Opaque

An Oblivious and Encrypted Distributed Analytics Platform

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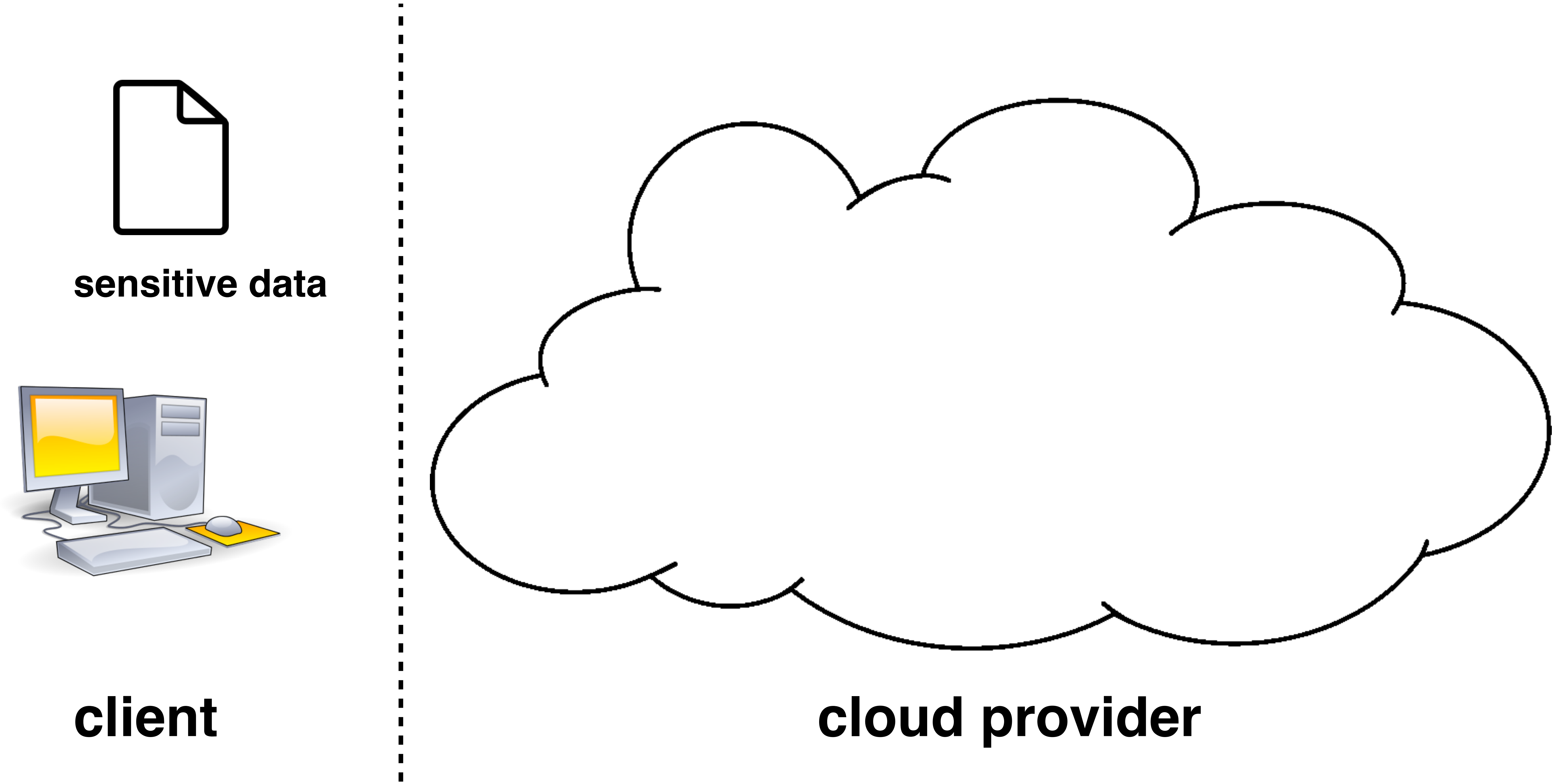
Raluca Ada Popa, Joseph E. Gonzalez, Ion Stoica

UC Berkeley

Complex analytics run on sensitive data



sensitive data

client

cloud provider

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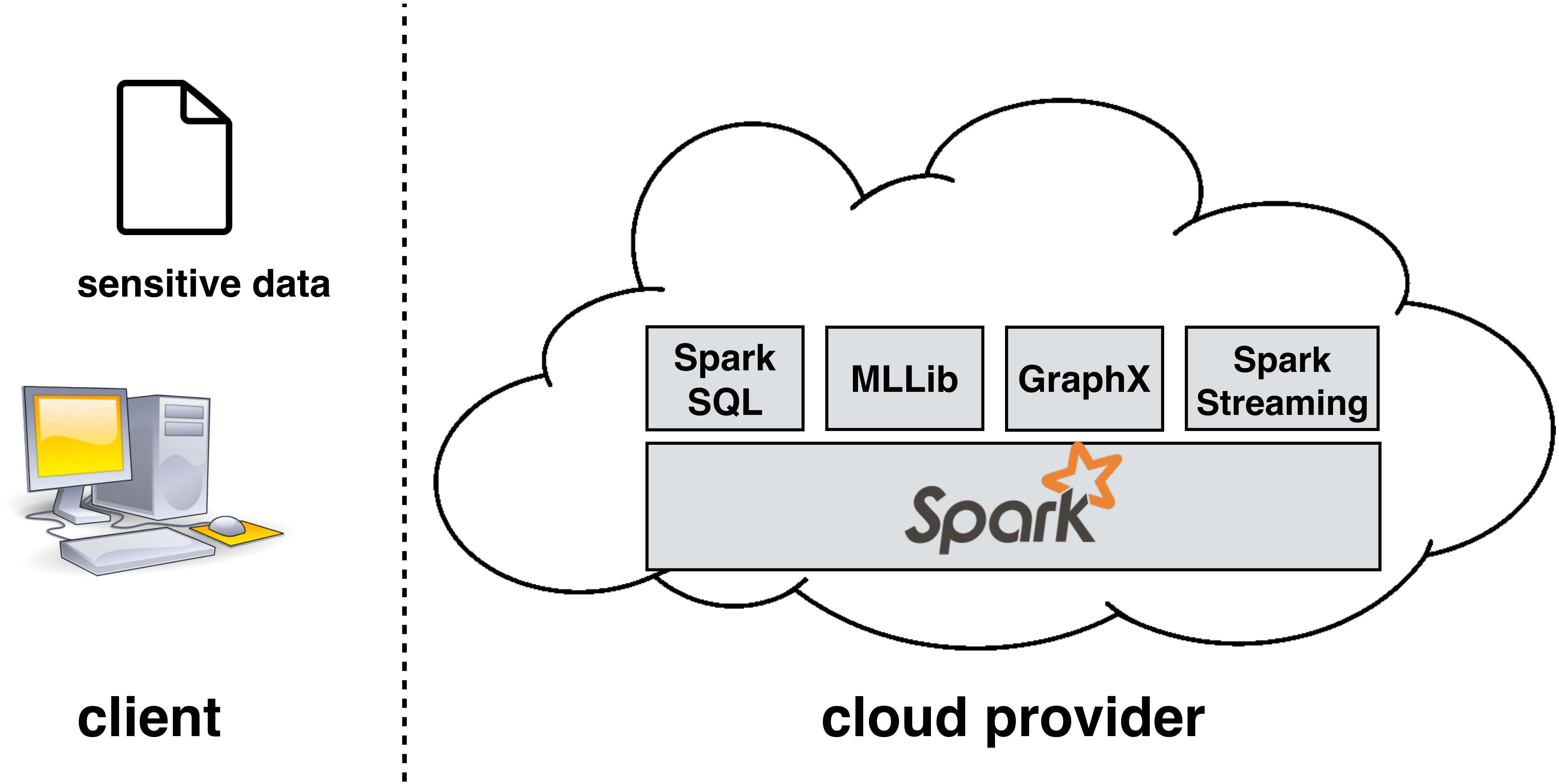

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Spark SQL

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GraphX

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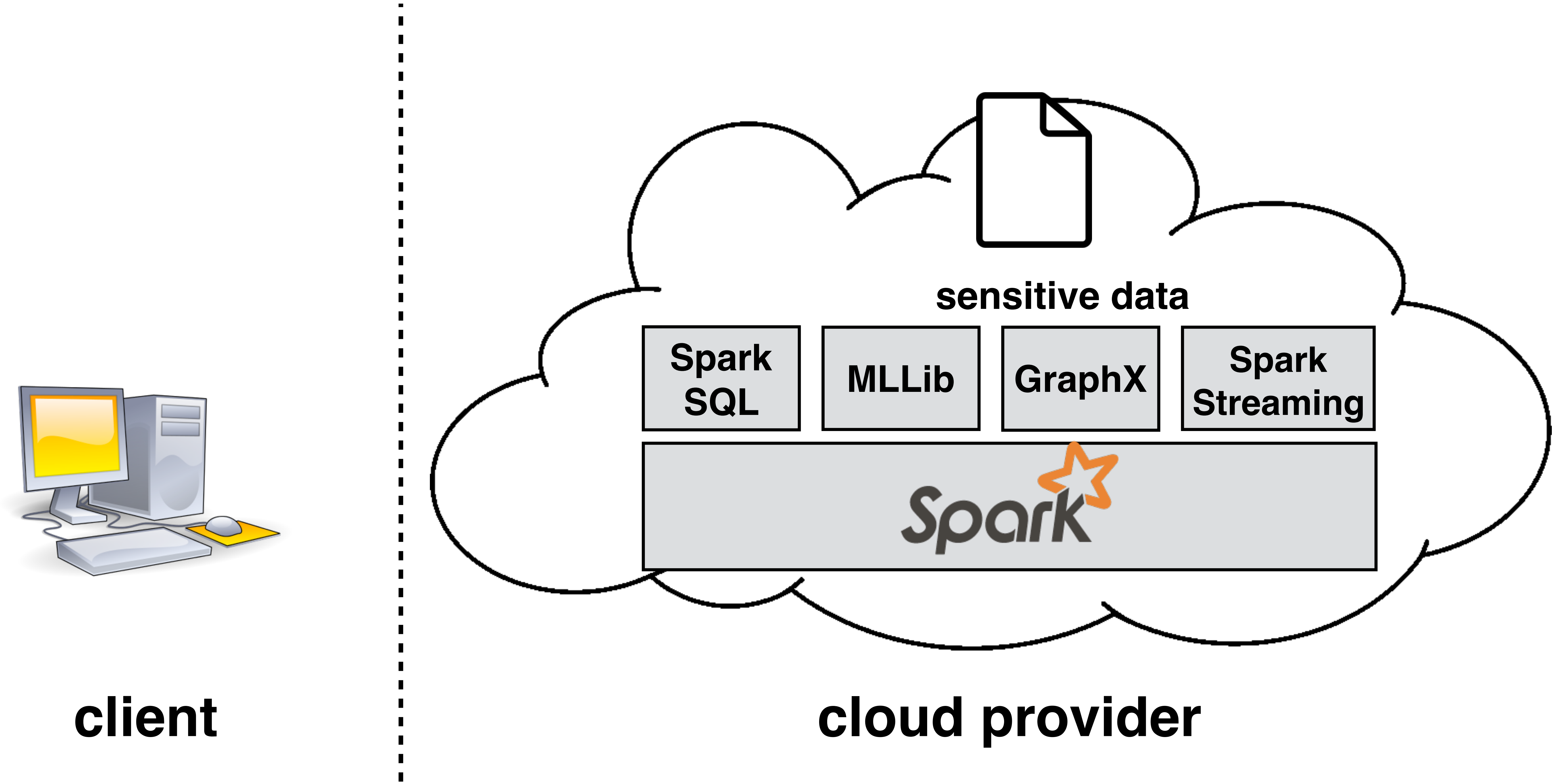

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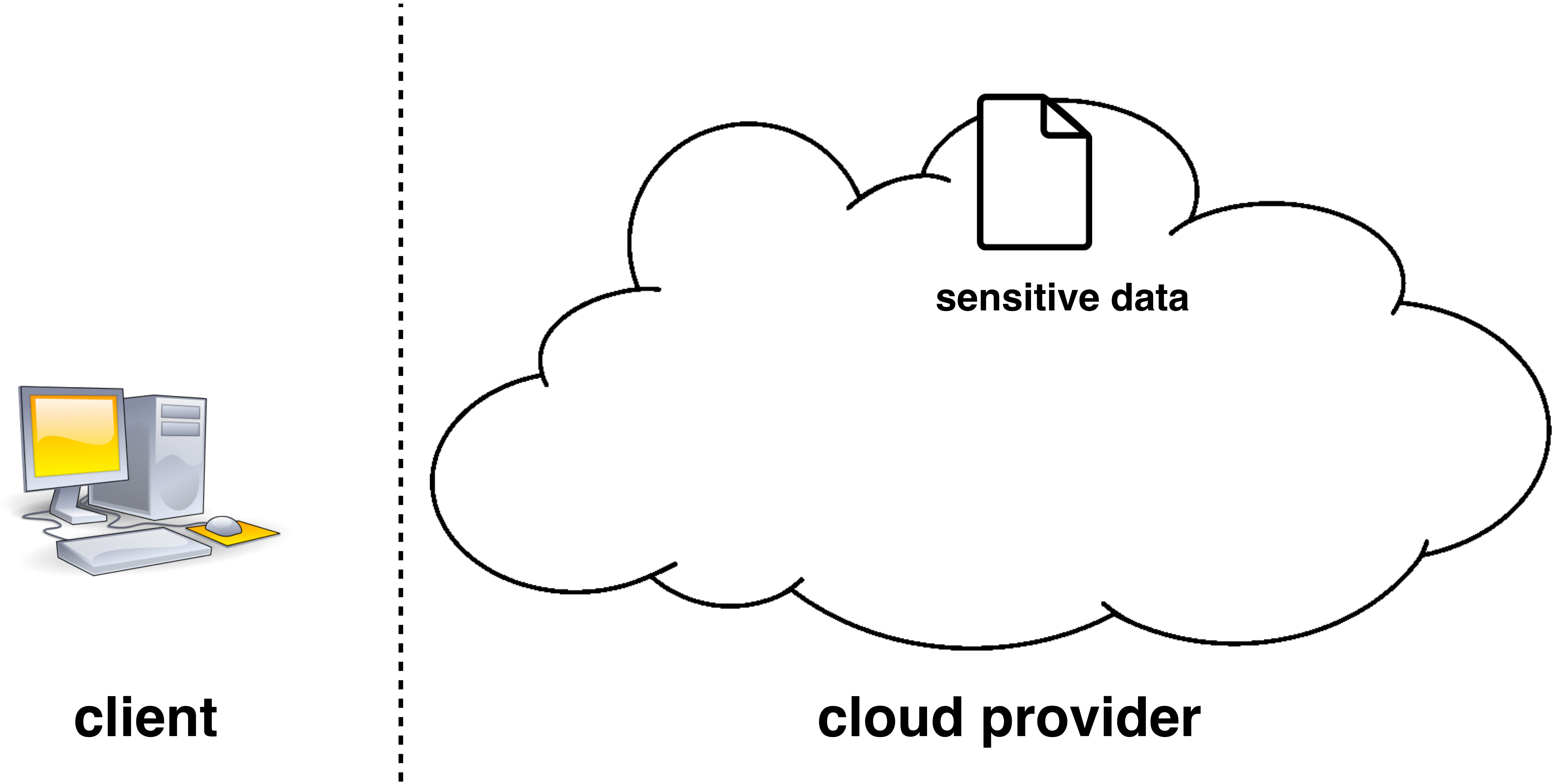

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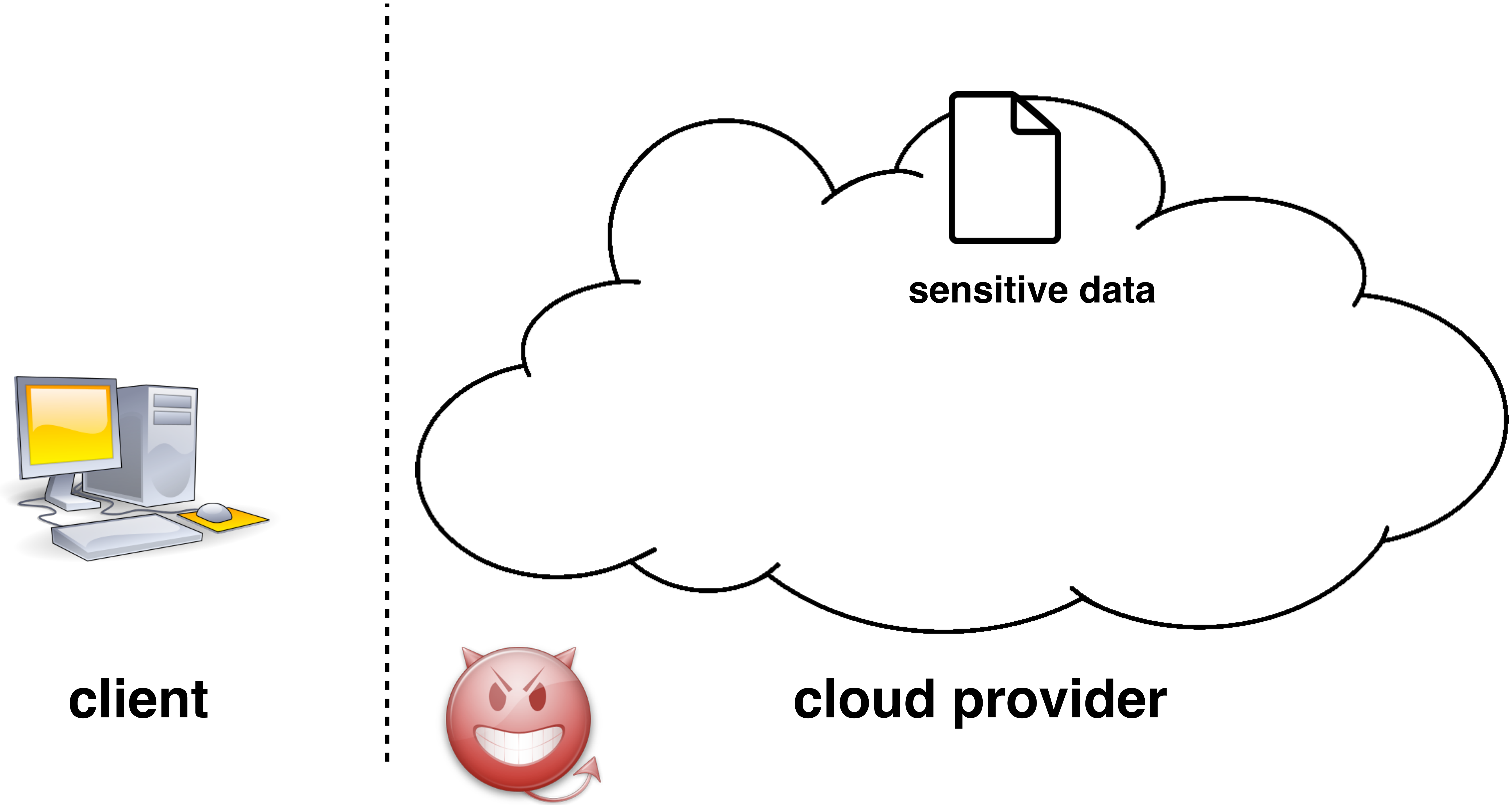

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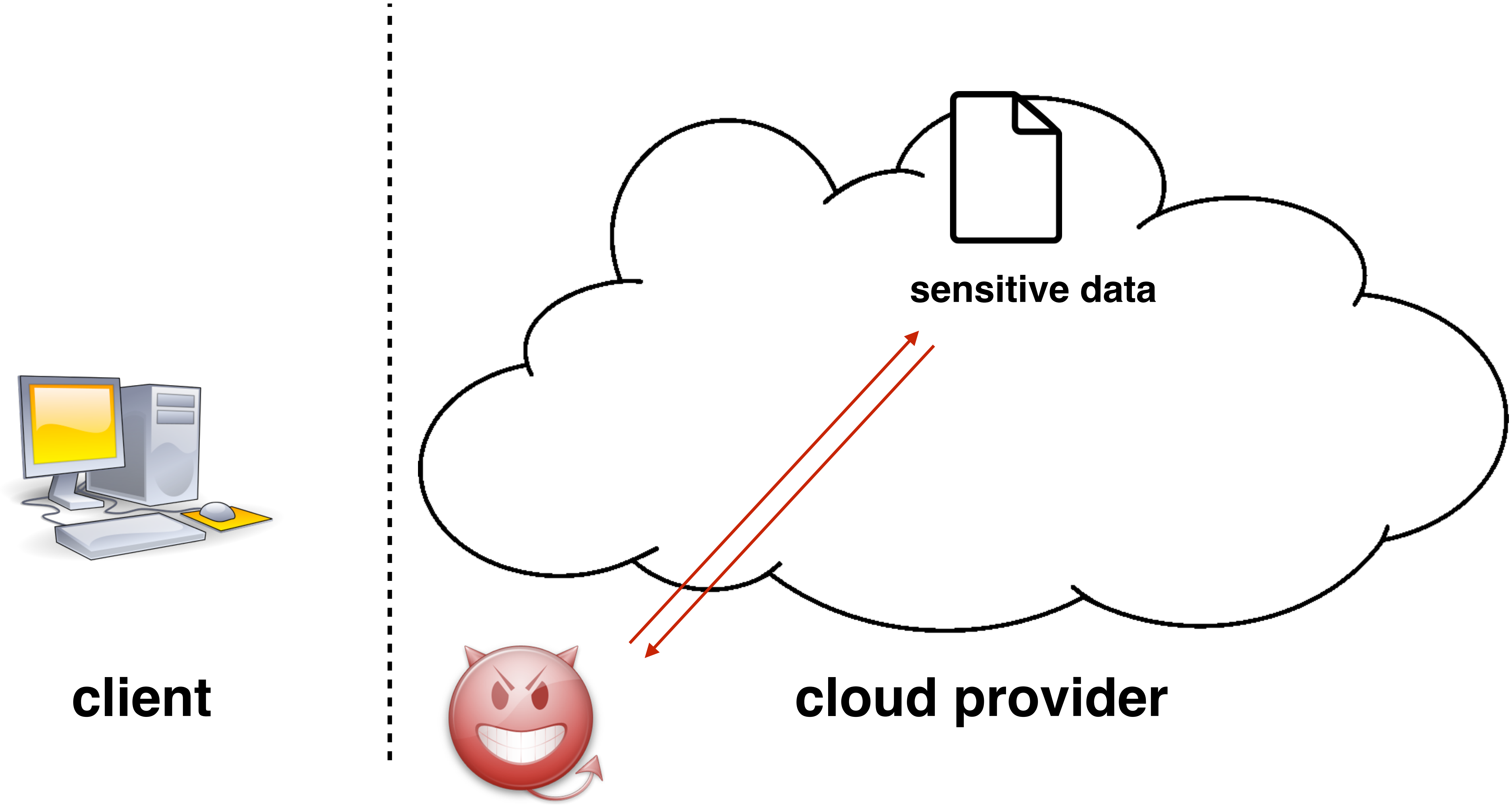

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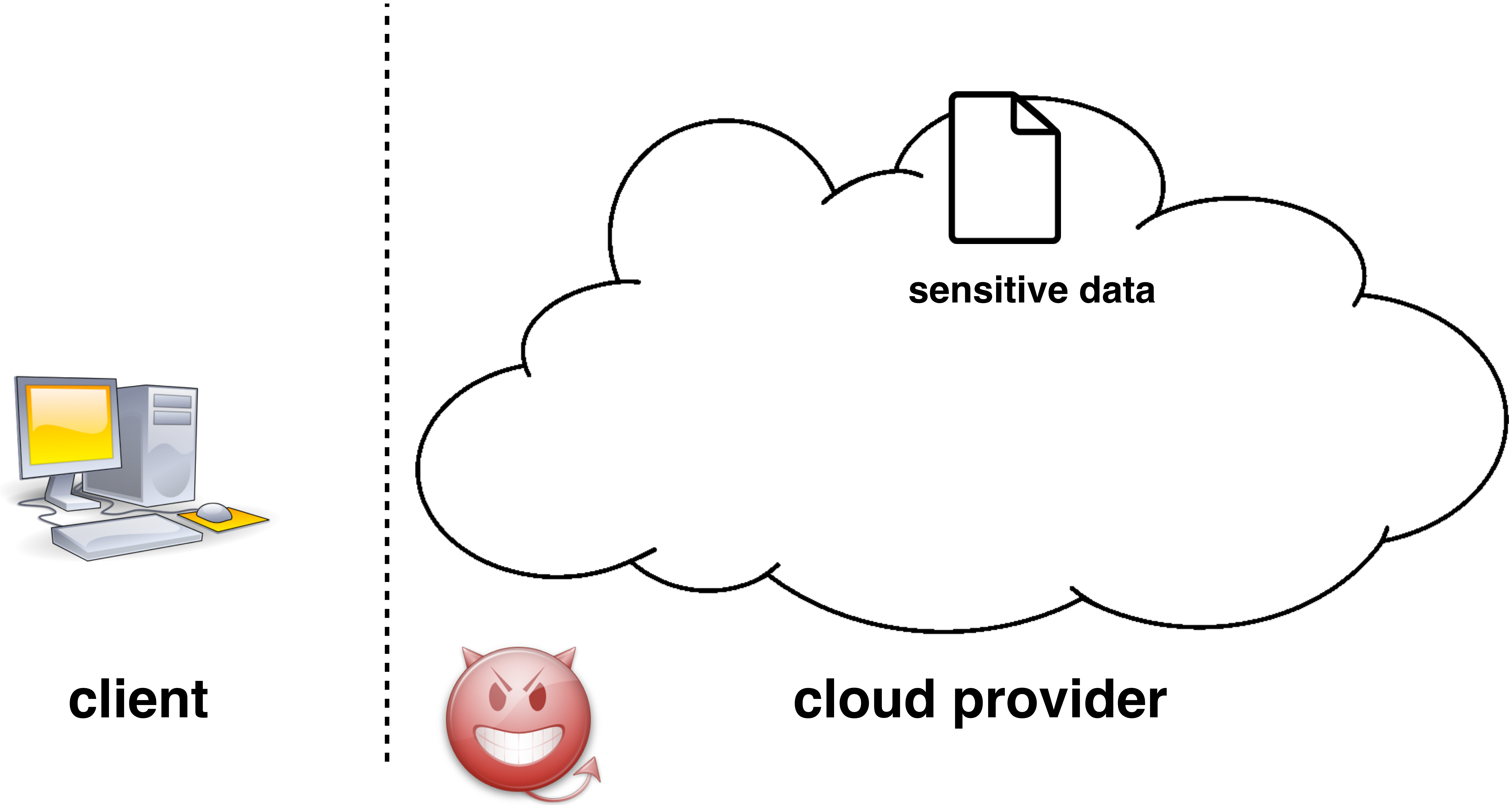

