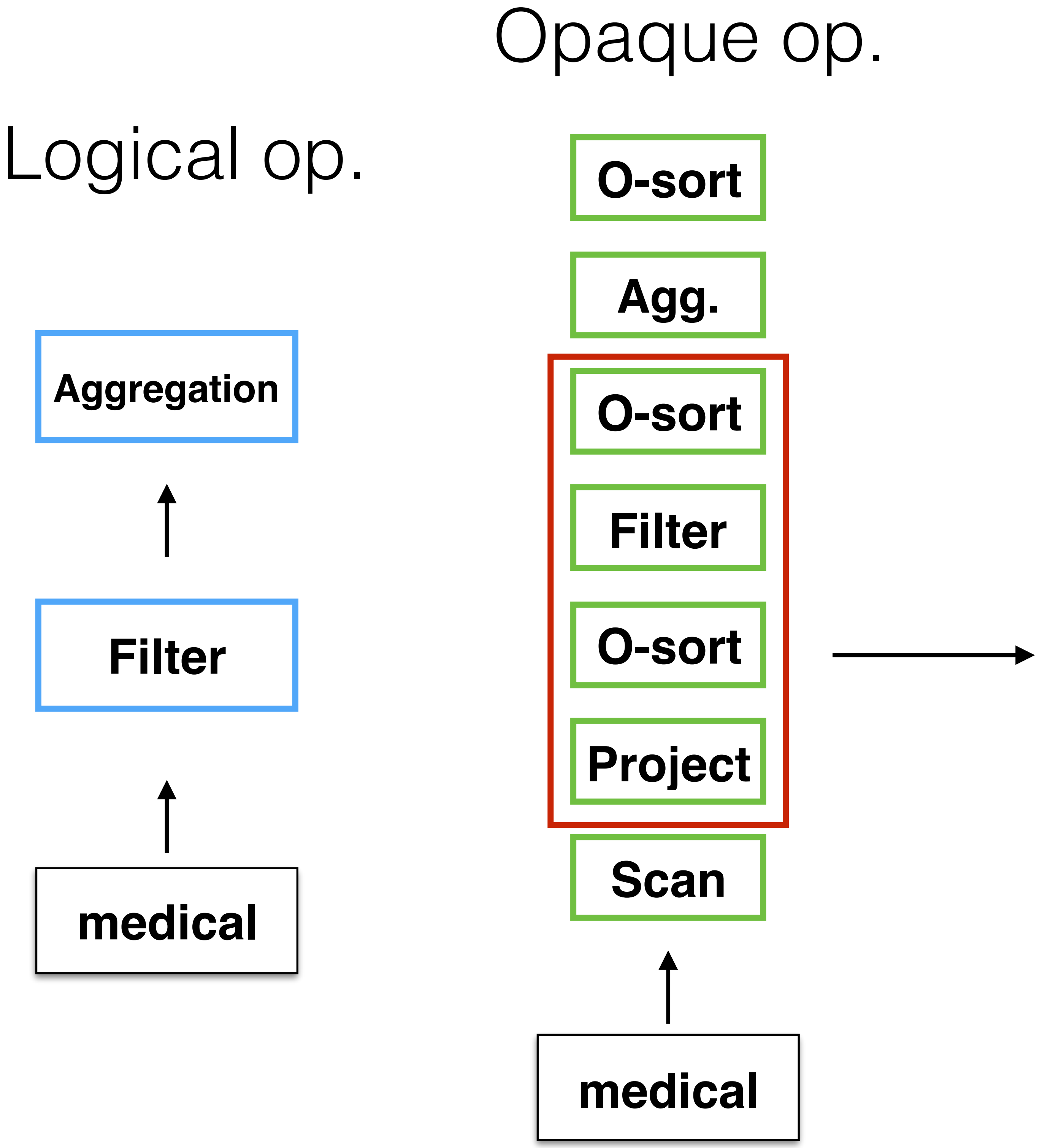
Scan

medical

Rule-based optimization



Rule-based optimization


Opaque op.

Logical op.

Aggregation

Filter

medical

O-sort

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O-sort

Filter

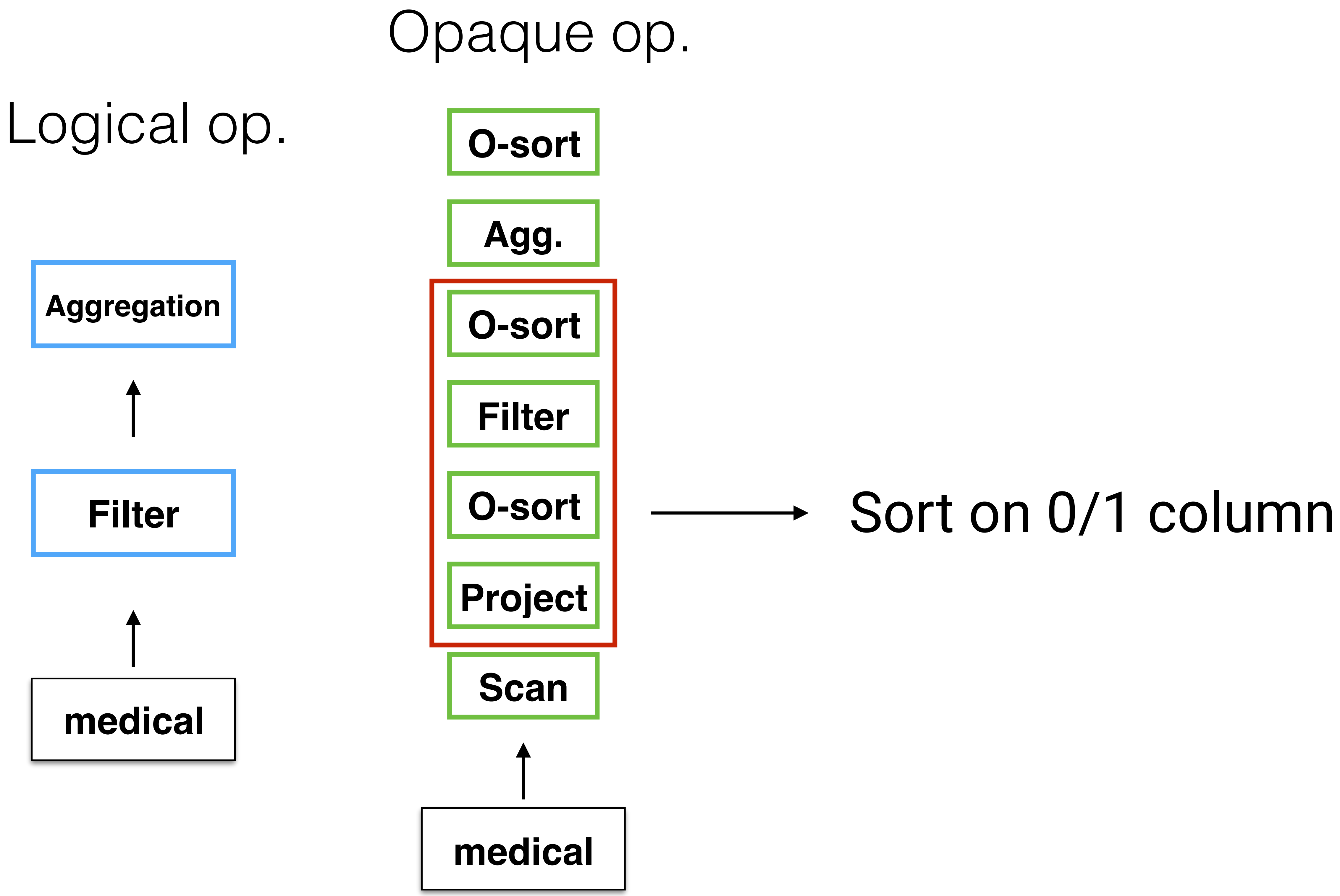
O-sort

Project

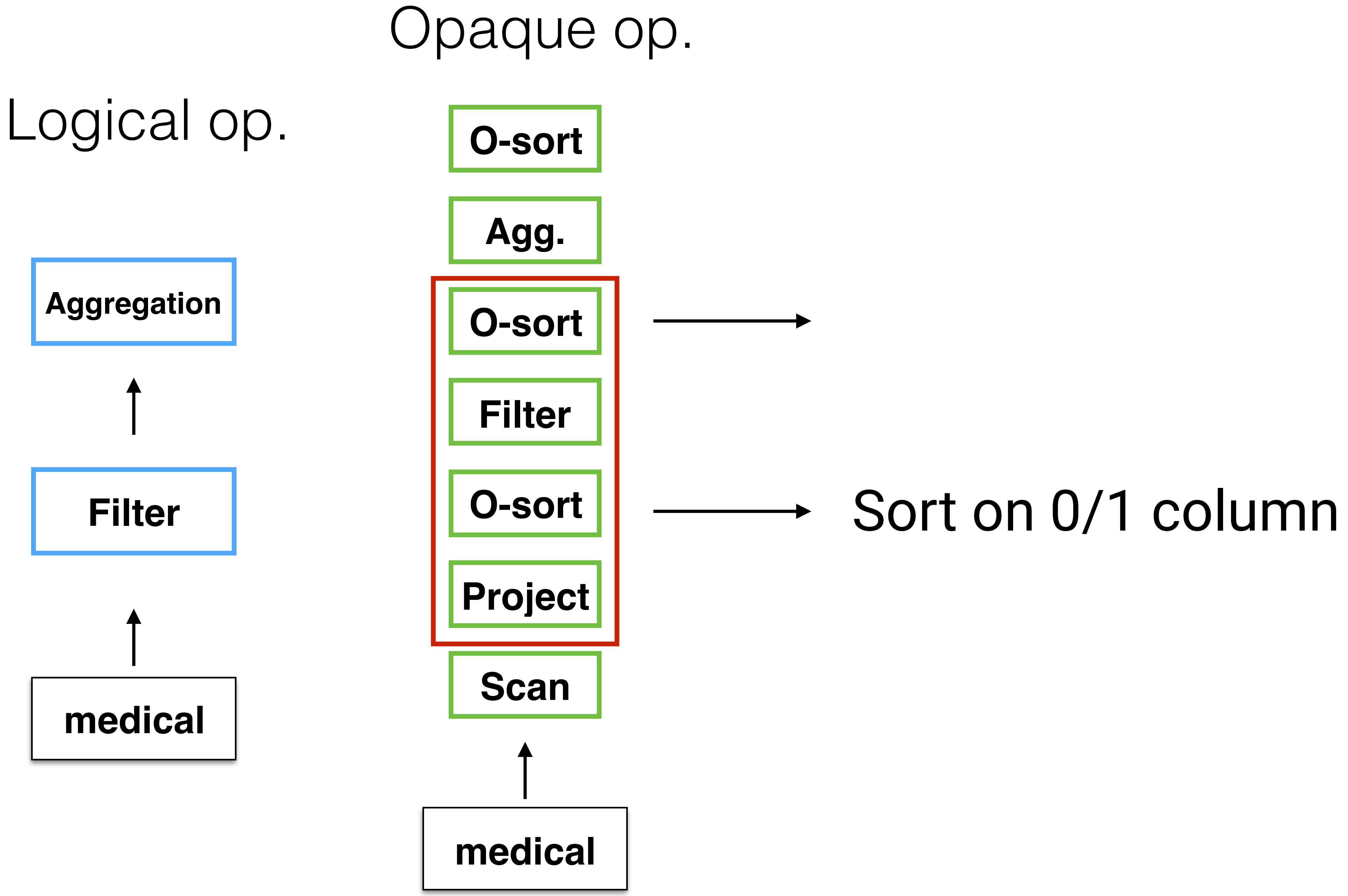
Scan

medical

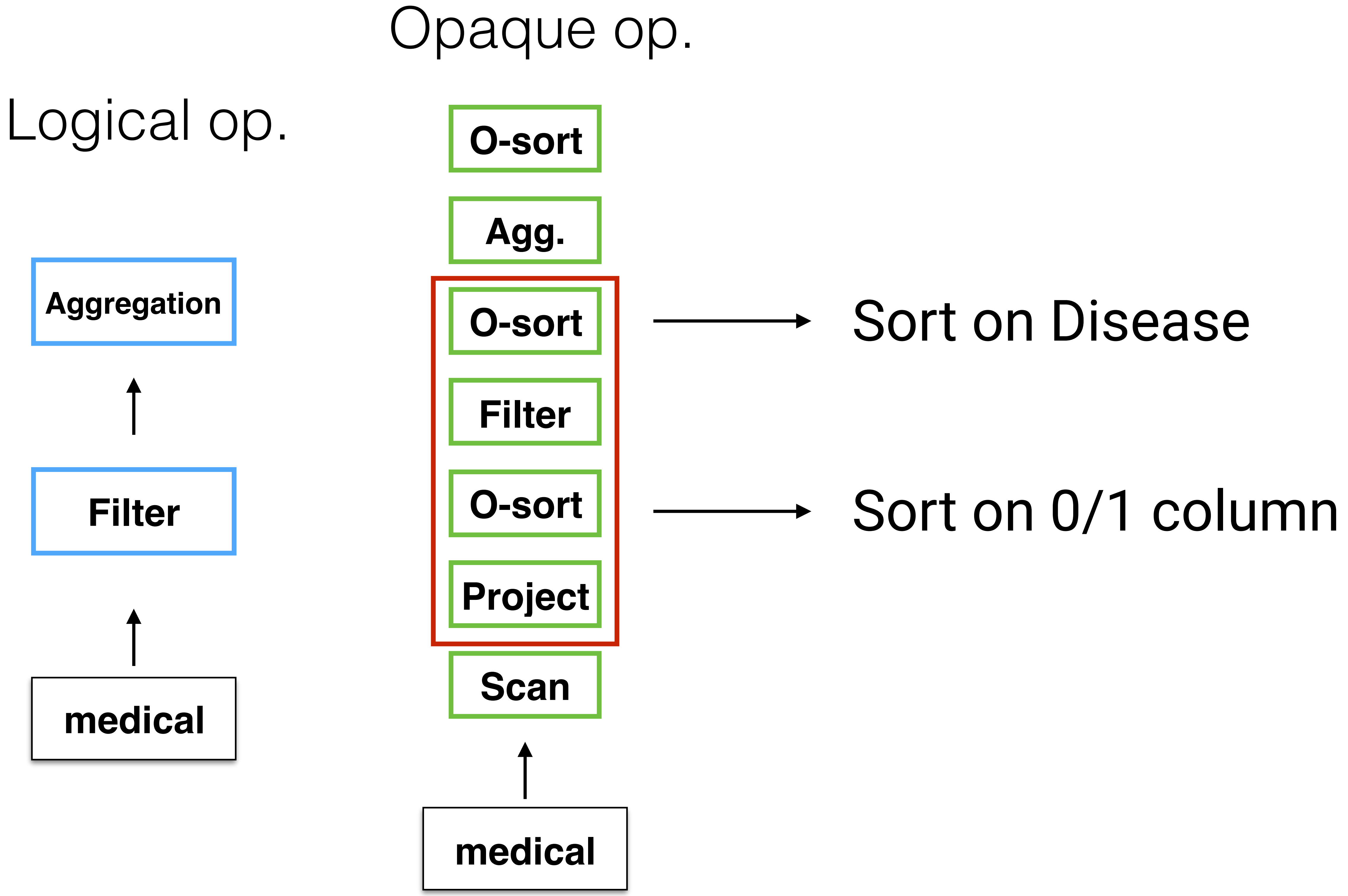
Rule-based optimization



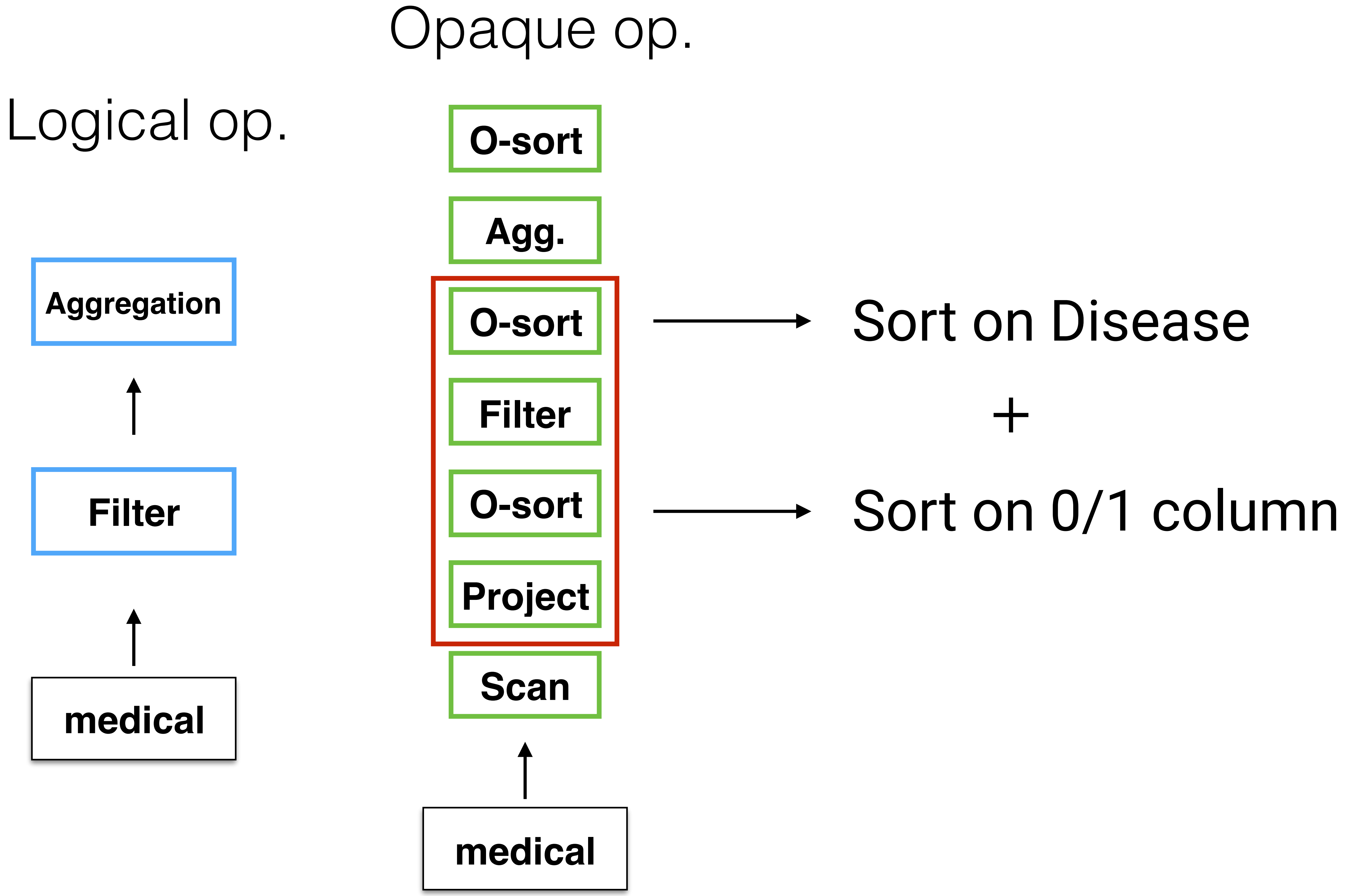
Rule-based optimization



Rule-based optimization



Rule-based optimization


Opaque op.

Logical op.

Aggregation

Filter

medical

O-sort

Agg.

O-sort

Filter

O-sort

Project

Scan

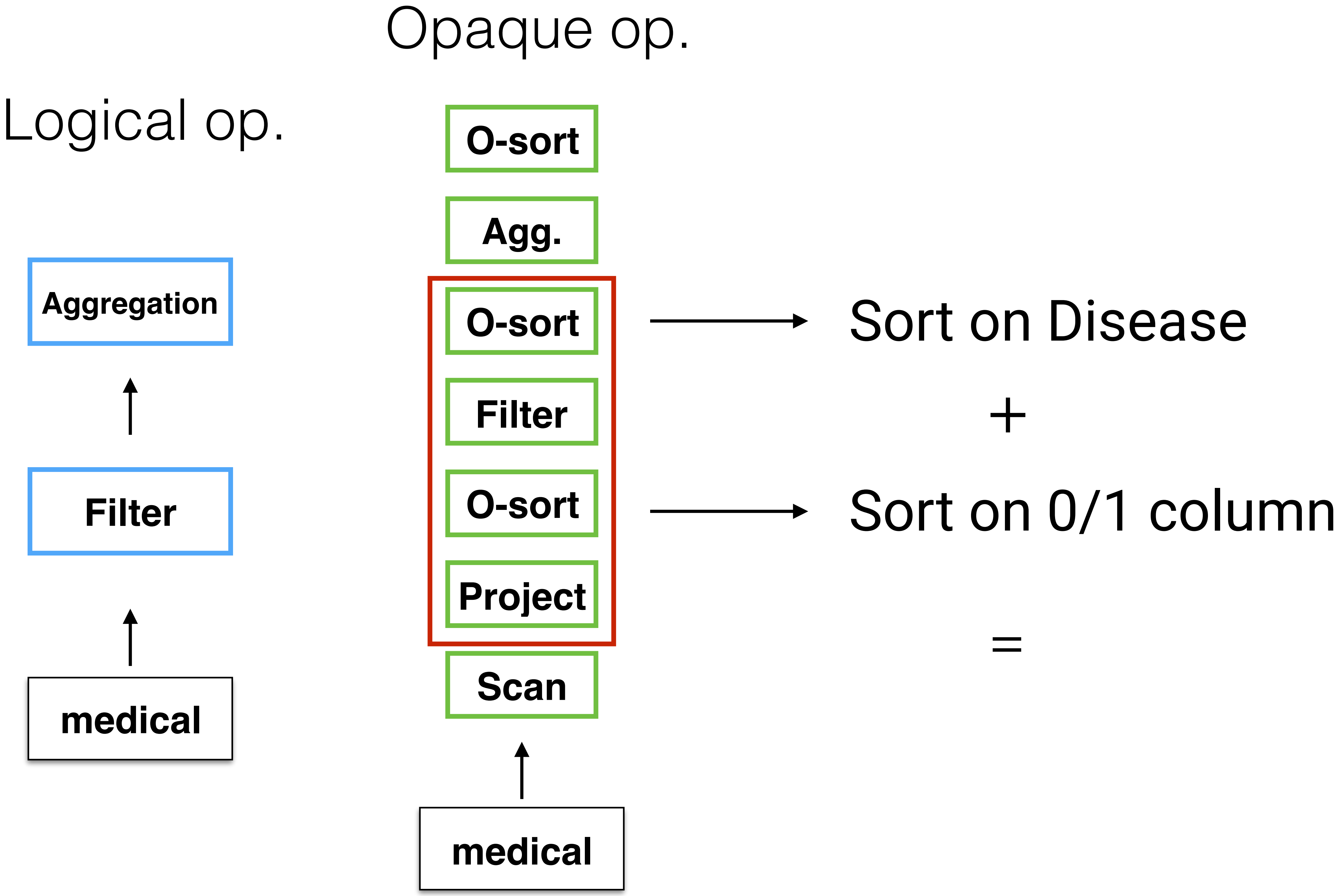
medical

Sort on Disease

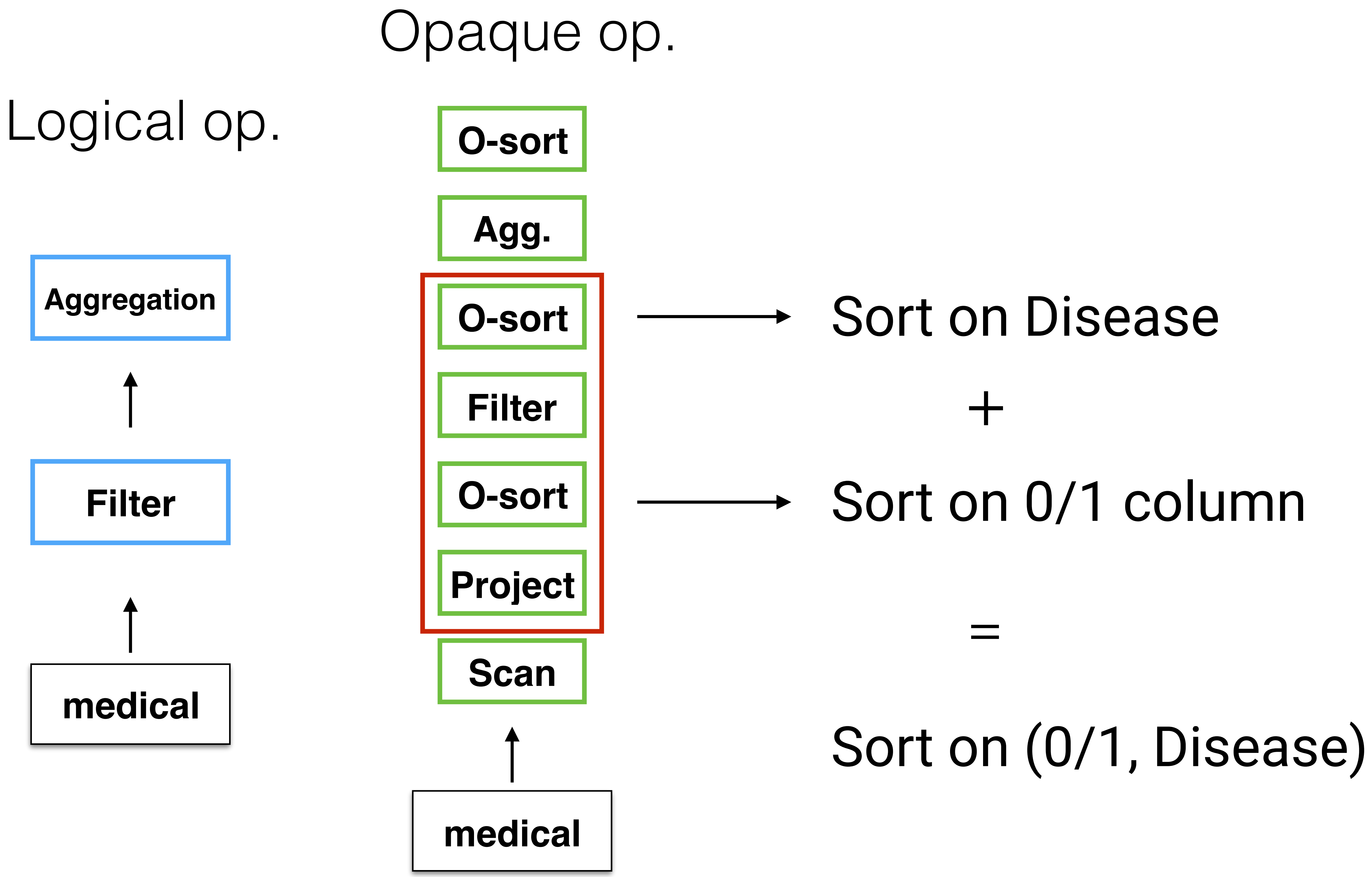
+

Sort on 0/1 column

Rule-based optimization



Rule-based optimization



Opaque op.

Logical op.

Aggregation

Filter

medical

O-sort

Agg.