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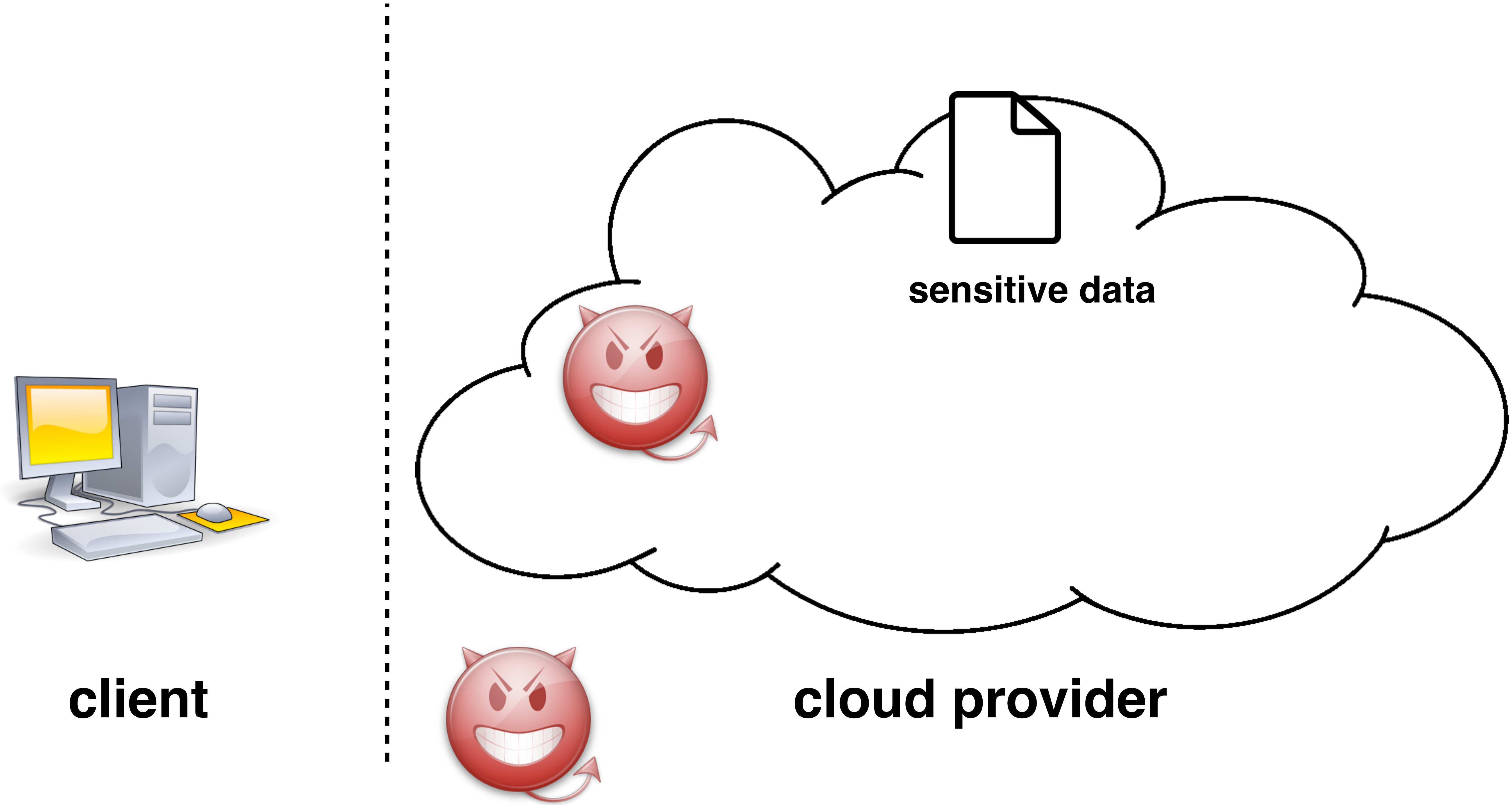

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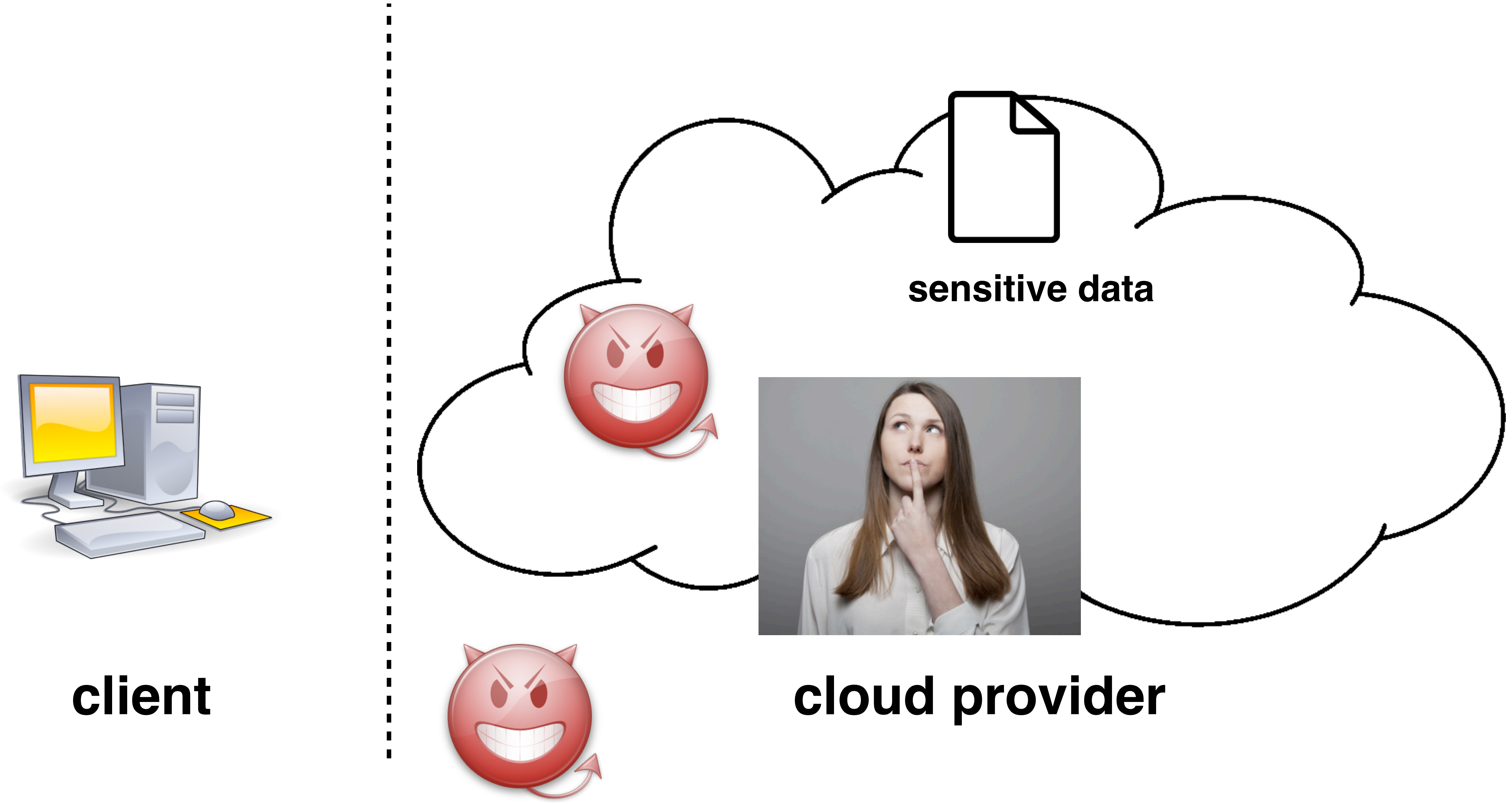

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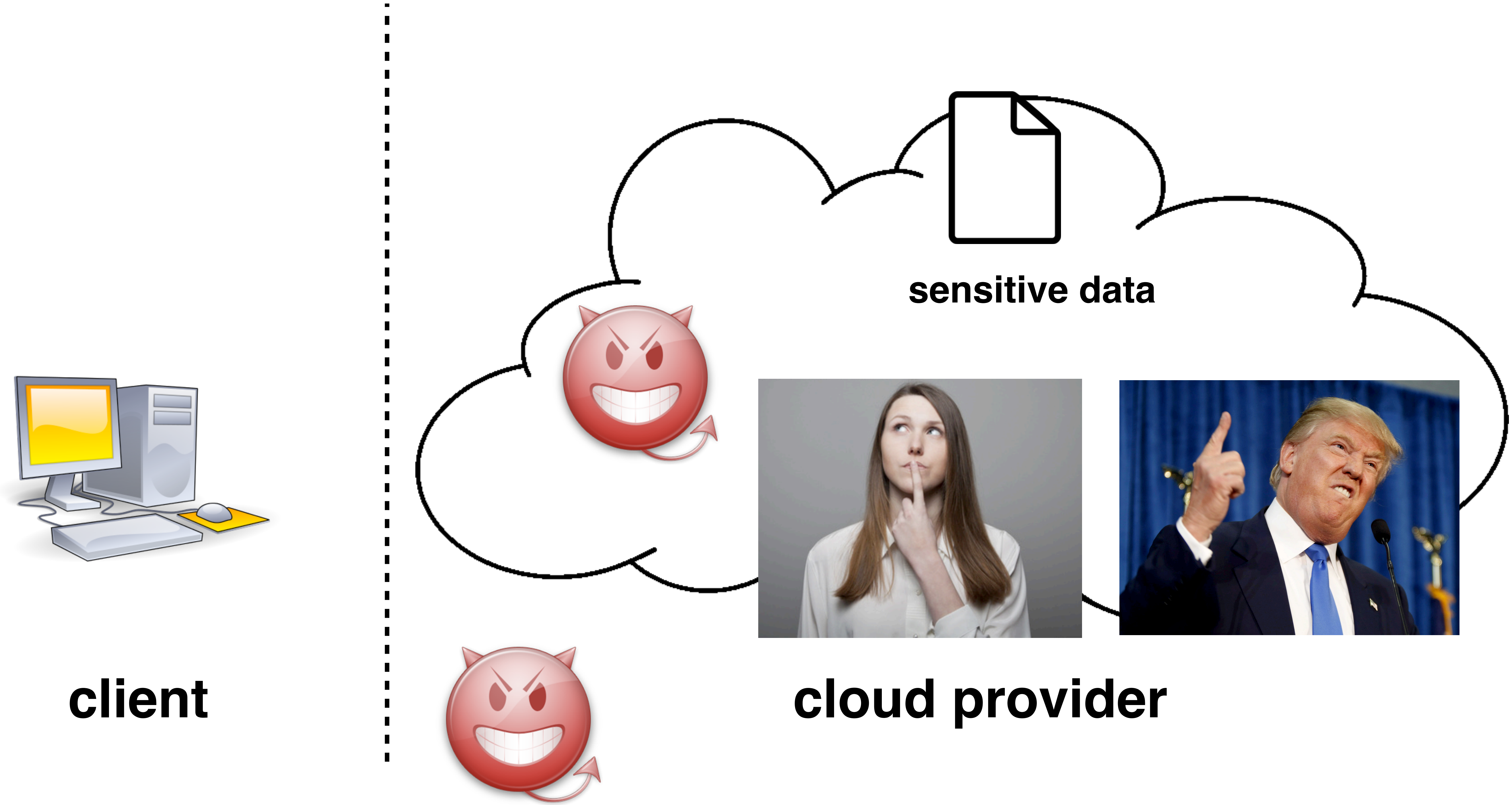

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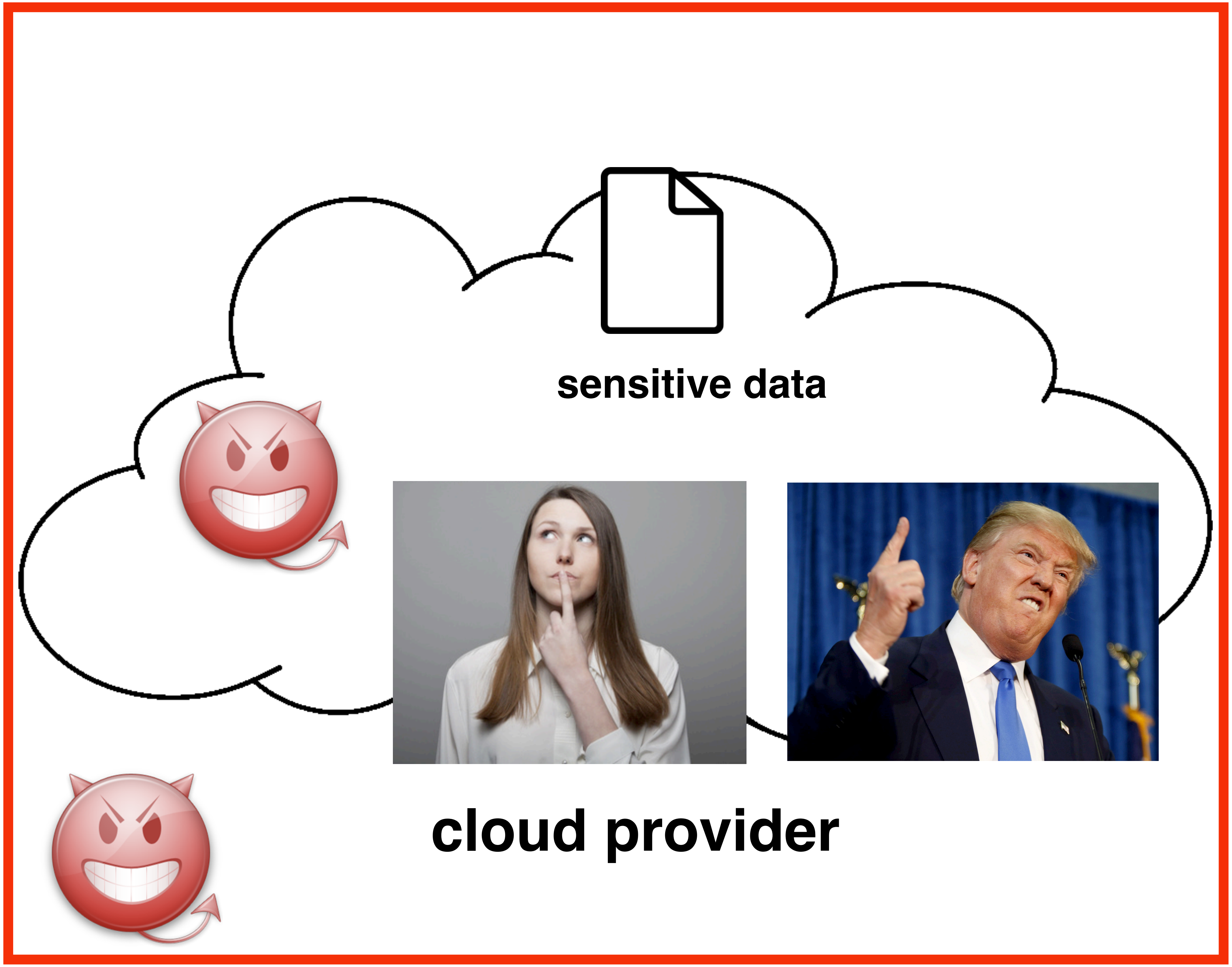

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How to protect data
while preserving functionality?

Cryptographic approach?

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Alternative: hardware enclaves

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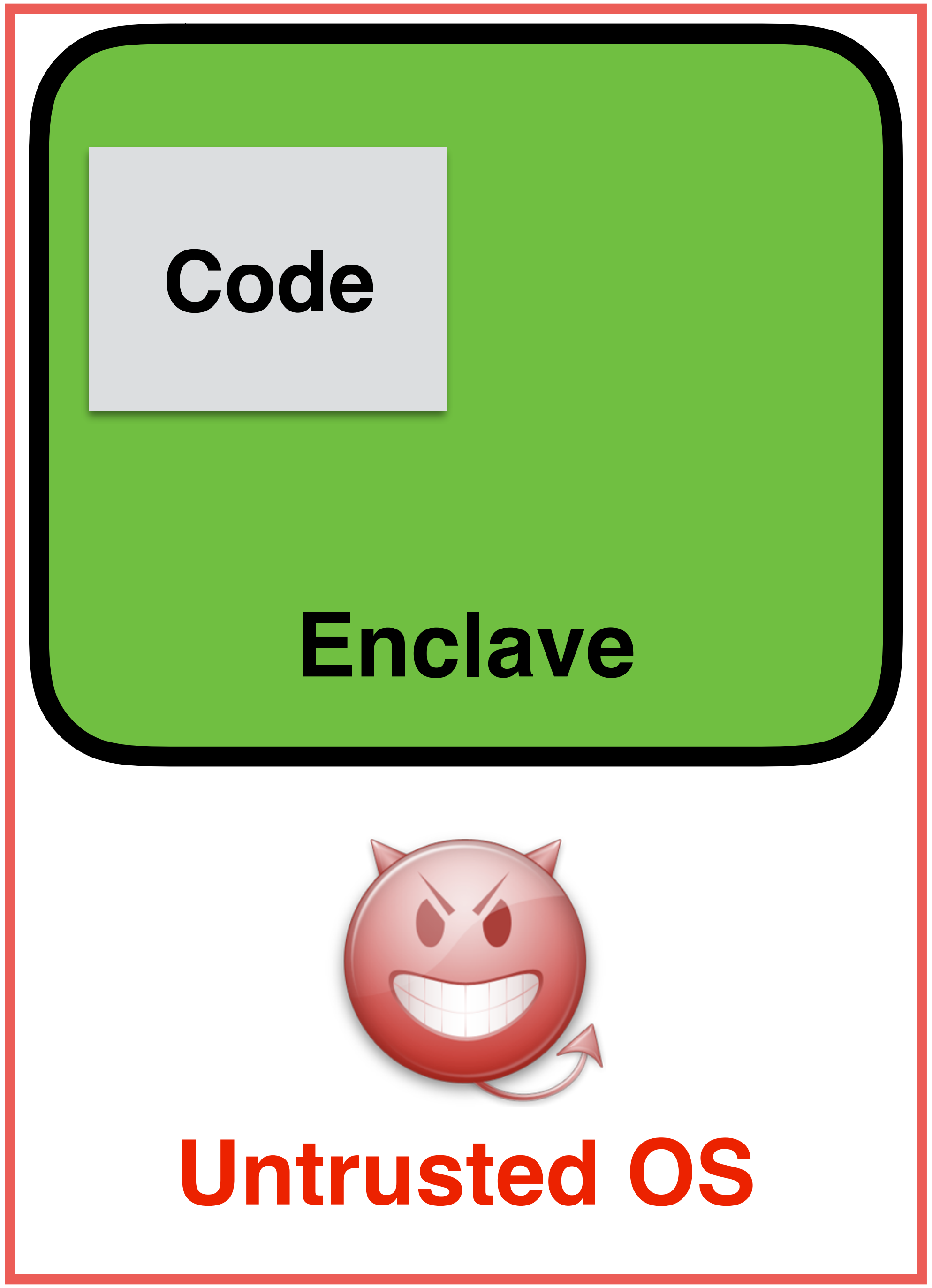

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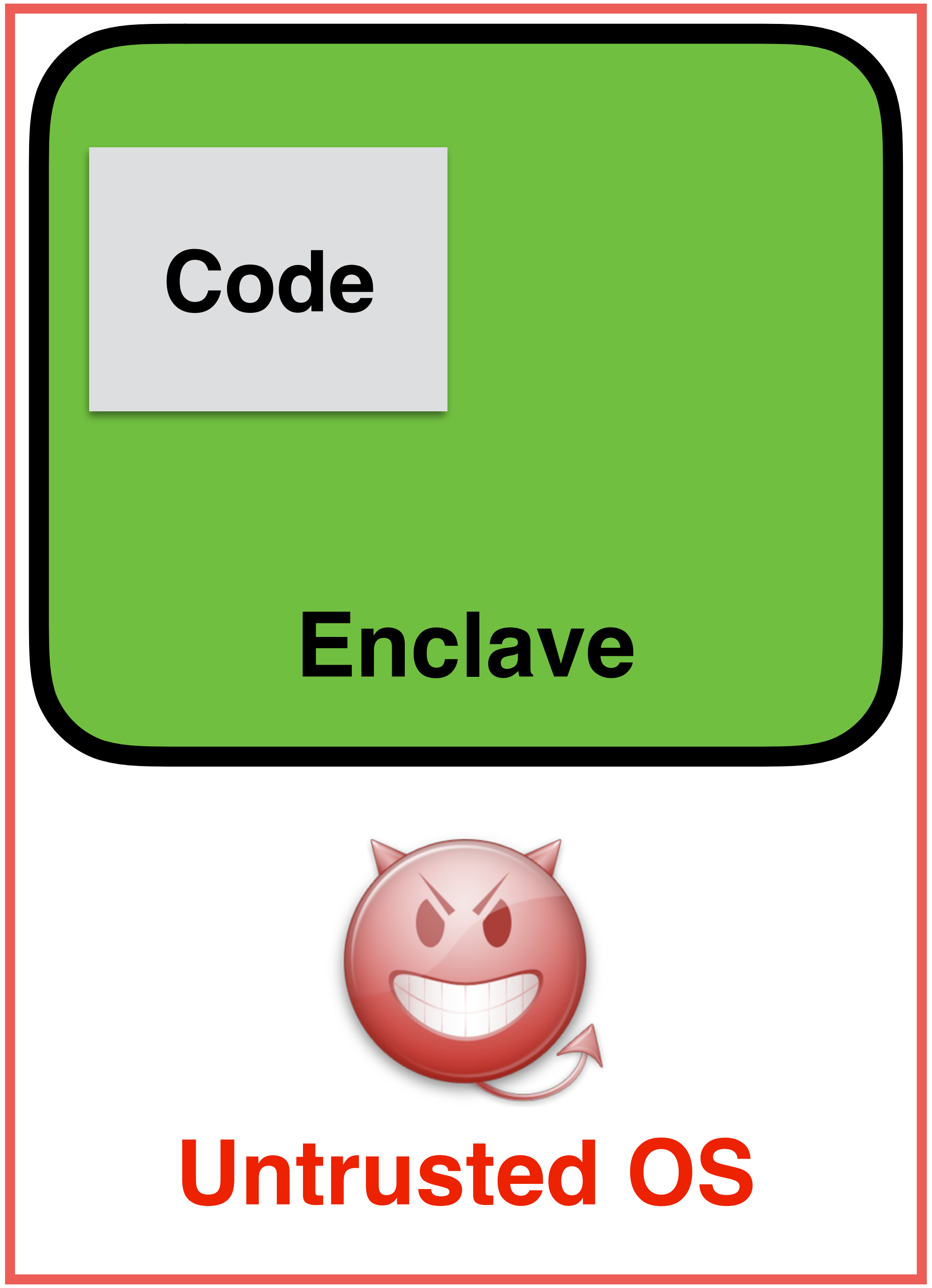

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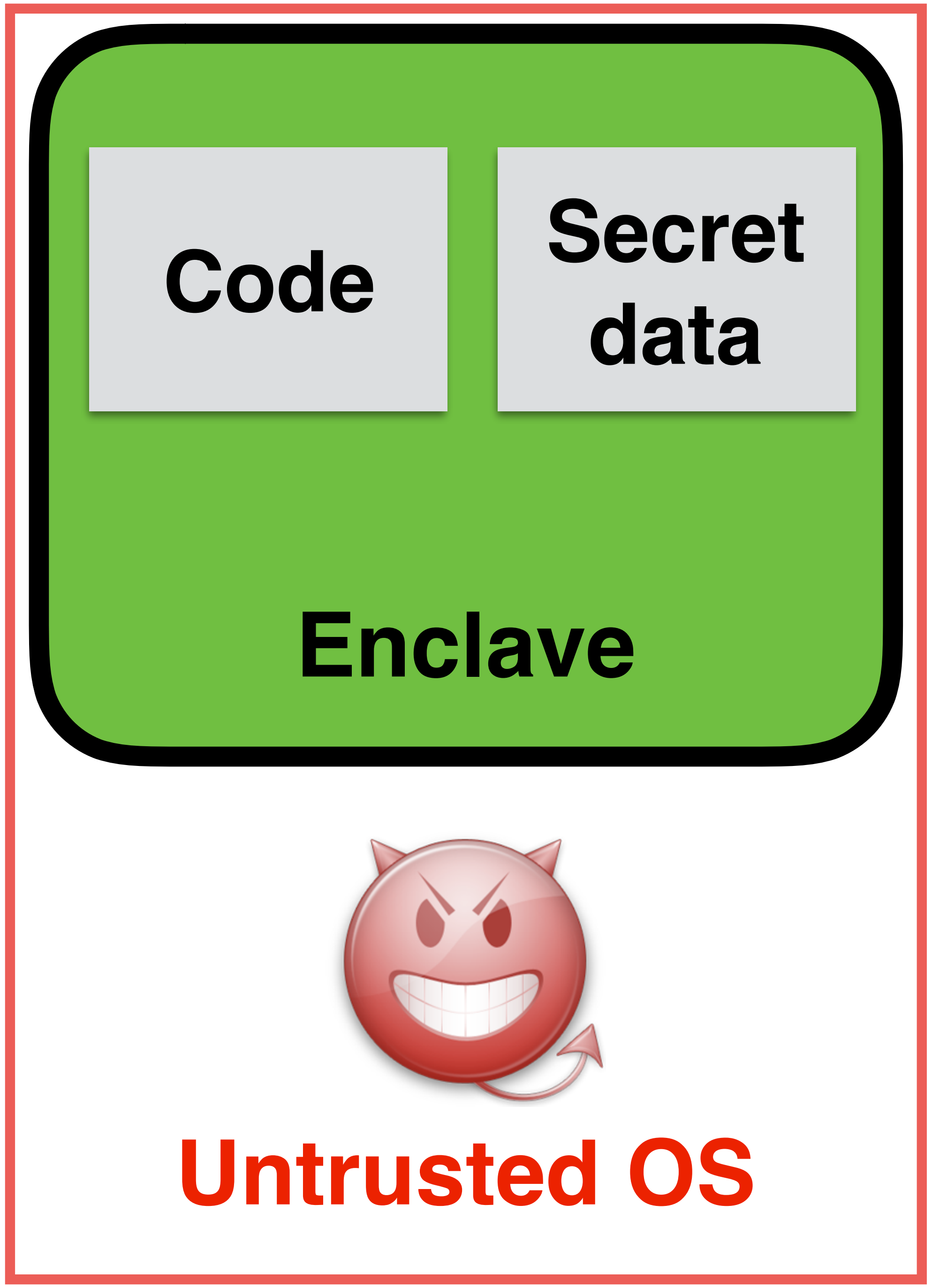

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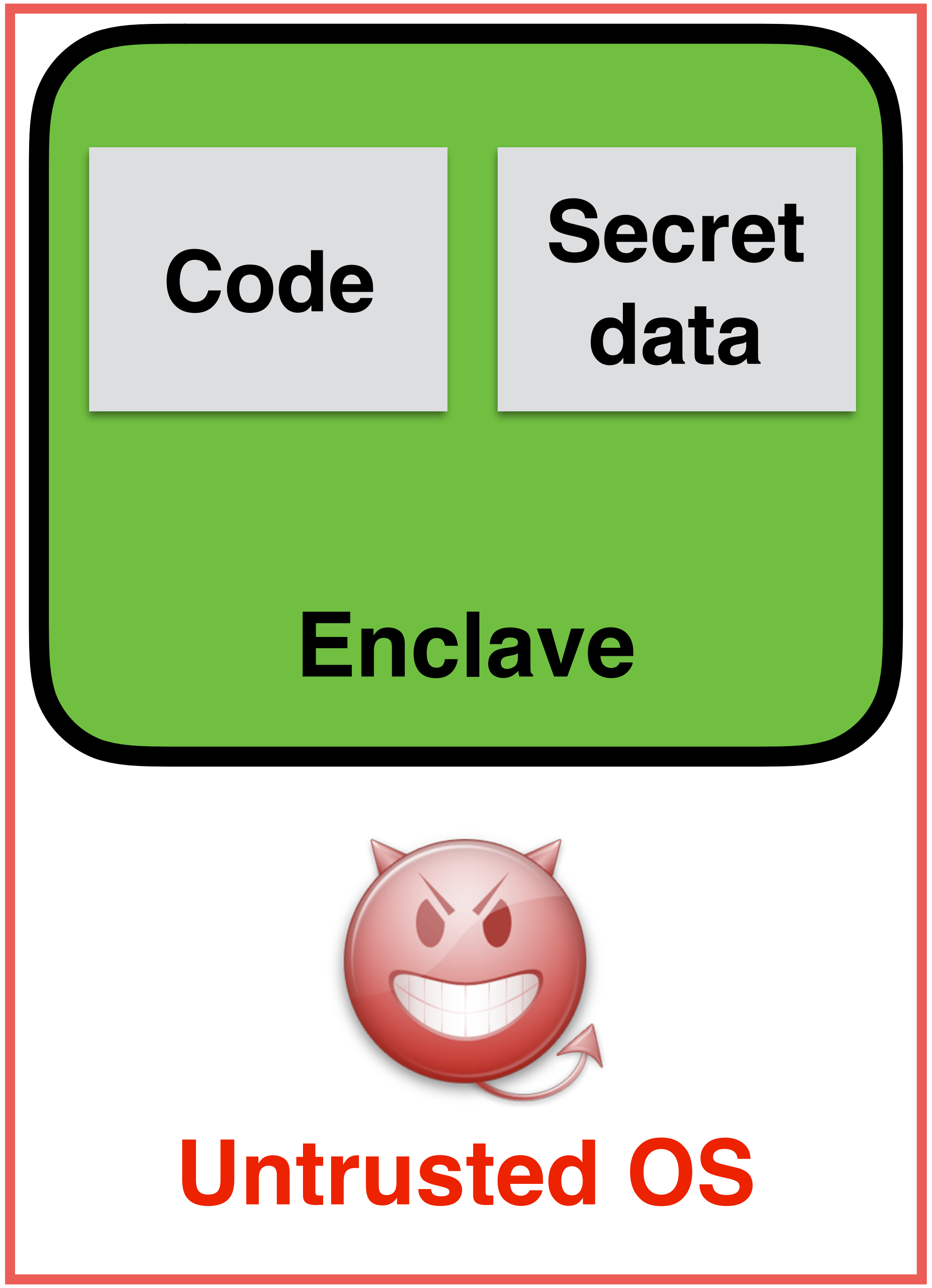
- Protect against an attacker who has root access



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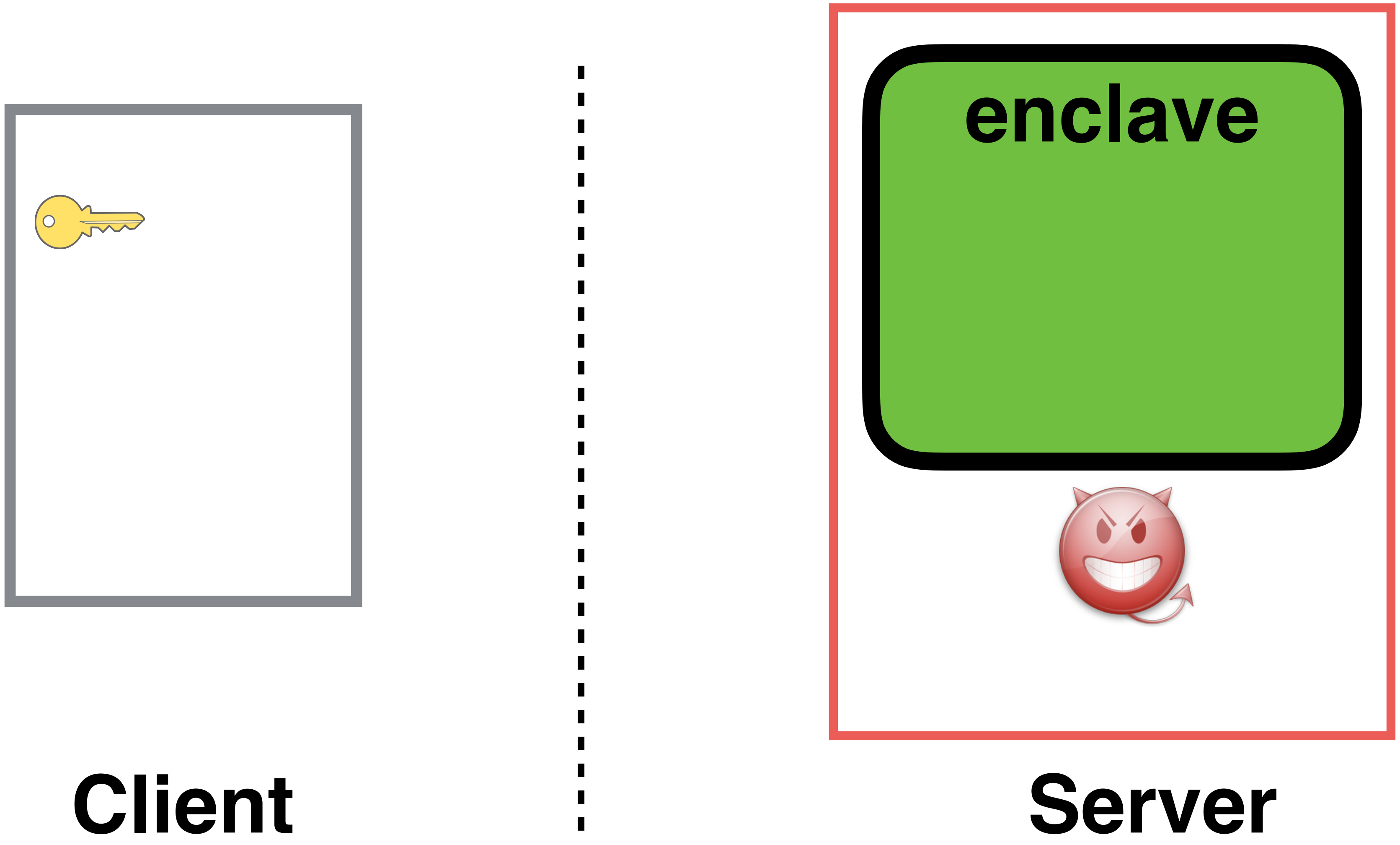


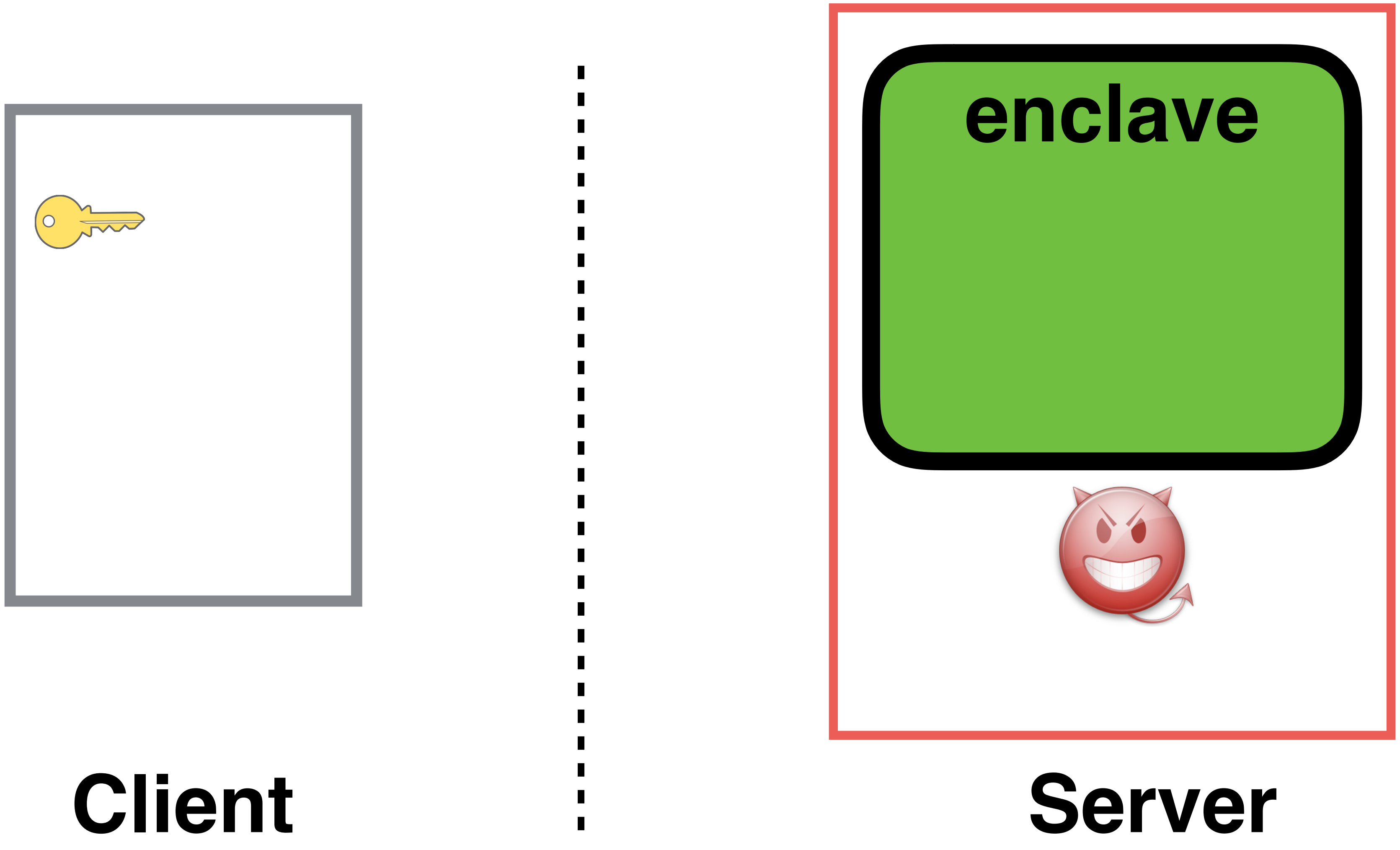
enclave

Client

Server

Remote attestation

Enables verifying which code runs in the enclave and performing key exchange



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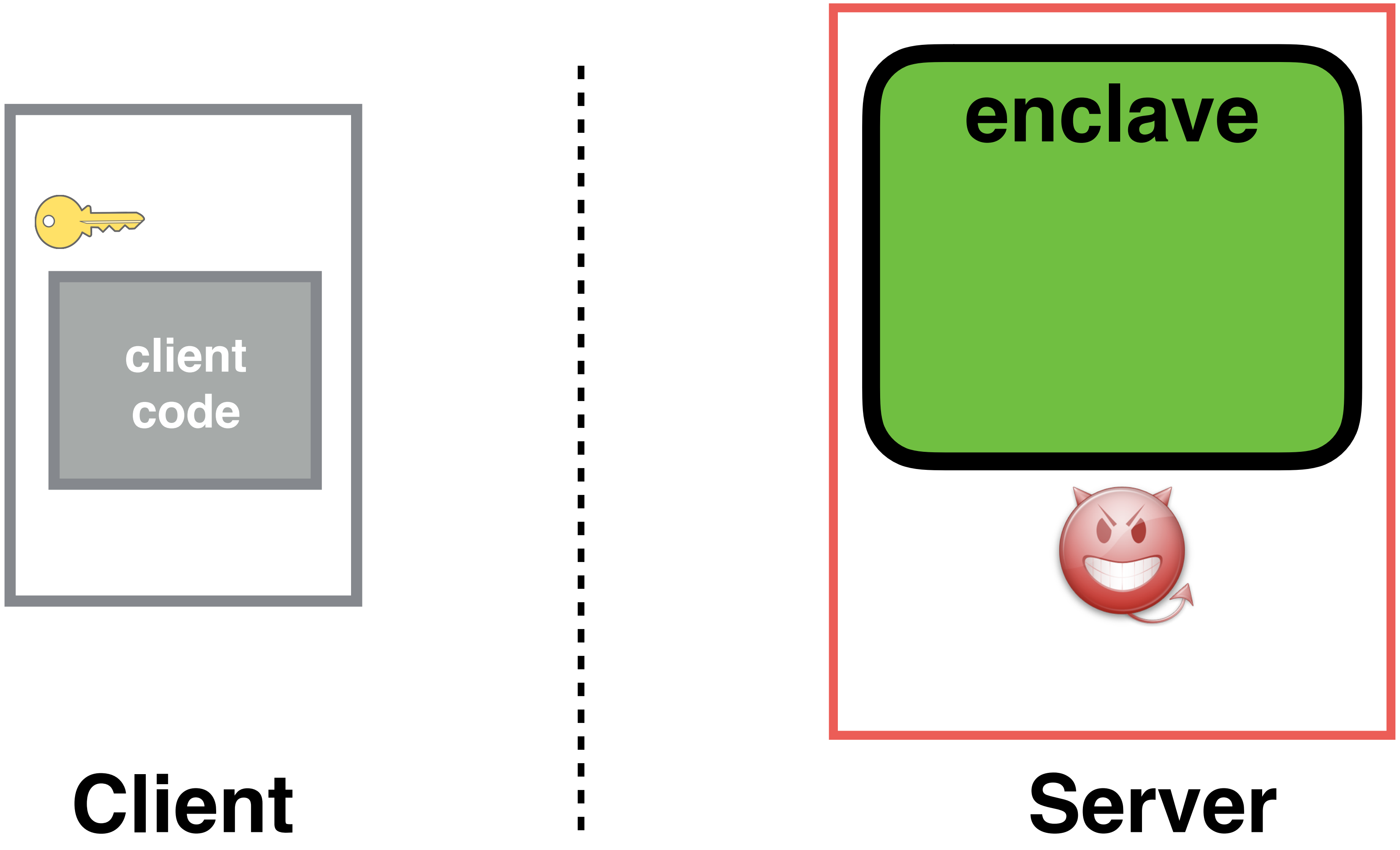

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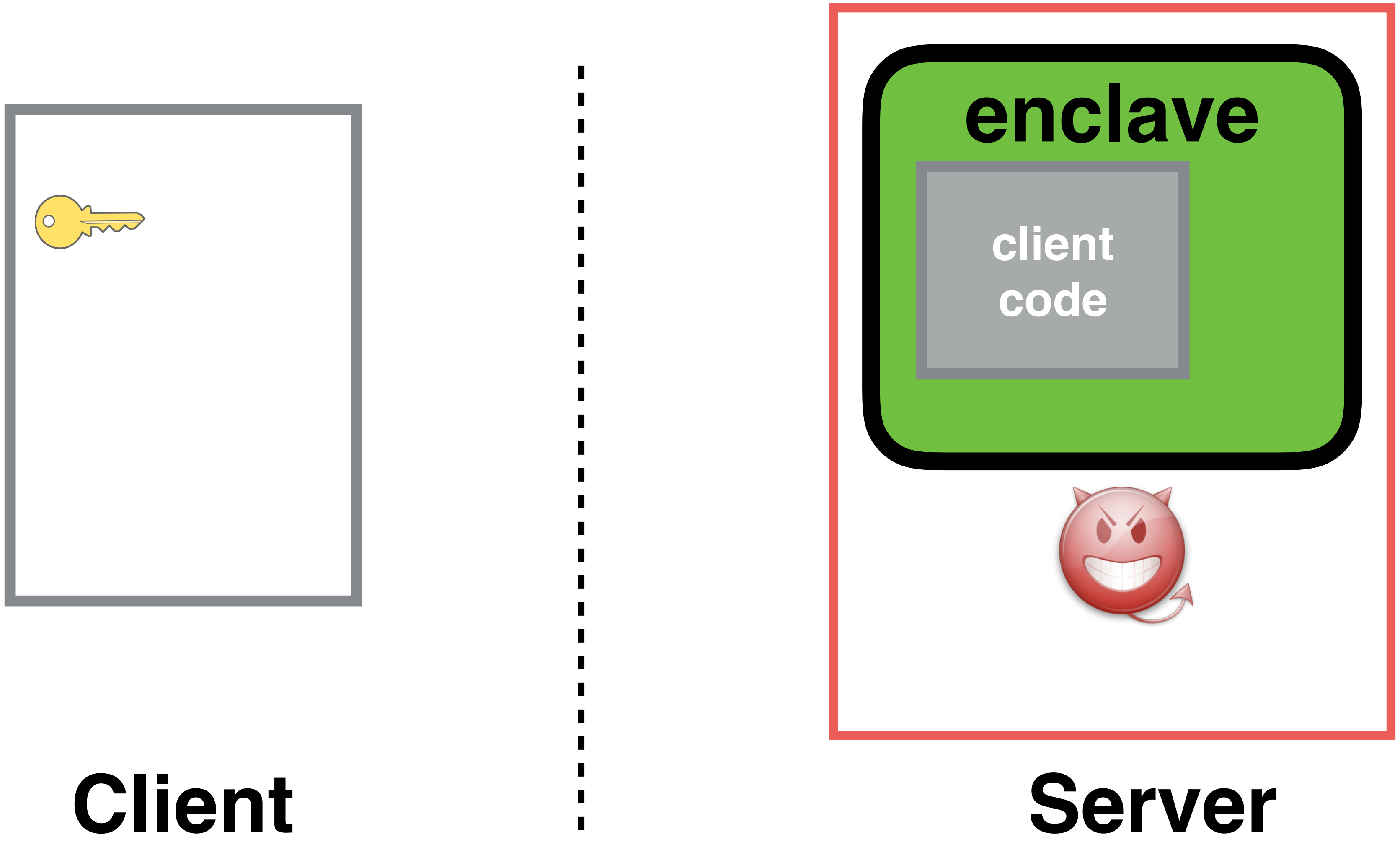

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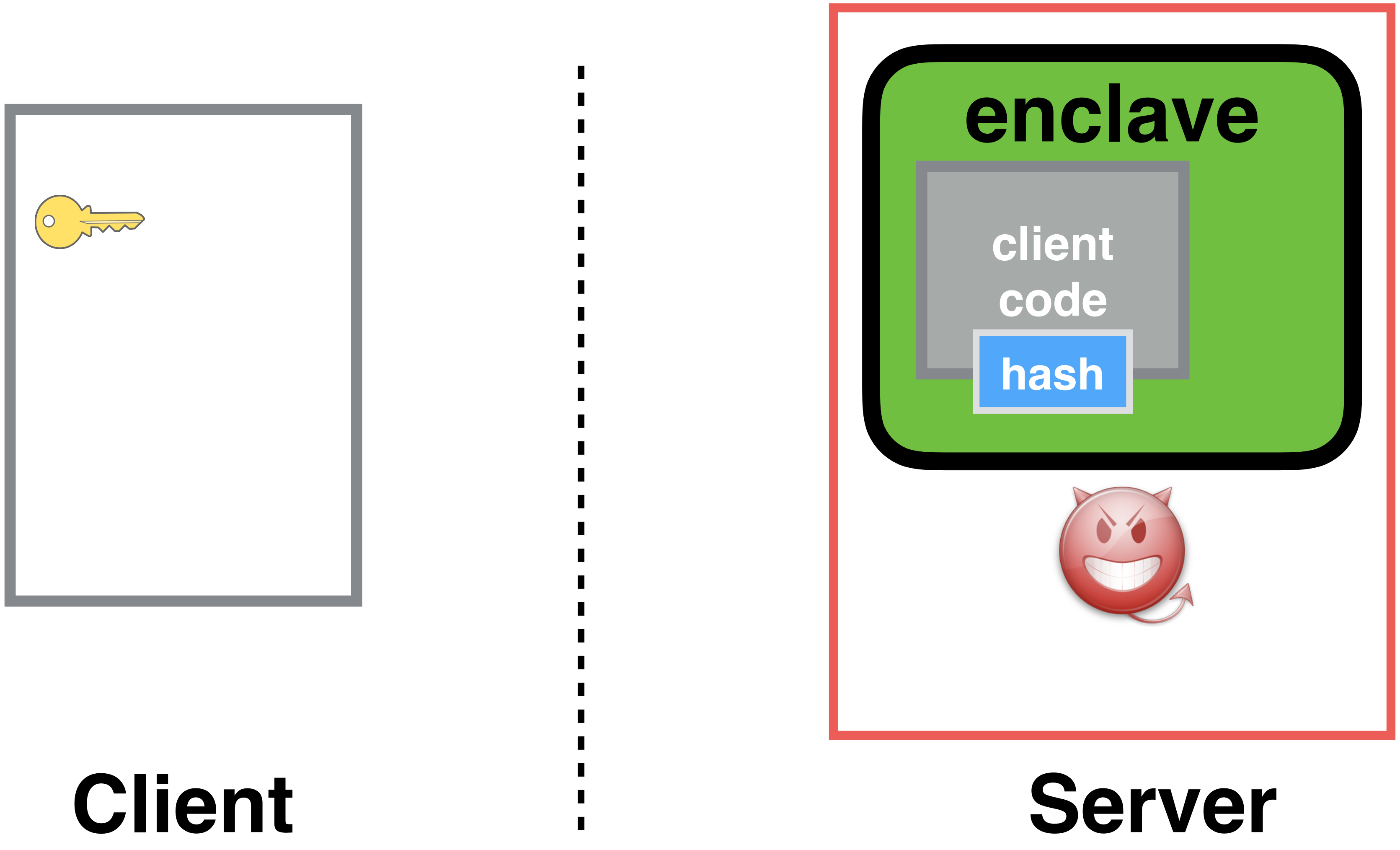

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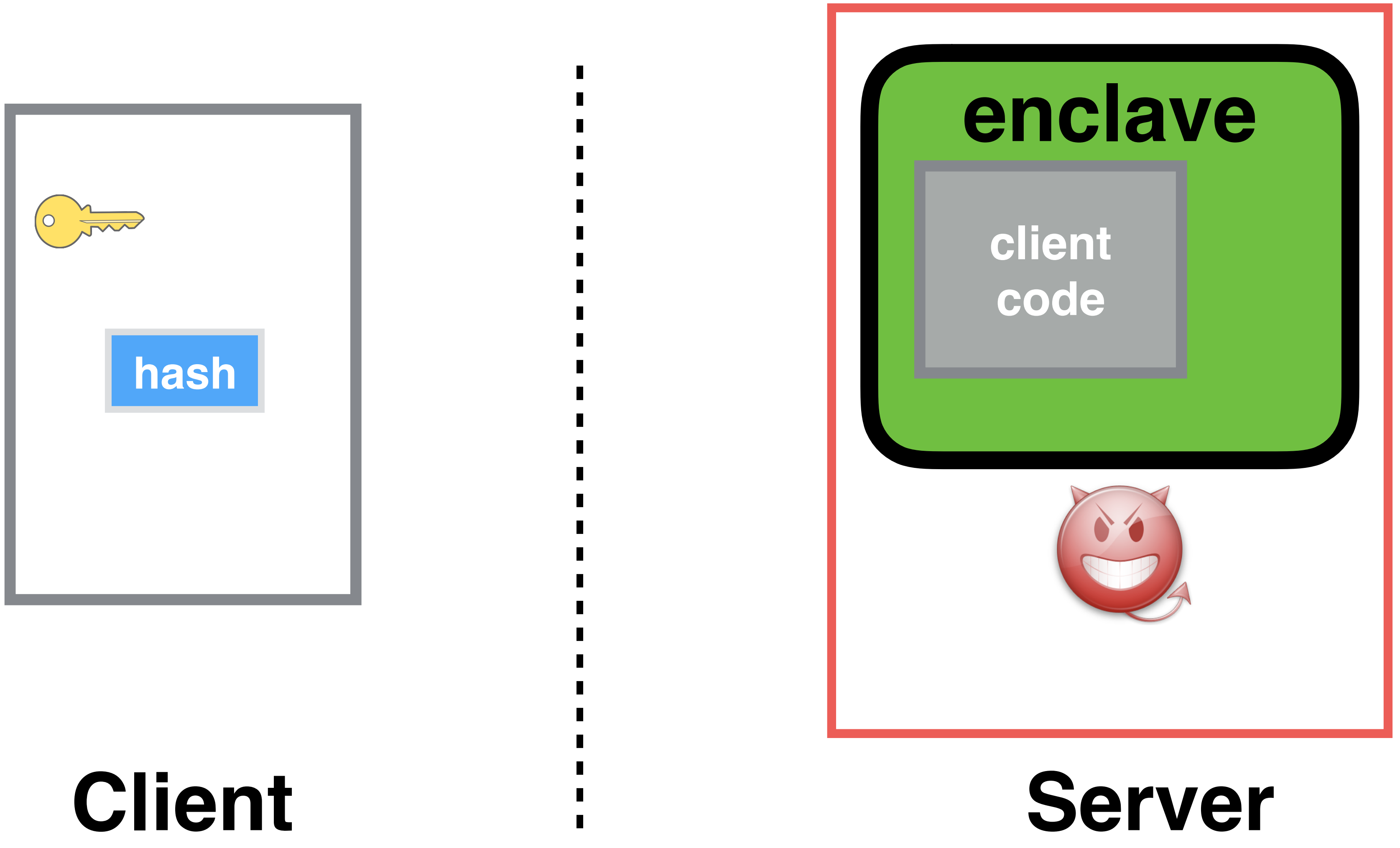

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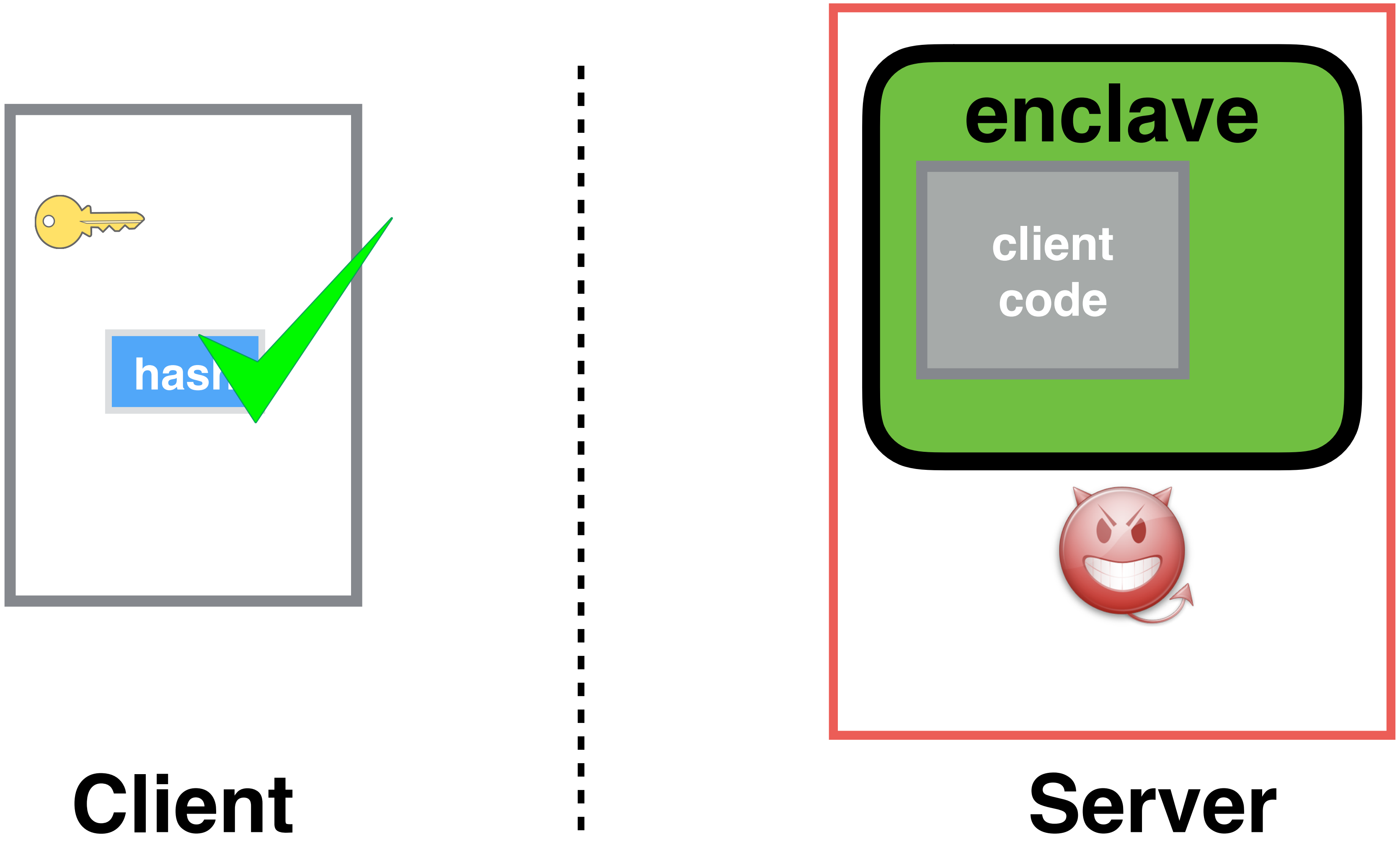