O-sort

Filter

O-sort

Project

Scan

medical

Sort on Disease

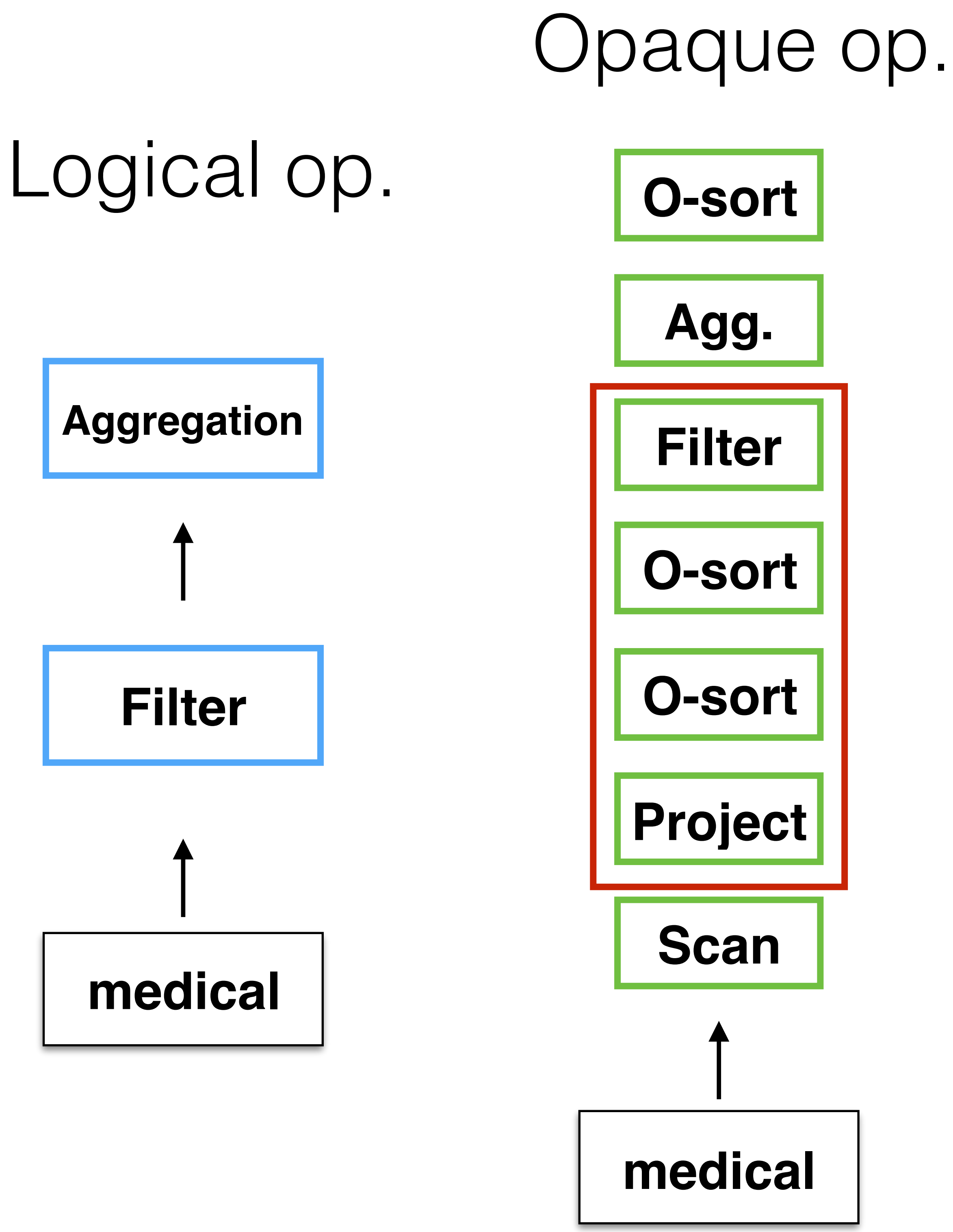
+

Sort on 0/1 column

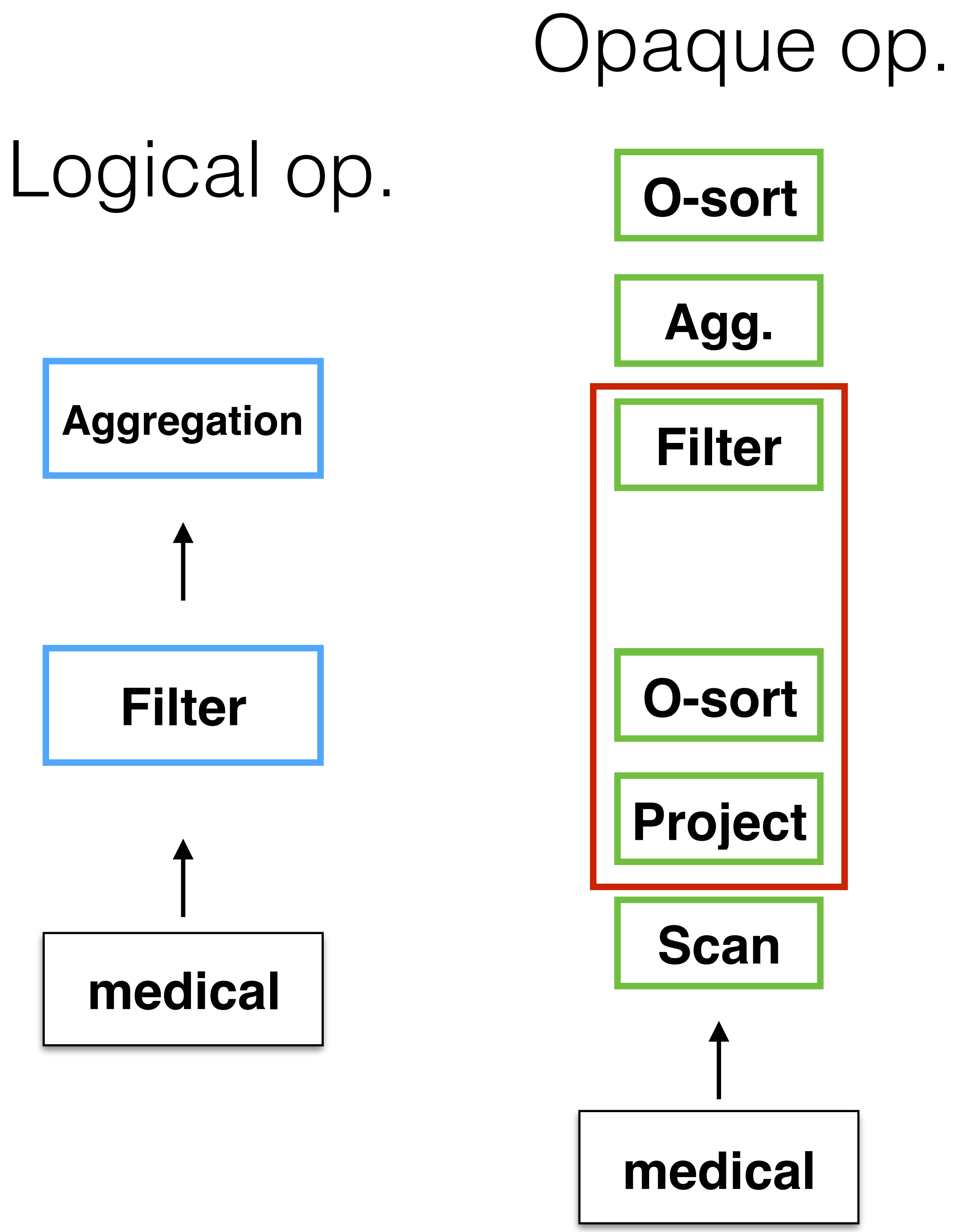
=

Sort on (0/1, Disease)

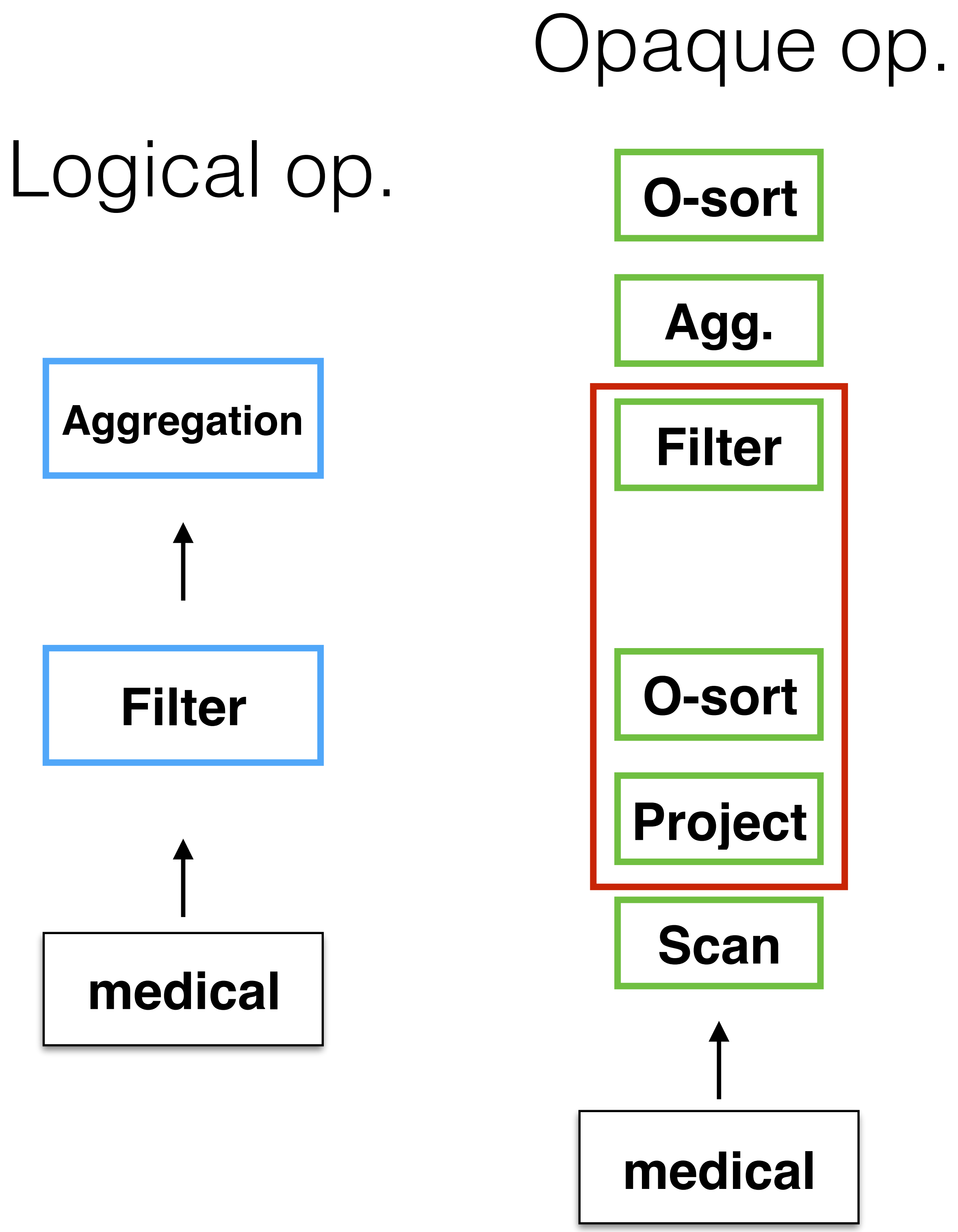
Rule-based optimization



Rule-based optimization



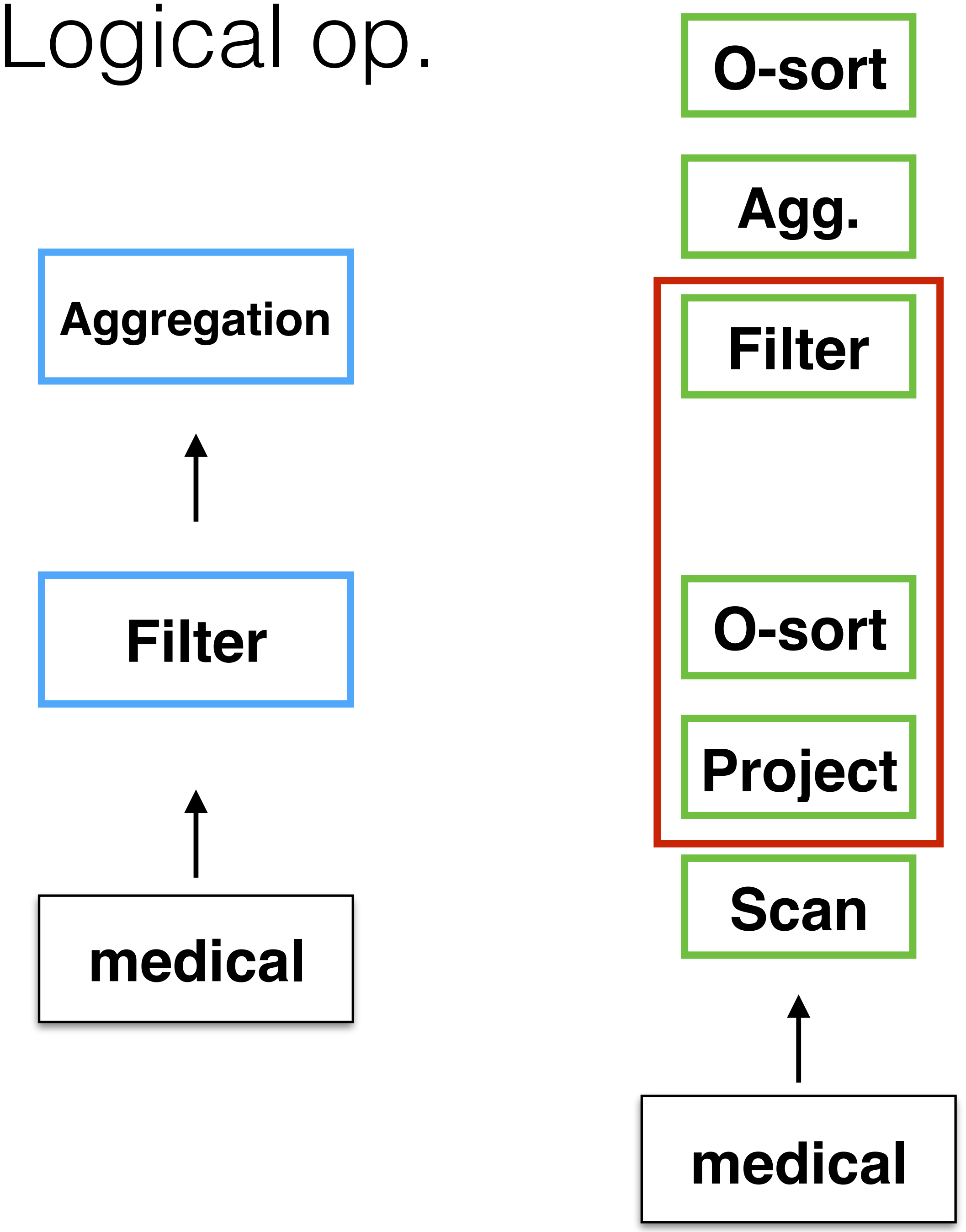
Rule-based optimization



Rule-based optimization

Opaque op.

Logical op.



Aggregation

Filter

medical

O-sort

Agg.

Filter

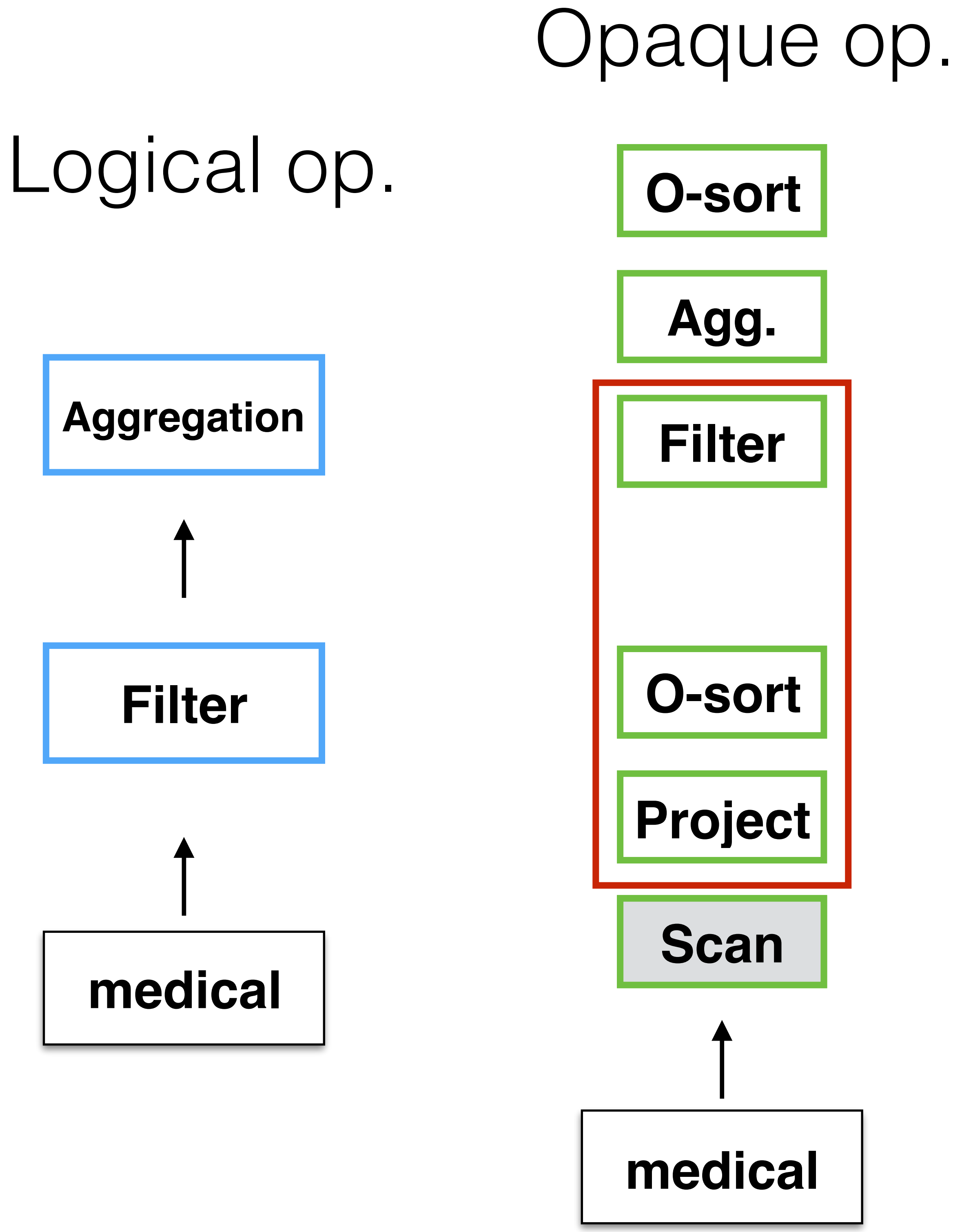
O-sort

Project

Scan

medical

Rule-based optimization



Opaque op.

Logical op.

O-sort

Agg.

Aggregation

Filter

Filter

O-sort

Project

Scan

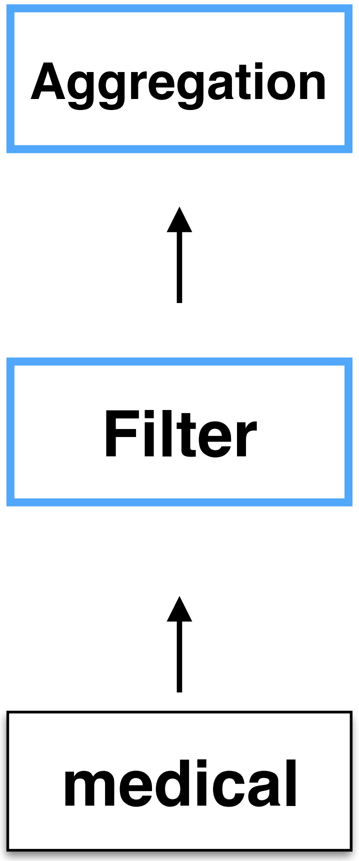
medical

medical

Rule-based optimization

Opaque op.

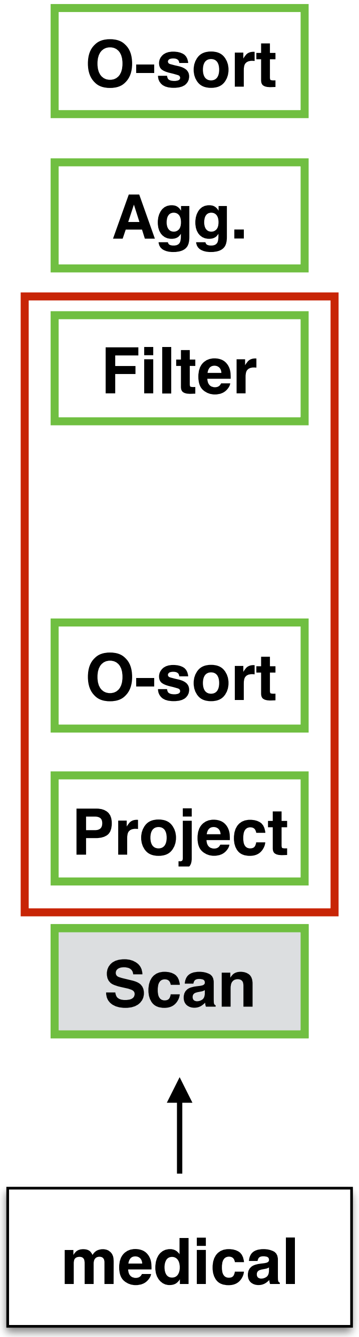
Logical op.



Aggregation

Filter

medical



O-sort

Agg.

Filter

O-sort

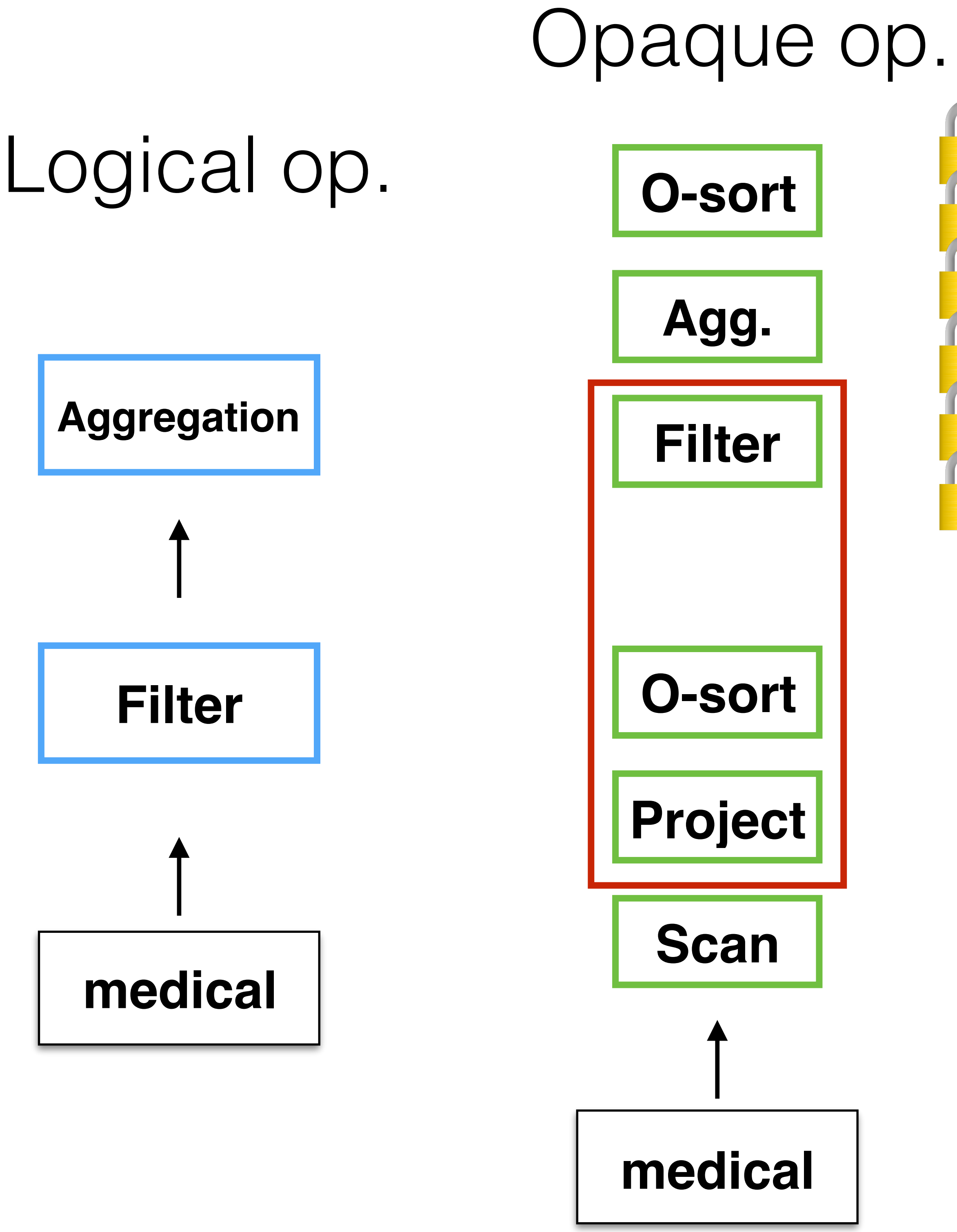
Project

Scan

medical

🔒	12809	Amanda D. Edwards	40	Diabetes
🔒	29489	Robert R. McGowan	56	Diabetes
🔒	13744	Kimberly R. Seay	51	Cancer
🔒	18740	Dennis G. Bates	32	Diabetes
🔒	32591	Donna R. Bridges	26	Diabetes
	98329	Ronald S. Ogden	53	Cancer

Rule-based optimization



🔒	12809	Amanda D. Edwards	40	Diabetes
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🔒	13744	Kimberly R. Seay	51	Cancer
🔒	18740	Dennis G. Bates	32	Diabetes
🔒	32591	Donna R. Bridges	26	Diabetes
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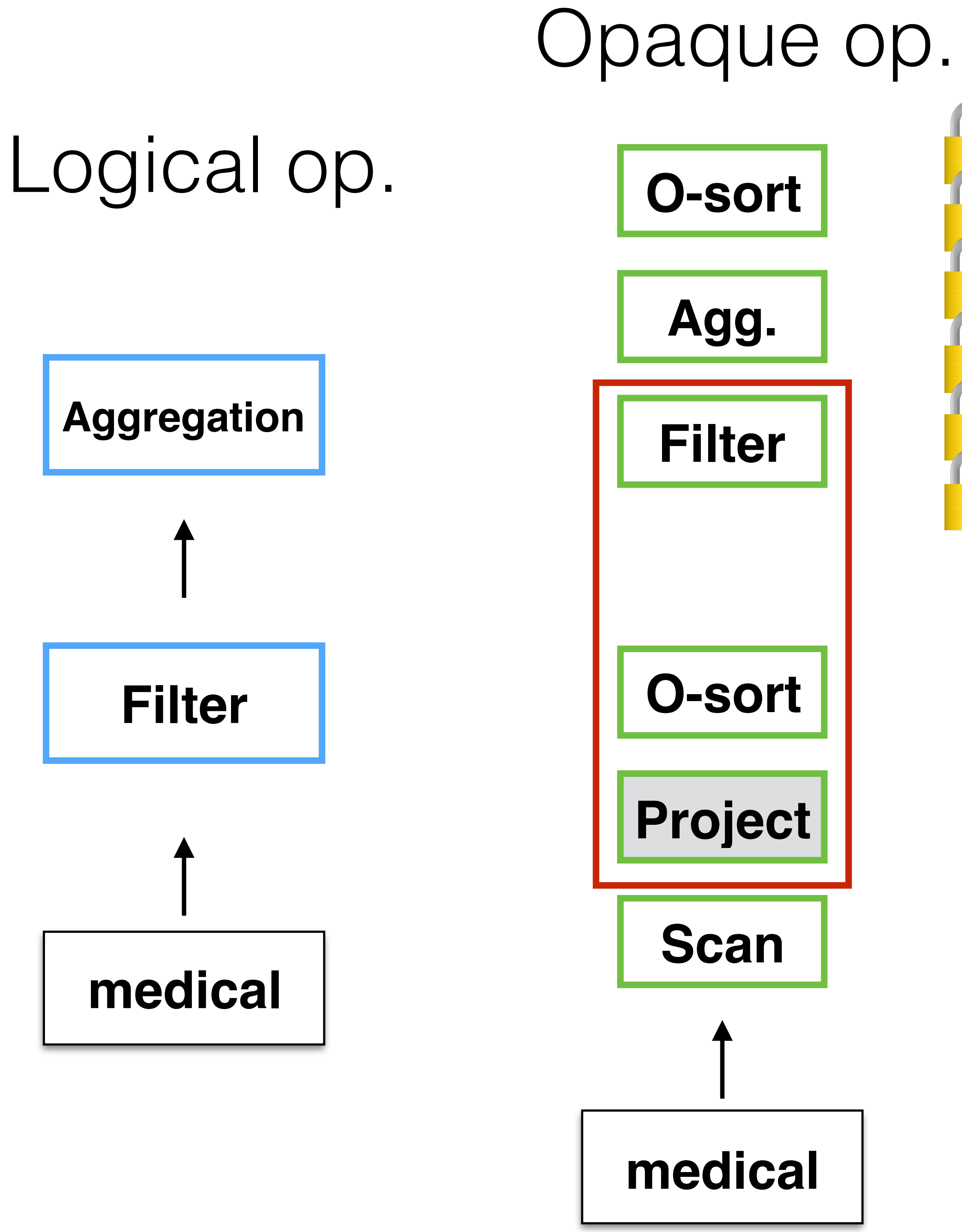
Rule-based optimization