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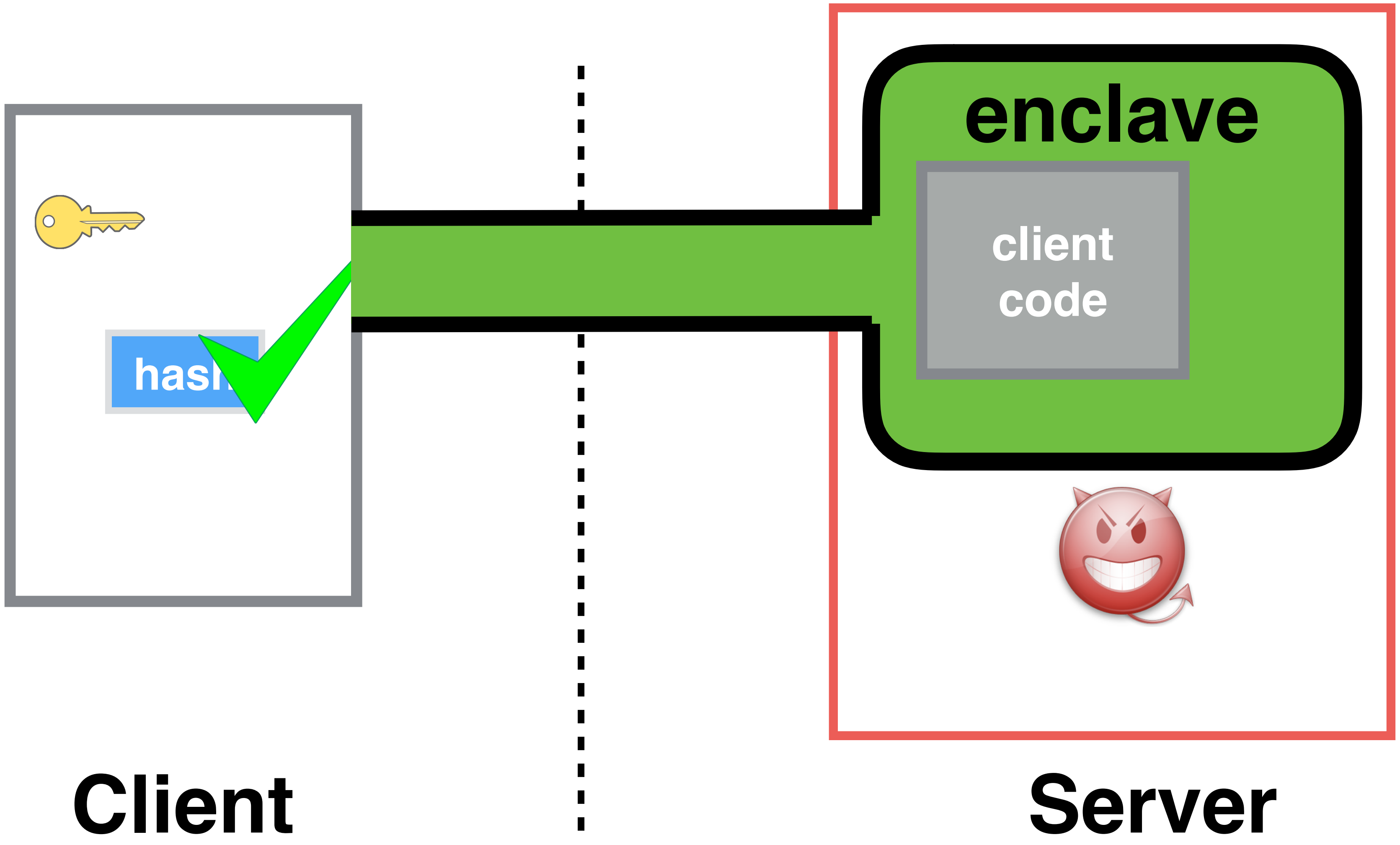

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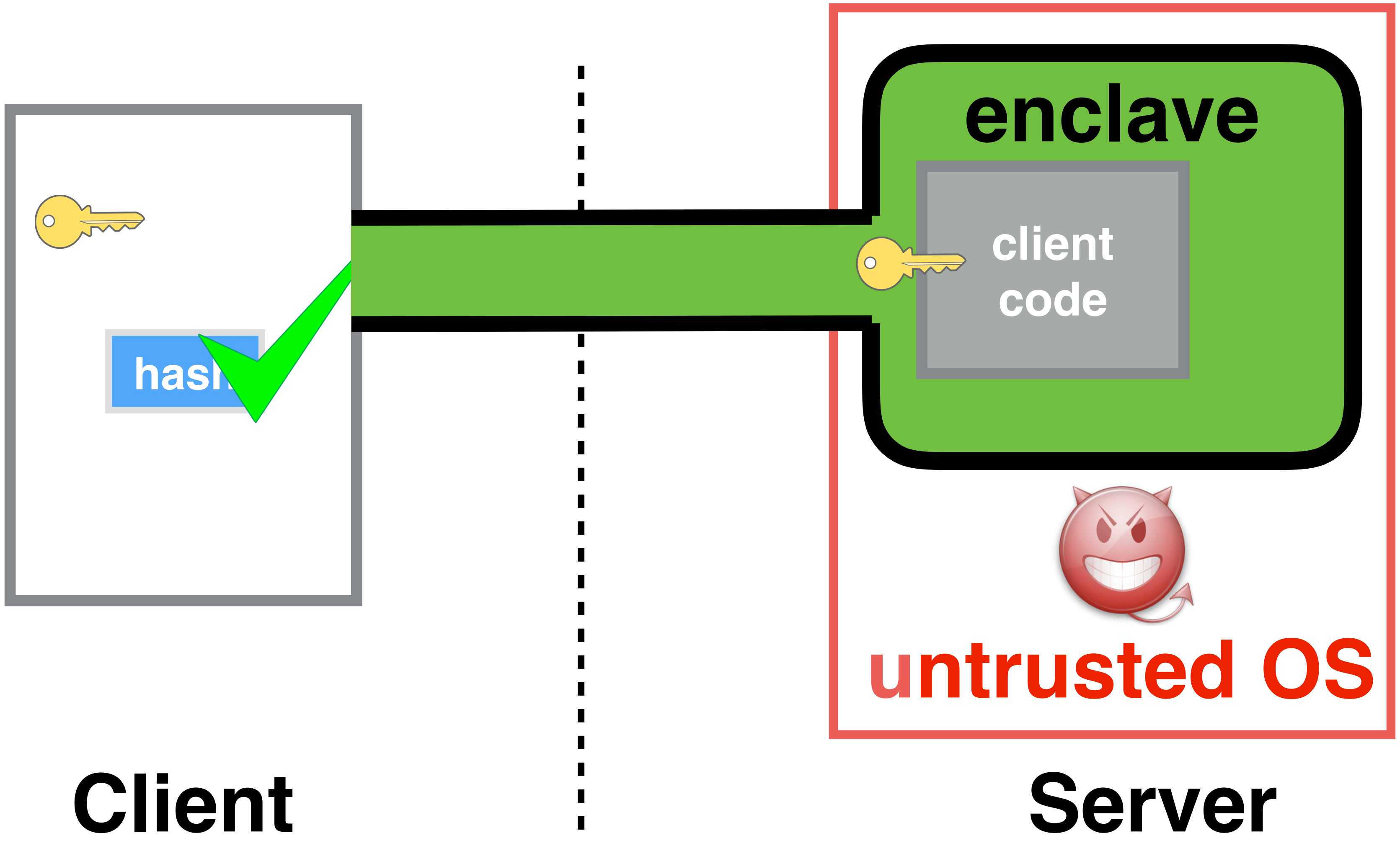

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Problem: access pattern leakage [XCP ‘15, OCFGKS ‘15]

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🔒 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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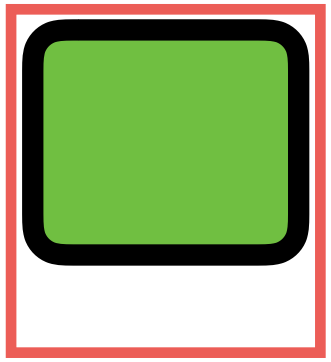

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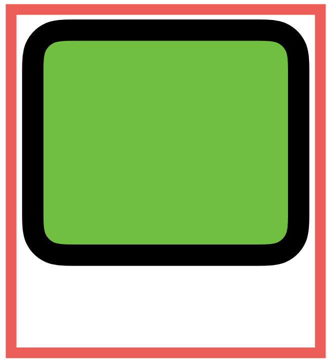

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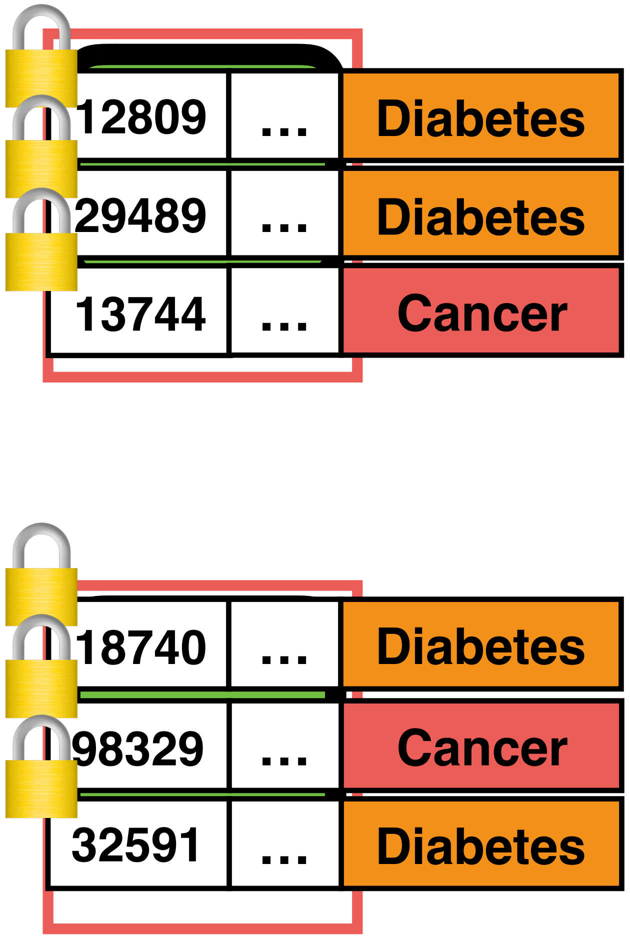

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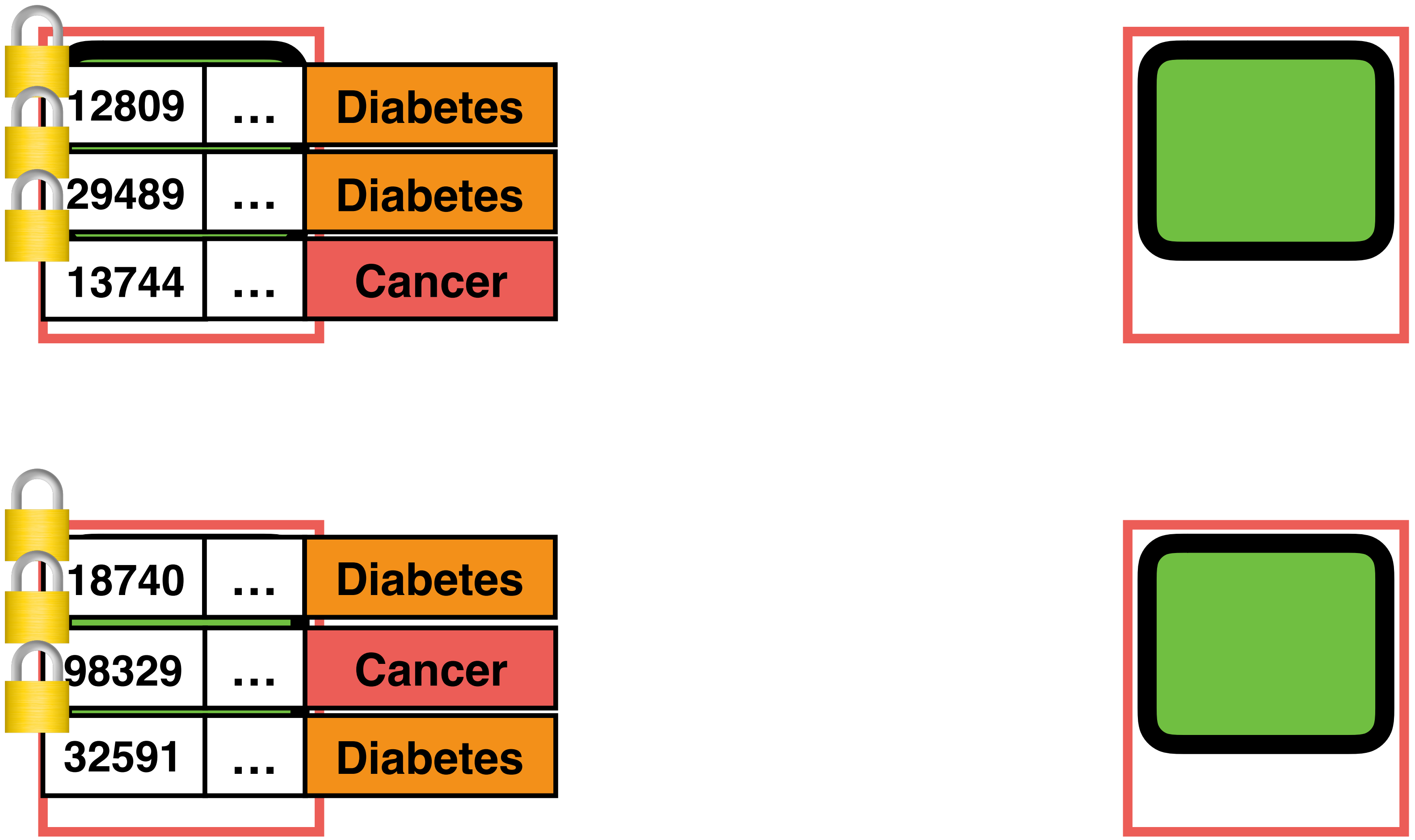

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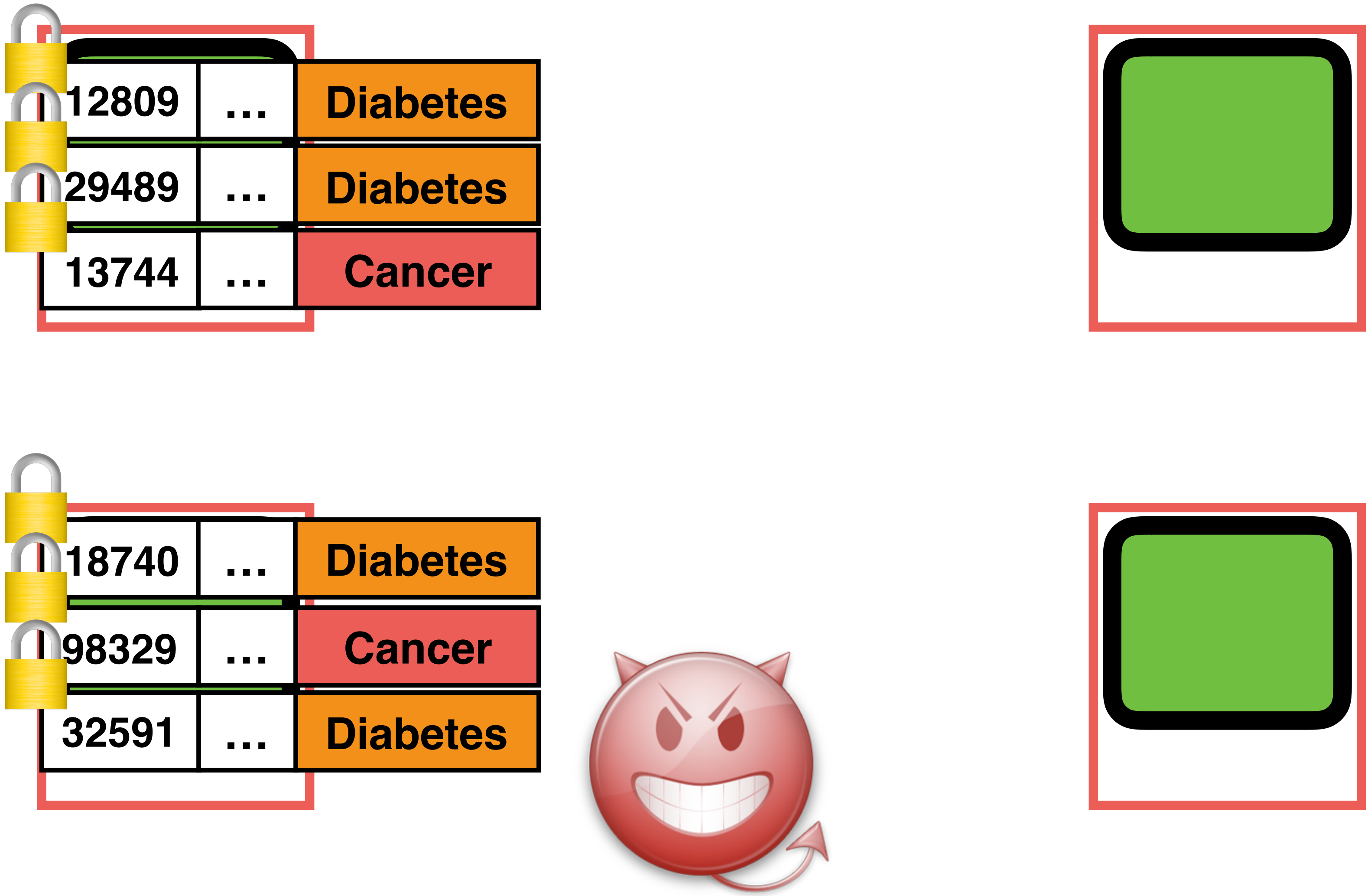

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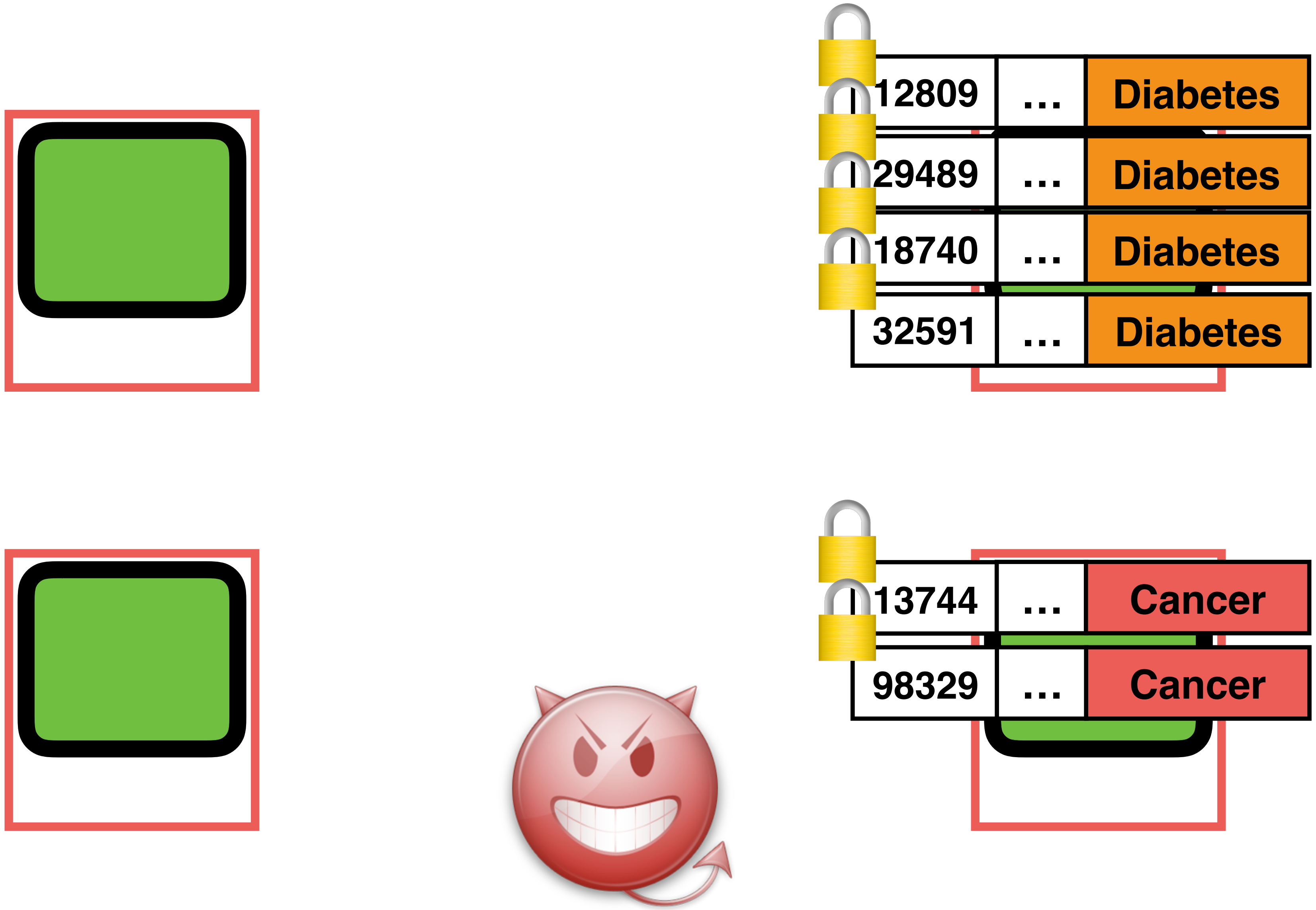

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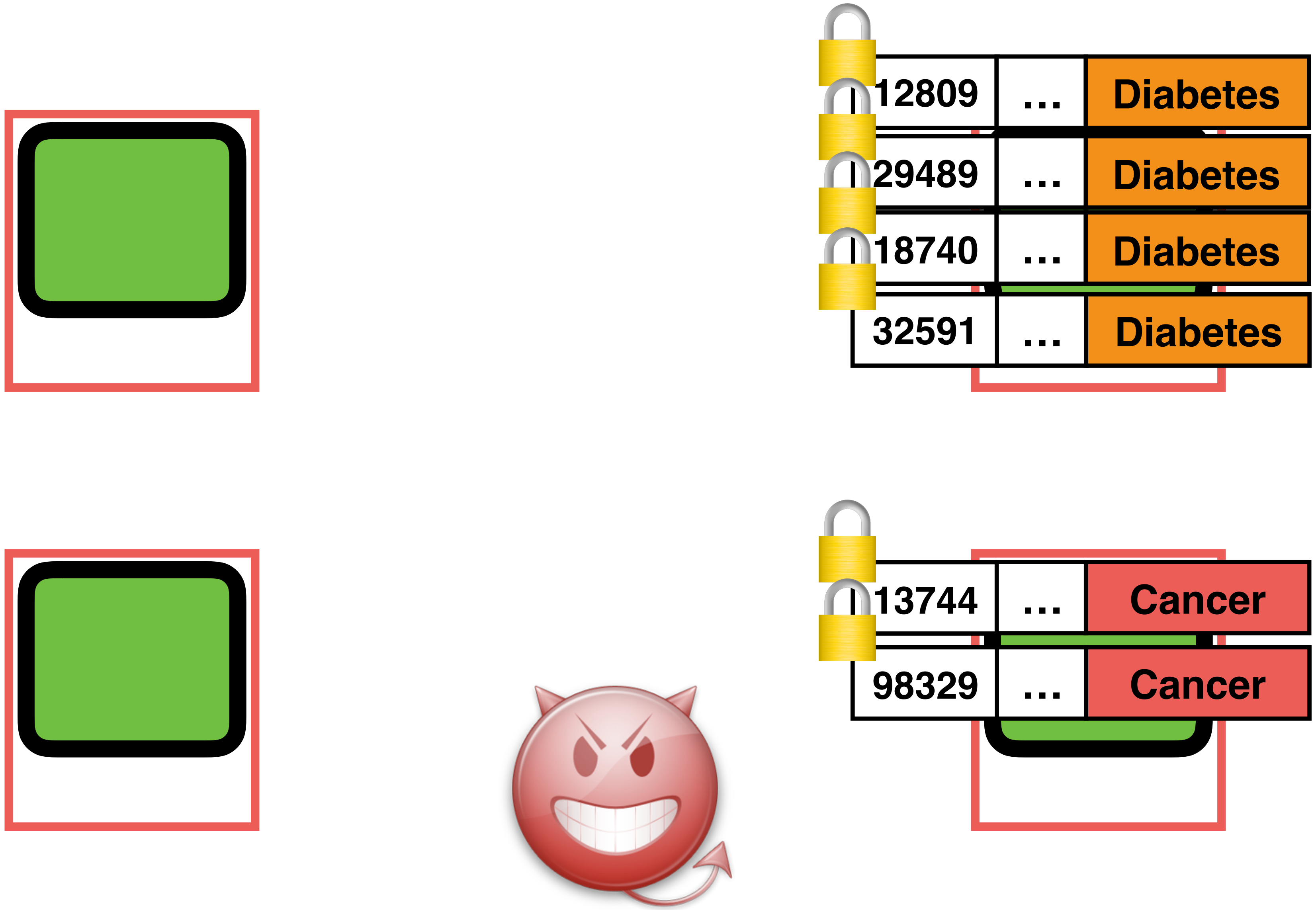

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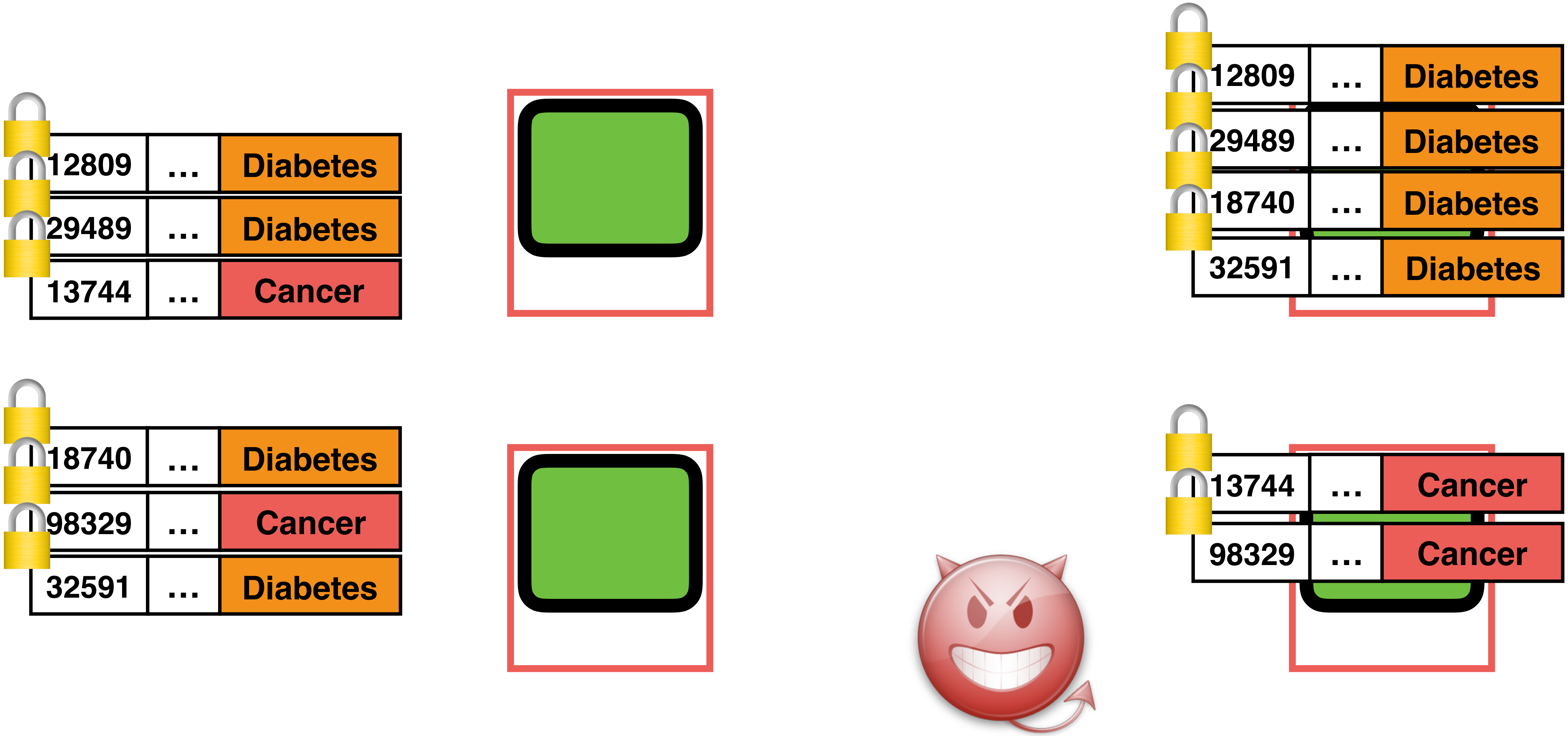