12809	Amanda D. Edwards	40	Diabetes
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13744	Kimberly R. Seay	51	Cancer
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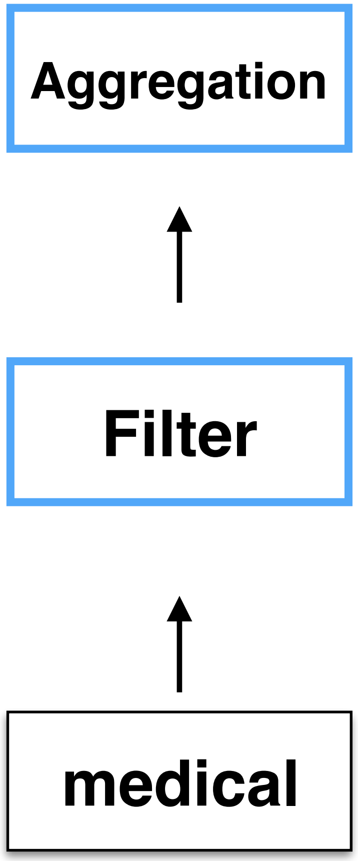
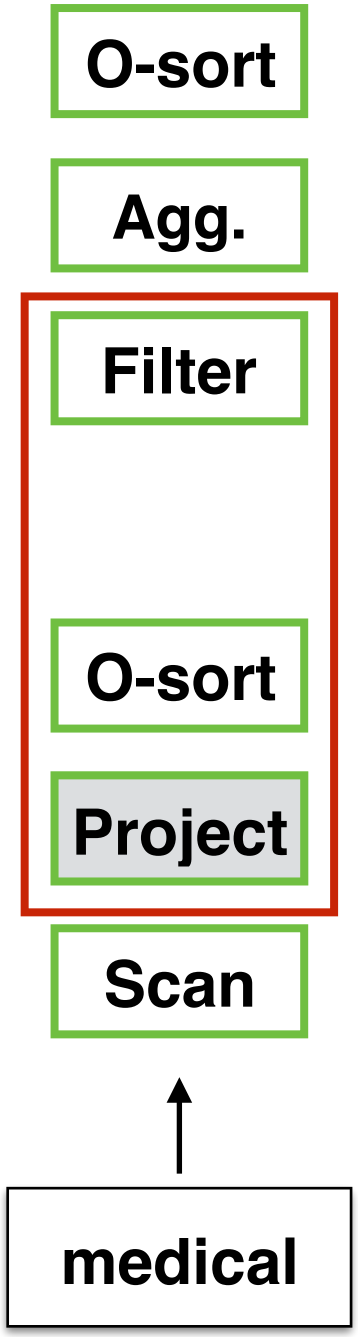
32591	Donna R. Bridges	26	Diabetes
98329	Ronald S. Ogden	53	Cancer

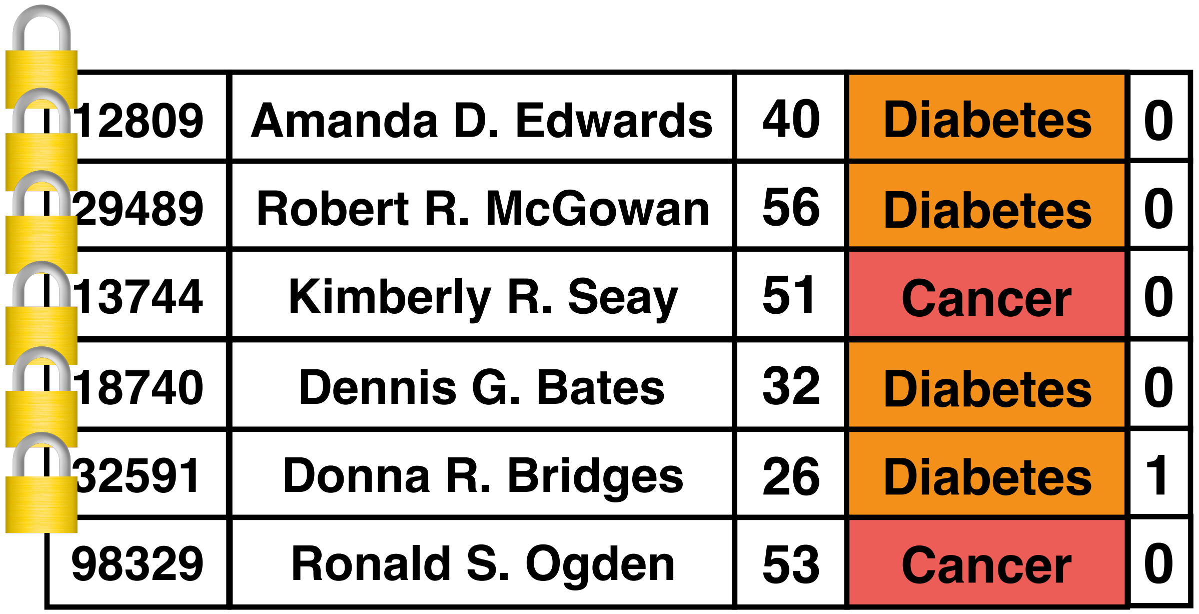
Rule-based optimization

Logical op.



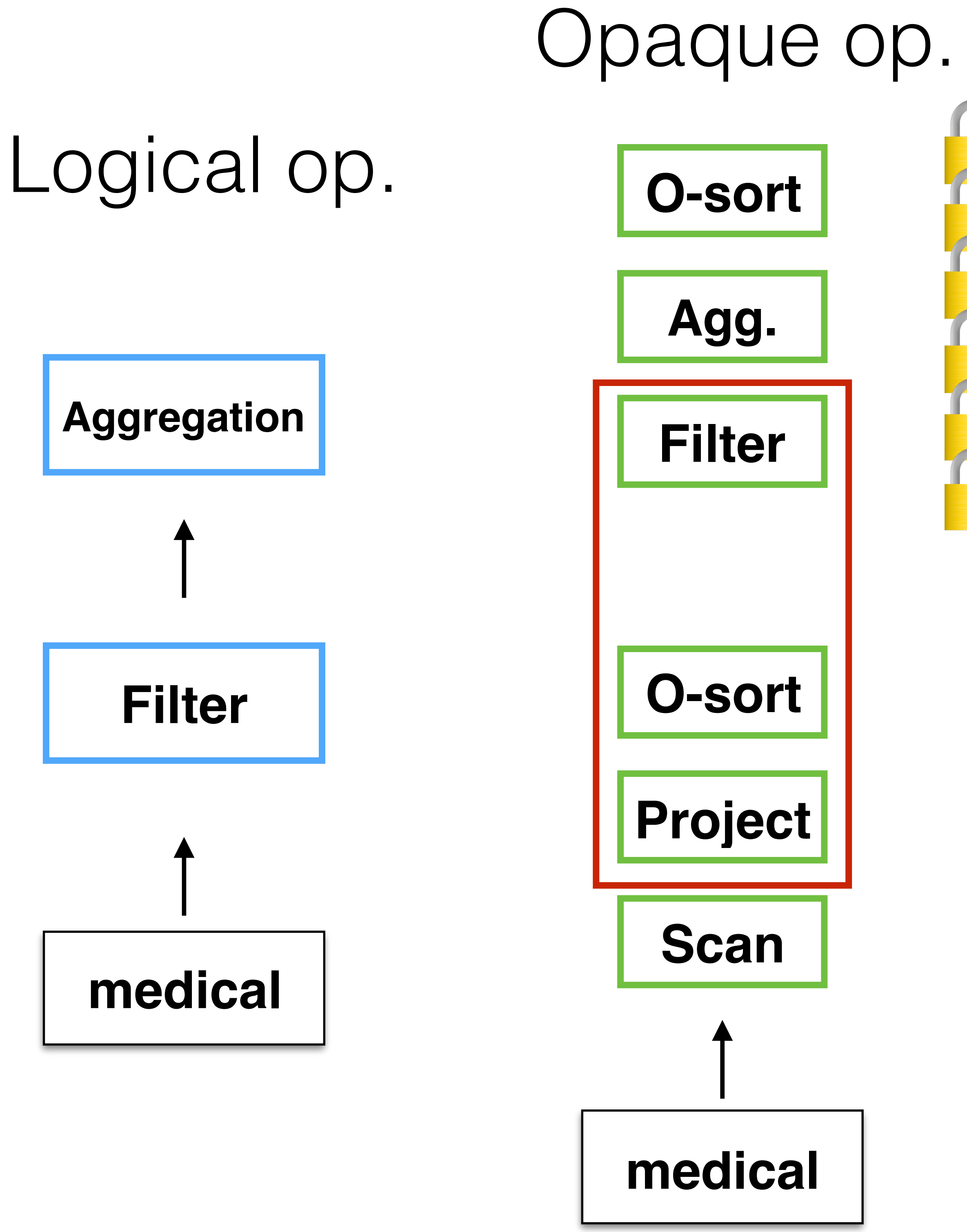
Opaque op.





12809	Amanda D. Edwards	40	Diabetes	0
29489	Robert R. McGowan	56	Diabetes	0
13744	Kimberly R. Seay	51	Cancer	0
18740	Dennis G. Bates	32	Diabetes	0
32591	Donna R. Bridges	26	Diabetes	1
98329	Ronald S. Ogden	53	Cancer	0

Rule-based optimization



Logical op.

Opaque op.

🔒 12809	Amanda D. Edwards	40	Diabetes	0
🔒 29489	Robert R. McGowan	56	Diabetes	0
🔒 13744	Kimberly R. Seay	51	Cancer	0
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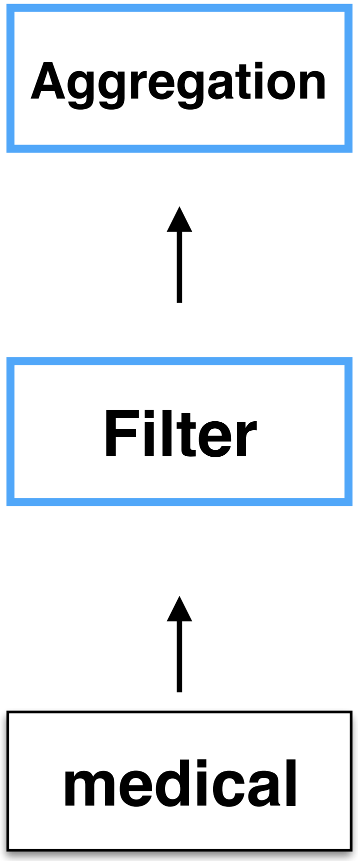
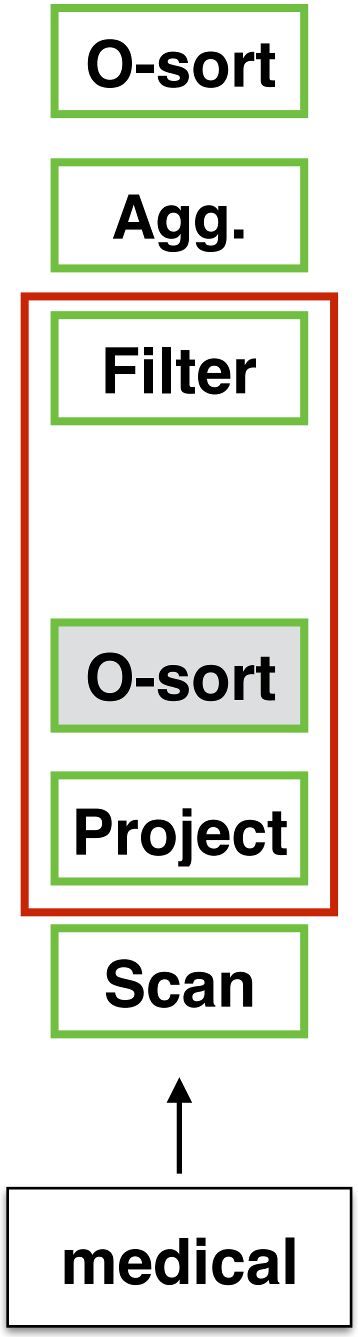
Rule-based optimization

Logical op.



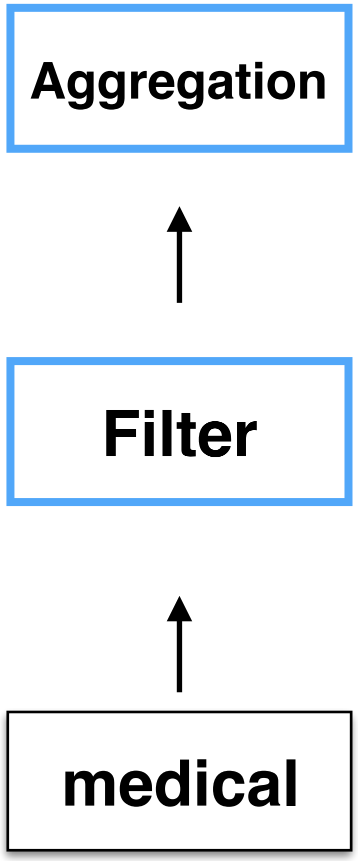
Opaque op.



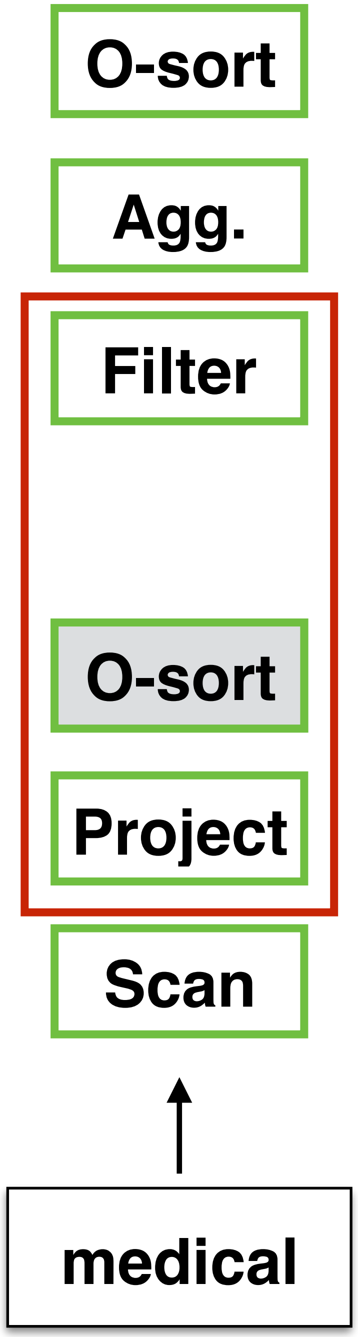
🔒 12809	Amanda D. Edwards	40	Diabetes	0
🔒 29489	Robert R. McGowan	56	Diabetes	0
🔒 13744	Kimberly R. Seay	51	Cancer	0
🔒 18740	Dennis G. Bates	32	Diabetes	0
🔒 32591	Donna R. Bridges	26	Diabetes	1
98329	Ronald S. Ogden	53	Cancer	0

Rule-based optimization

Logical op.



Opaque op.

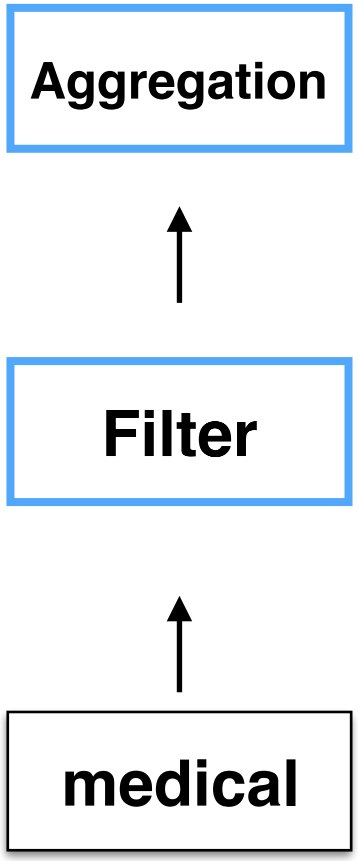


multi-column sort

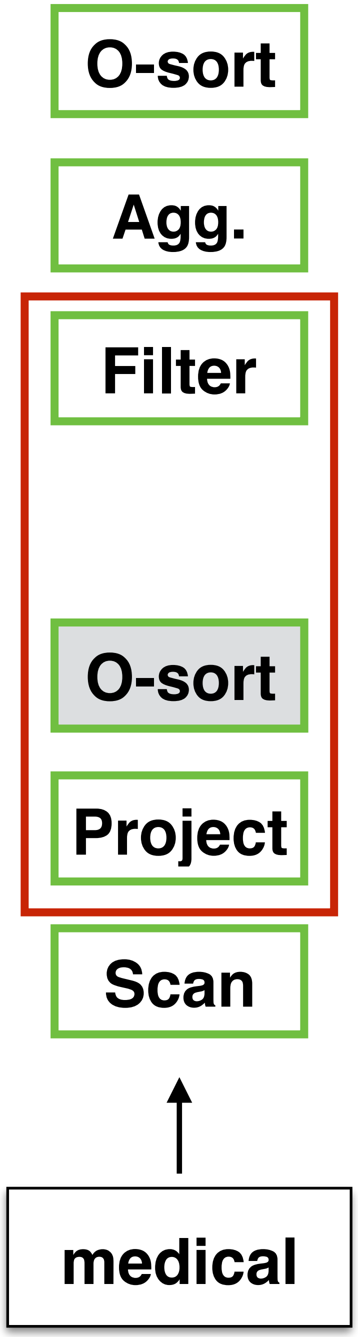
🔒	12809	Amanda D. Edwards	40	Diabetes	0
🔒	29489	Robert R. McGowan	56	Diabetes	0
🔒	13744	Kimberly R. Seay	51	Cancer	0
🔒	18740	Dennis G. Bates	32	Diabetes	0
🔒	32591	Donna R. Bridges	26	Diabetes	1
	98329	Ronald S. Ogden	53	Cancer	0

Rule-based optimization

Logical op.



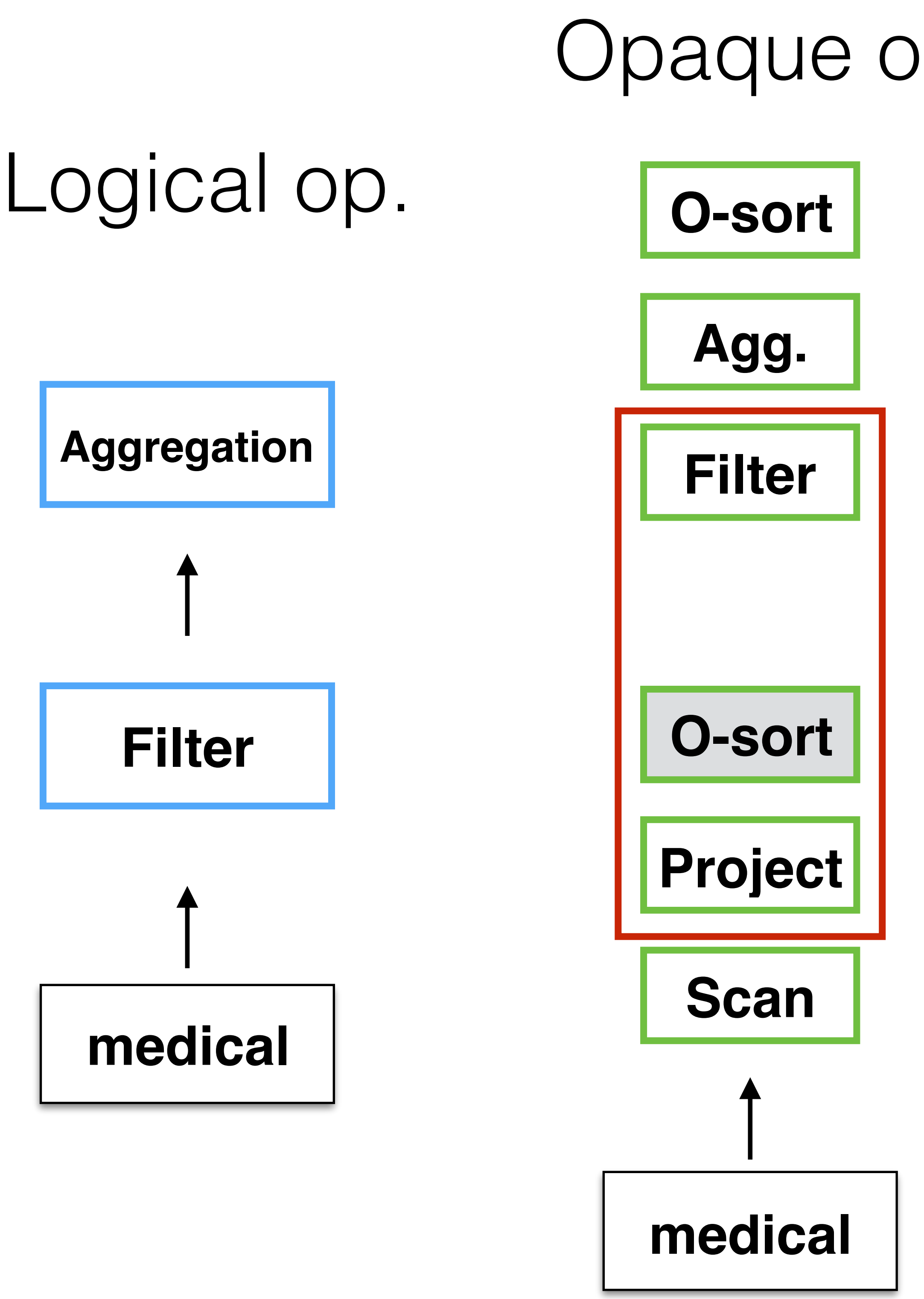
Opaque op.



multi-column sort

🔒 12809	Amanda D. Edwards	40	Diabetes	0
🔒 29489	Robert R. McGowan	56	Diabetes	0
🔒 13744	Kimberly R. Seay	51	Cancer	0
🔒 18740	Dennis G. Bates	32	Diabetes	0
🔒 32591	Donna R. Bridges	26	Diabetes	1
98329	Ronald S. Ogden	53	Cancer	0

Rule-based optimization



Opaque op.

Logical op.

O-sort

Agg.

Aggregation

Filter

Filter

O-sort

Project

Scan

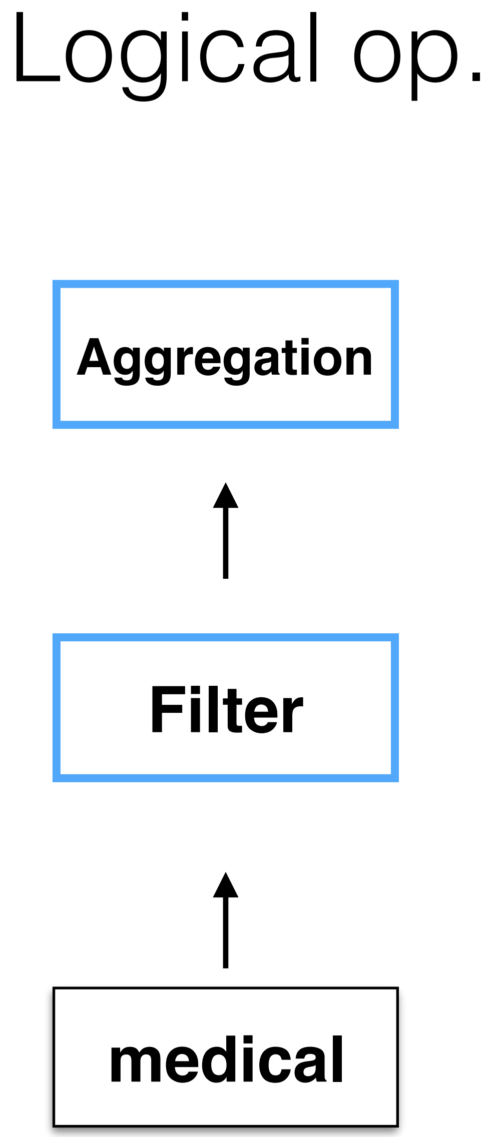
medical

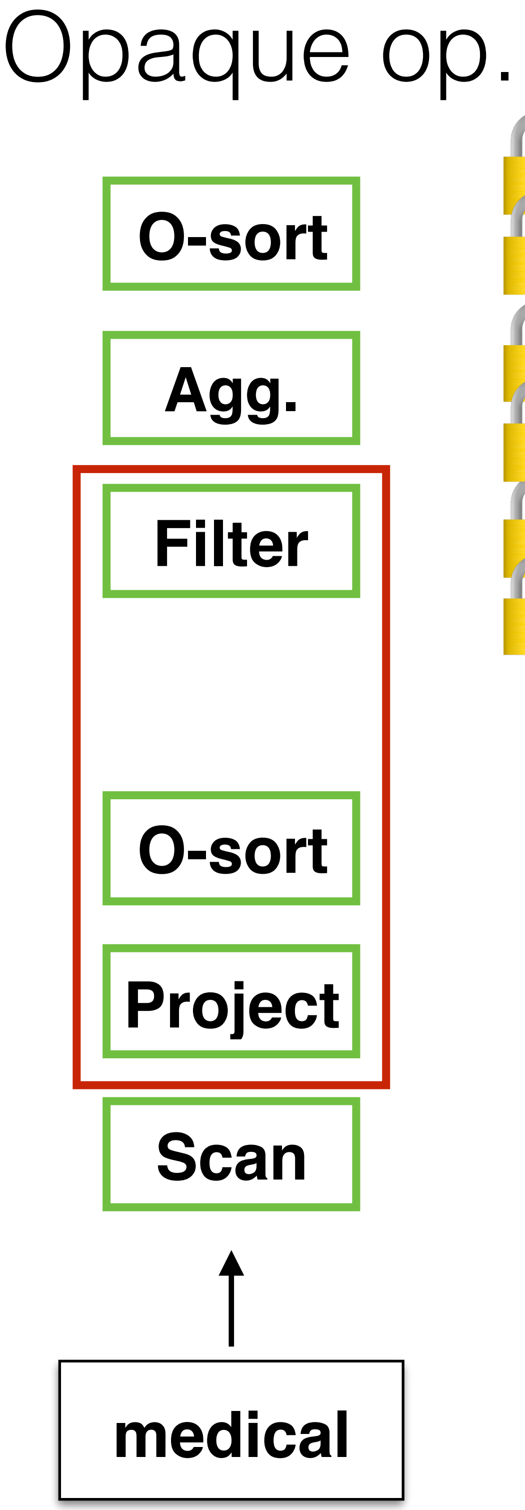
medical

multi-column sort

13744	Kimberly R. Seay	51	Cancer	0
98329	Ronald S. Ogden	53	Cancer	0
12809	Amanda D. Edwards	40	Diabetes	0
18740	Dennis G. Bates	32	Diabetes	0
29489	Robert R. McGowan	56	Diabetes	0
32591	Donna R. Bridges	26	Diabetes	1

Rule-based optimization

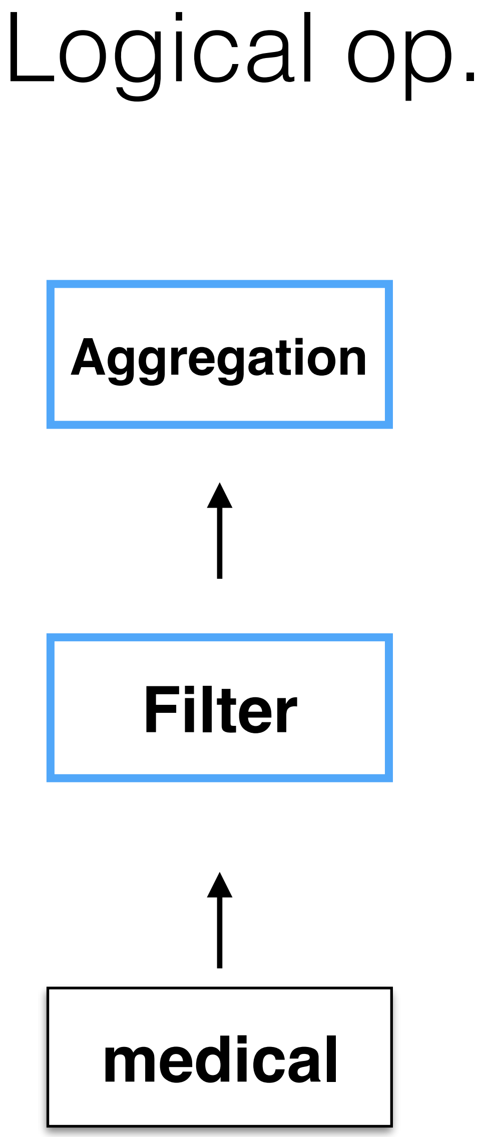


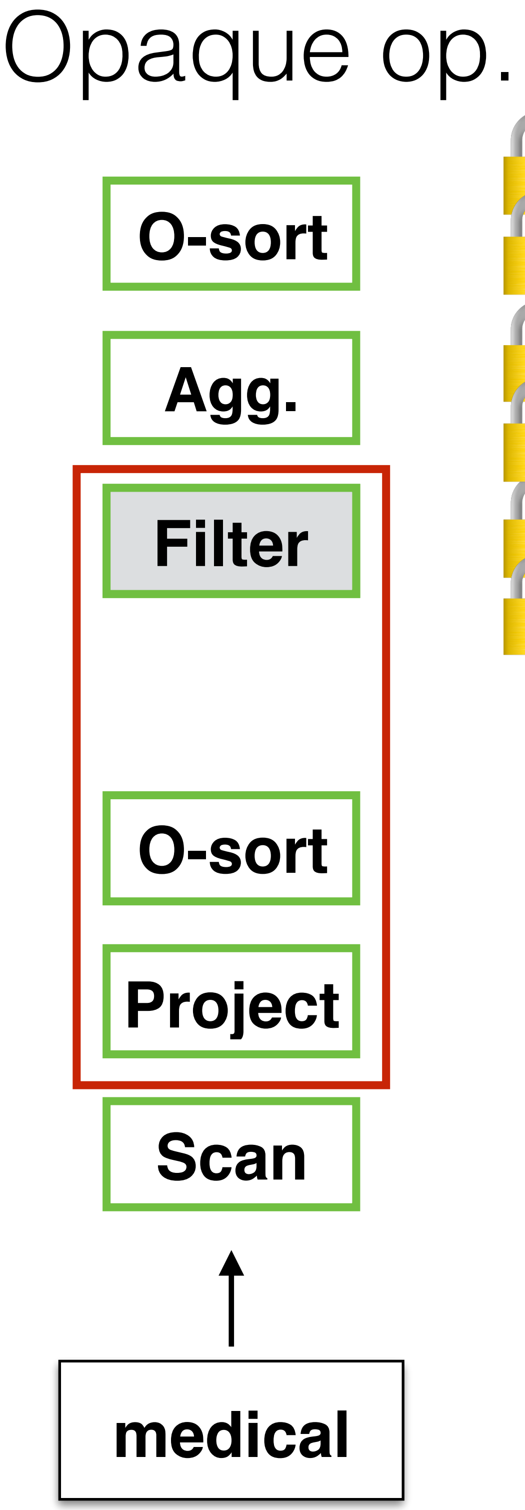


multi-column sort

🔒 13744	Kimberly R. Seay	51	Cancer	0
🔒 98329	Ronald S. Ogden	53	Cancer	0
🔒 12809	Amanda D. Edwards	40	Diabetes	0
🔒 18740	Dennis G. Bates	32	Diabetes	0
🔒 29489	Robert R. McGowan	56	Diabetes	0
32591	Donna R. Bridges	26	Diabetes	1

Rule-based optimization

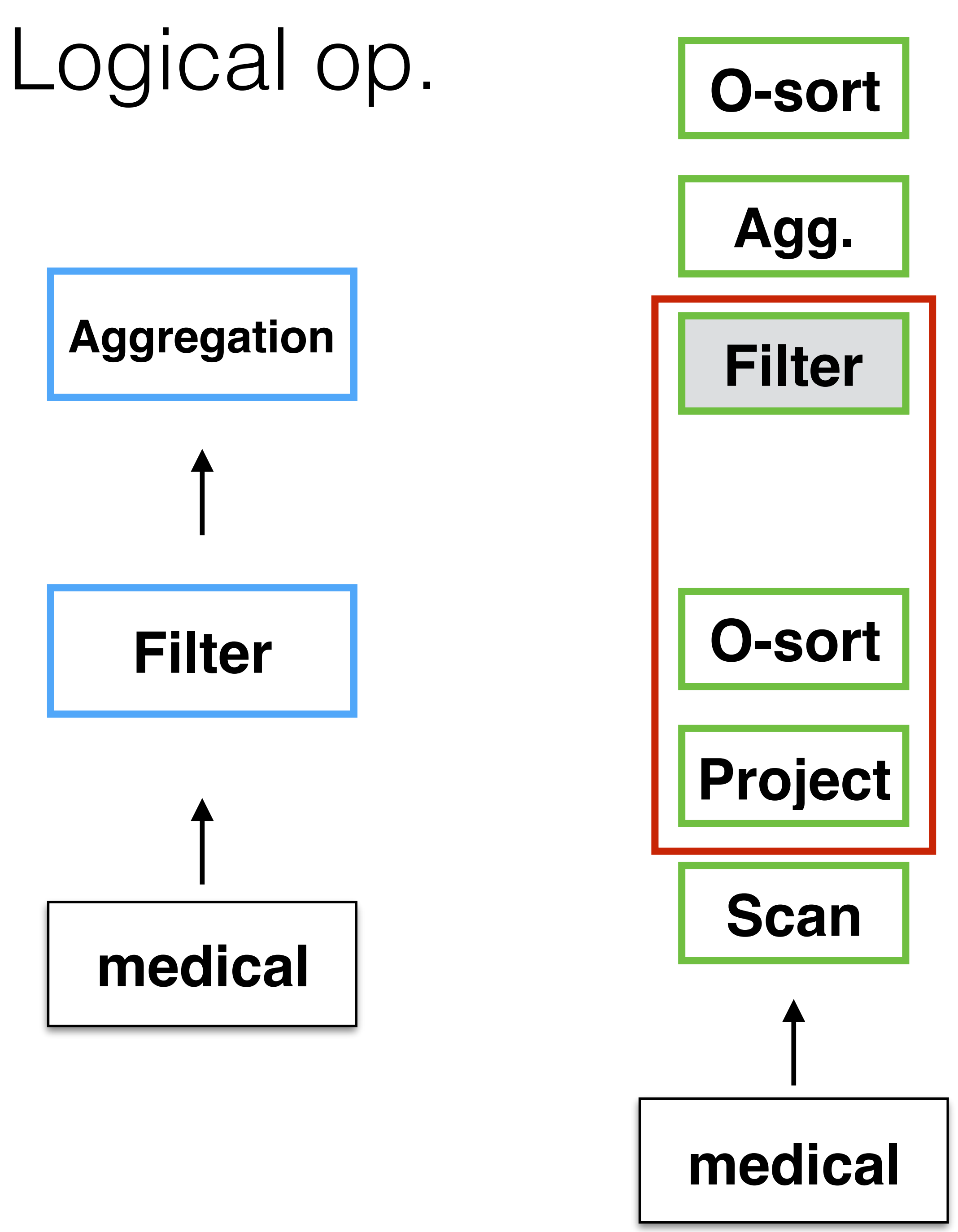




multi-column sort

13744	Kimberly R. Seay	51	Cancer	0
98329	Ronald S. Ogden	53	Cancer	0
12809	Amanda D. Edwards	40	Diabetes	0
18740	Dennis G. Bates	32	Diabetes	0
29489	Robert R. McGowan	56	Diabetes	0
32591	Donna R. Bridges	26	Diabetes	1

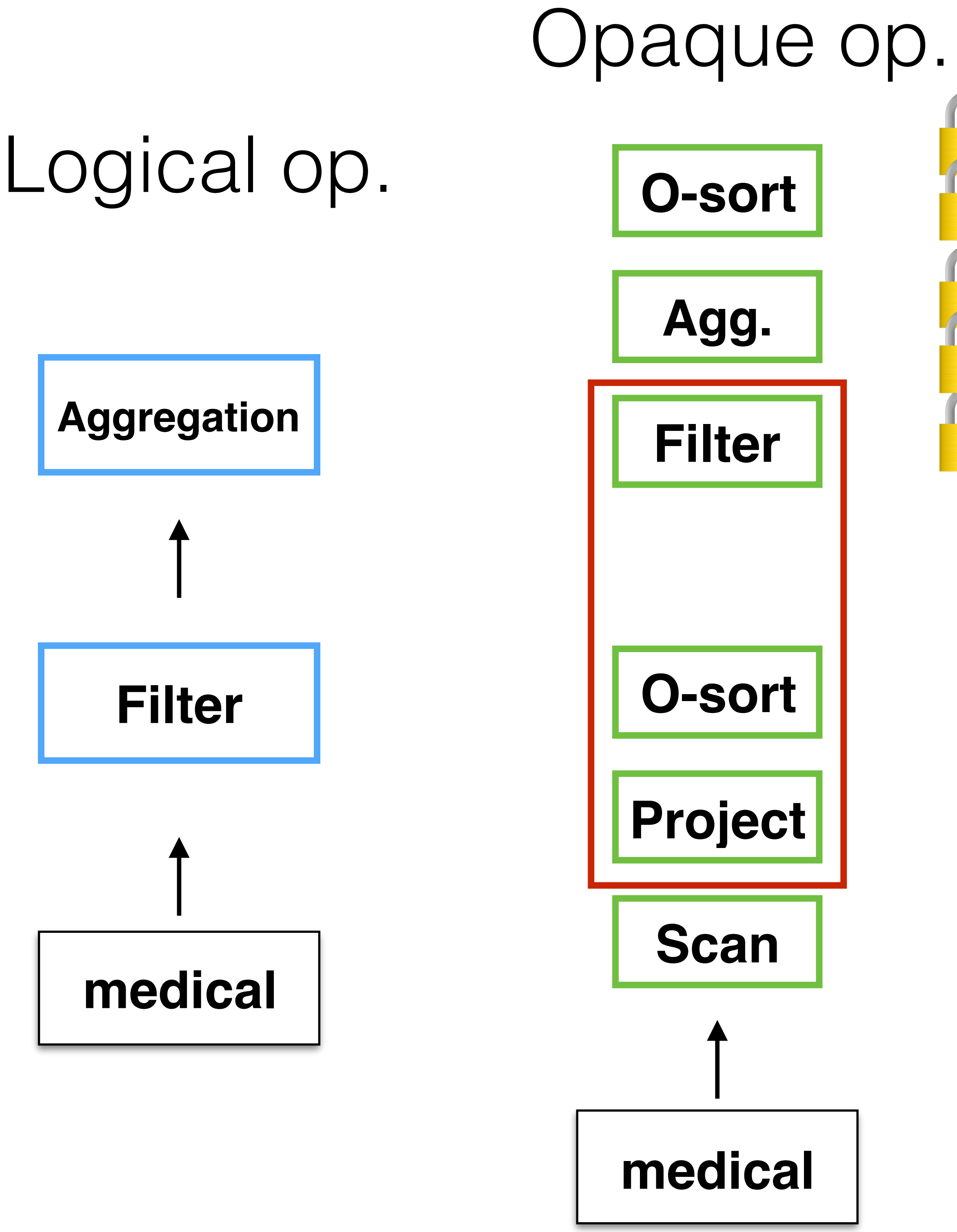
Rule-based optimization



multi-column sort

13744	Kimberly R. Seay	51	Cancer	0
98329	Ronald S. Ogden	53	Cancer	0
12809	Amanda D. Edwards	40	Diabetes	0
18740	Dennis G. Bates	32	Diabetes	0
29489	Robert R. McGowan	56	Diabetes	0

Rule-based optimization



Logical op.

Aggregation

Filter

medical

Opaque op.

O-sort

Agg.

Filter

O-sort

Project

Scan

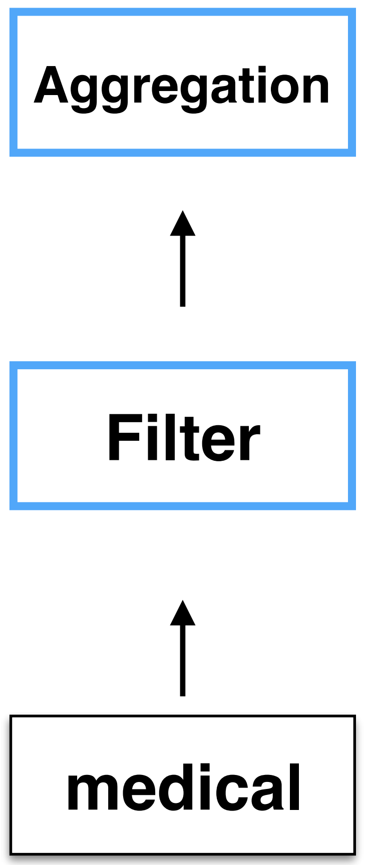
medical

multi-column sort

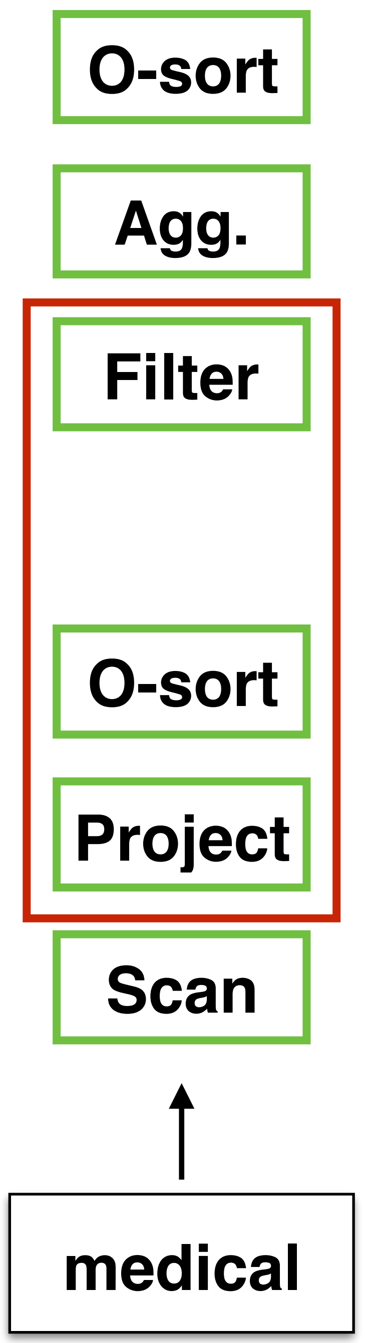
13744	Kimberly R. Seay	51	Cancer	0
98329	Ronald S. Ogden	53	Cancer	0
12809	Amanda D. Edwards	40	Diabetes	0
18740	Dennis G. Bates	32	Diabetes	0
29489	Robert R. McGowan	56	Diabetes	0

Rule-based optimization

Logical op.



Opaque op.



multi-column sort

13744	Kimberly R. Seay	51	Cancer	0
98329	Ronald S. Ogden	53	Cancer	0
12809	Amanda D. Edwards	40	Diabetes	0
18740	Dennis G. Bates	32	Diabetes	0
29489	Robert R. McGowan	56	Diabetes	0

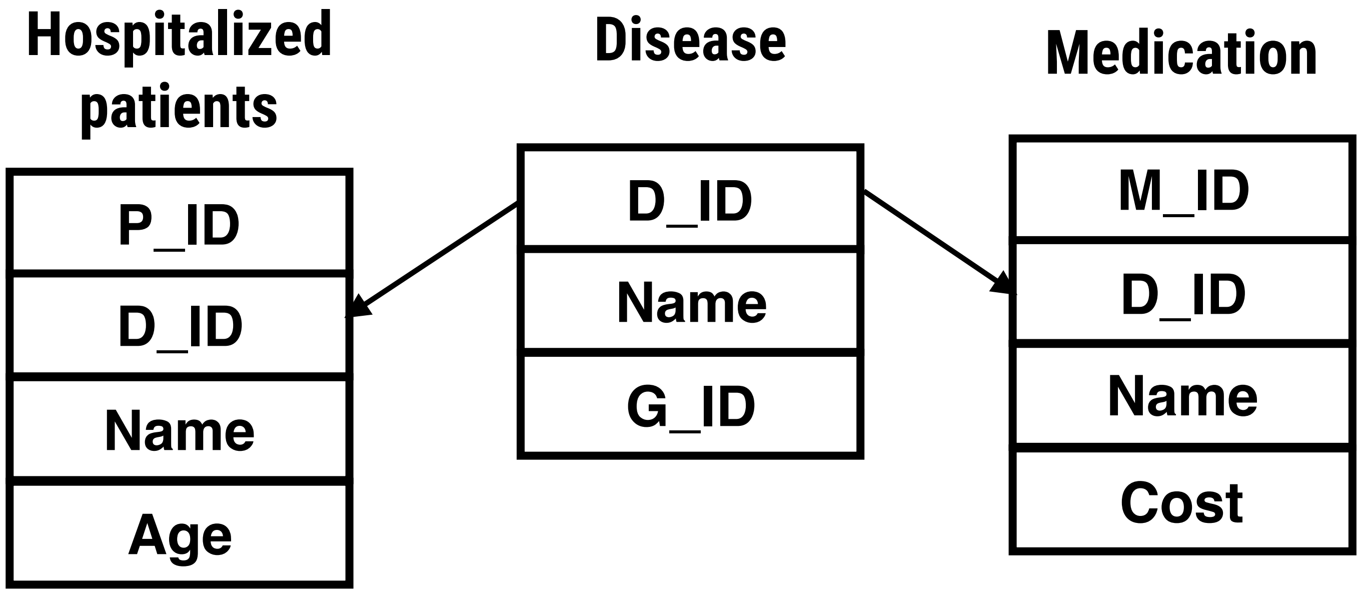
Eliminated one oblivious sort!

Two-part solution:

- Distributed oblivious SQL operators
  - Oblivious filter
  - Oblivious sort
  - Oblivious aggregation
  - Oblivious join
- Novel query planning techniques
  - Rule-based optimization
  - Cost model
  - **Cost-based optimization**

Observation: not all tables are sensitive

Observation: not all tables are sensitive



Hospitalized patients

P_ID

D_ID

Name

Age

Disease

D_ID

Name

G_ID

Medication

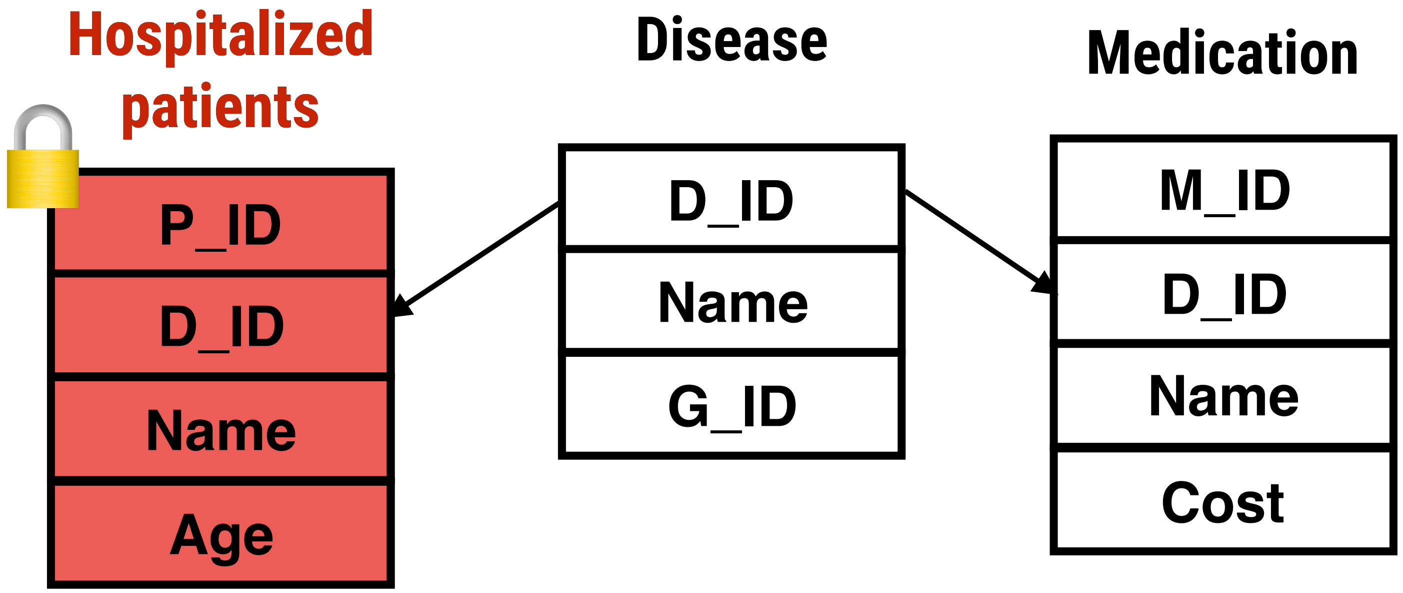
M_ID

D_ID

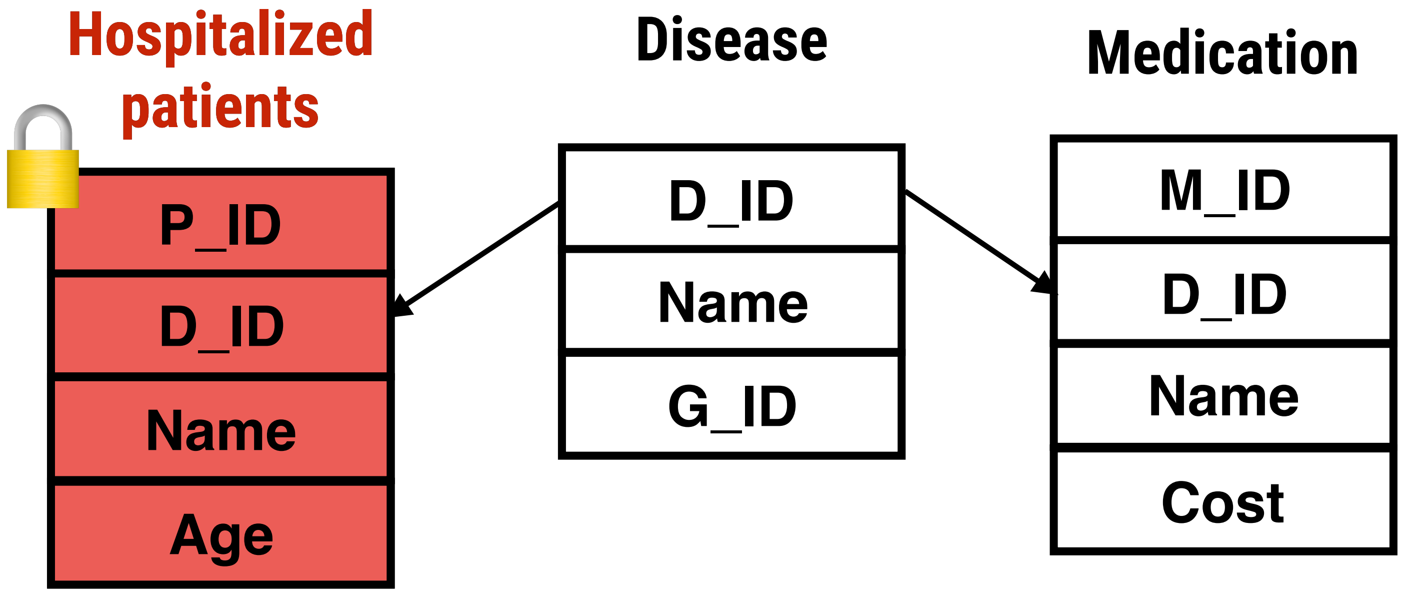
Name

Cost

Observation: not all tables are sensitive

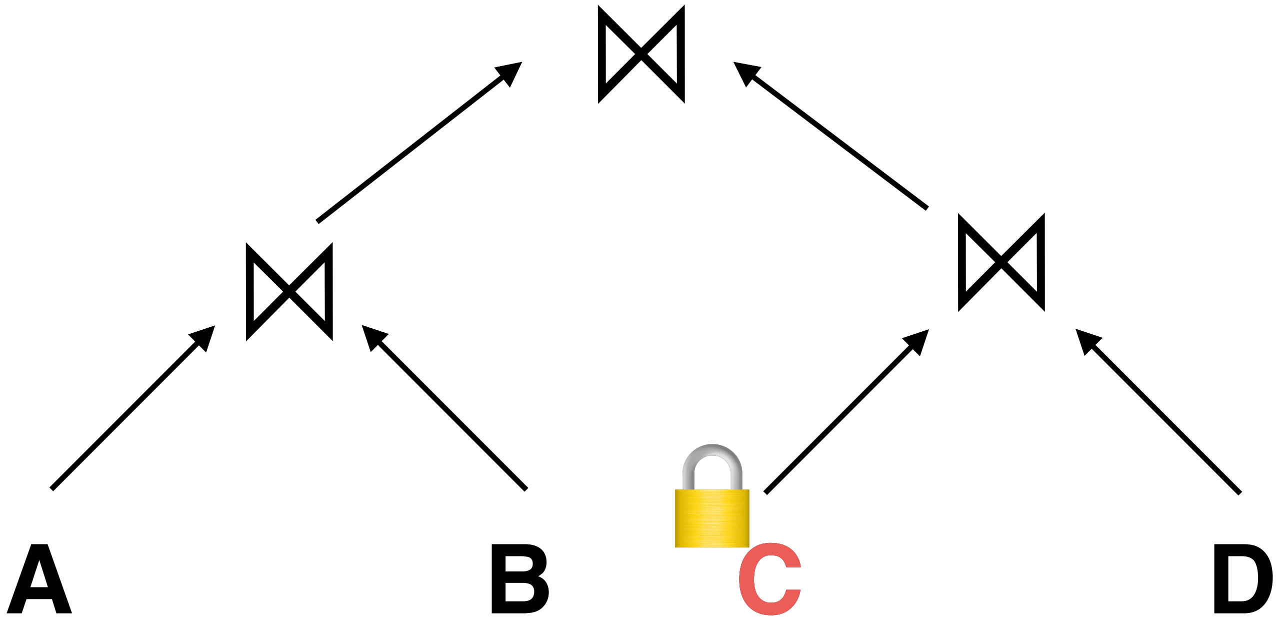


Observation: not all tables are sensitive

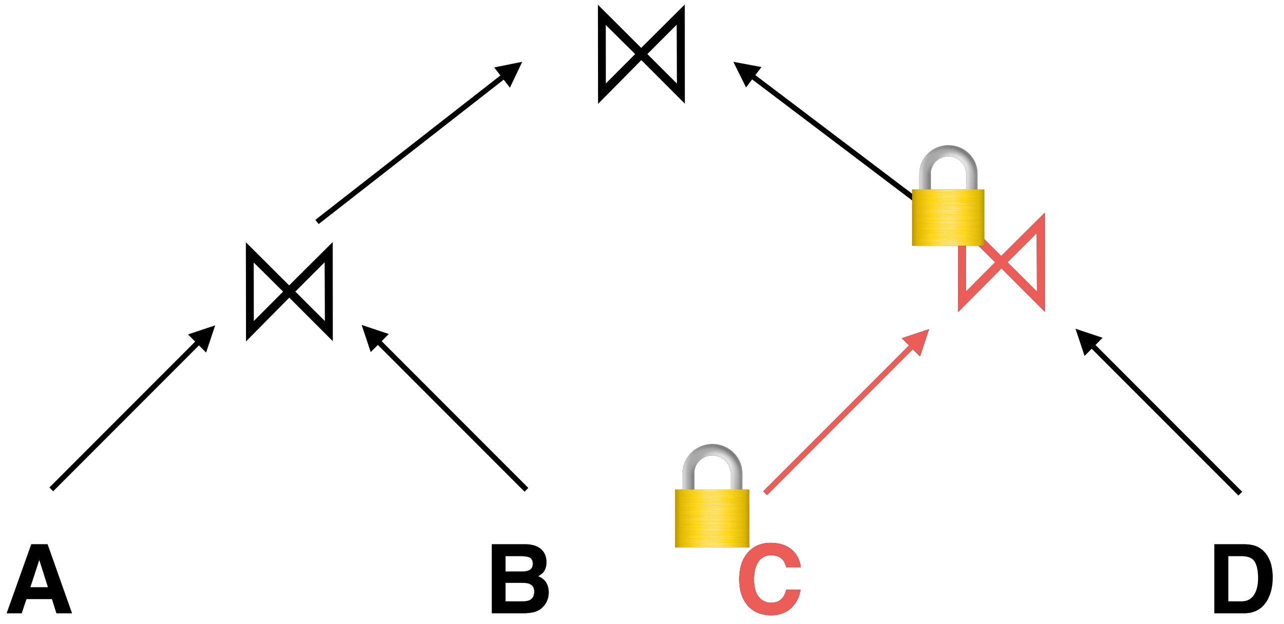


Opaque can operate in *mixed sensitivity*:
sensitive tables are run with oblivious operators