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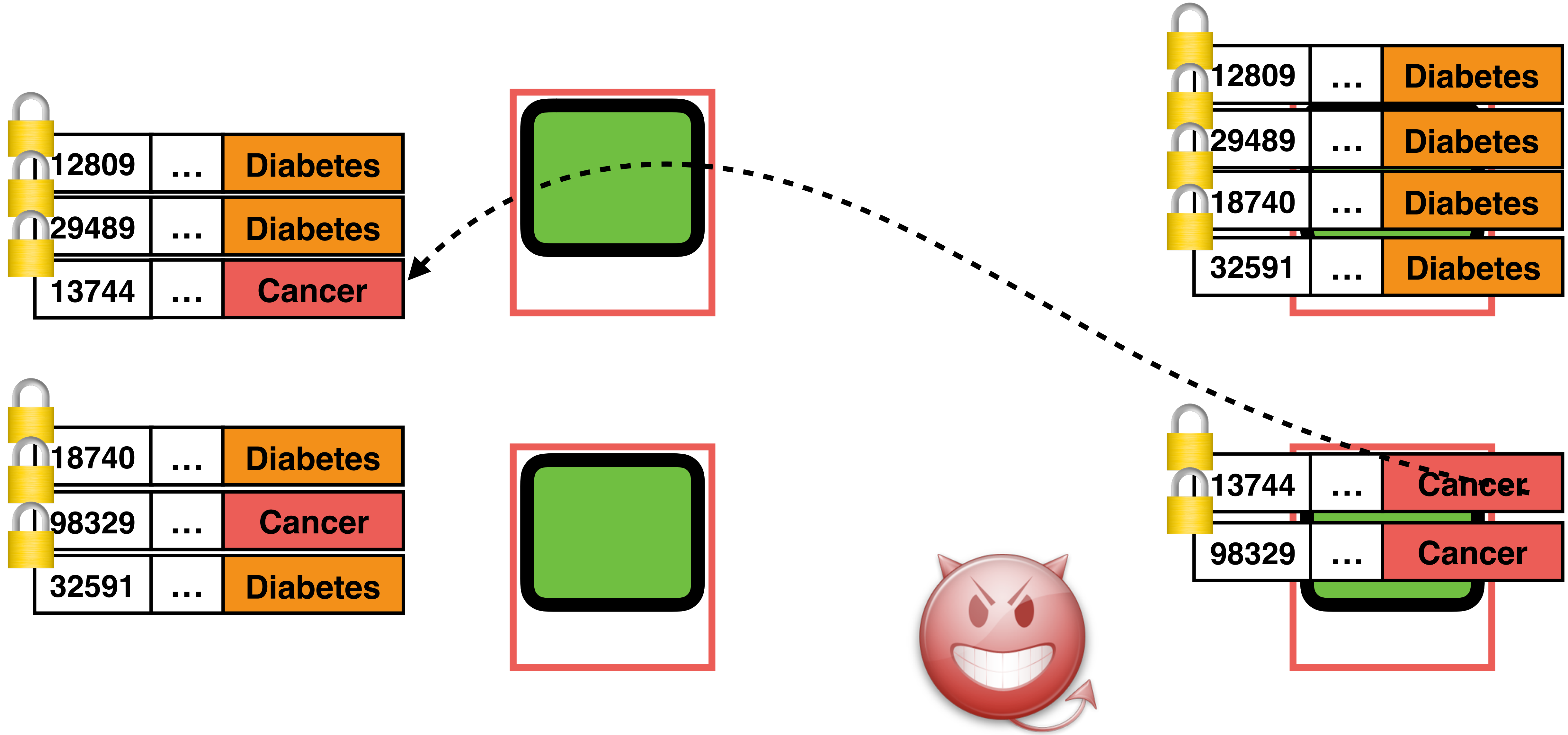

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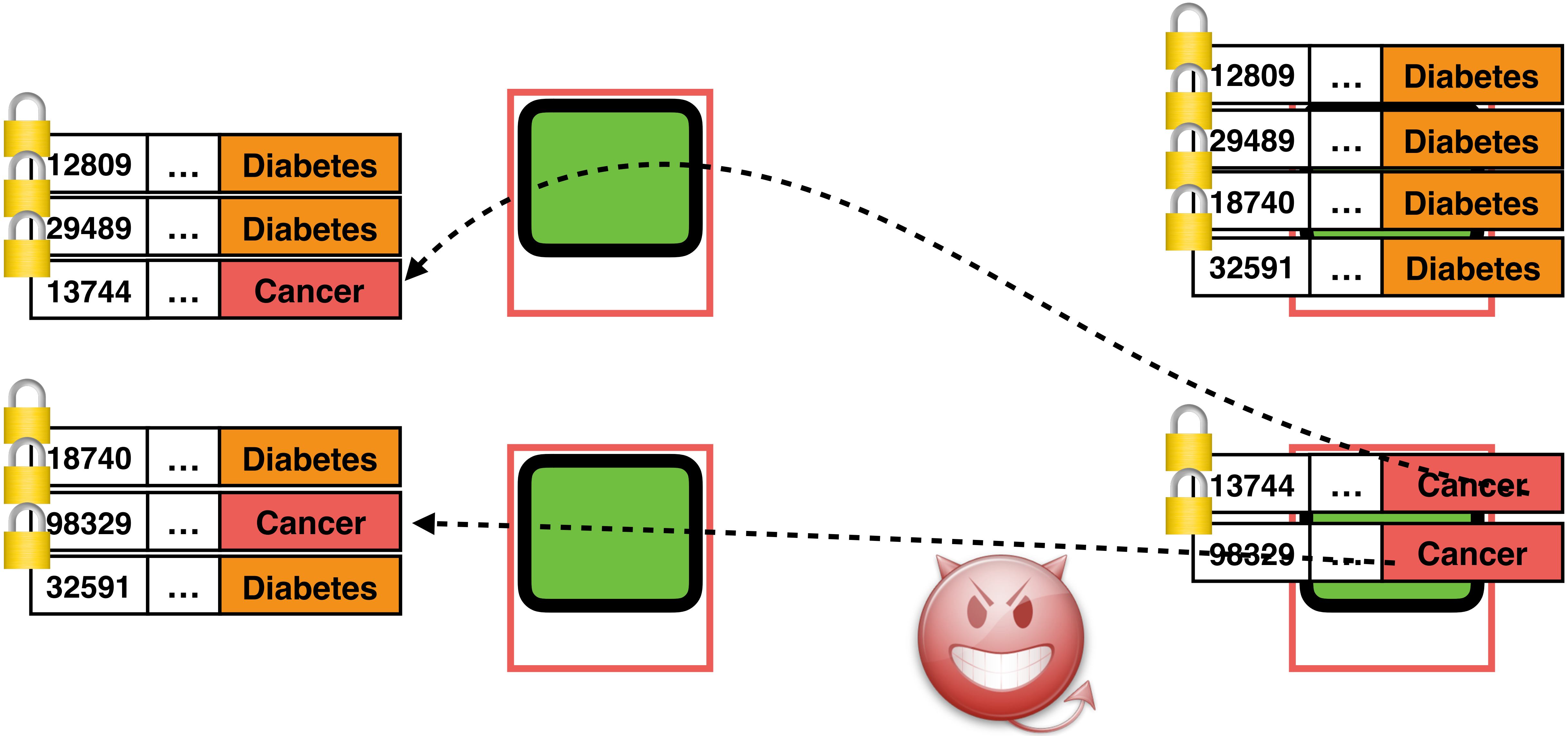

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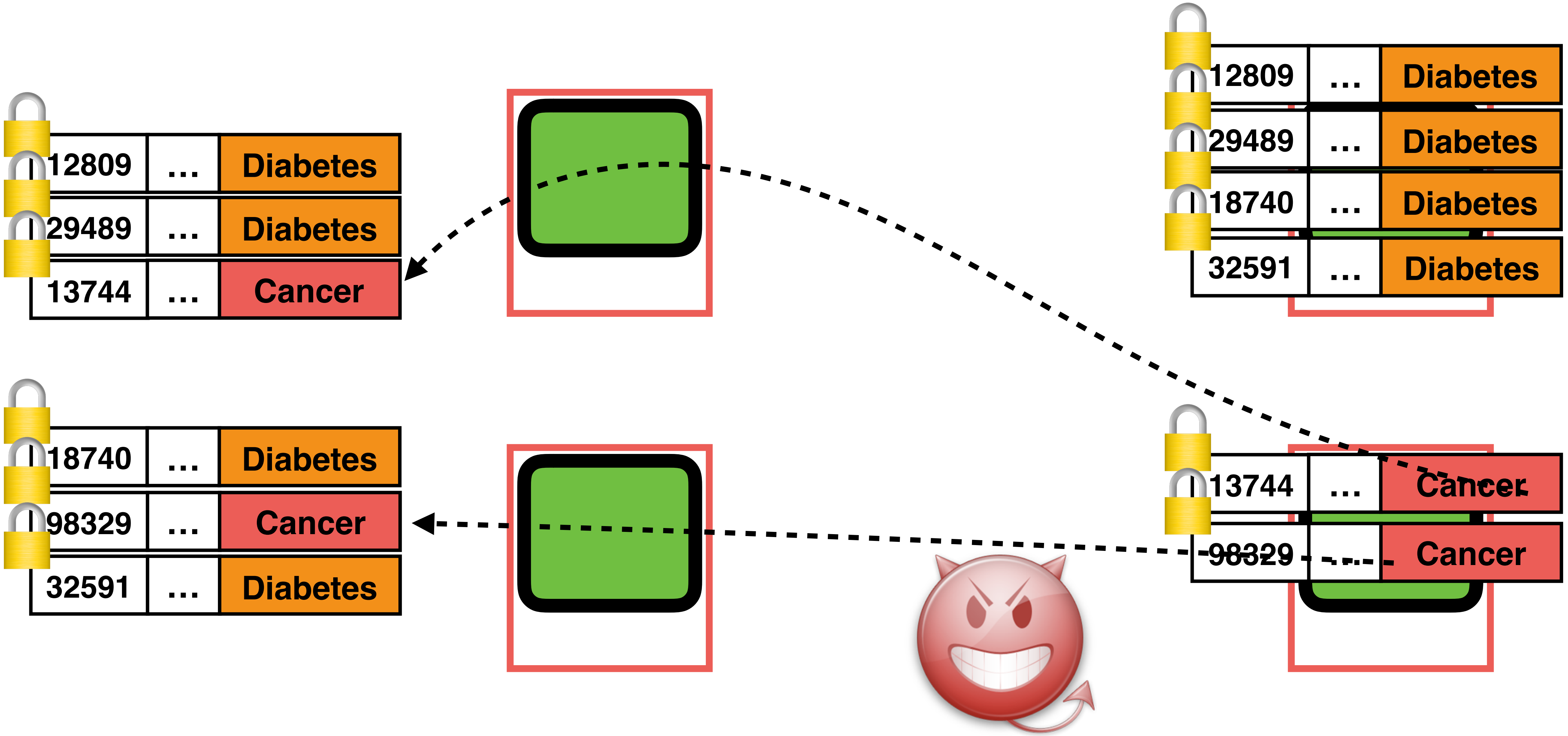

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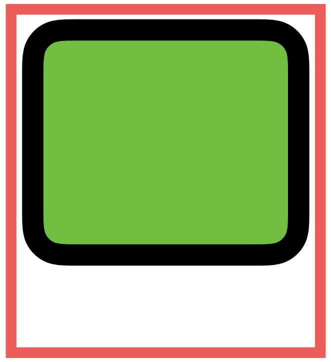

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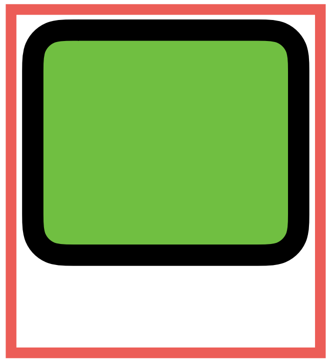

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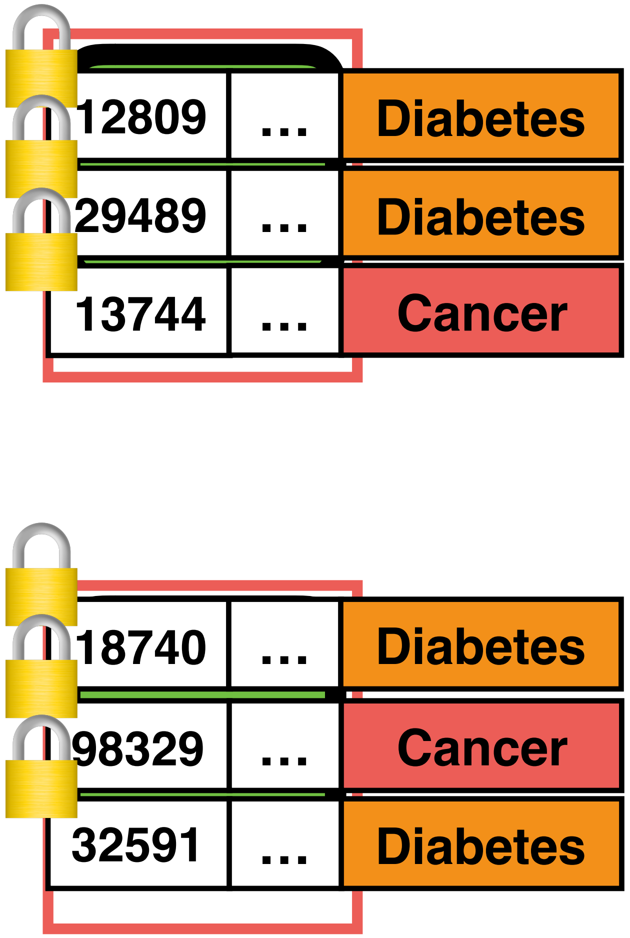

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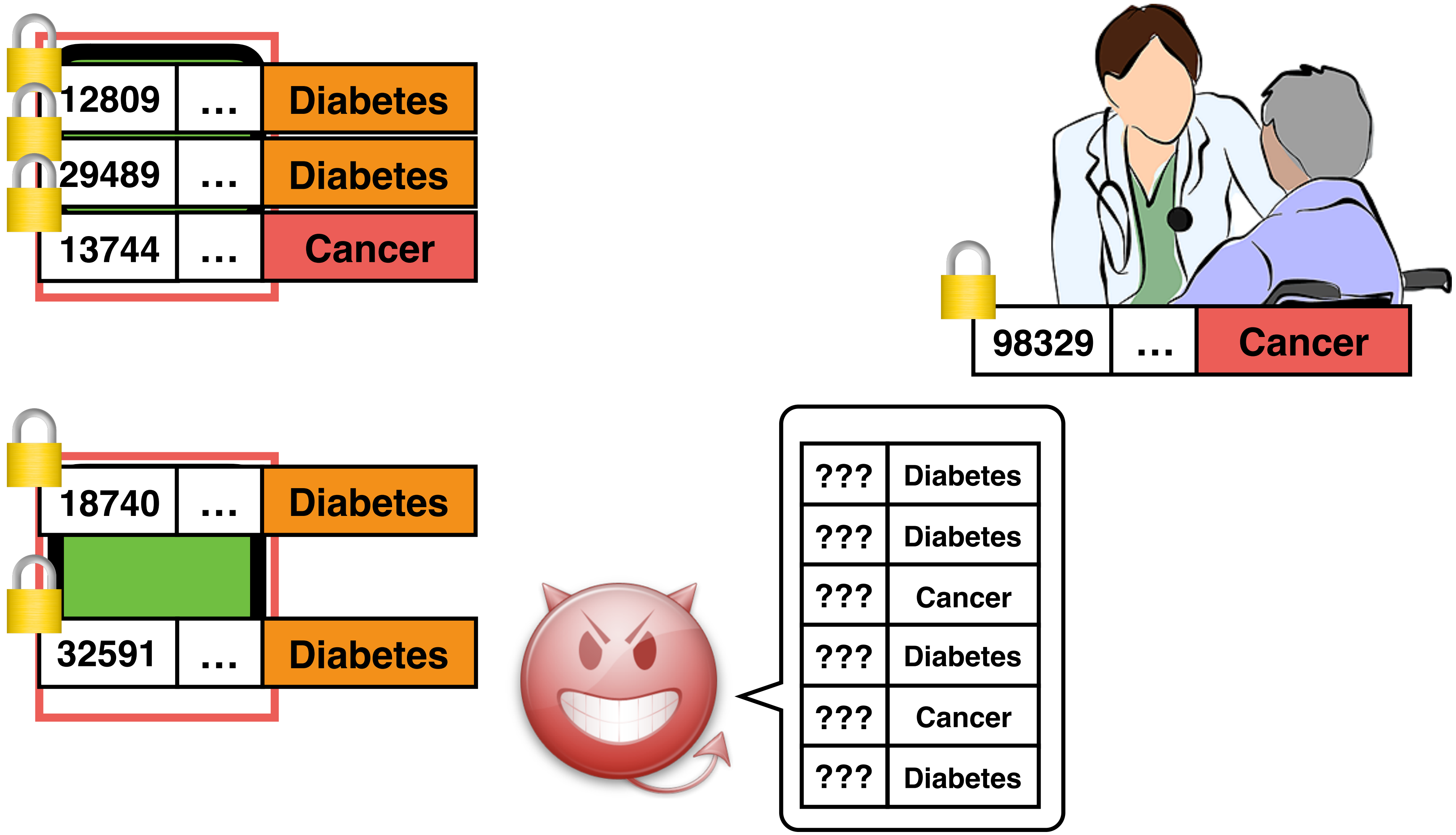

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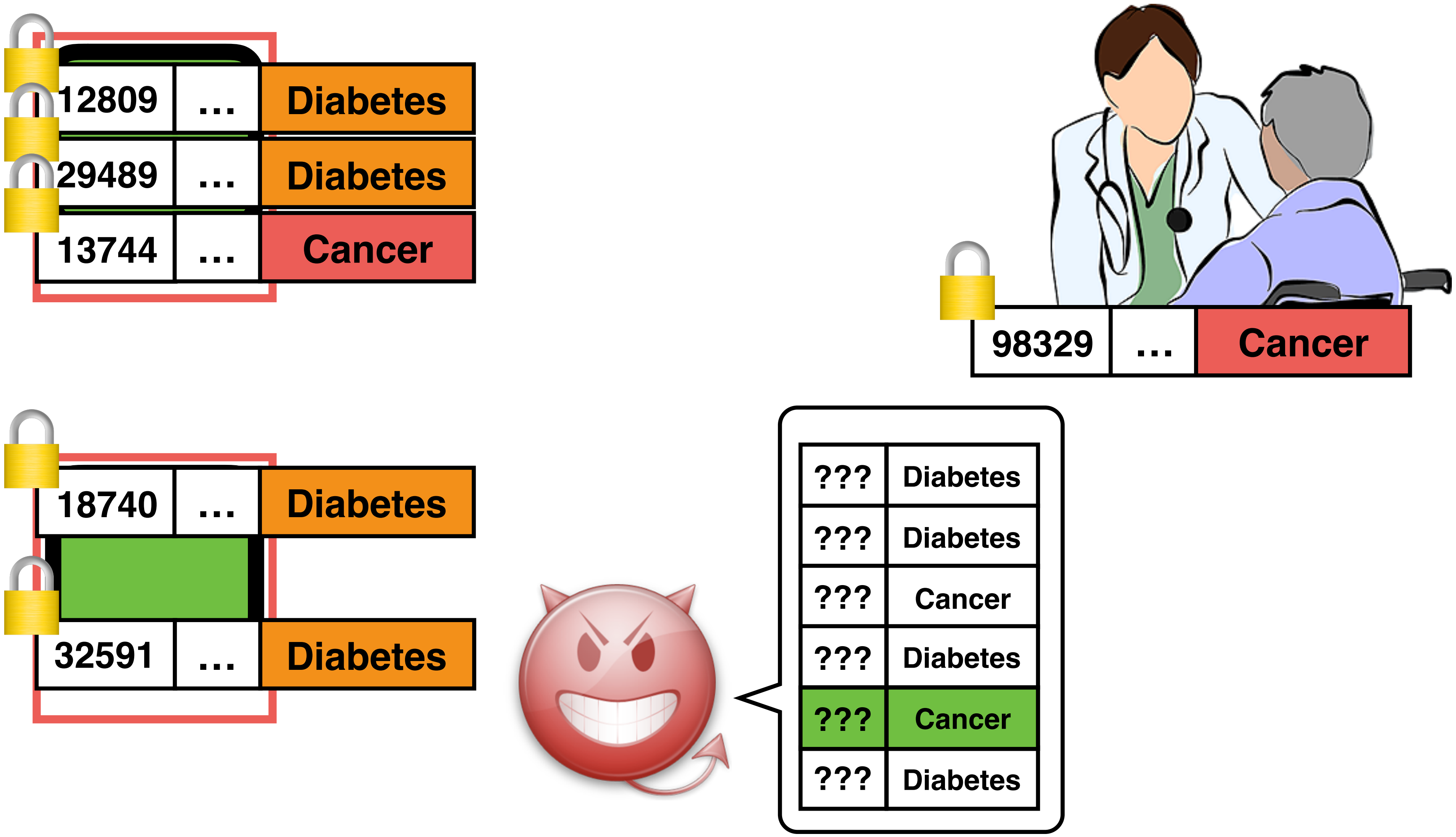

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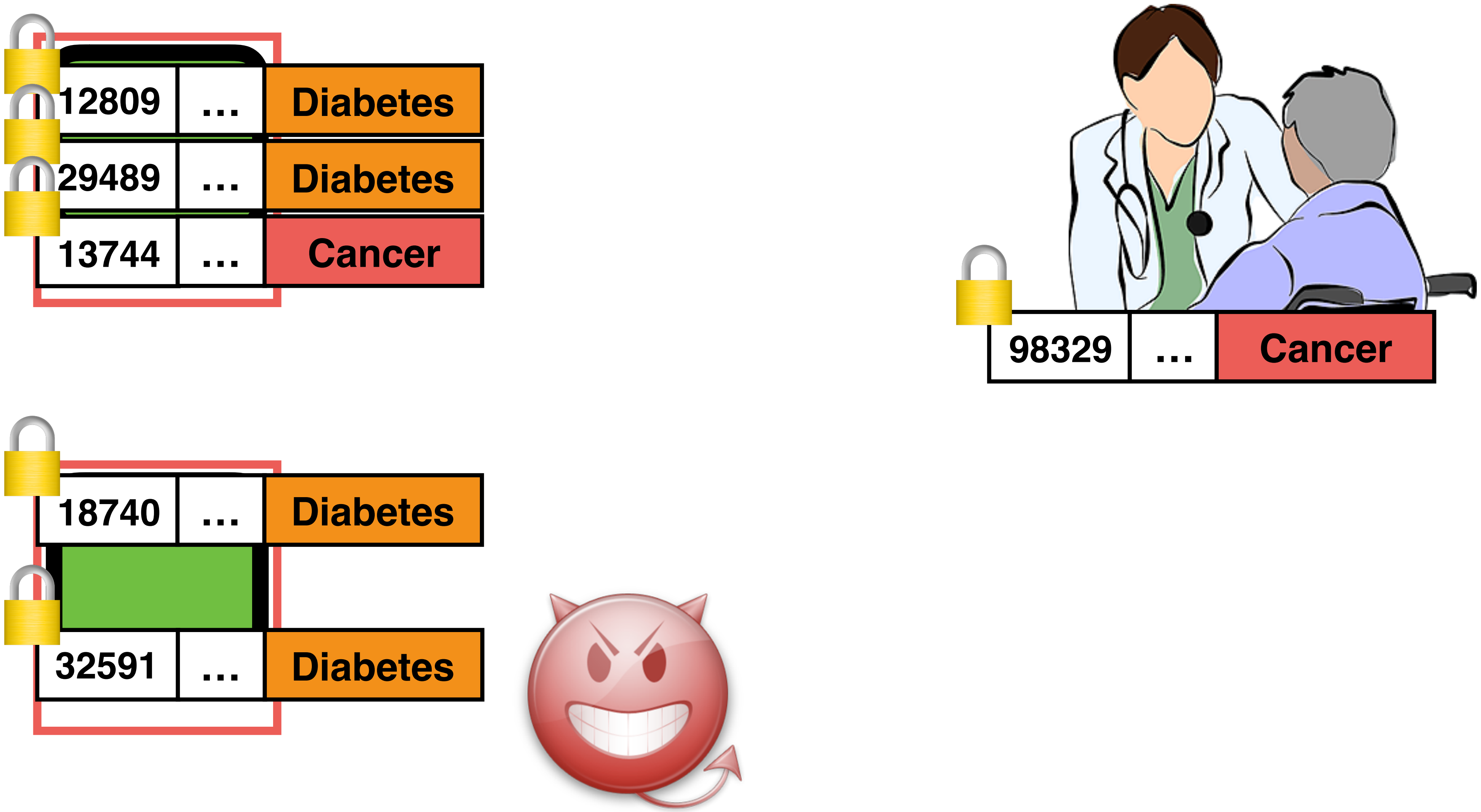

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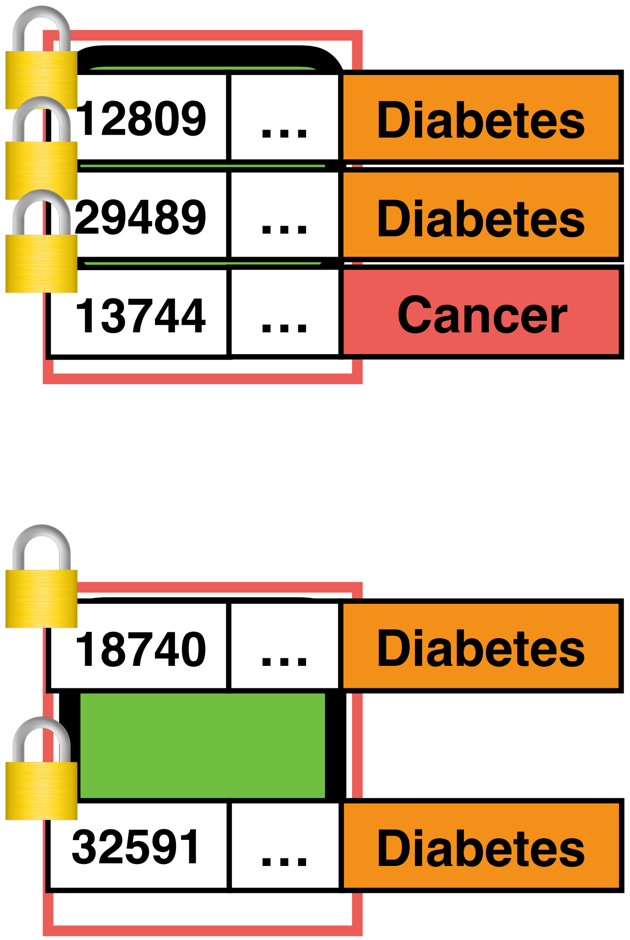

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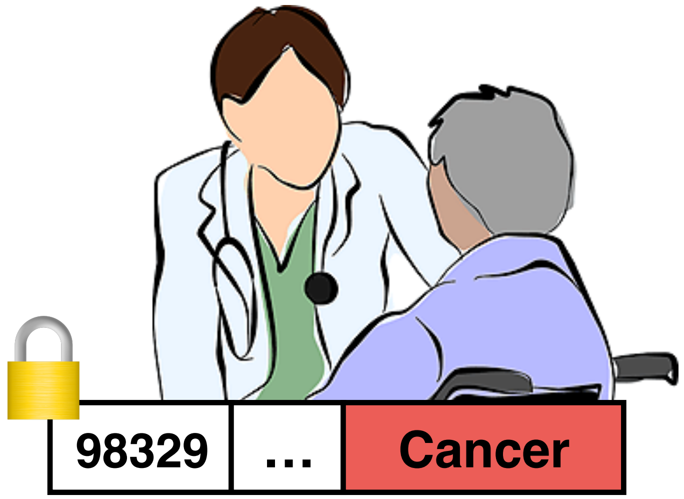

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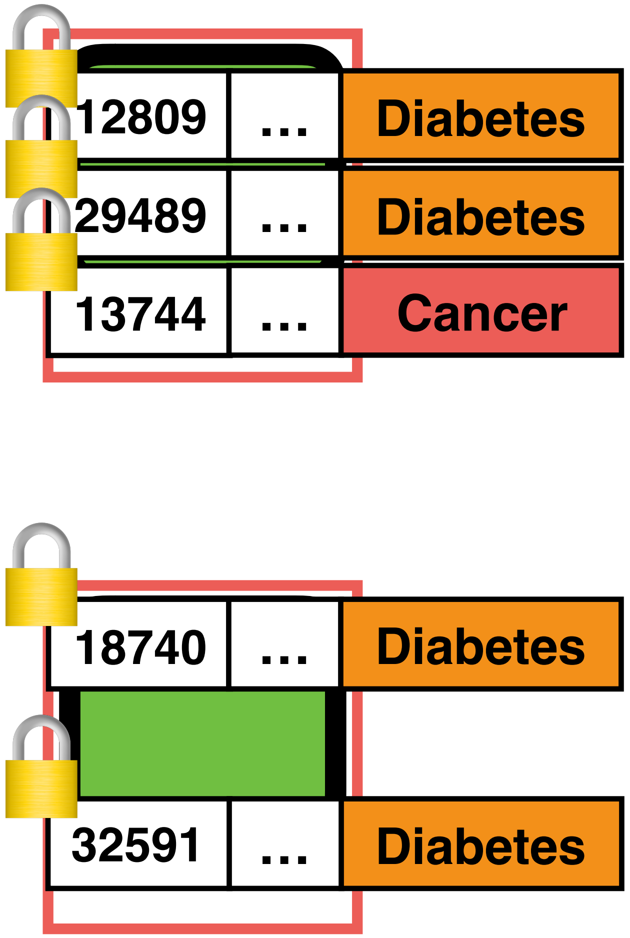