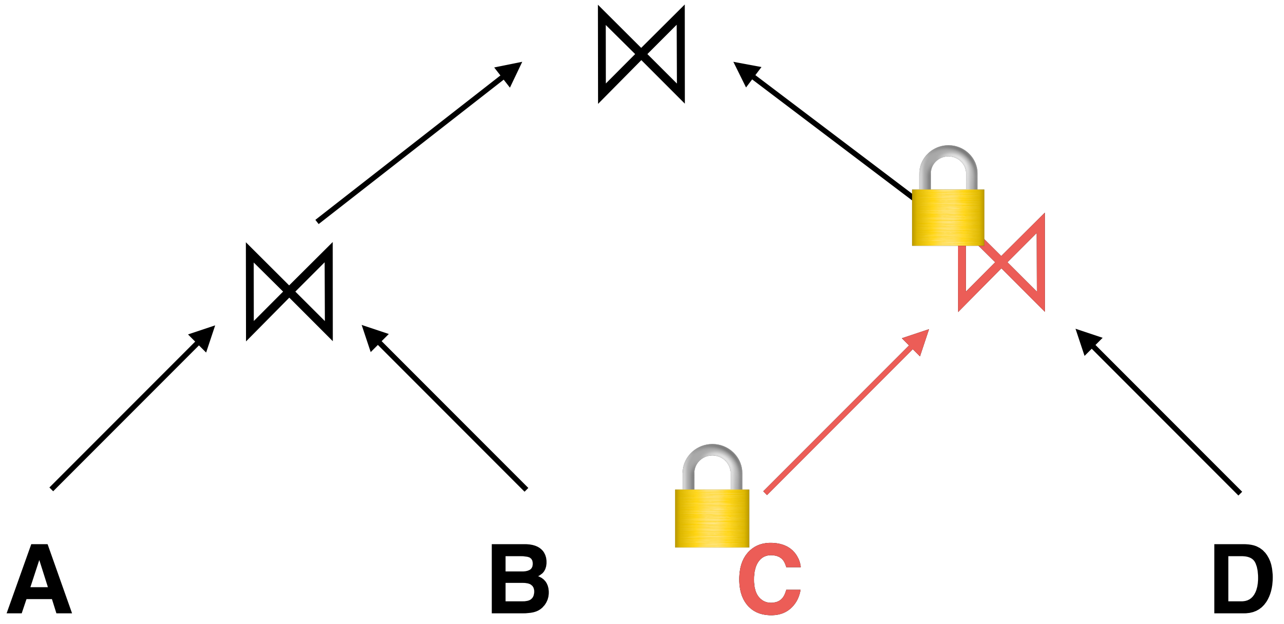
Observation: not all tables are sensitive



Observation: not all tables are sensitive

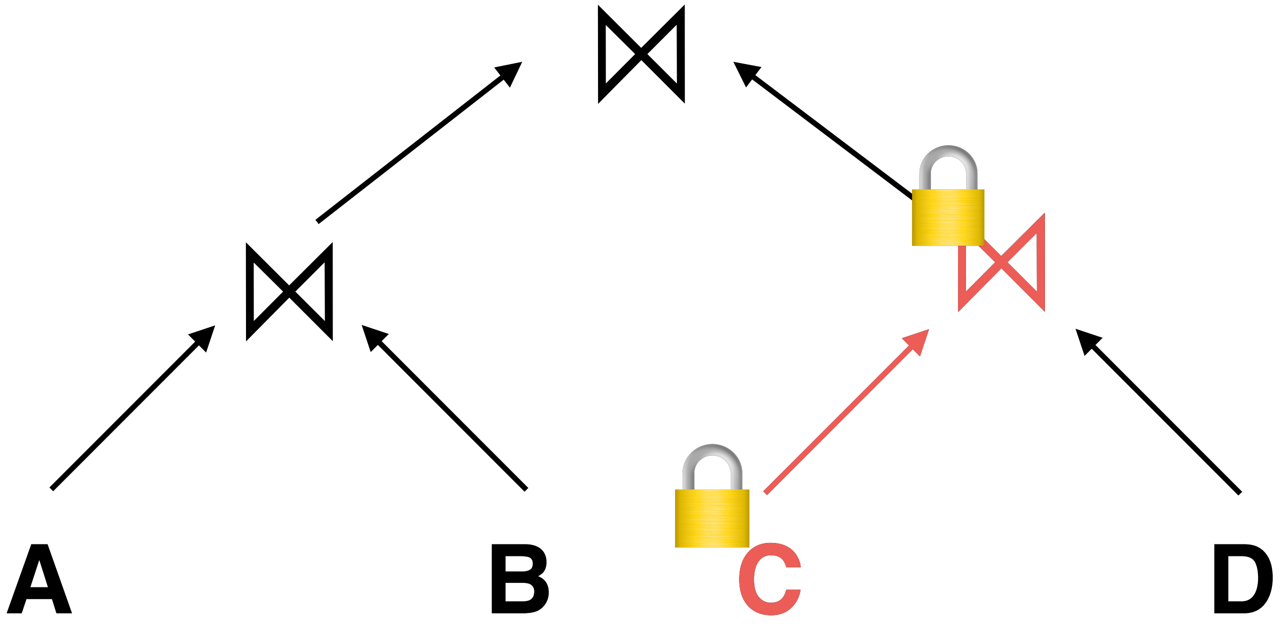


Observation: not all tables are sensitive

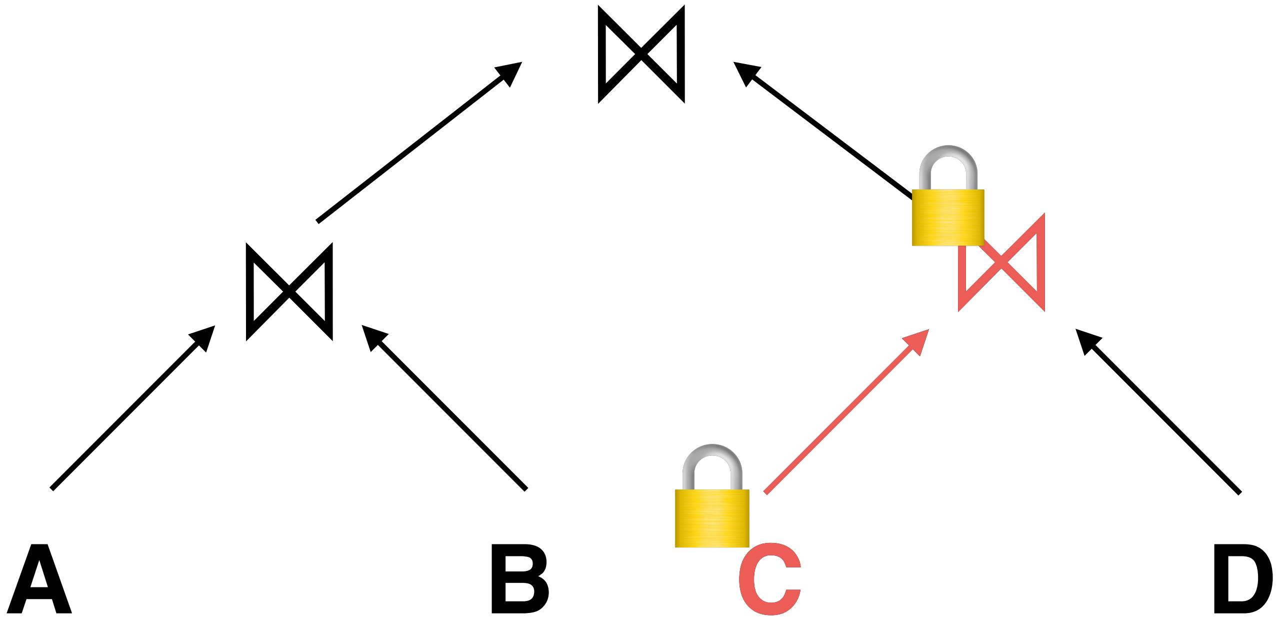


Not oblivious!

Observation: not all tables are sensitive

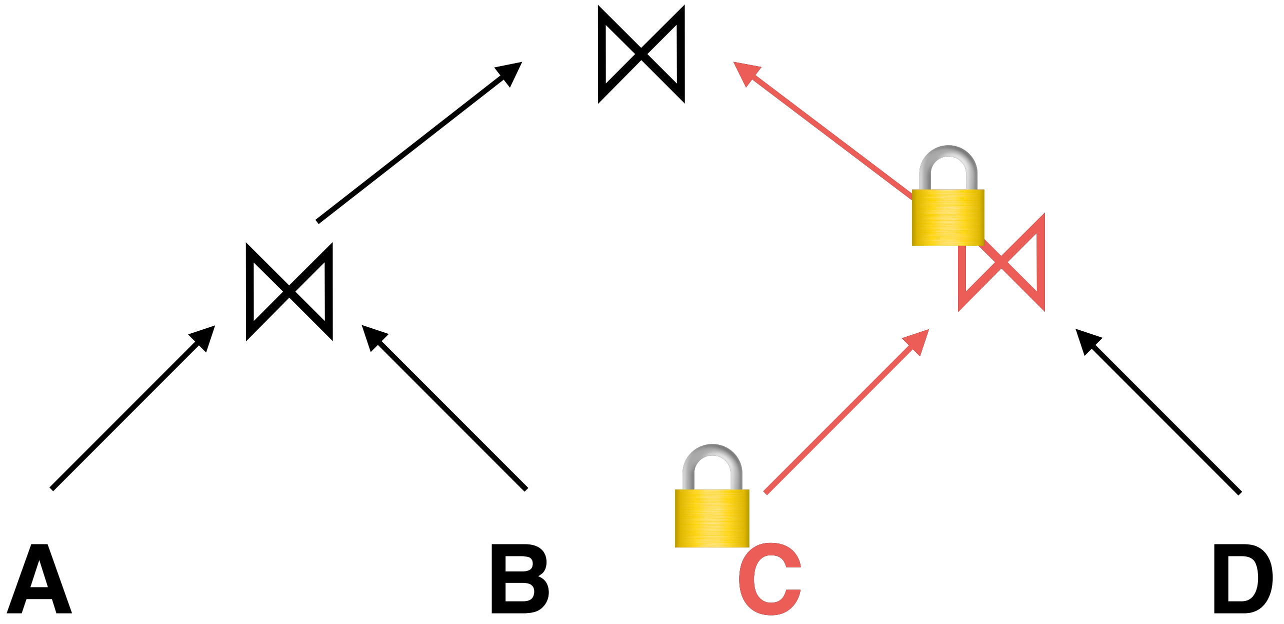


Observation: not all tables are sensitive



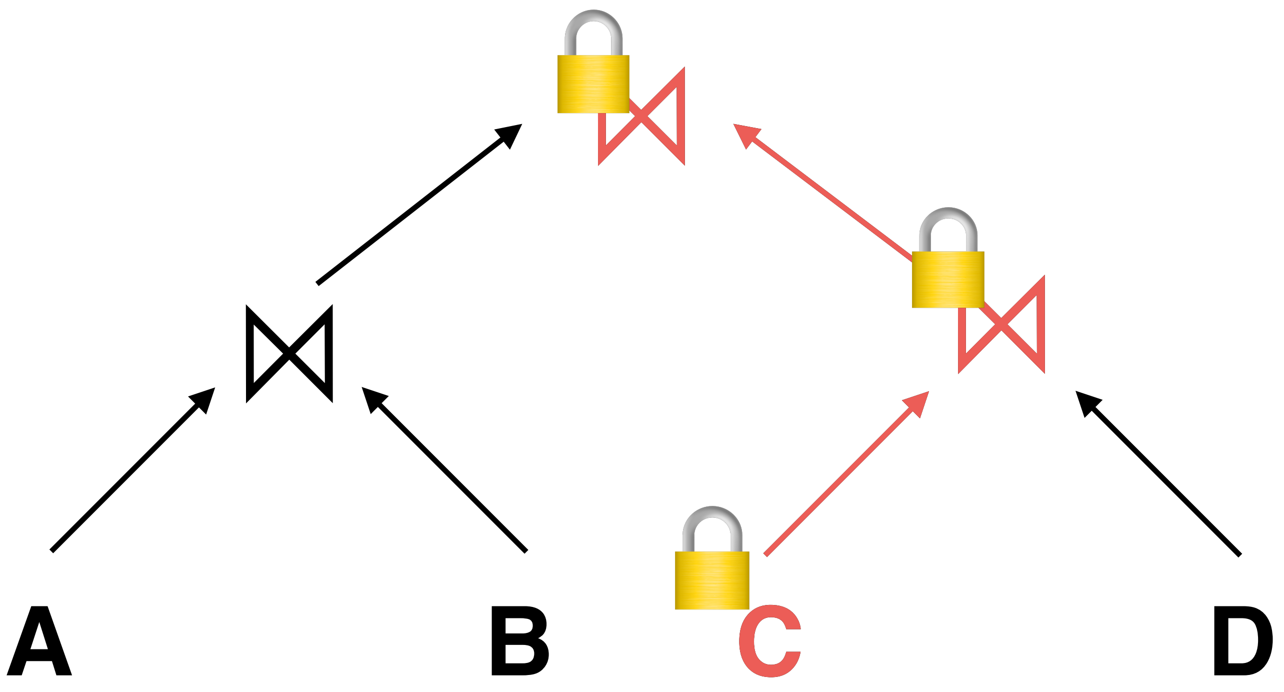
Sensitivity propagation: propagate obliviousness from leaf to root

Observation: not all tables are sensitive



Sensitivity propagation: propagate obliviousness from leaf to root

Observation: not all tables are sensitive

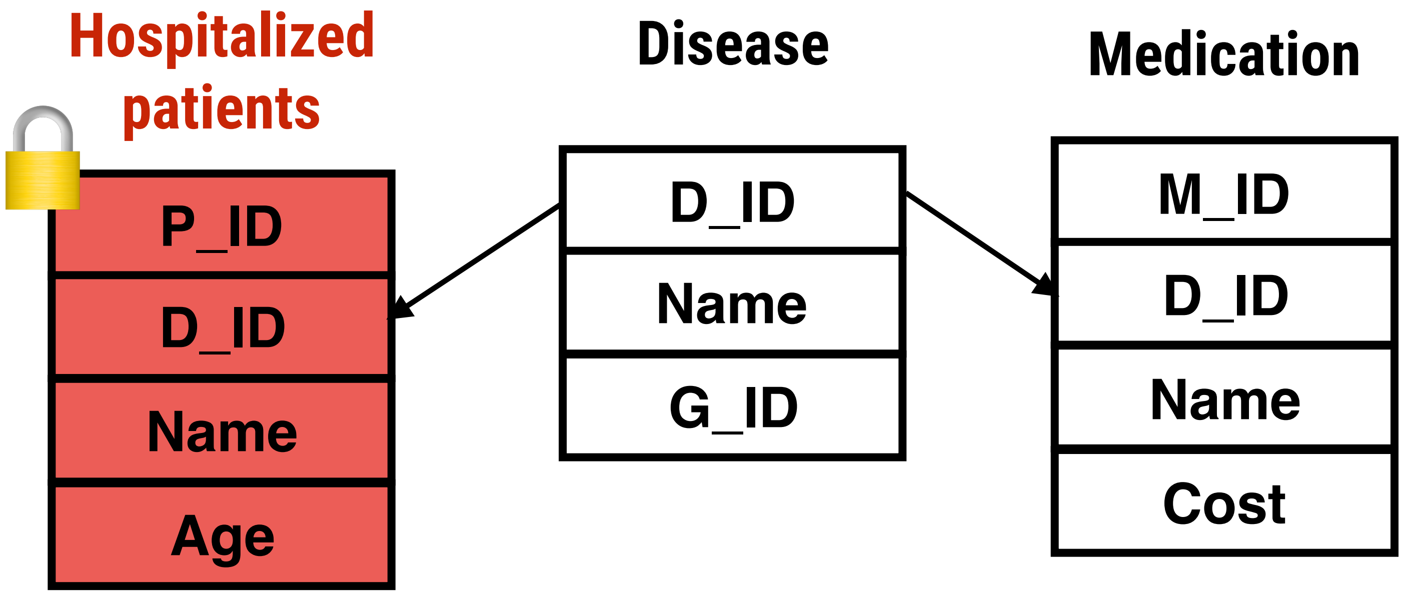


Sensitivity propagation: propagate obliviousness from leaf to root

Insight 2

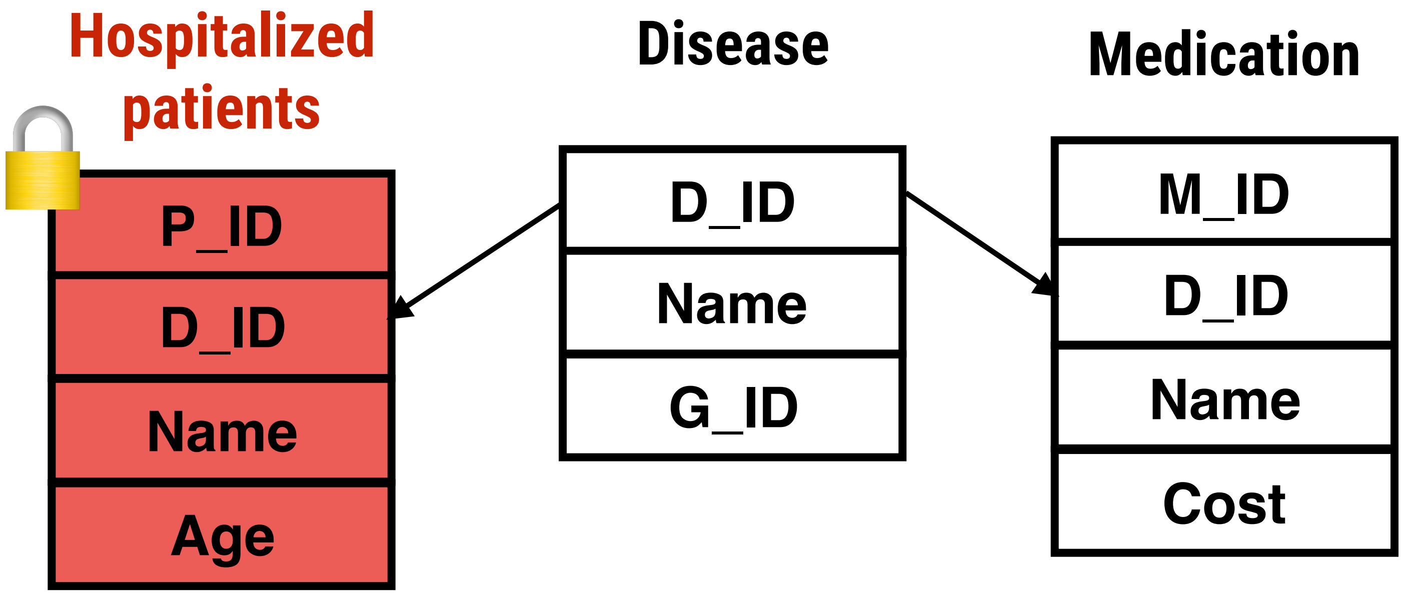
Sensitivity propagation introduces a new dimension to query optimization

Cost-based optimization



Find the least costly medication for each patient

Cost-based optimization



Hospitalized patients

P_ID
D_ID
Name
Age

Disease

D_ID
Name
G_ID

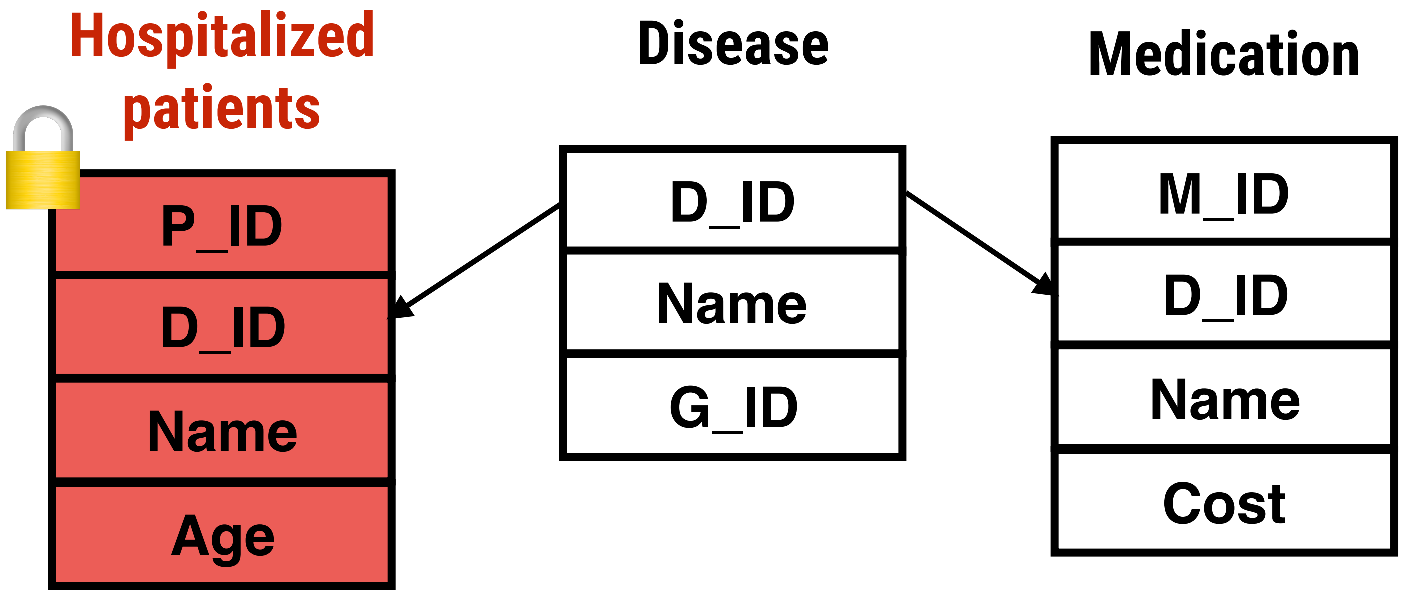
Medication

M_ID
D_ID
Name
Cost

Find the least costly medication for each patient

Assumption: |P| < |D| < |M|

Cost-based optimization

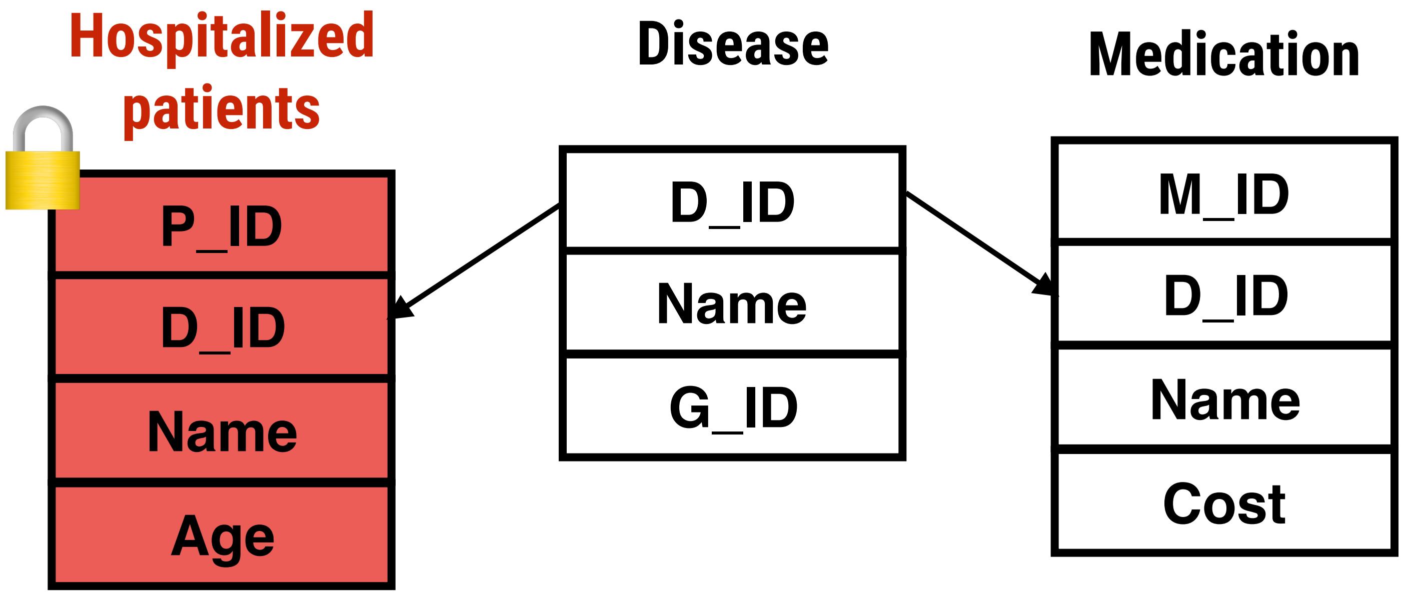


Find the least costly medication for each patient

Assumption: |P| < |D| < |M|

```
SELECT p_name, d_name, med_cost
FROM patient, disease,
     (SELECT d_id, min(cost) AS med_cost
        FROM medication
        GROUP BY d_id) AS med
WHERE disease.d_id = patient.d_id
      AND disease.d_id = med.d_id
```