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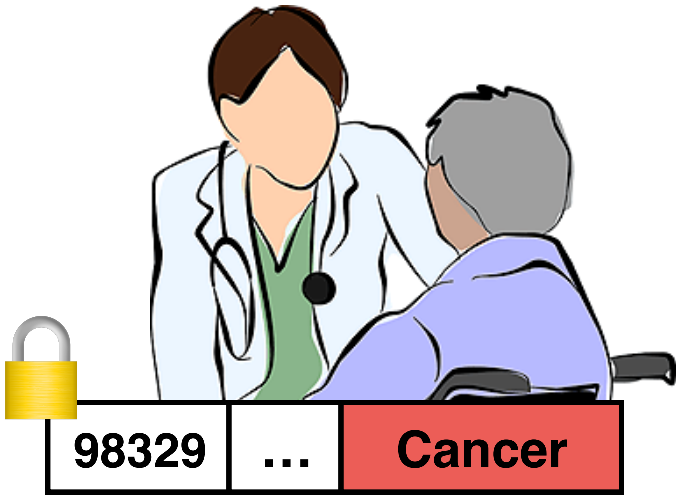

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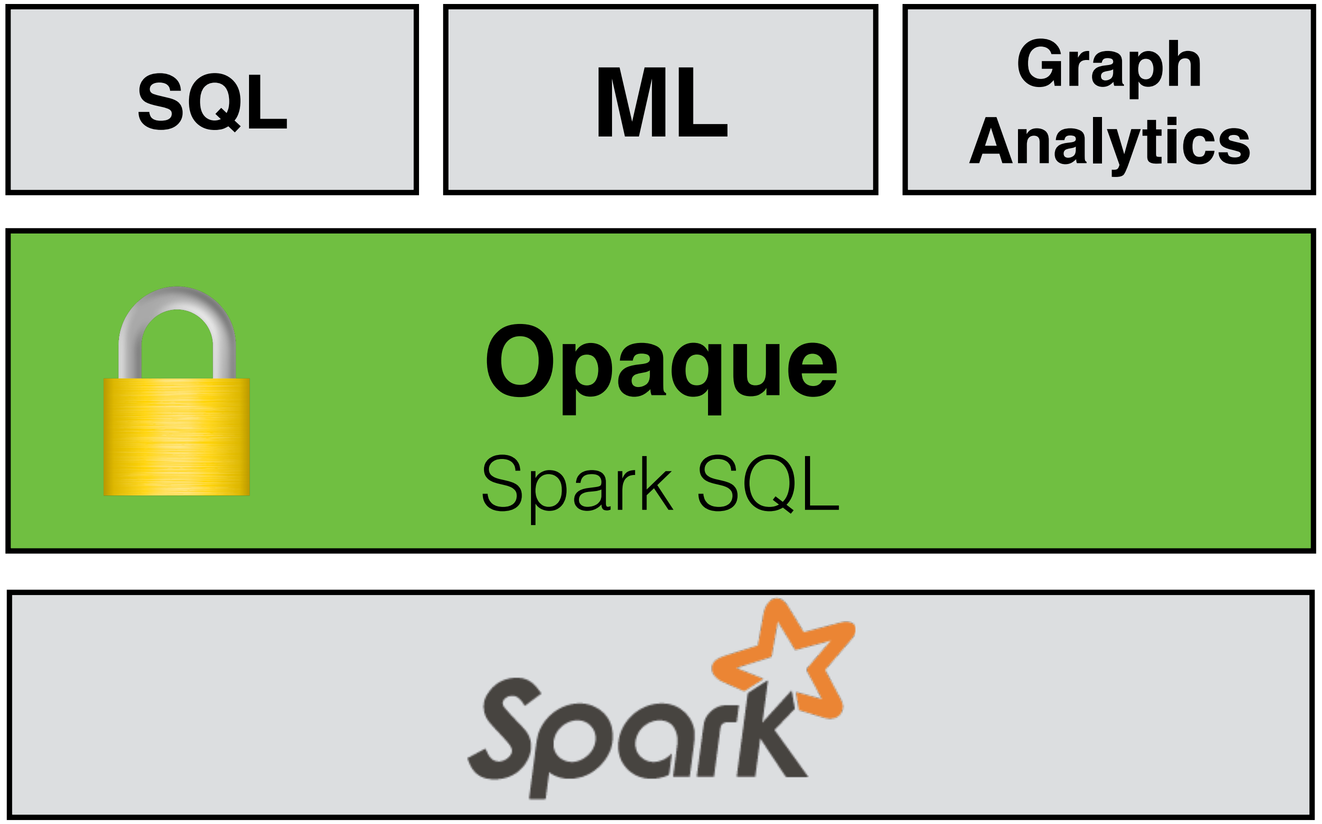
Attack viable by observing both memory and network accesses!

Opaque*: secure distributed analytics



* Oblivious Platform for Analytic QUEries

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  - see paper for more!

Security guarantees

- Data encryption and authentication
- Computation integrity: a check enforcing that the computation is executed correctly
  - see paper for more!
- **Obliviousness = hiding access patterns**

Security guarantees

- Data encryption and authentication
- Computation integrity: a check enforcing that the computation is executed correctly
  - see paper for more!
- **Obliviousness = hiding access patterns**
  - *Informal statement*

Security guarantees

- Data encryption and authentication
- Computation integrity: a check enforcing that the computation is executed correctly
  - see paper for more!
- **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

Challenge: obliviousness is expensive

Two-part solution:

Challenge: obliviousness is expensive

Two-part solution:

Distributed oblivious SQL operators

Challenge: obliviousness is expensive

Two-part solution:

Distributed oblivious SQL operators

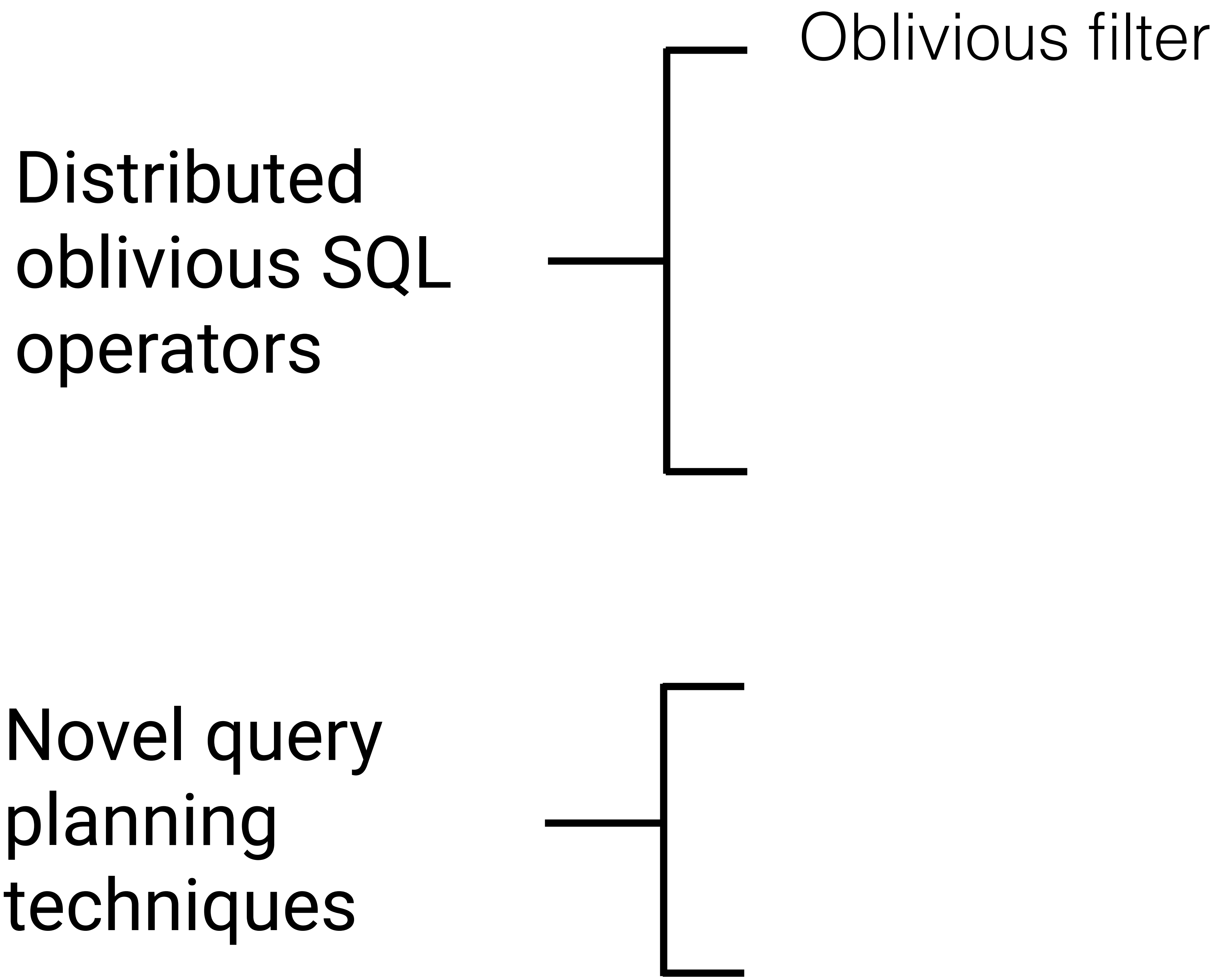
Novel query planning techniques

Two-part solution:

Distributed oblivious SQL operators

Novel query planning techniques

Two-part solution:



Distributed oblivious SQL operators

Oblivious filter

Novel query planning techniques

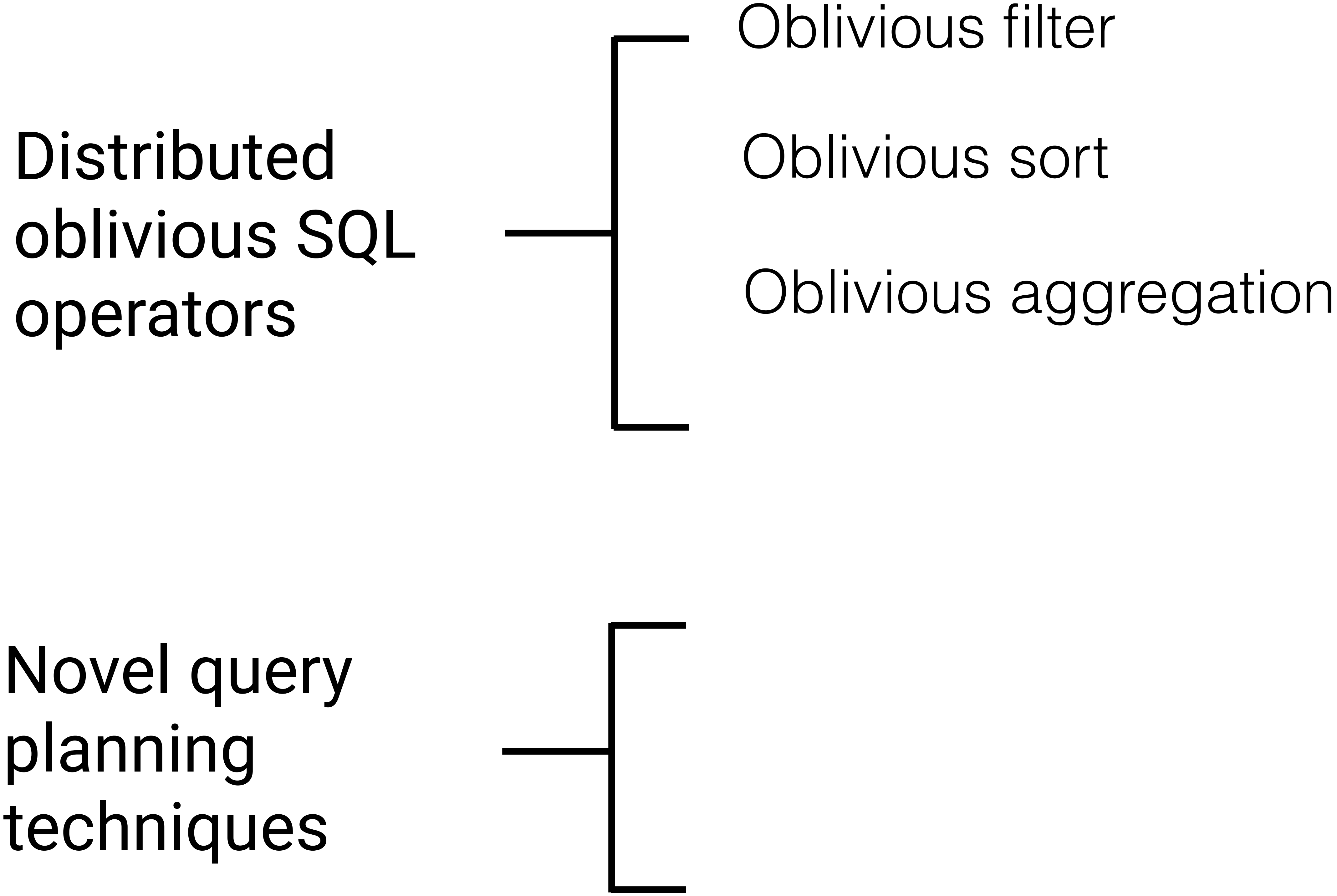
Two-part solution:

Distributed oblivious SQL operators

- Oblivious filter
- Oblivious sort

Novel query planning techniques

Two-part solution:



Distributed oblivious SQL operators

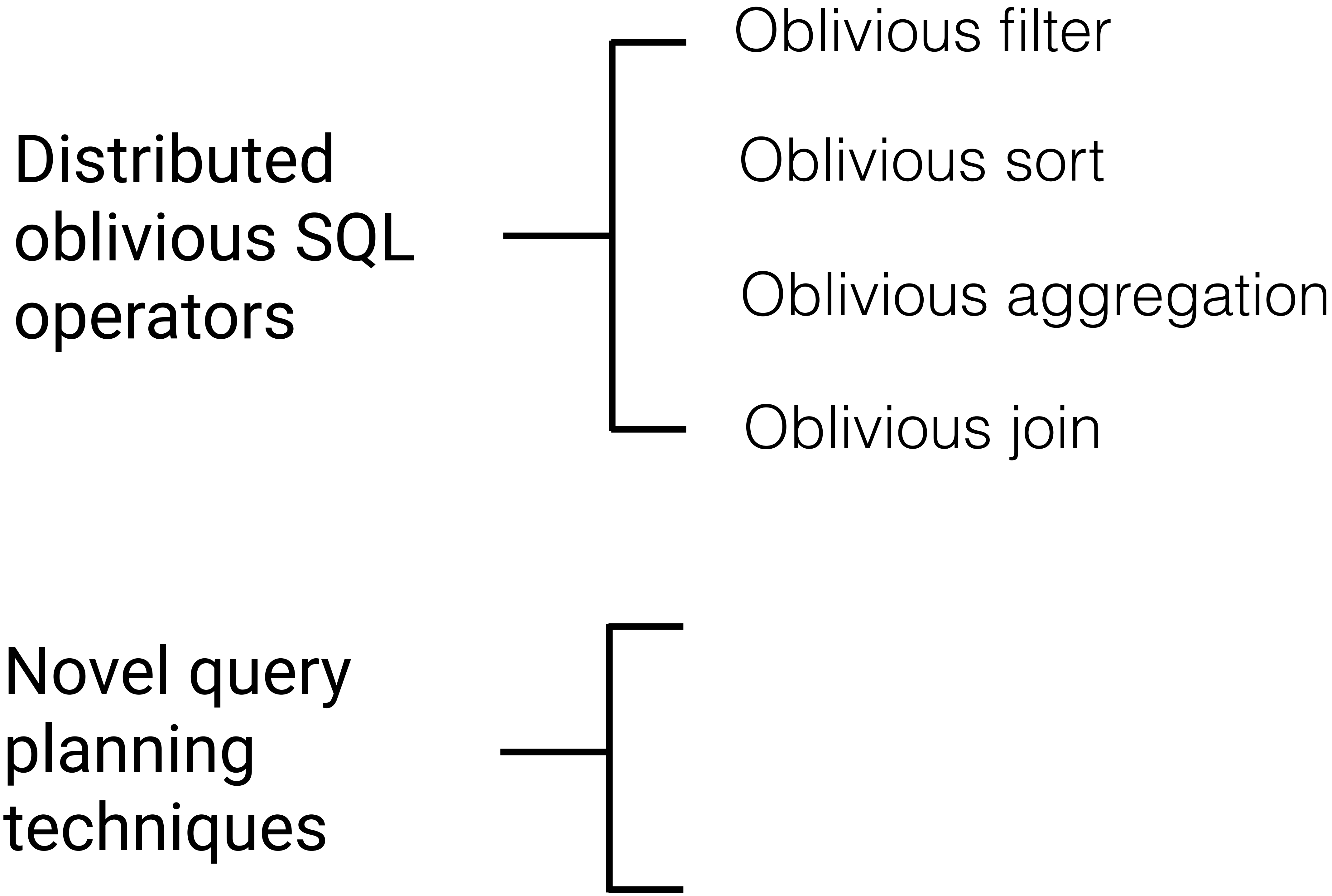
Oblivious filter

Oblivious sort

Oblivious aggregation

Novel query planning techniques

Two-part solution:



Distributed oblivious SQL operators

Oblivious filter

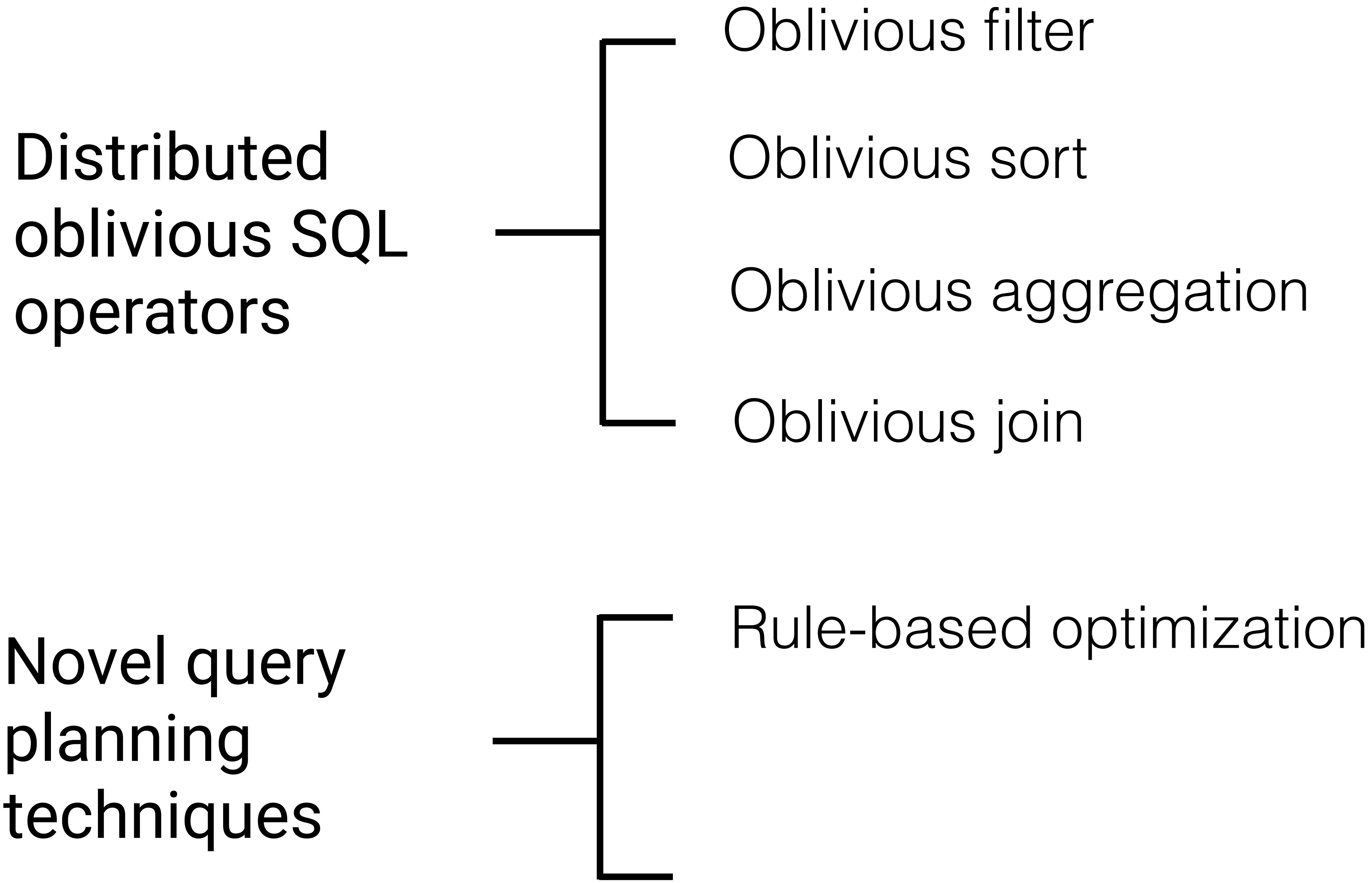
Oblivious sort

Oblivious aggregation

Oblivious join

Novel query planning techniques

Two-part solution:



Distributed oblivious SQL operators

Oblivious filter

Oblivious sort

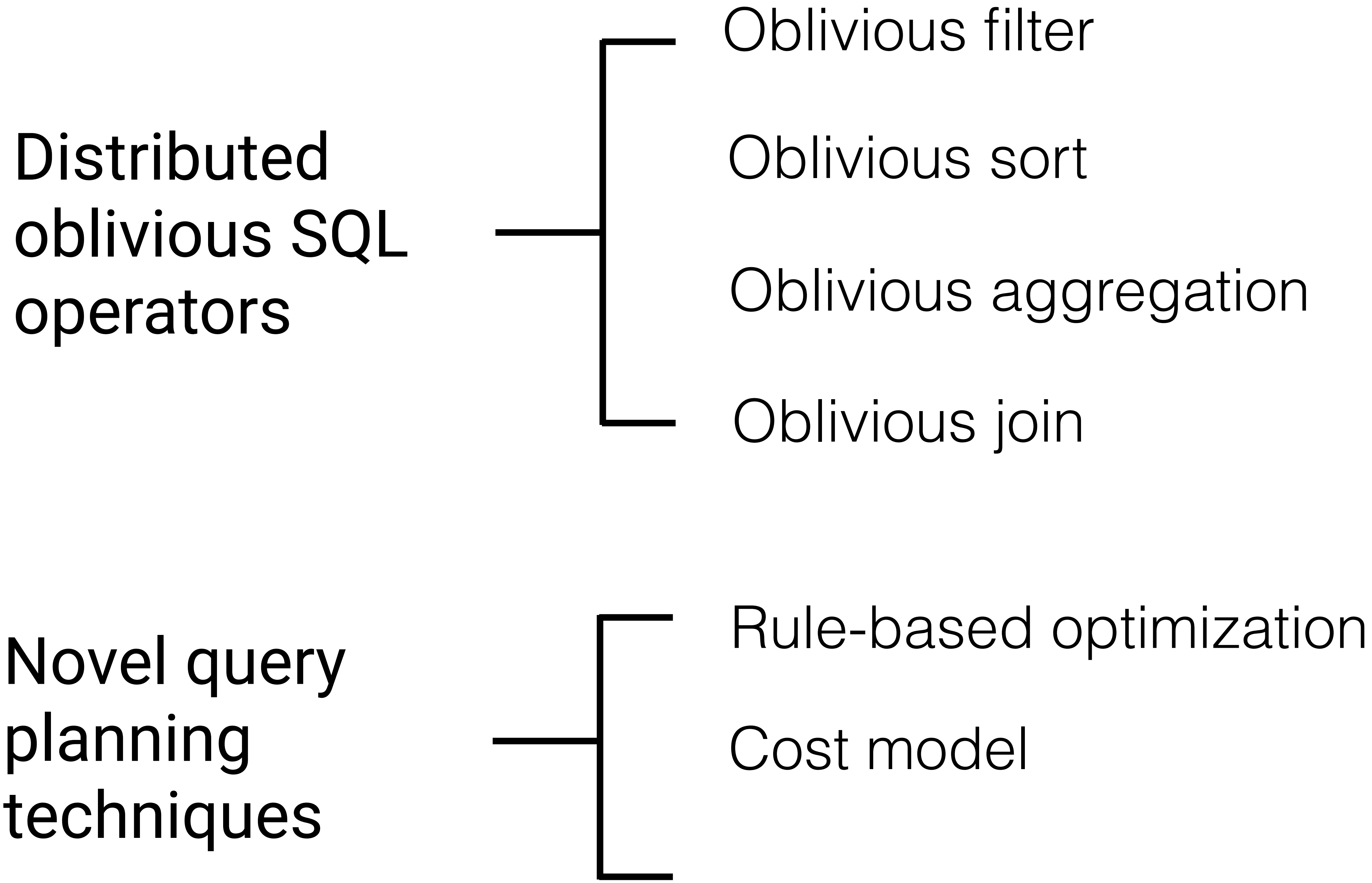
Oblivious aggregation

Oblivious join

Novel query planning techniques

Rule-based optimization

Two-part solution:



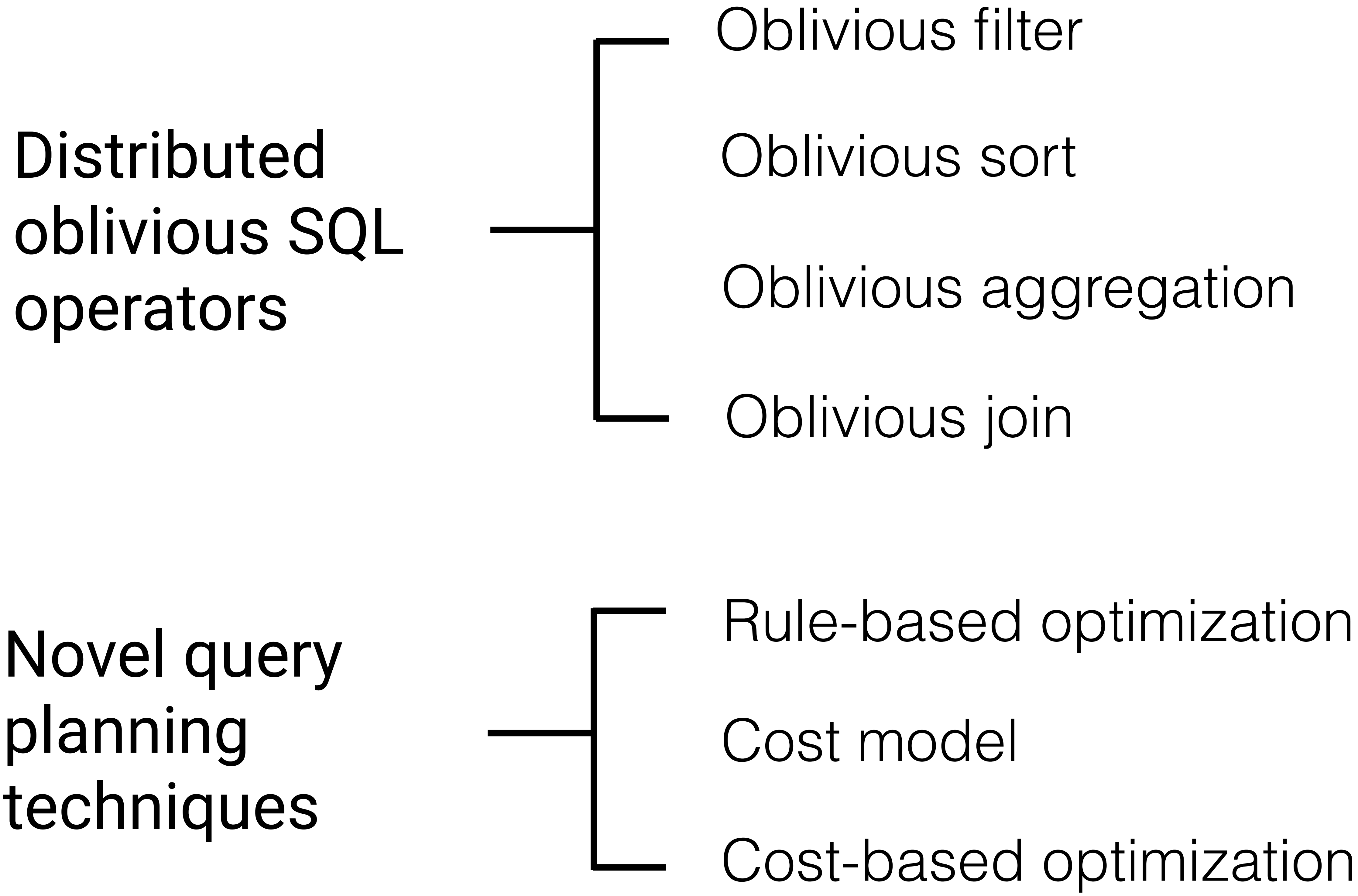
Distributed oblivious SQL operators

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

Novel query planning techniques

- Rule-based optimization
- Cost model

Two-part solution:



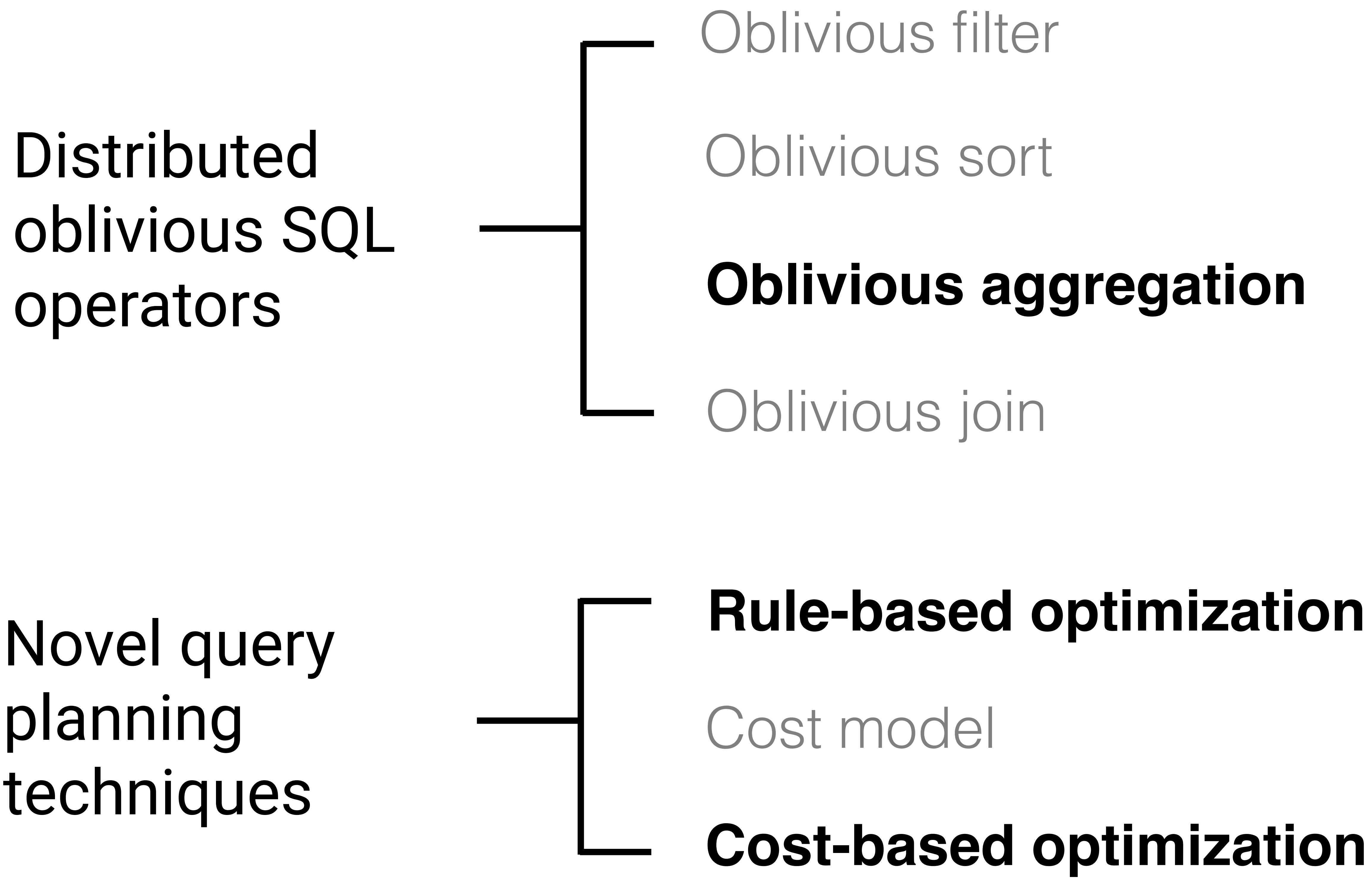
Distributed oblivious SQL operators

- 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**

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

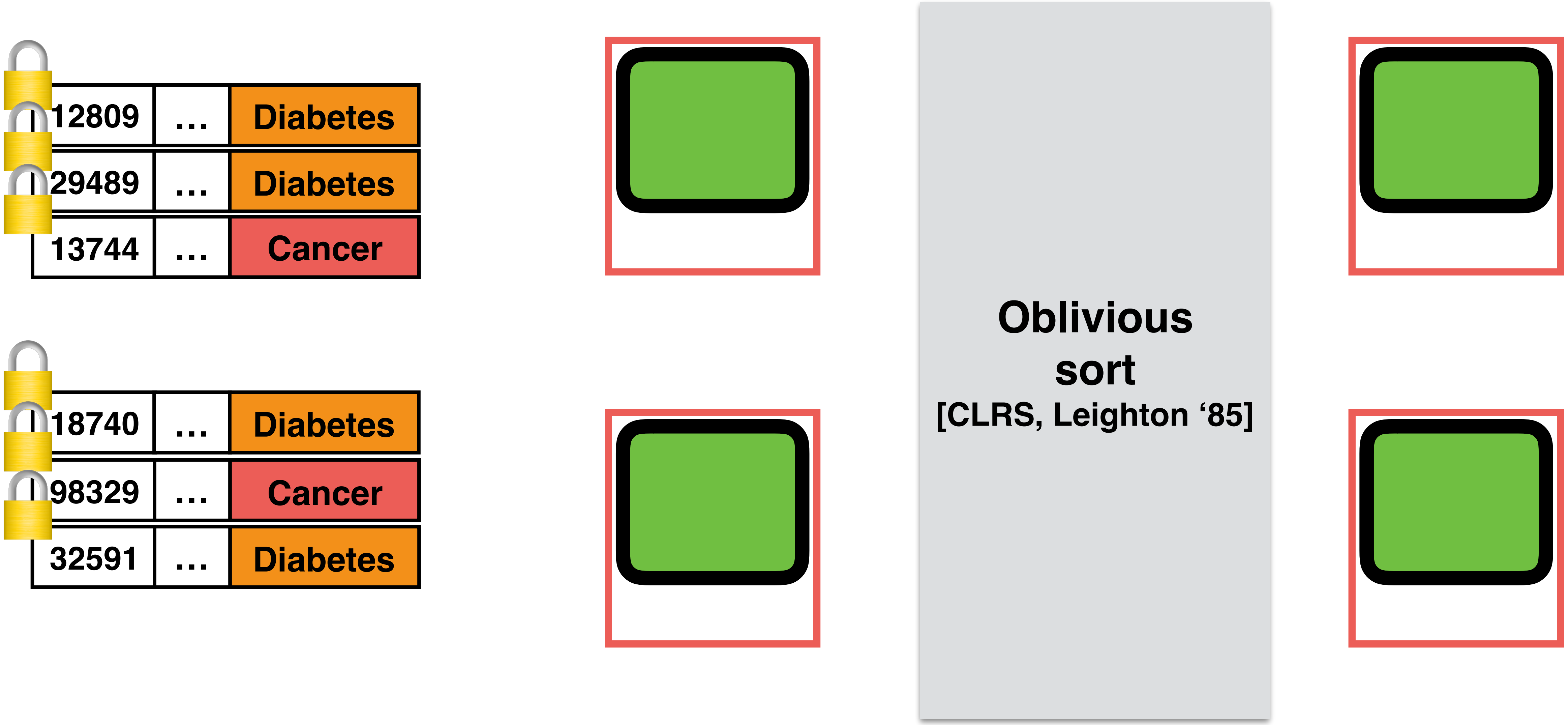
SELECT count(*) FROM medical GROUP BY disease

🔒	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

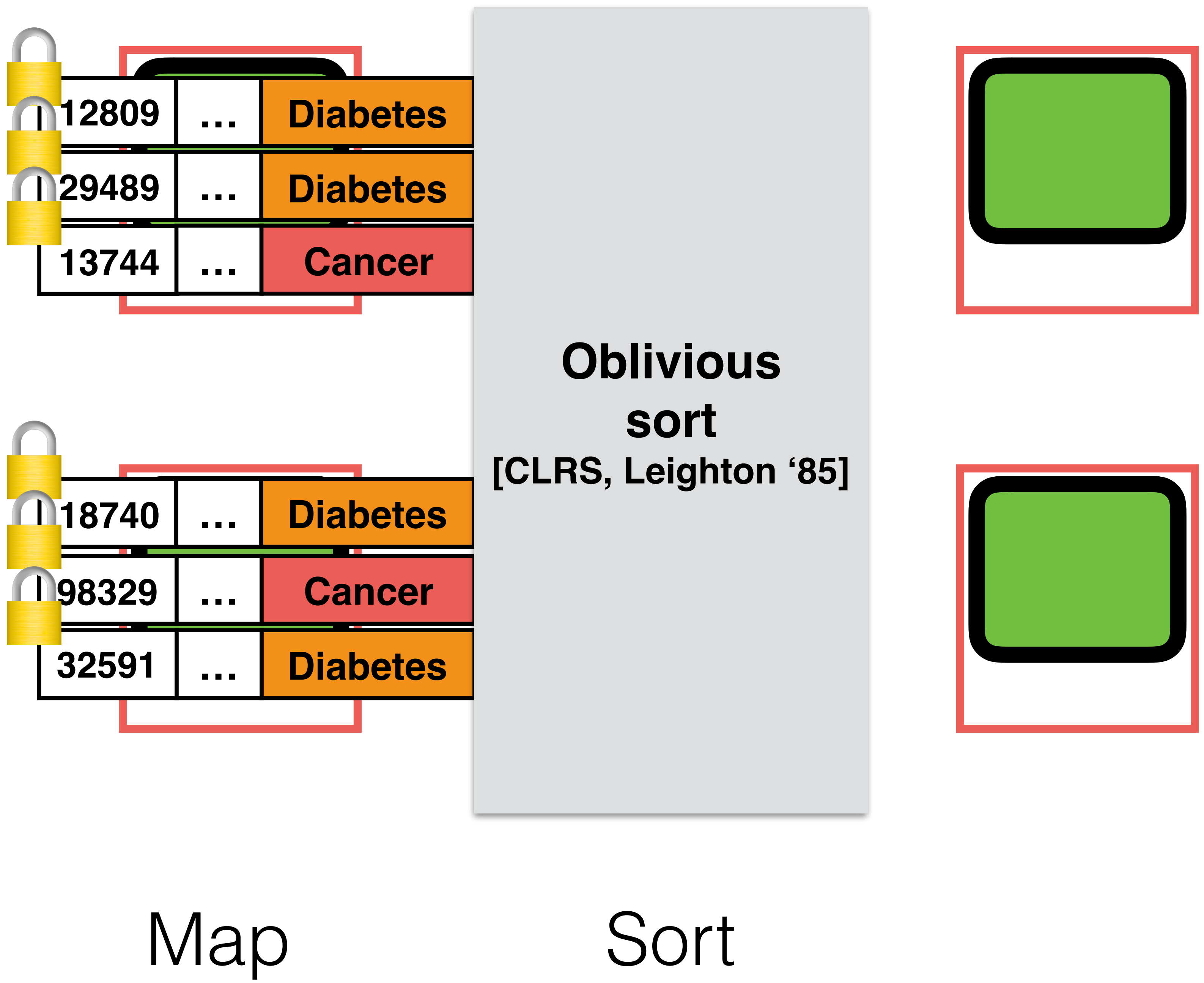
[CLRS, Leighton ‘85]

Map

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



12809	…	Diabetes
29489	…	Diabetes
13744	…	Cancer

18740	…	Diabetes
98329	…	Cancer
32591	…	Diabetes

Oblivious sort

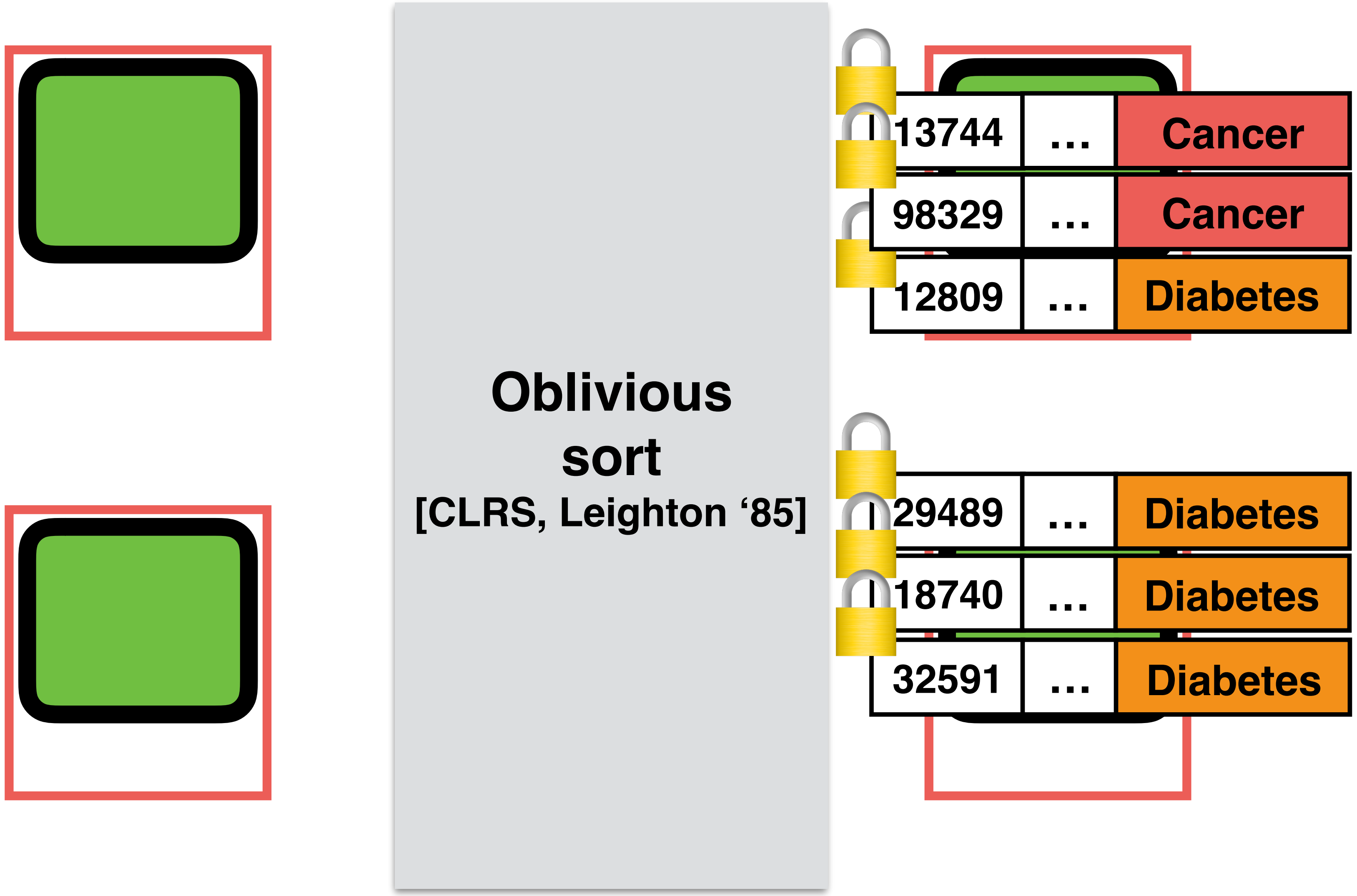
[CLRS, Leighton ‘85]

Map

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious sort
[CLRS, Leighton '85]

13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

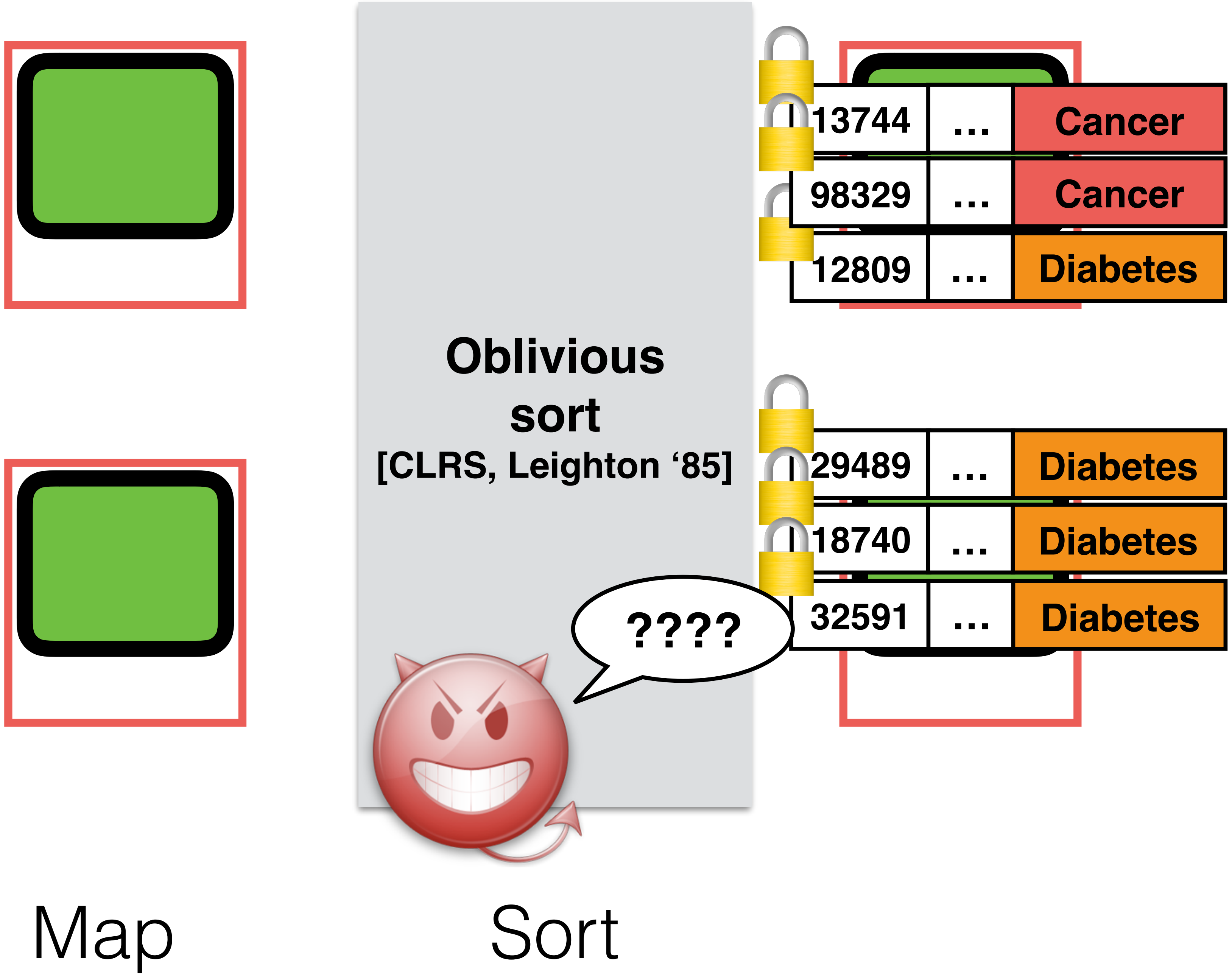
29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Map

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

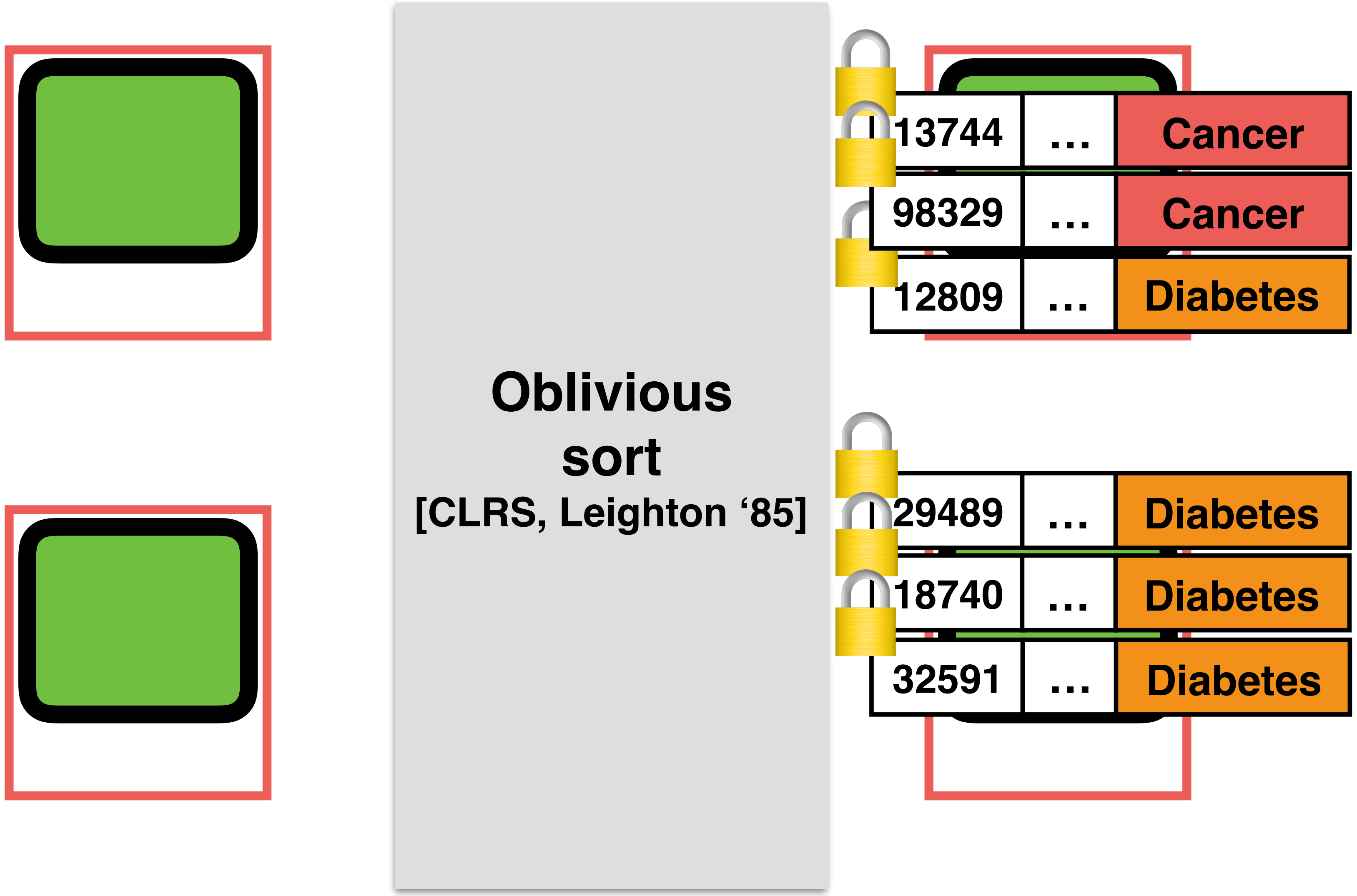


13744	...	Cancer
98329	...	Cancer
12809	...	Diabetes

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

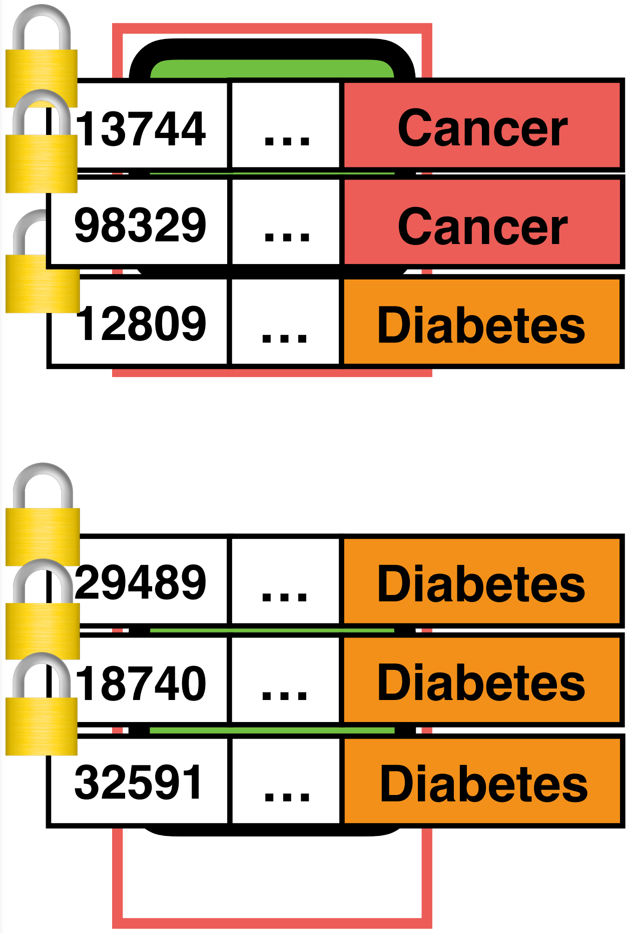
Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

s

n ‘85]

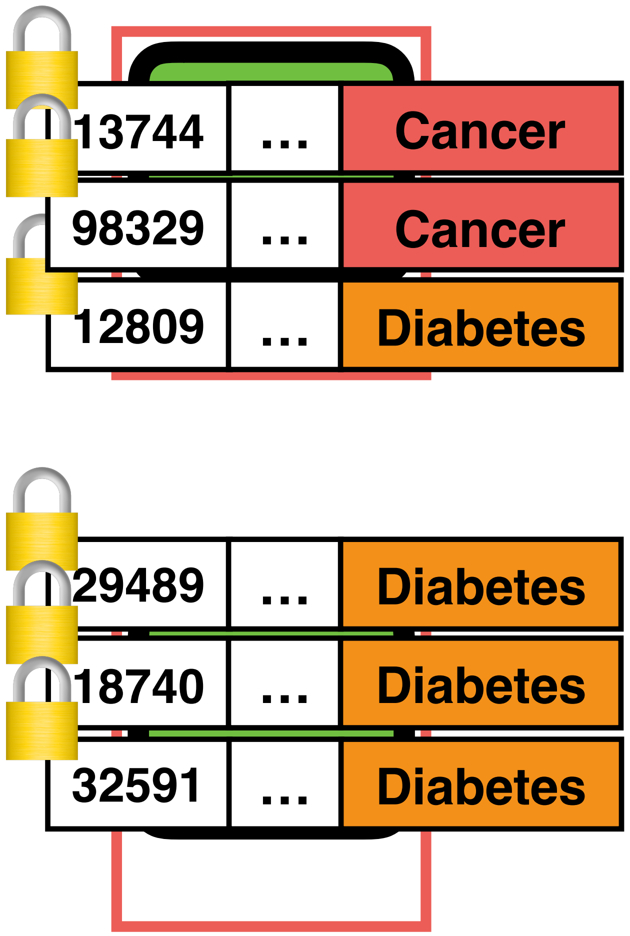


13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

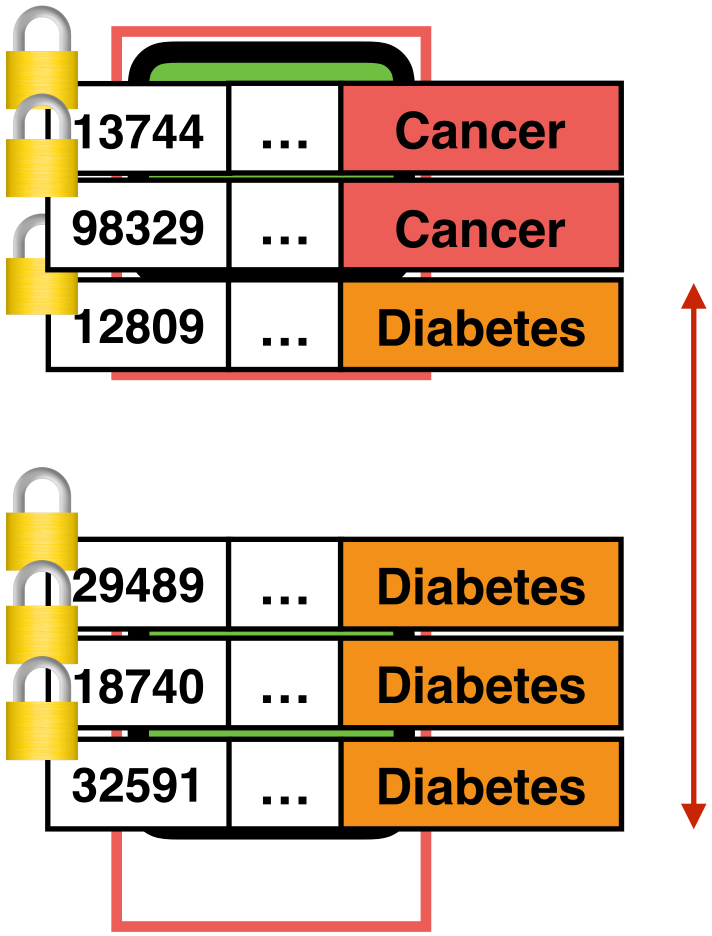


13744	...	Cancer
98329	...	Cancer
12809	...	Diabetes

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

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



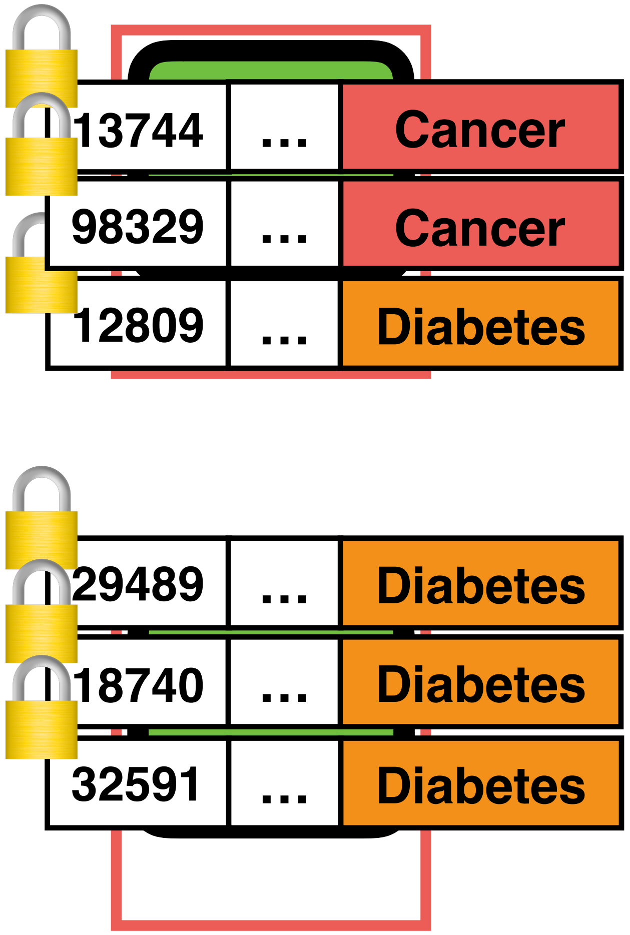
13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

The “Diabetes” group
is split!