Cost-based optimization



Hospitalized patients

P_ID
D_ID
Name
Age

Disease

D_ID
Name
G_ID

Medication

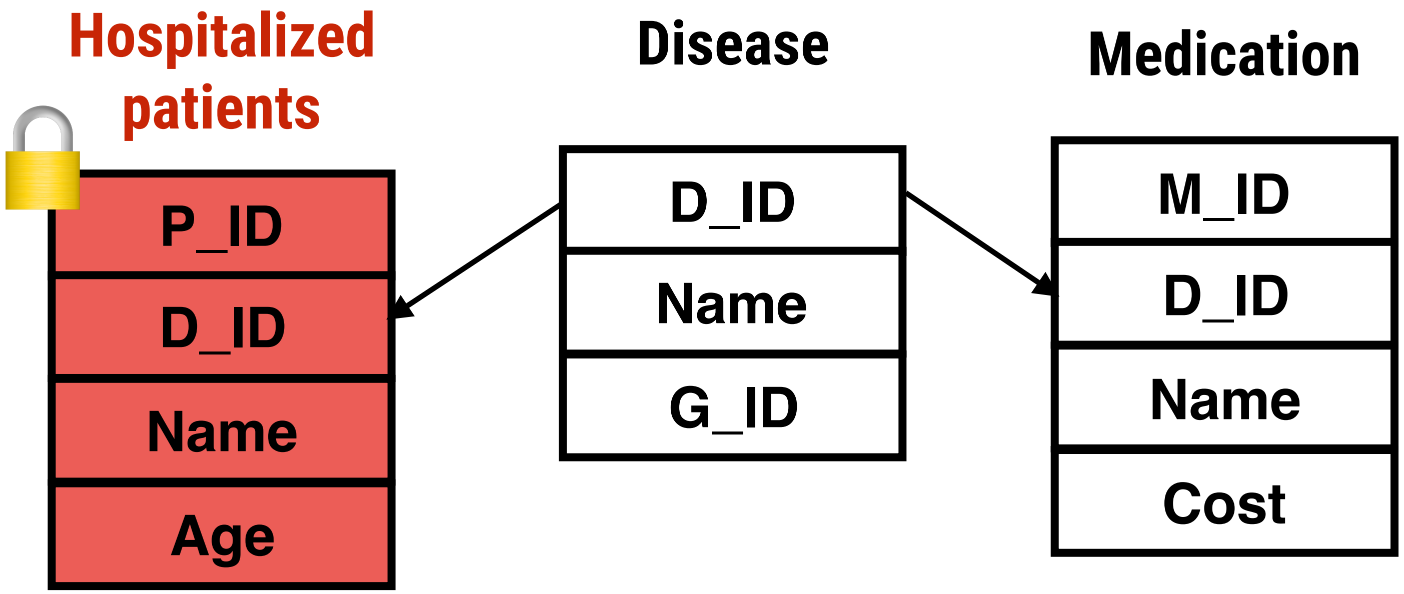
M_ID
D_ID
Name
Cost

Find the least costly medication for each patient

Assumption: |P| < |D| < |M|

```
SELECT p_name, d_name, med_cost
FROM patient, disease,
     (SELECT d_id, min(cost) AS med_cost
        FROM medication
        GROUP BY d_id) AS med
WHERE disease.d_id = patient.d_id
      AND disease.d_id = med.d_id
```

Cost-based optimization



Hospitalized patients

P_ID

D_ID

Name

Age

Disease

D_ID

Name

G_ID

Medication

M_ID

D_ID

Name

Cost

Find the least costly medication for each patient

Assumption: |P| < |D| < |M|

```
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     (SELECT d_id, min(cost) AS med_cost
        FROM medication
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WHERE disease.d_id = patient.d_id
      AND disease.d_id = med.d_id
```
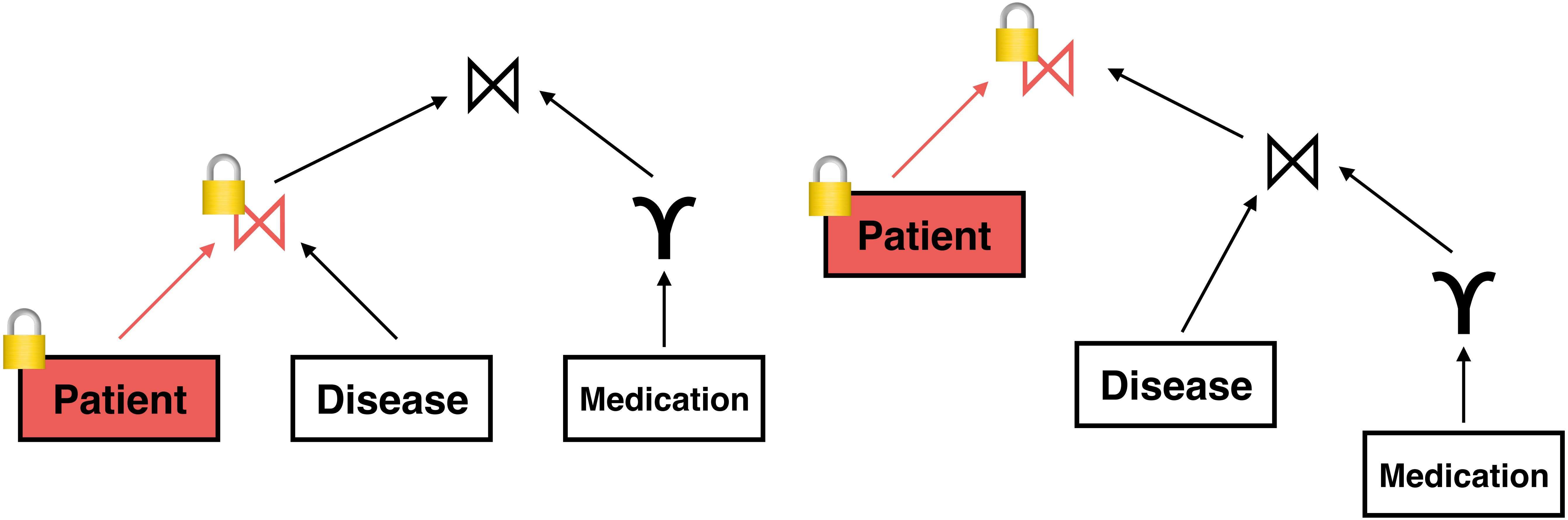

→ **3-way join**

Cost-based optimization

SQL optimizer with new cost:



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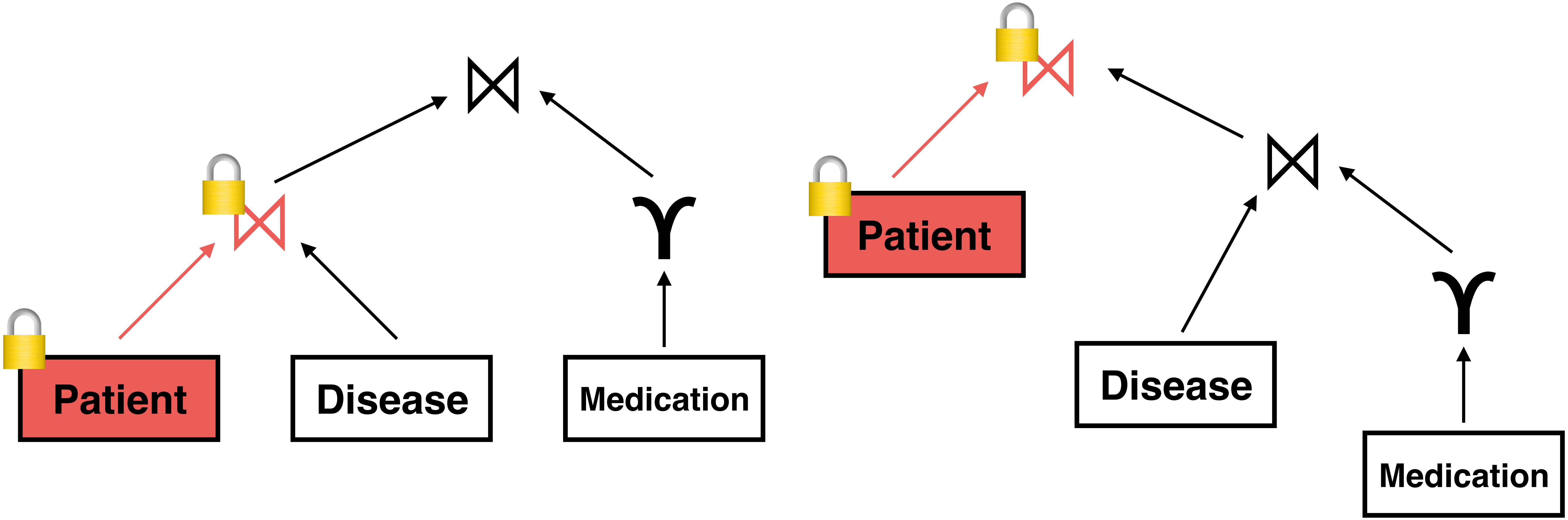

More selective
non-oblivious join

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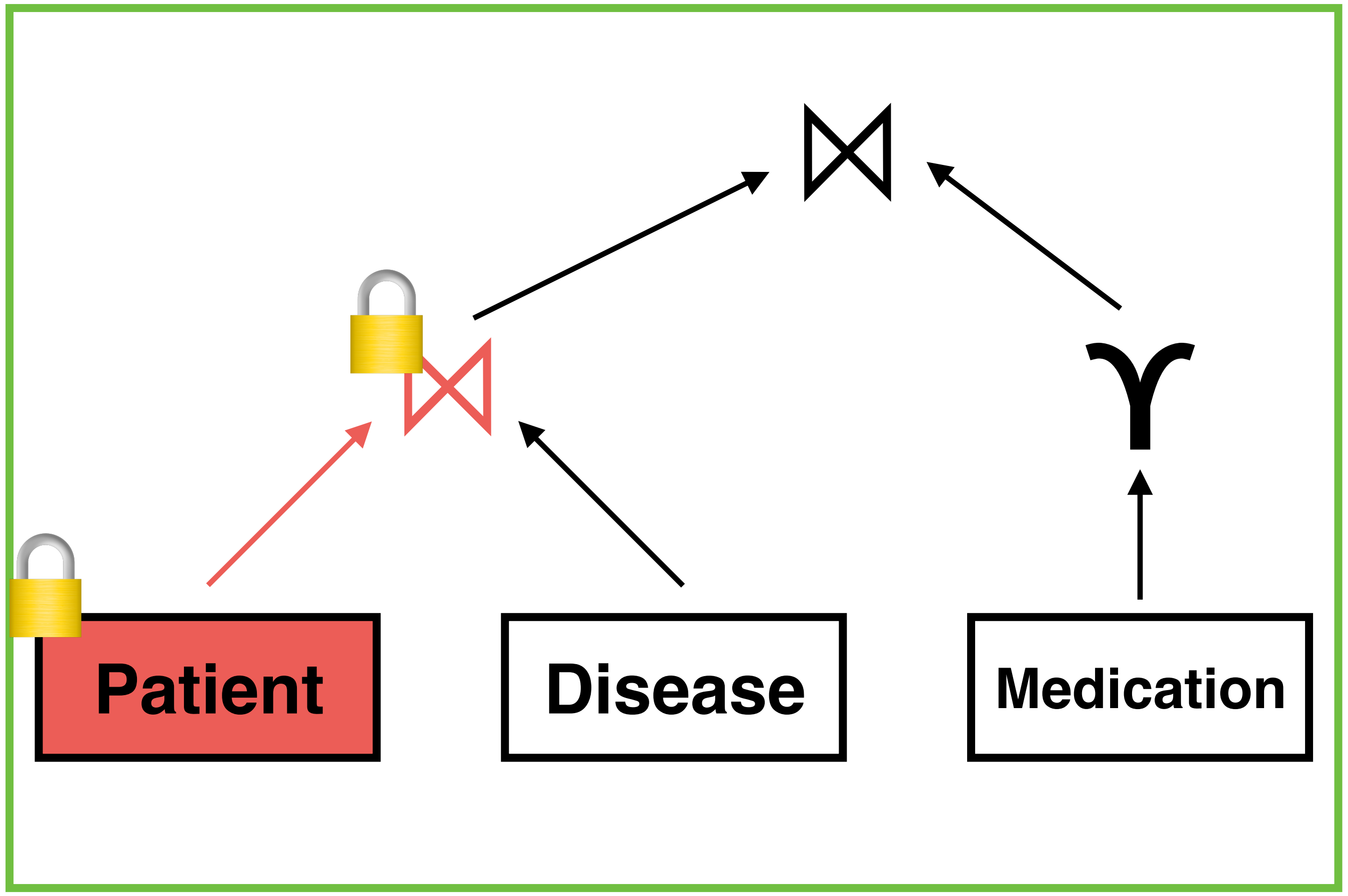

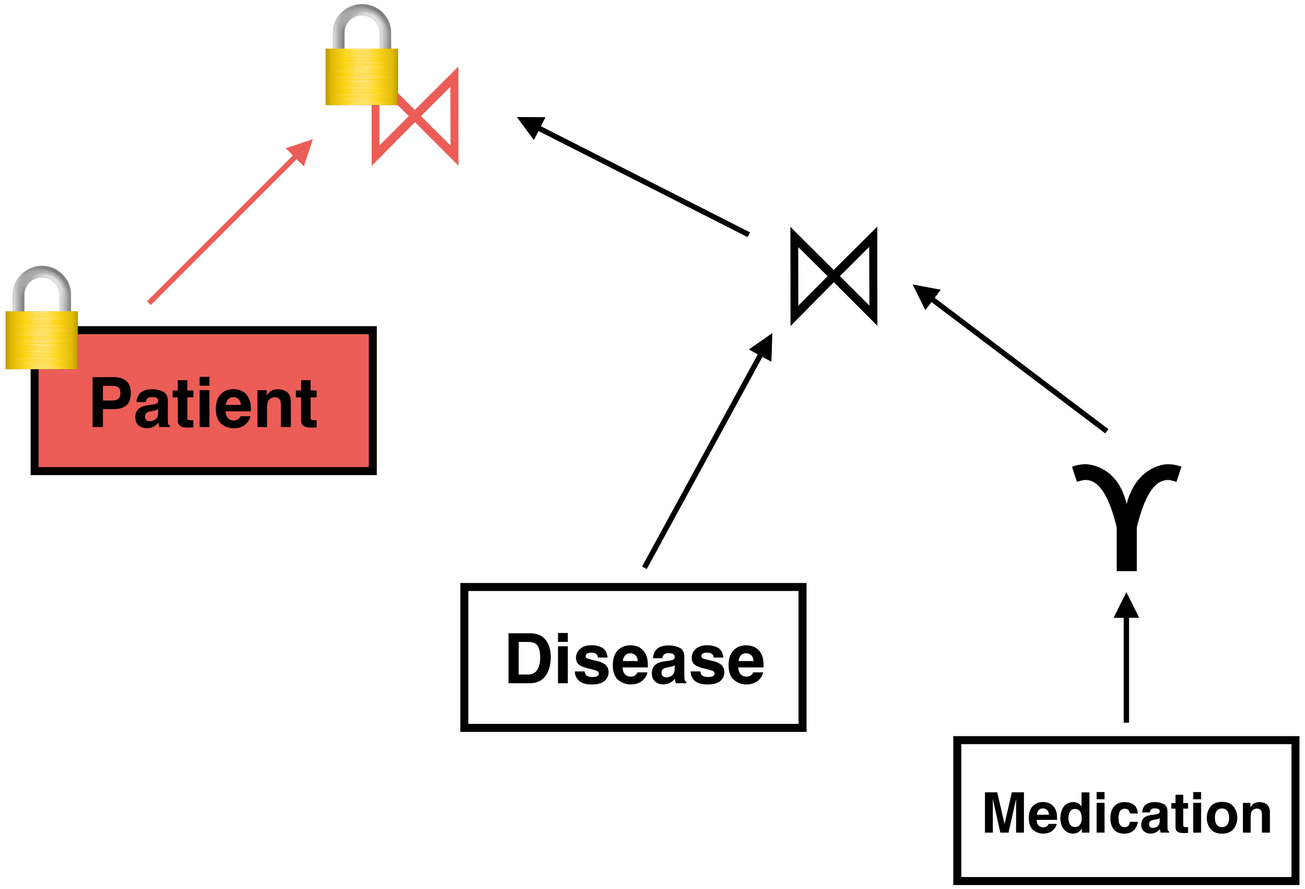

More selective
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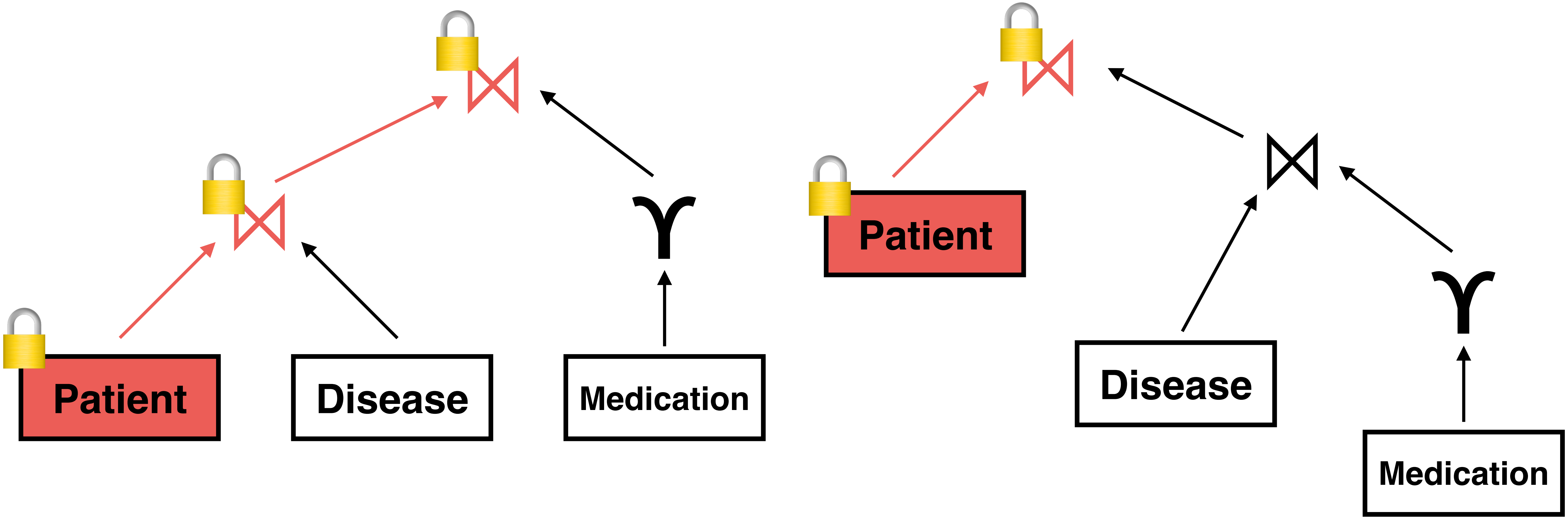
Cost-based optimization

SQL optimizer with new cost and **sensitivity propagation**:



Cost-based optimization

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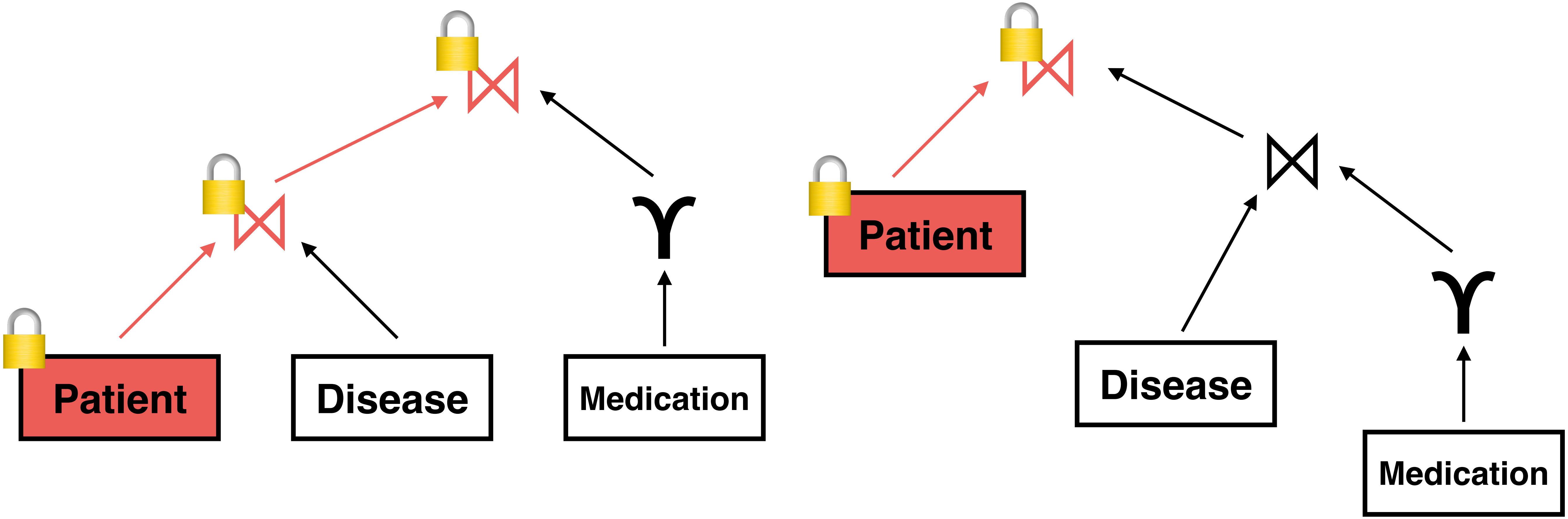

Fewer oblivious joins

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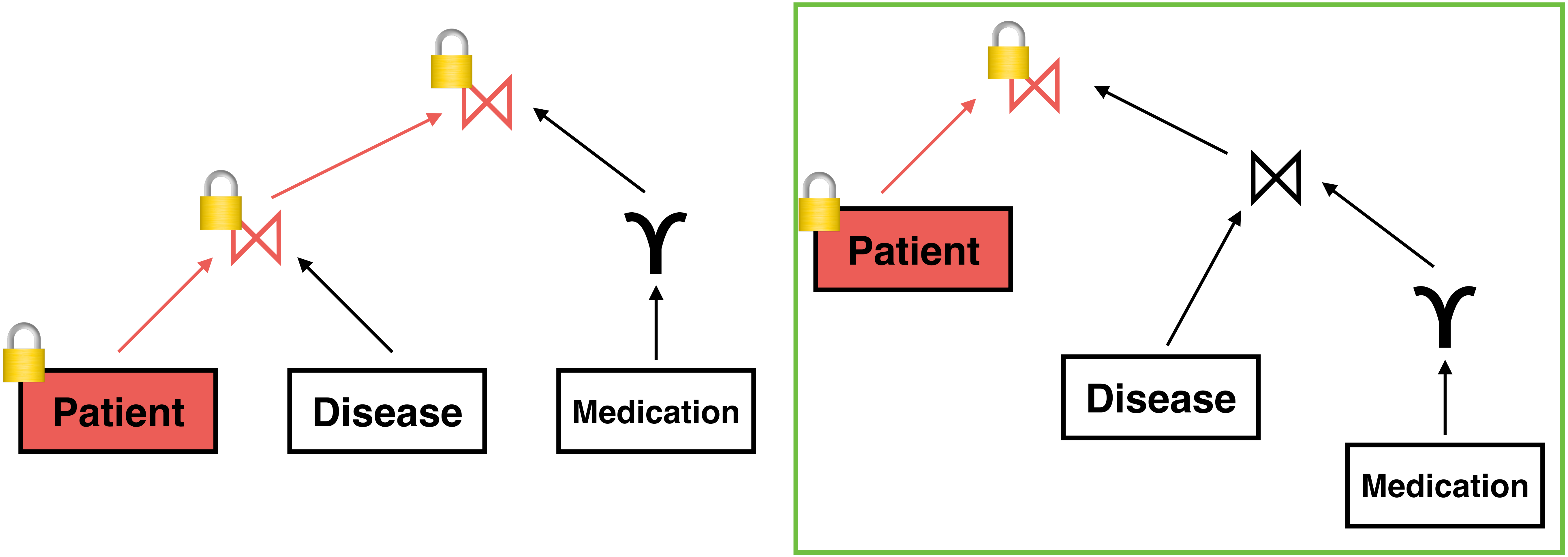

Fewer oblivious joins

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- Distributed experiments
  - A cluster of 5 SGX machines

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Data encryption, authentication, computation verification

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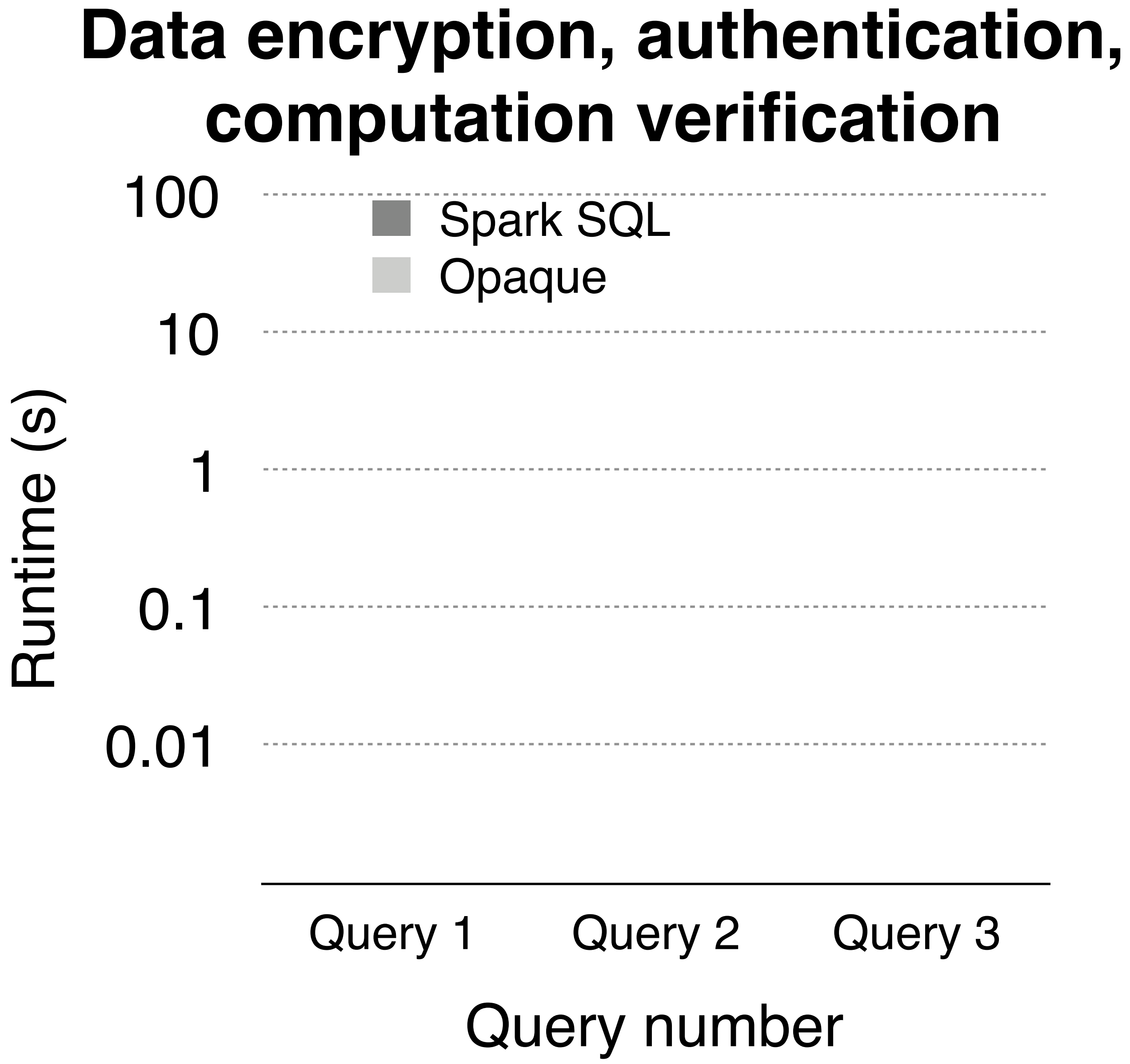
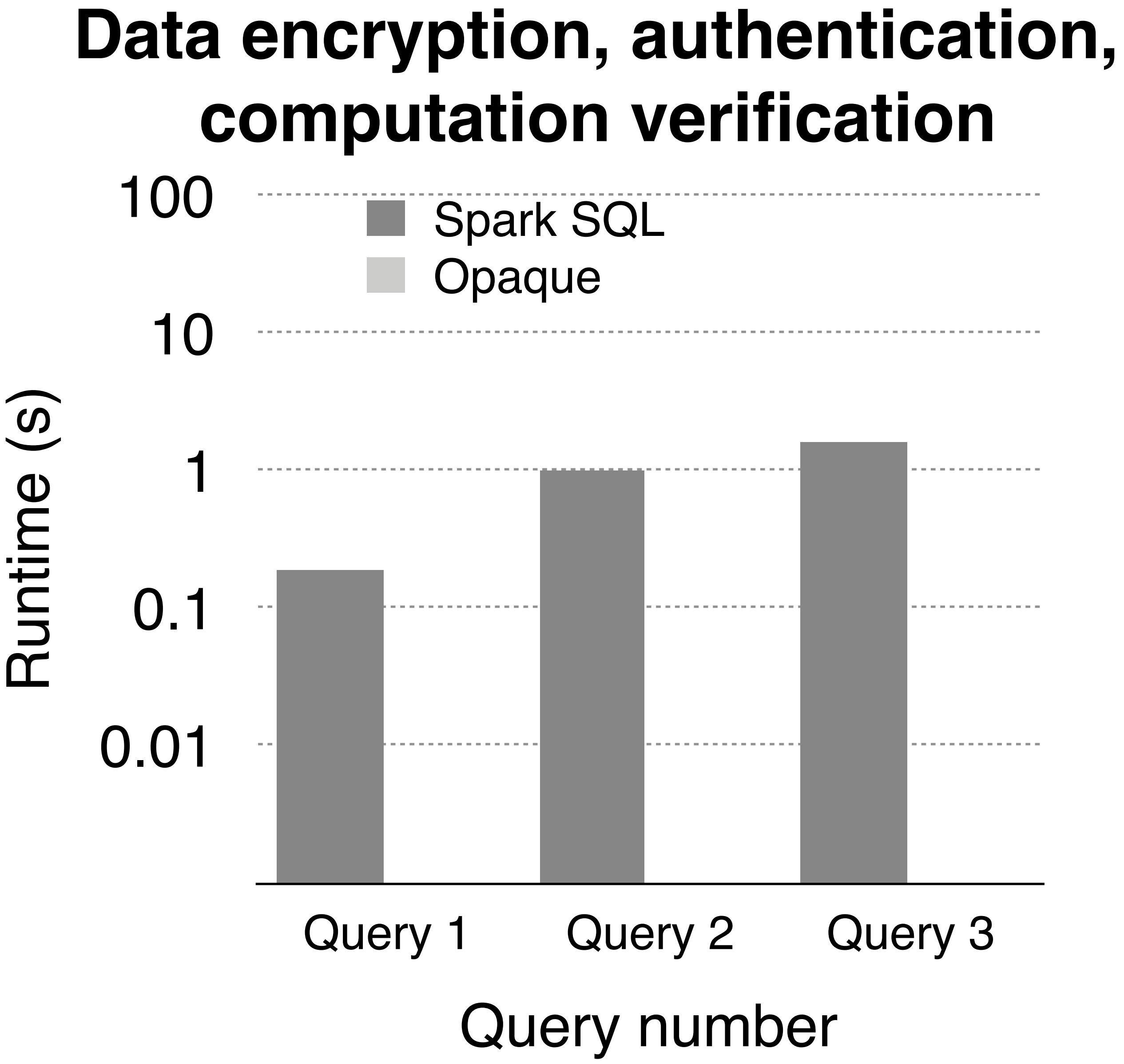


Big Data Benchmark (distributed)



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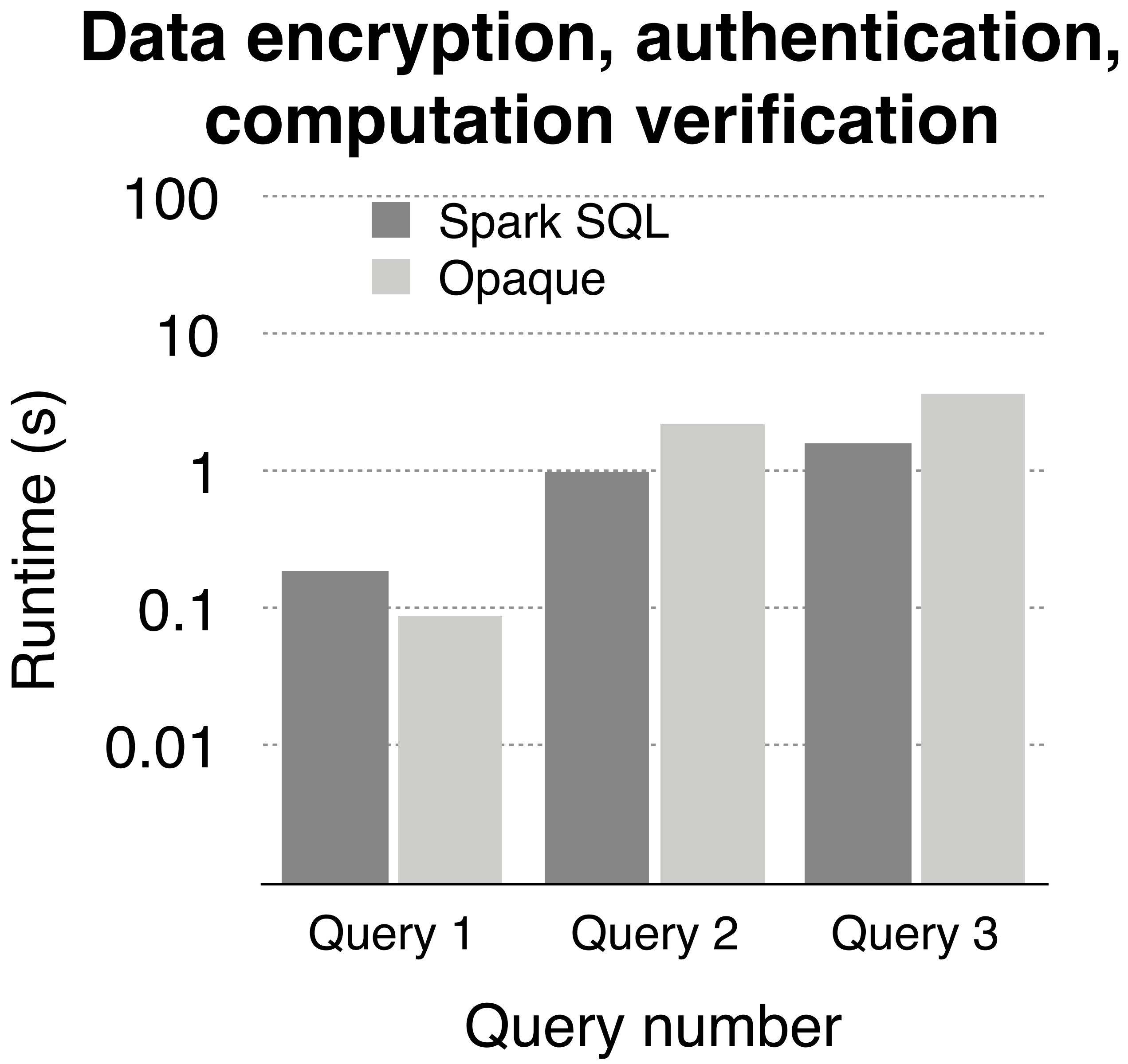

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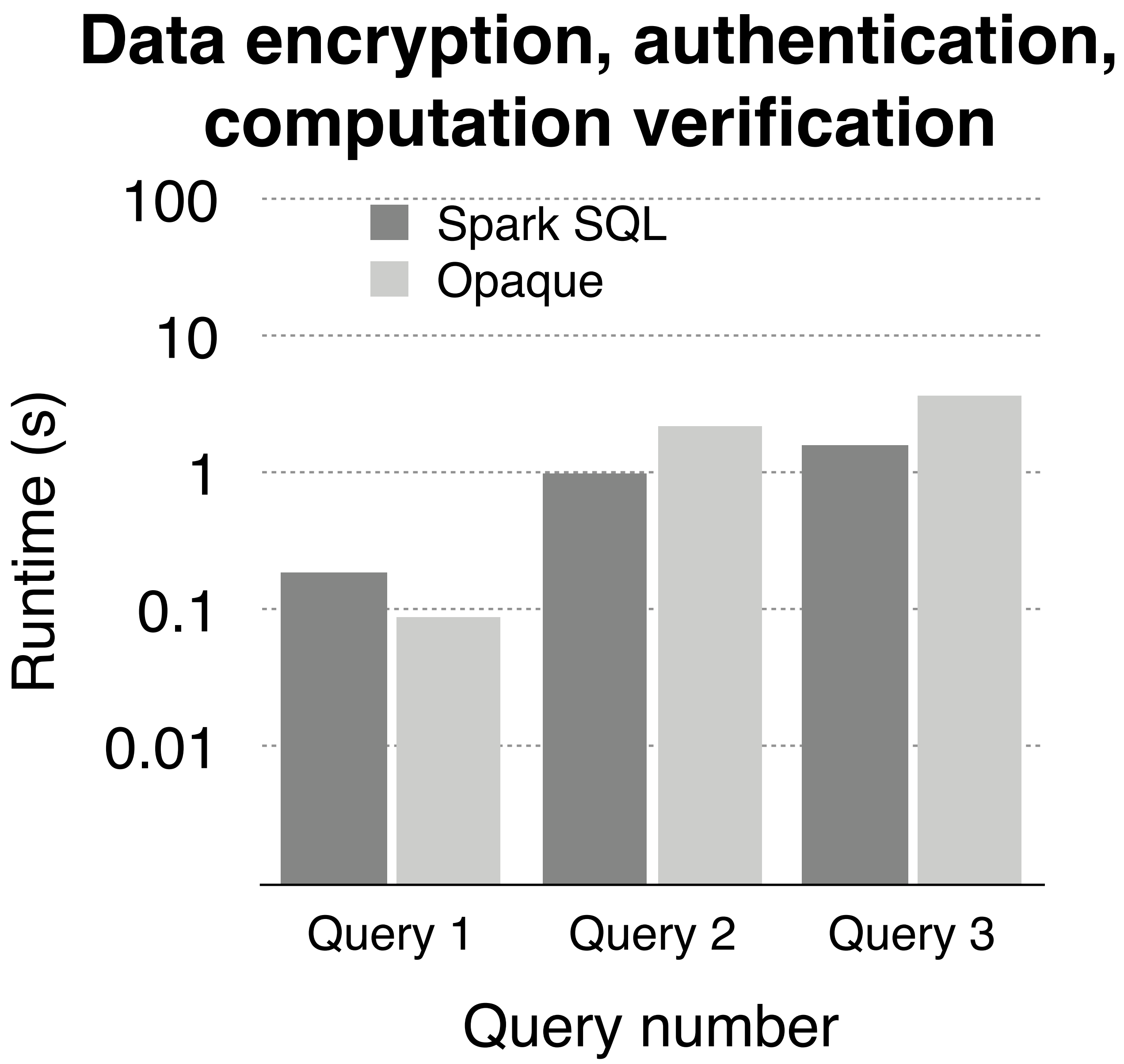
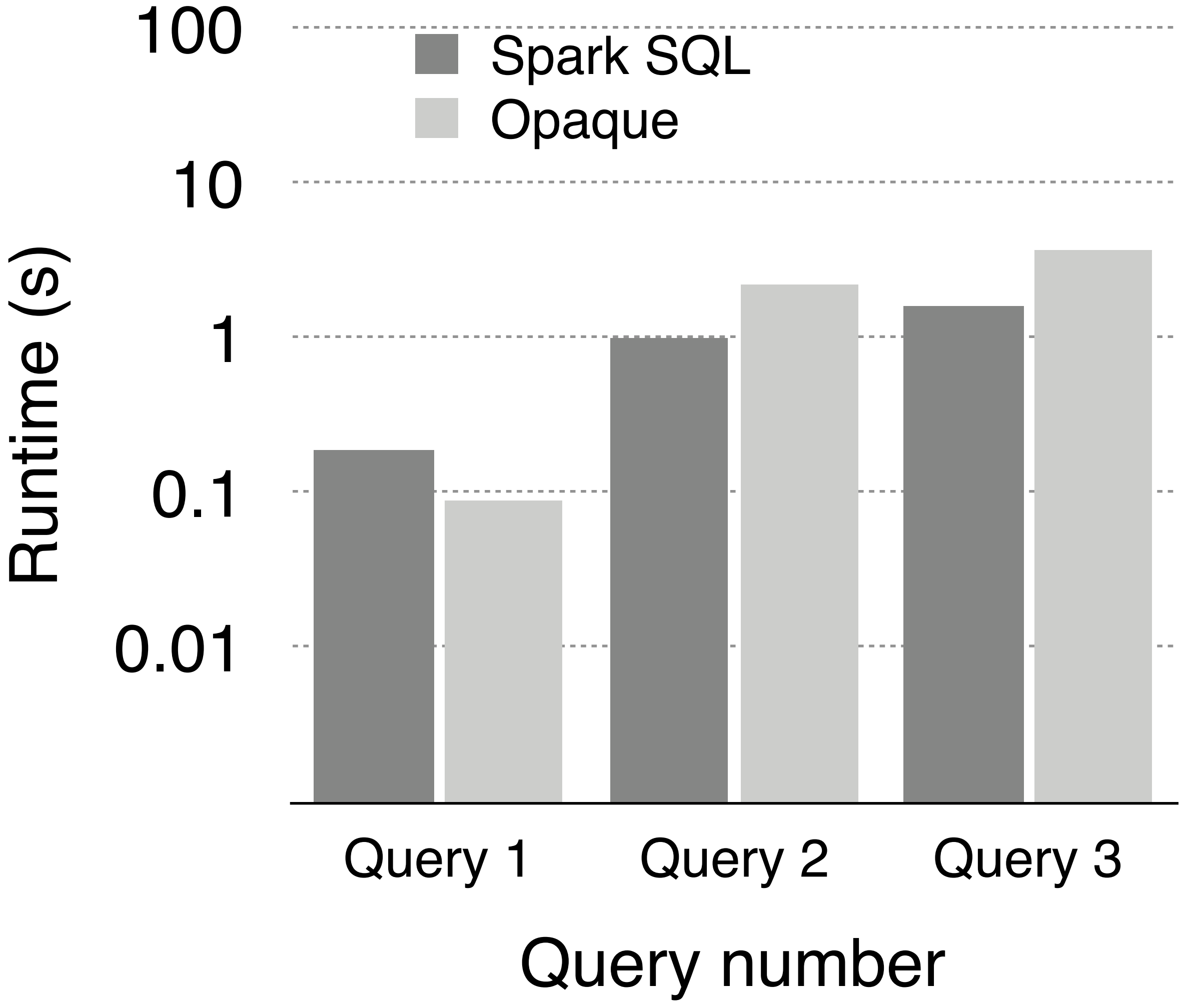


Overhead: 0.47x to 2.3x

Big Data Benchmark (distributed)

Data encryption, authentication, computation verification



+ Obliviousness

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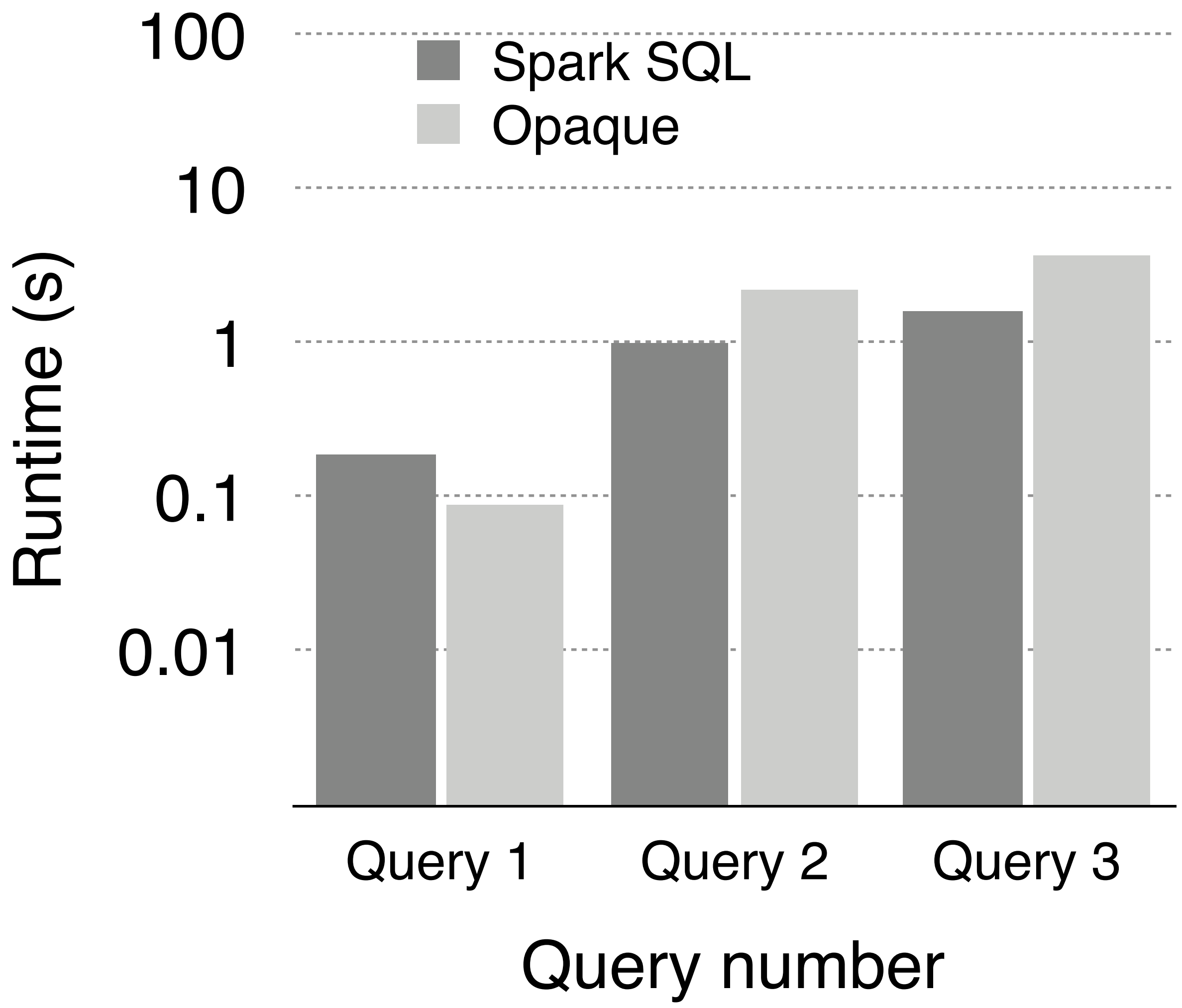

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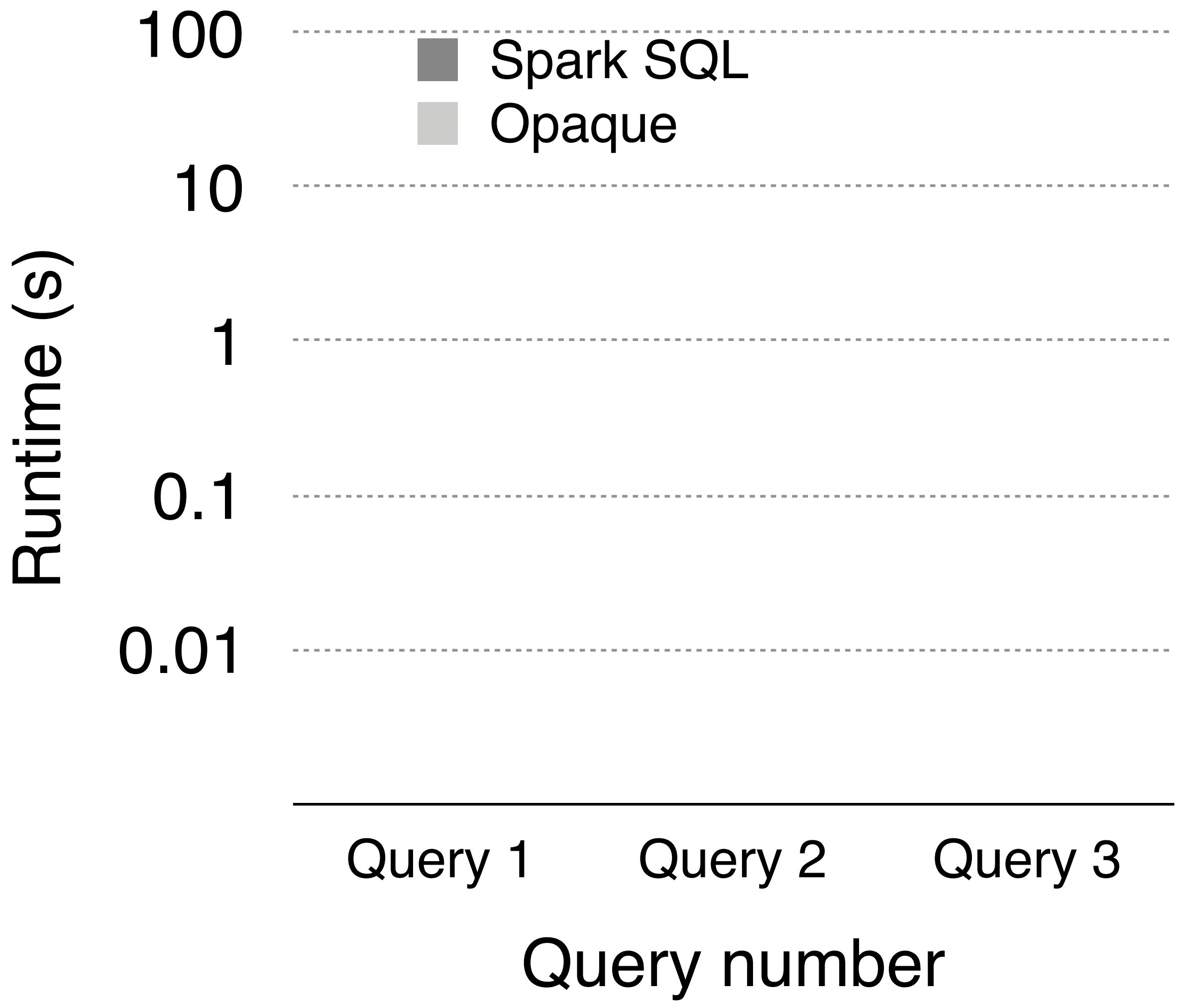

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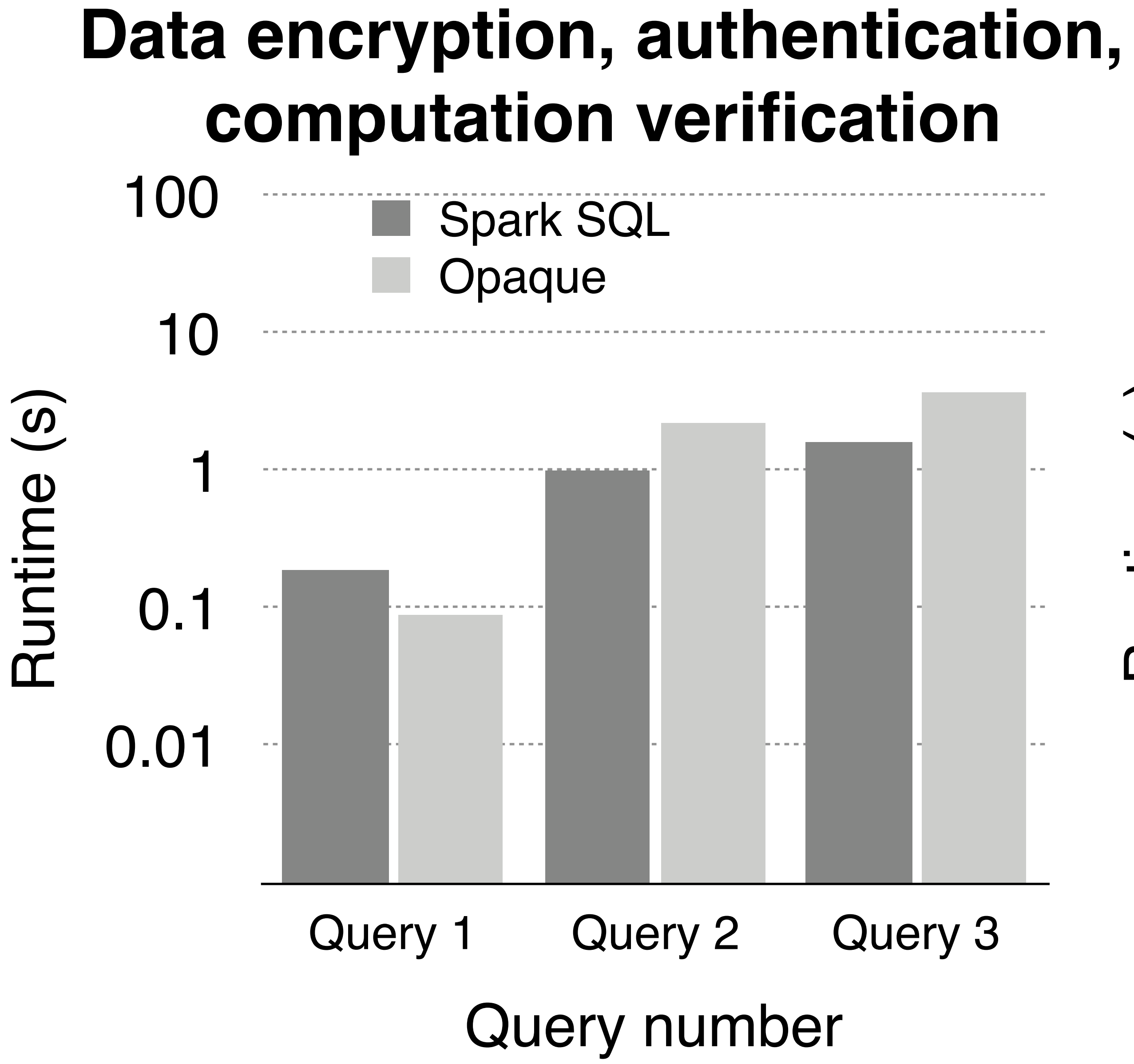

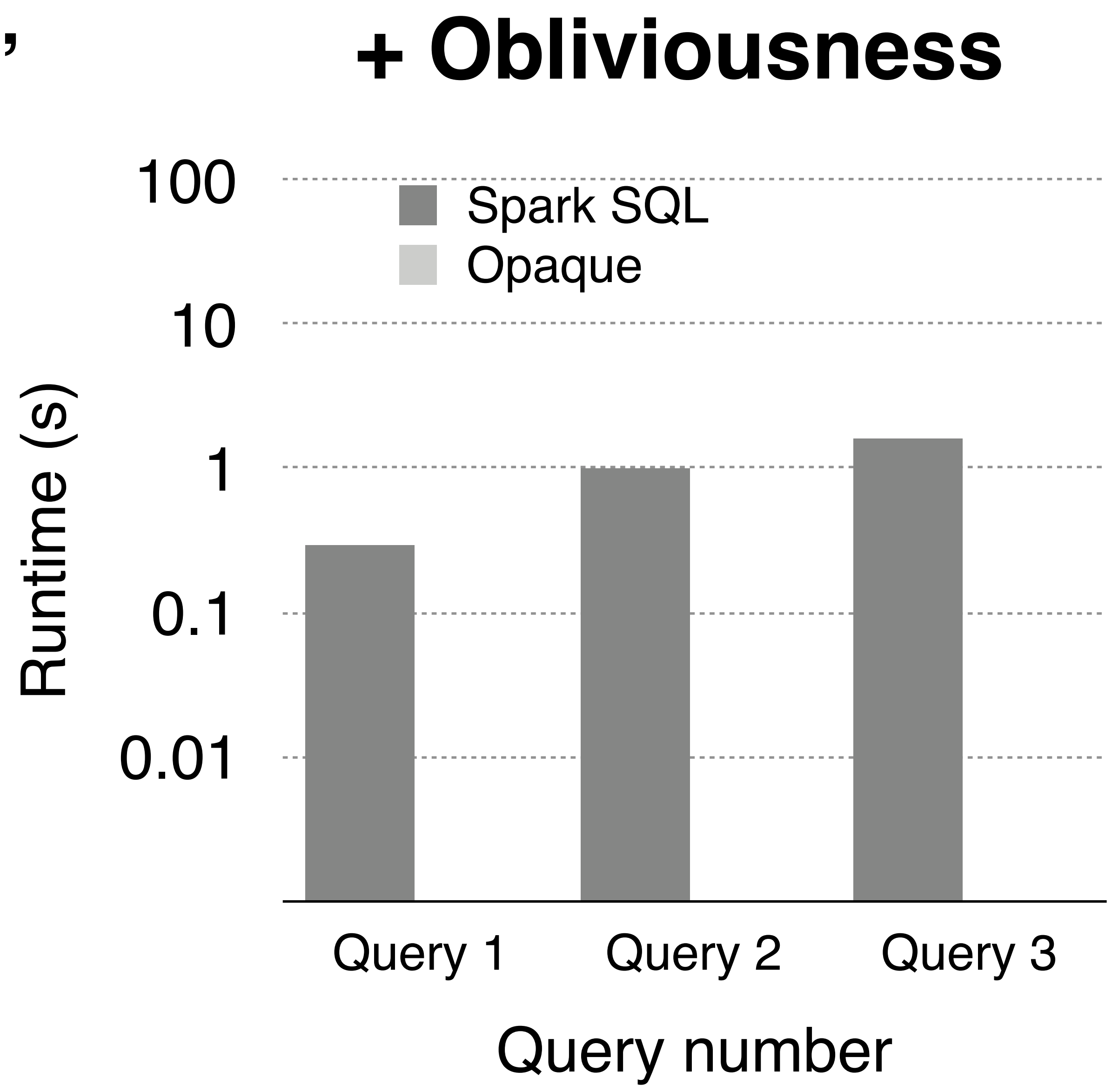

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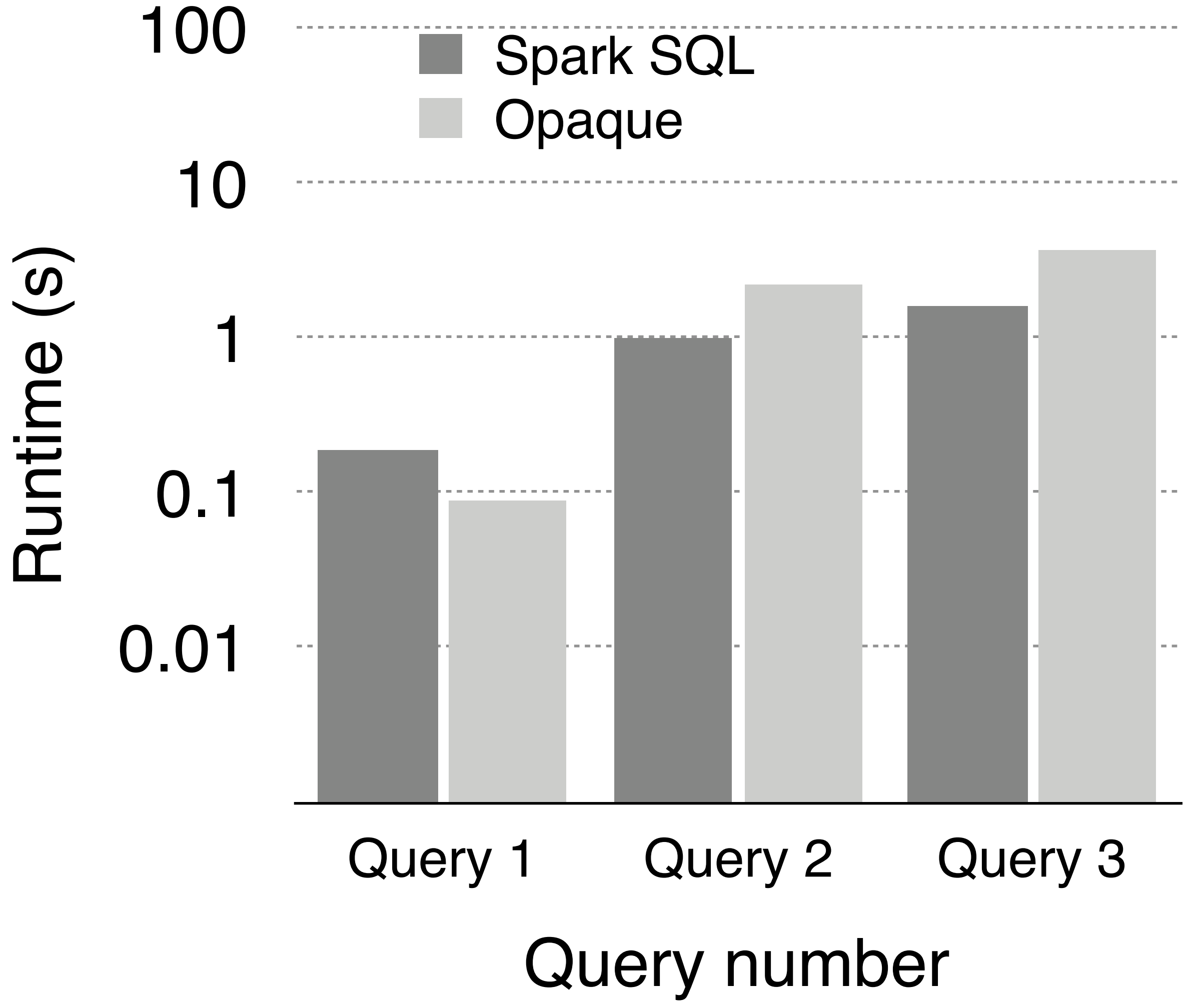

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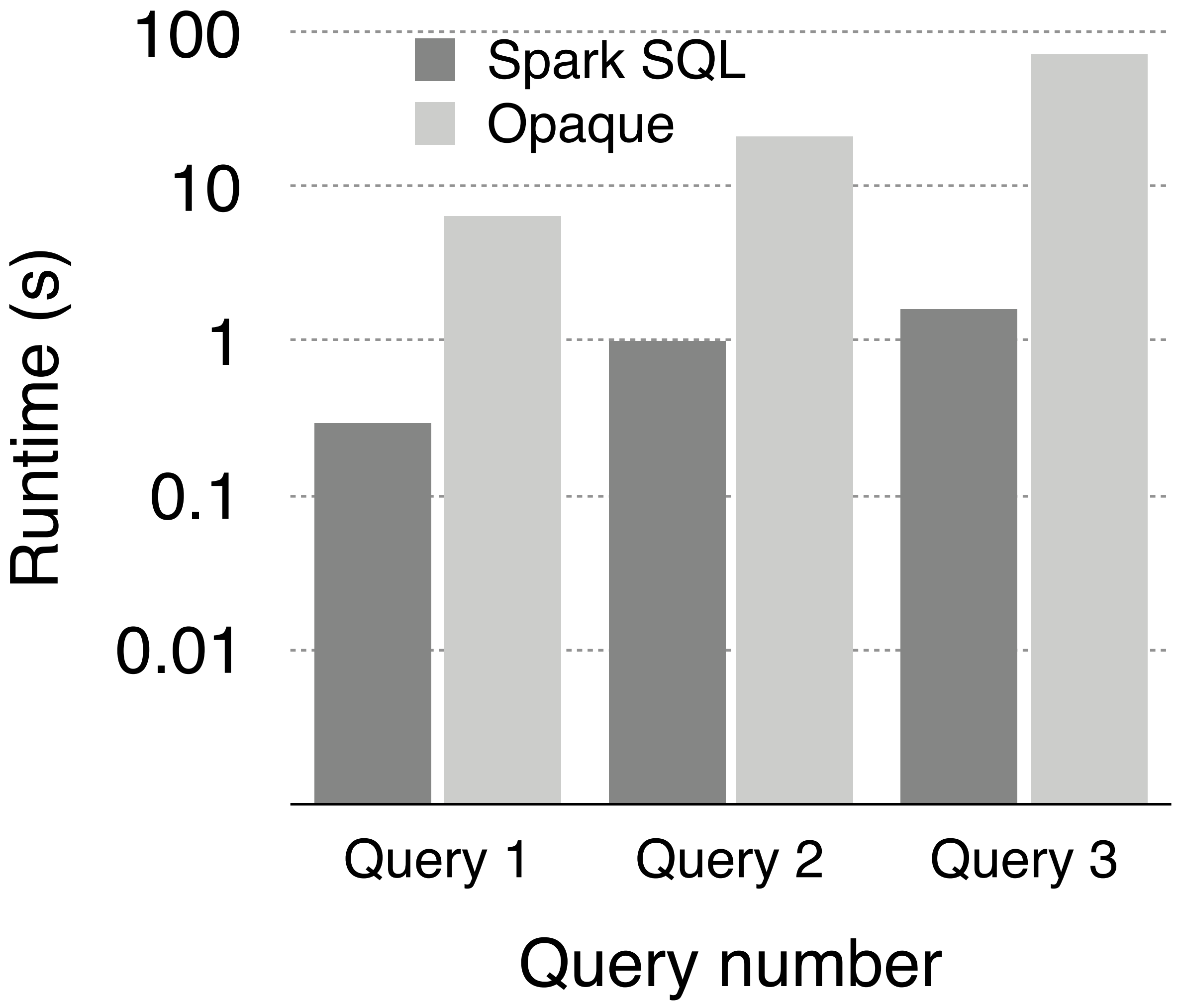

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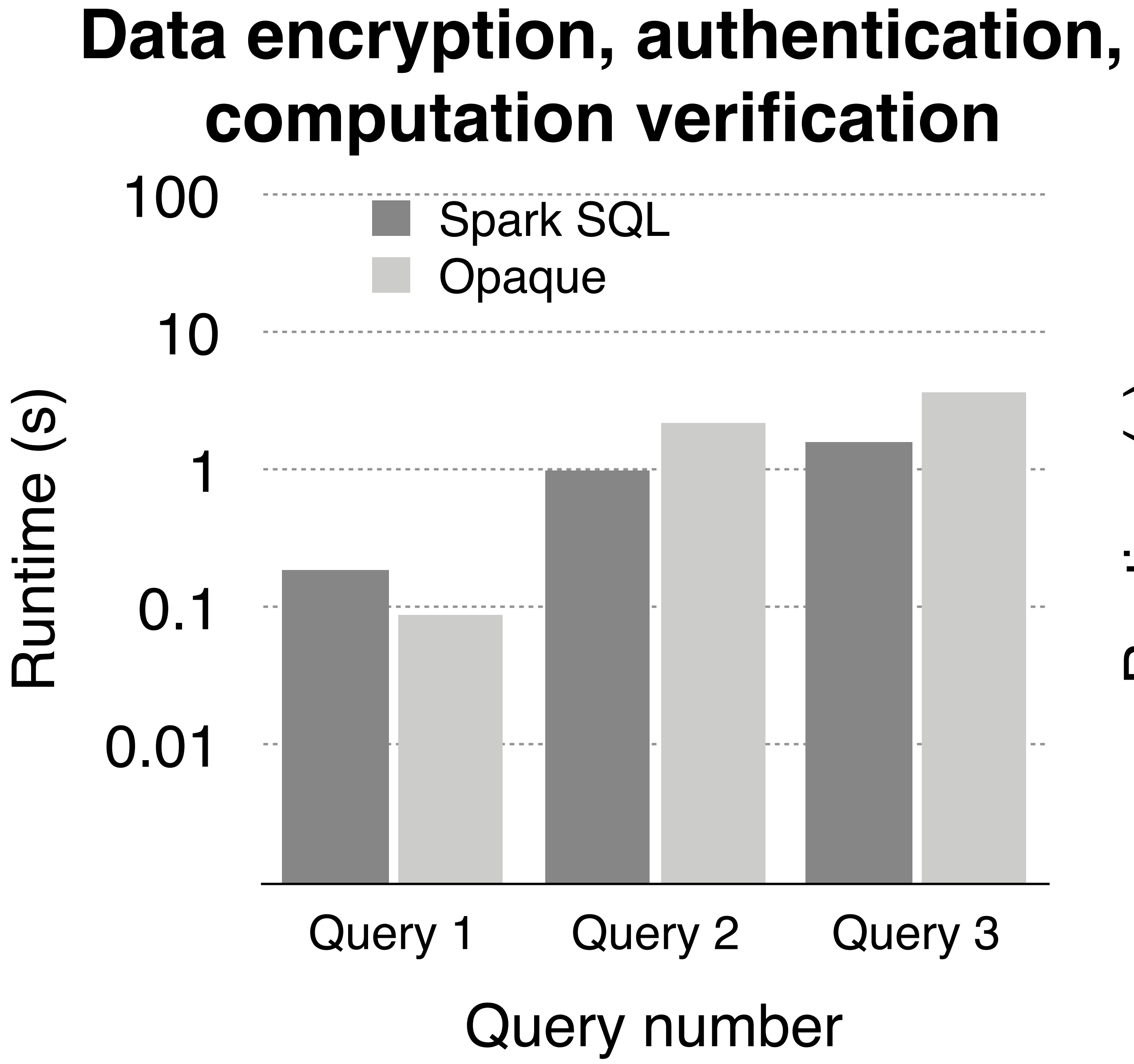
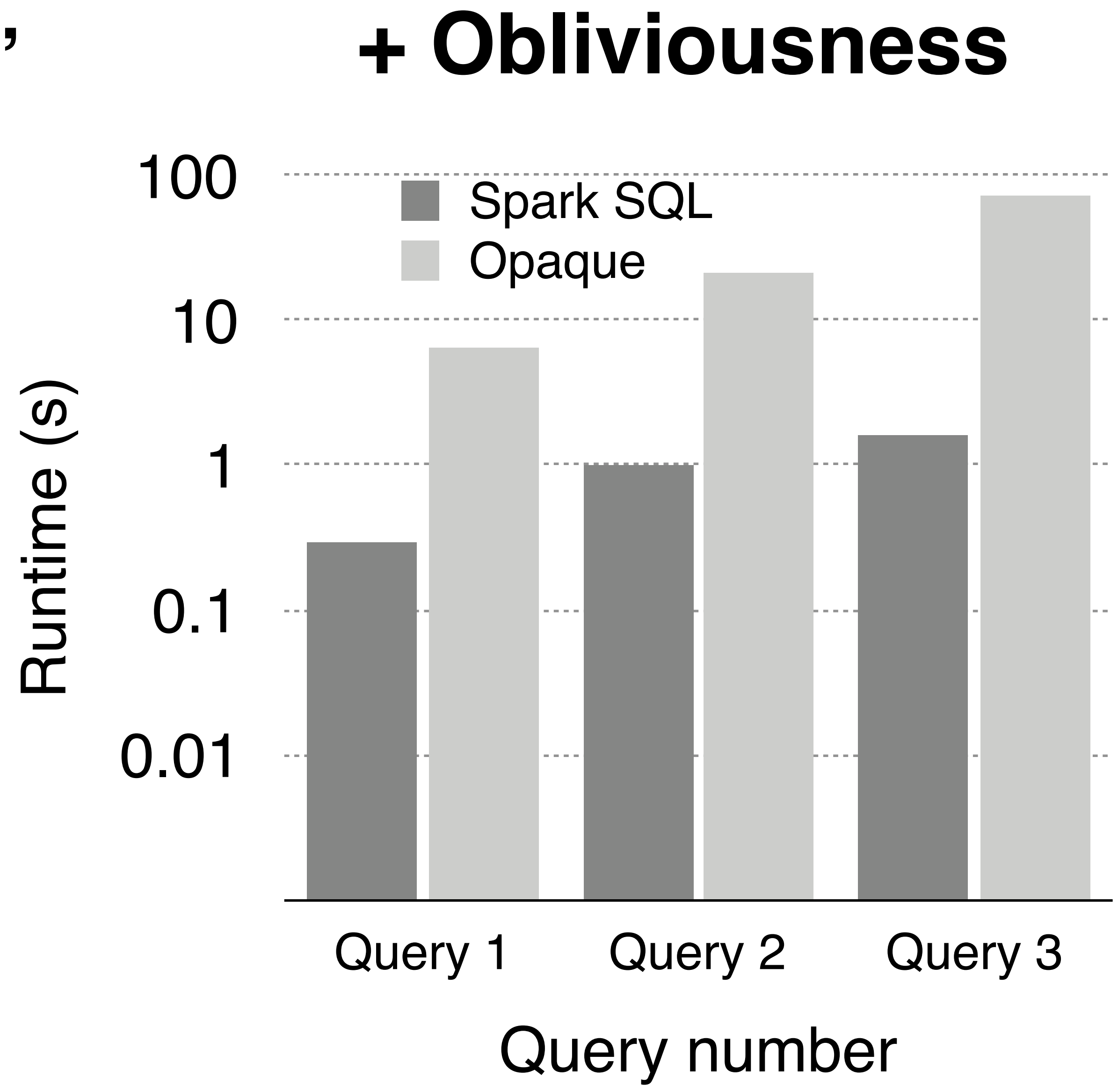
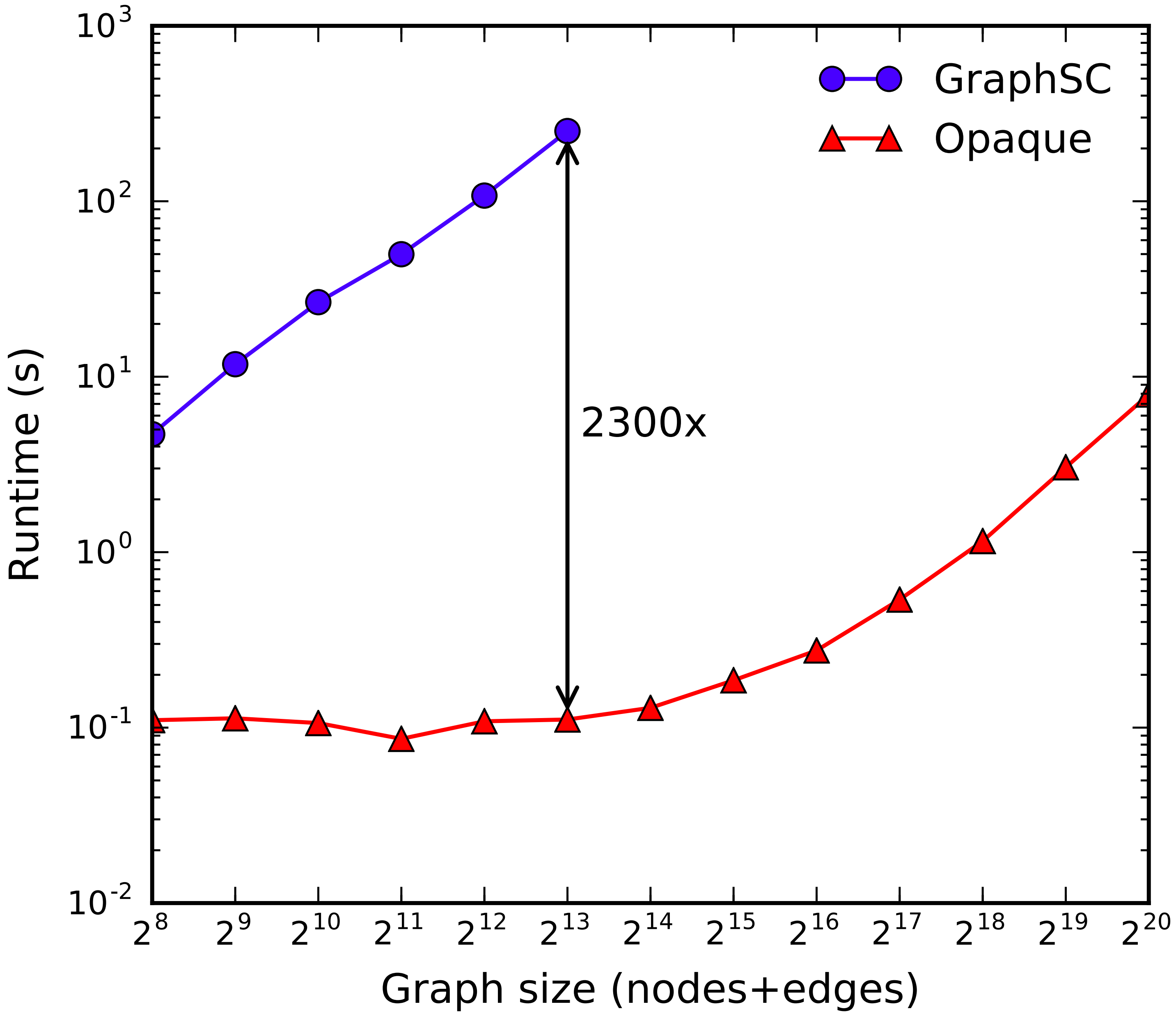




Overhead: 0.47x to 2.3x

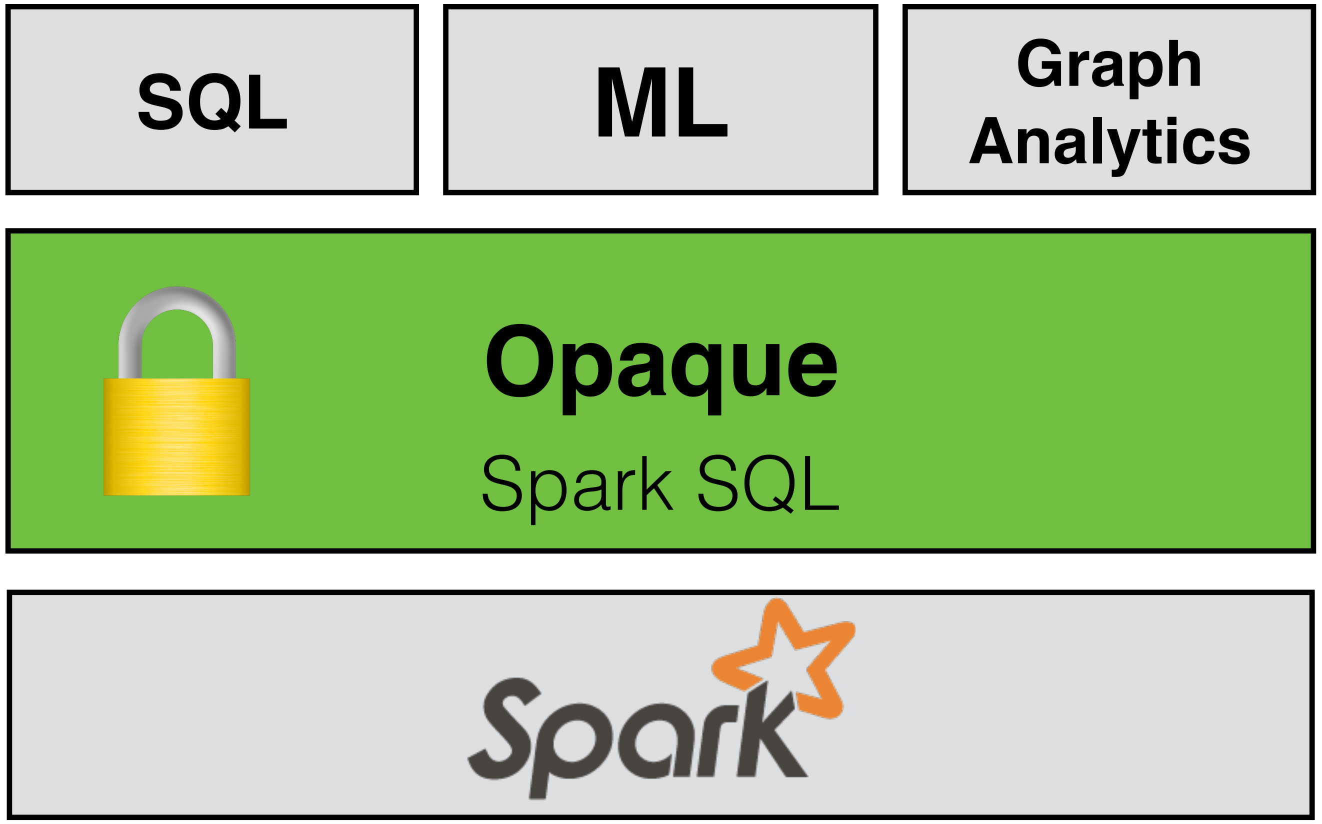
Overhead: 21x to 45x

PageRank: comparison with GraphSC (single machine)



Conclusion

Opaque is an oblivious and encrypted distributed analytics platform



Open source: github.com/ucbrise/opaque