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

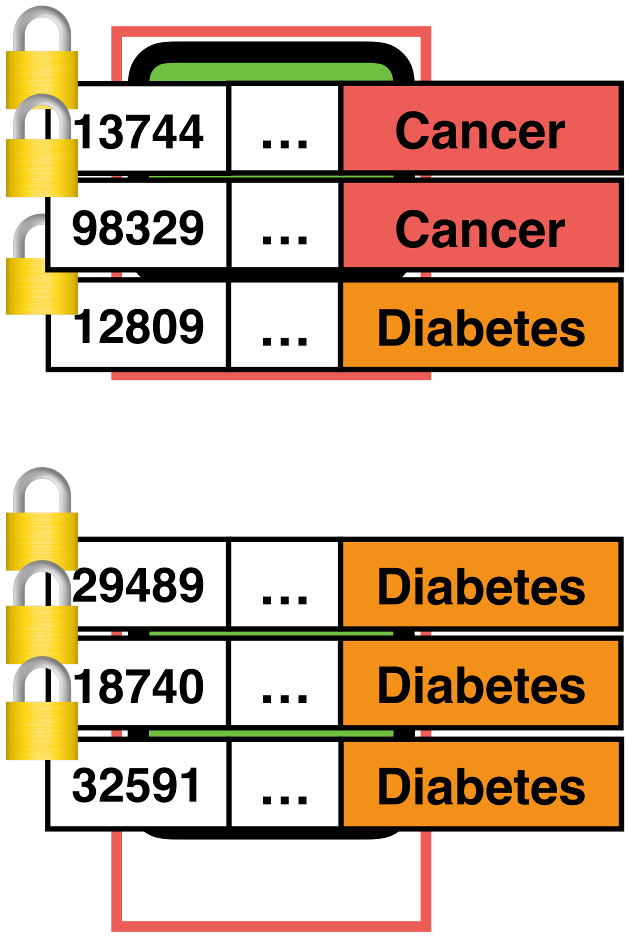


13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



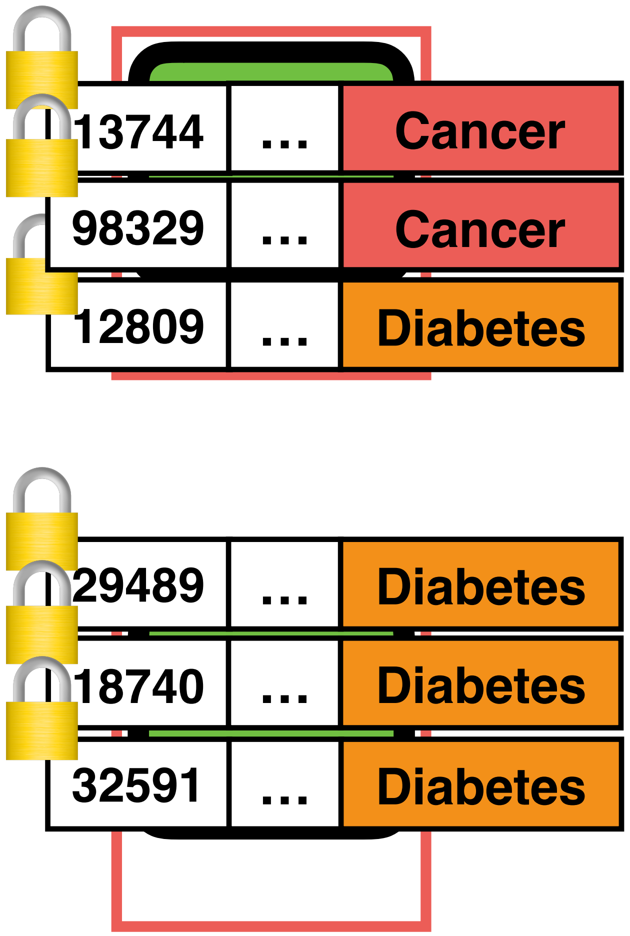
13744	...	Cancer
98329	...	Cancer
12809	...	Diabetes

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

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

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

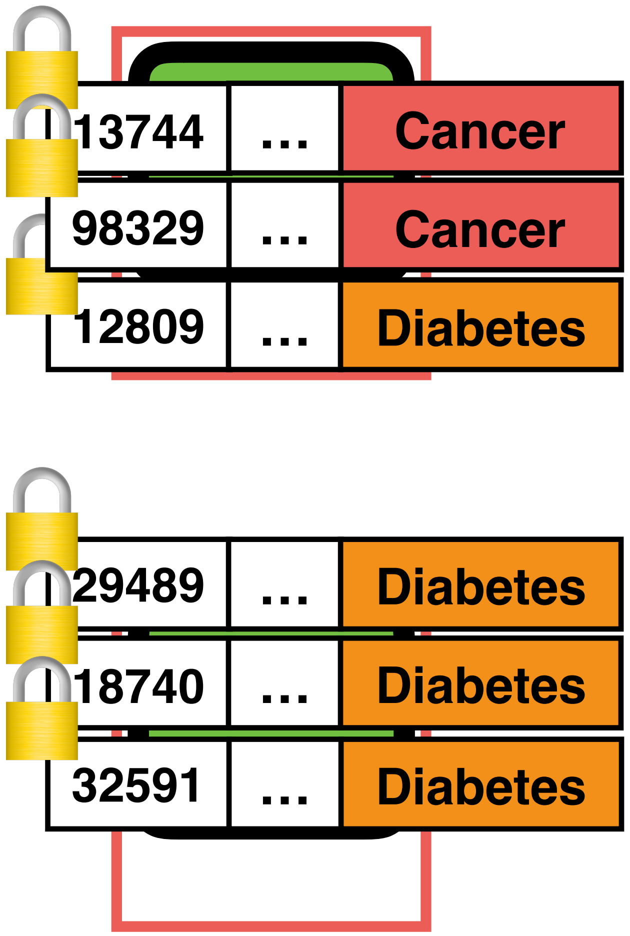


13744	...	Cancer
98329	...	Cancer
12809	...	Diabetes

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

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



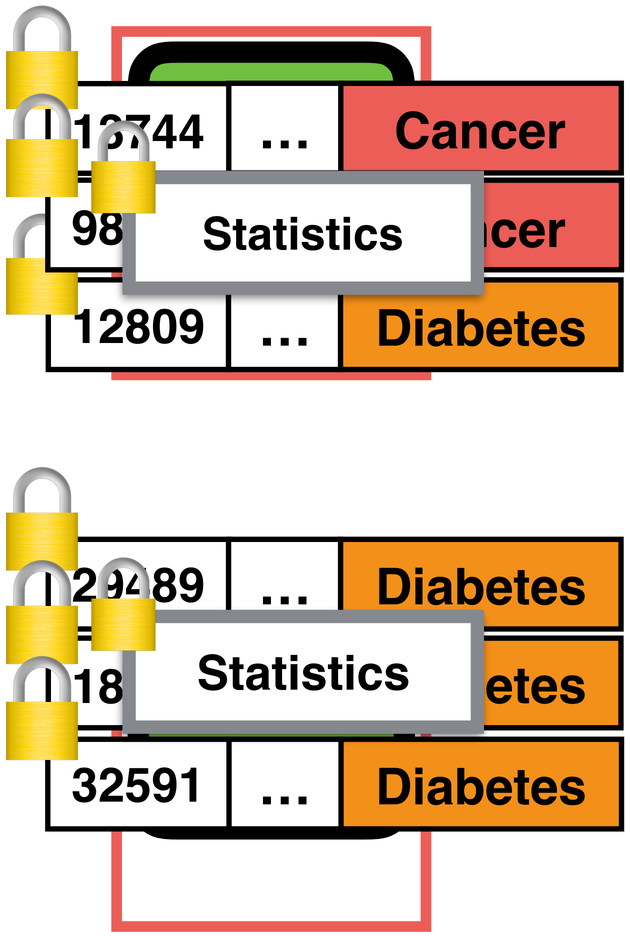
13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Scan

Oblivious aggregation

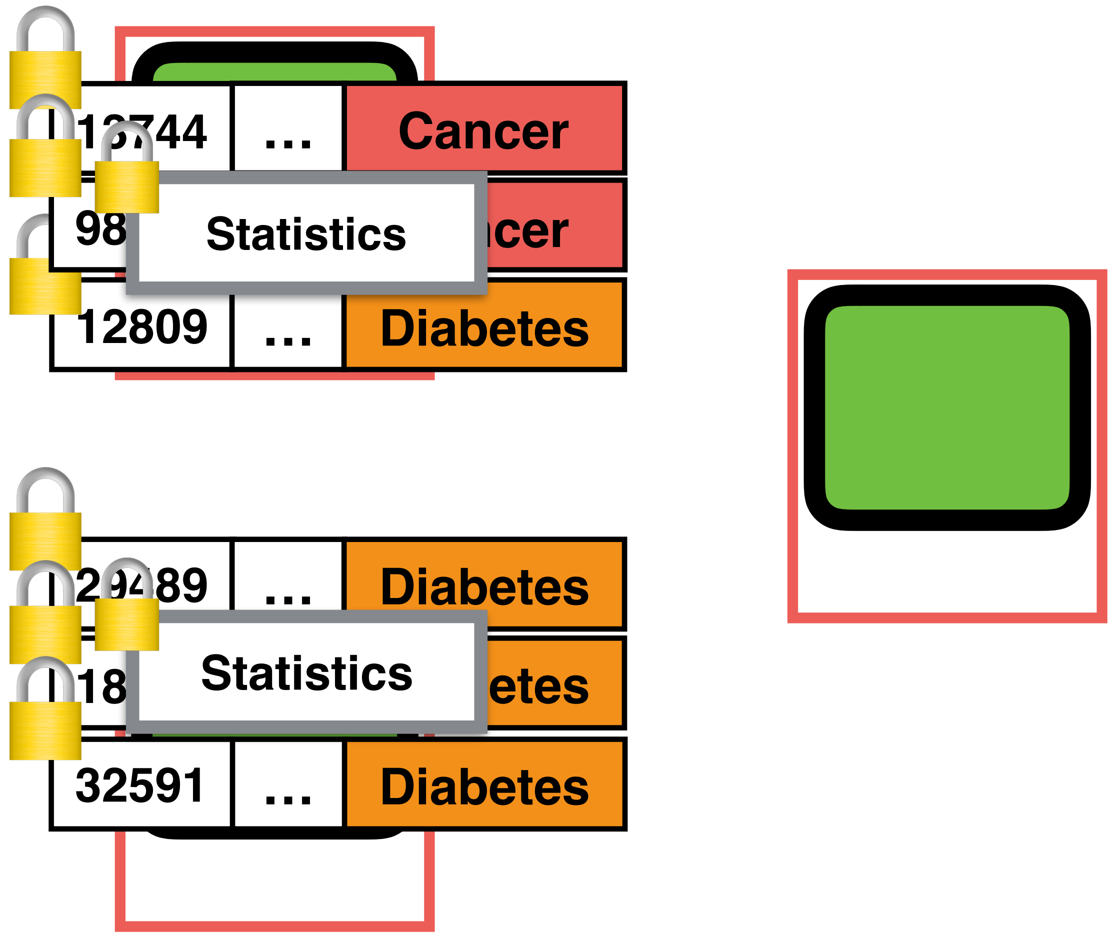
SELECT count(*) FROM medical GROUP BY disease



Scan

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

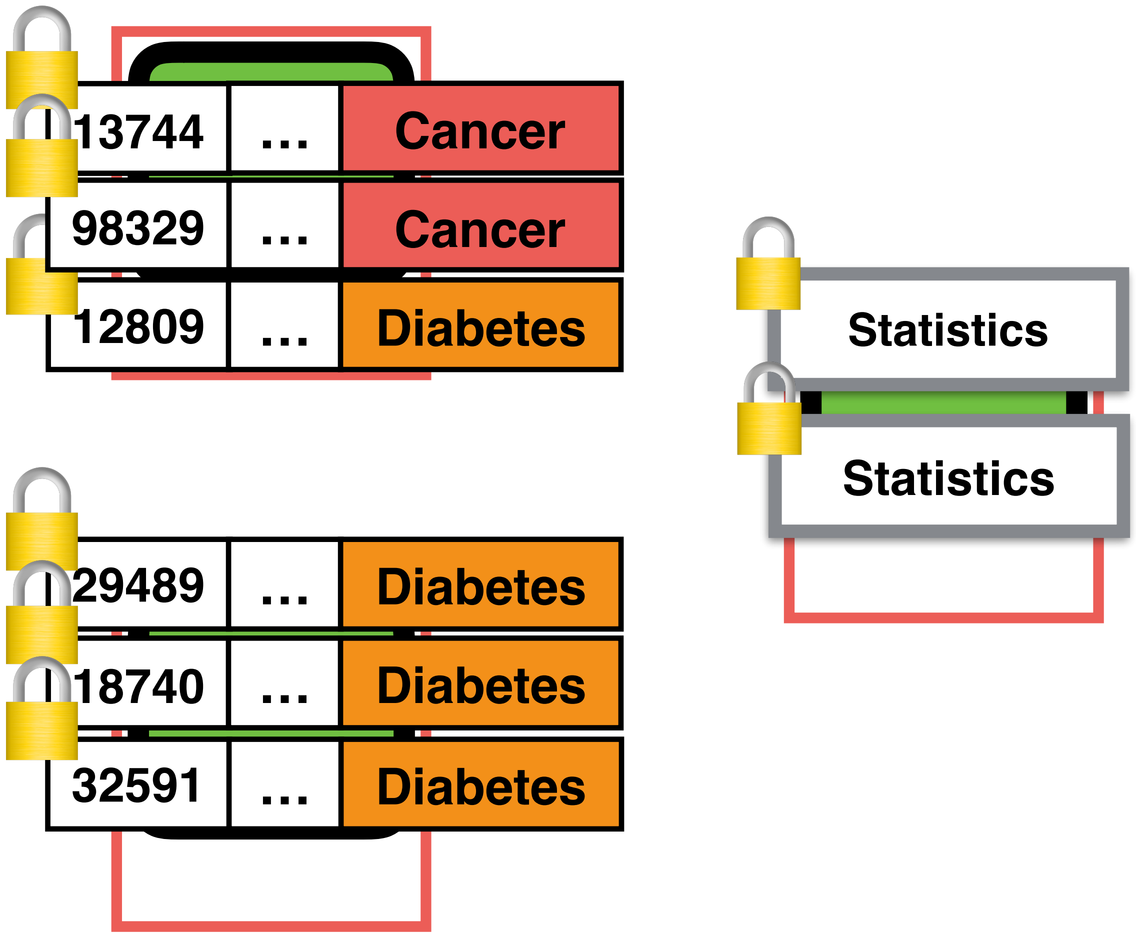


Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Statistics

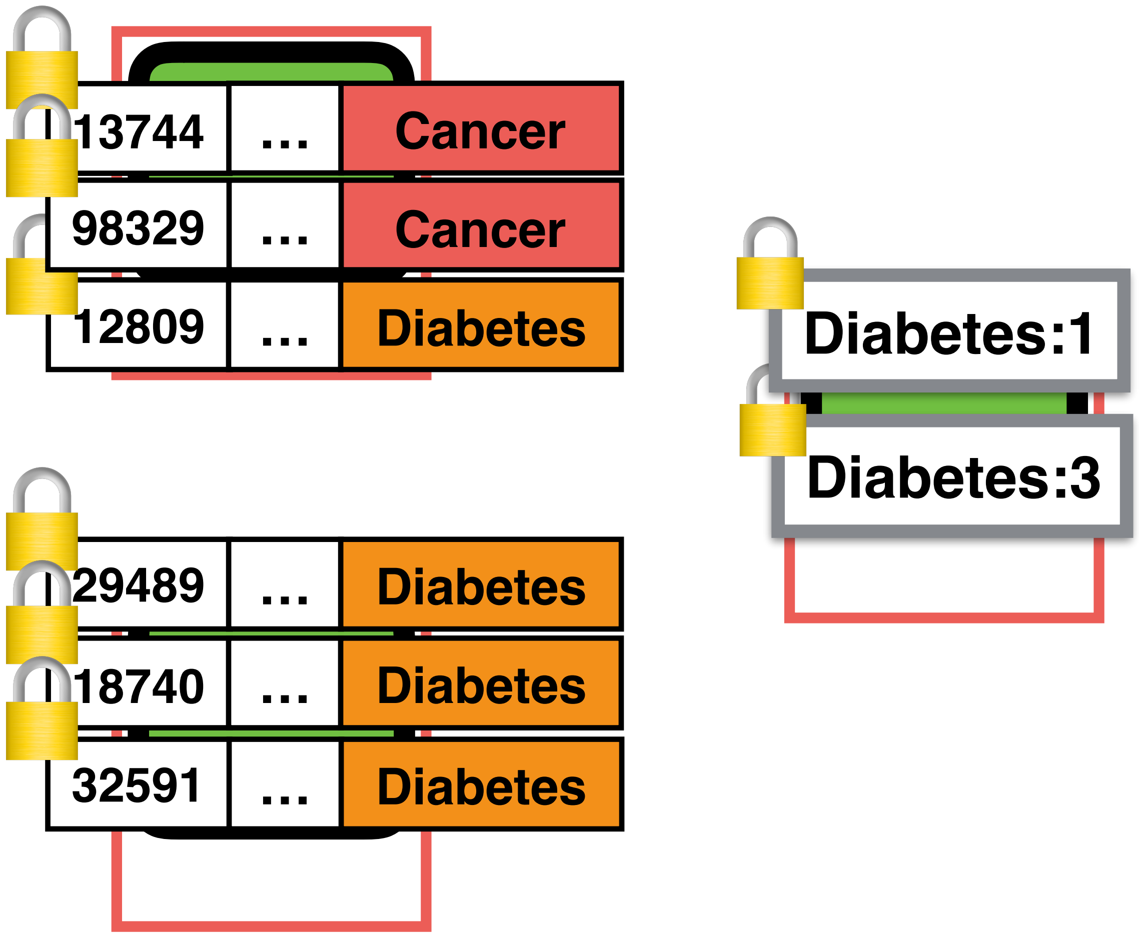
Statistics

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

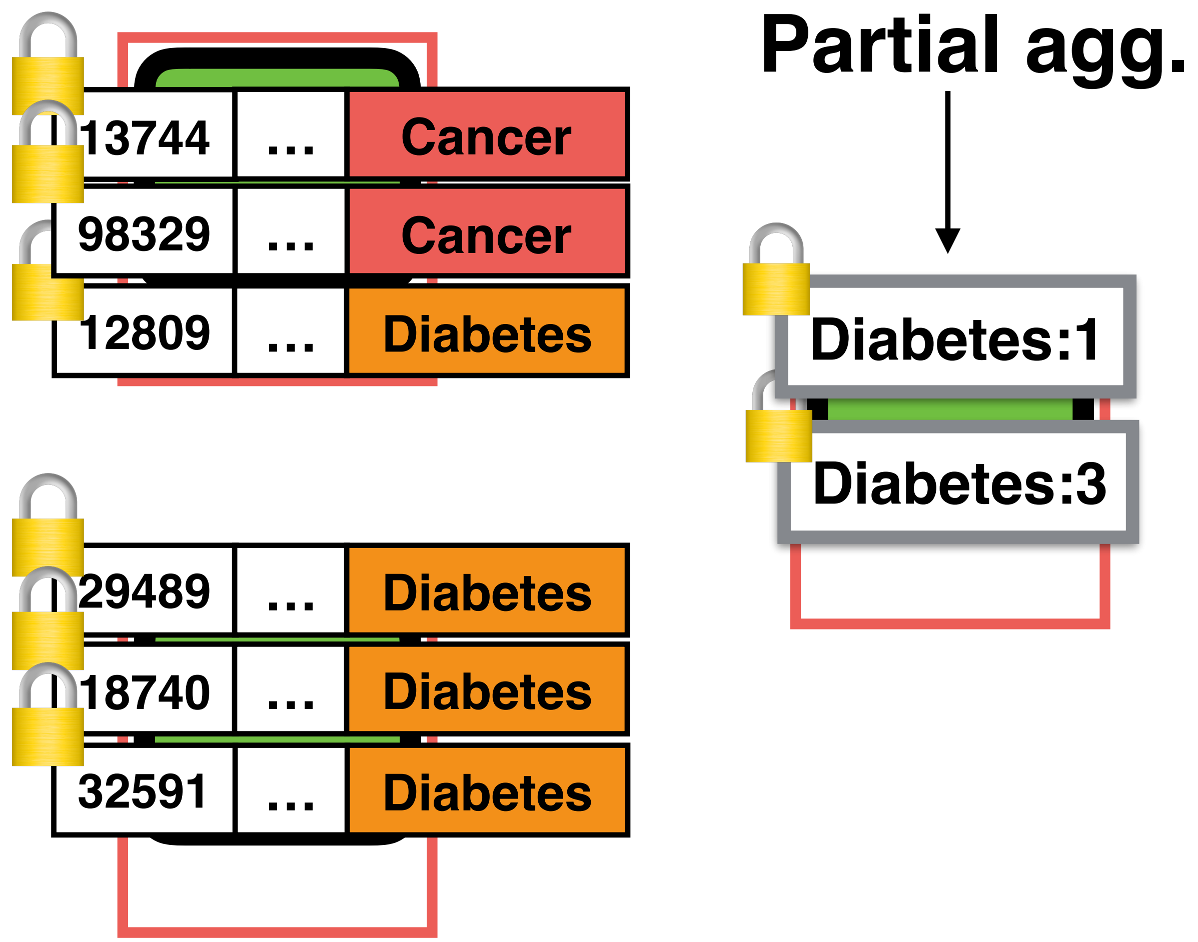
Diabetes:3

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Partial agg.

Diabetes:1

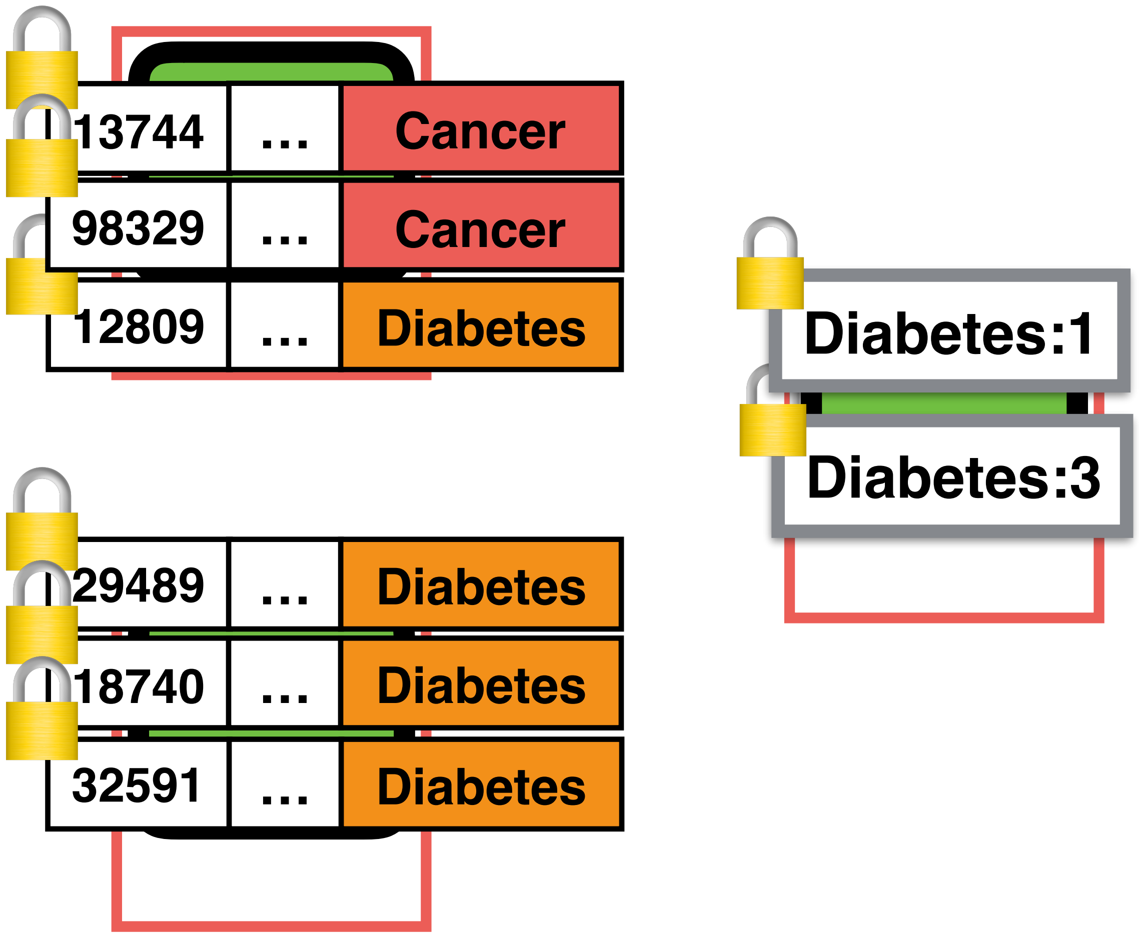
Diabetes:3

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

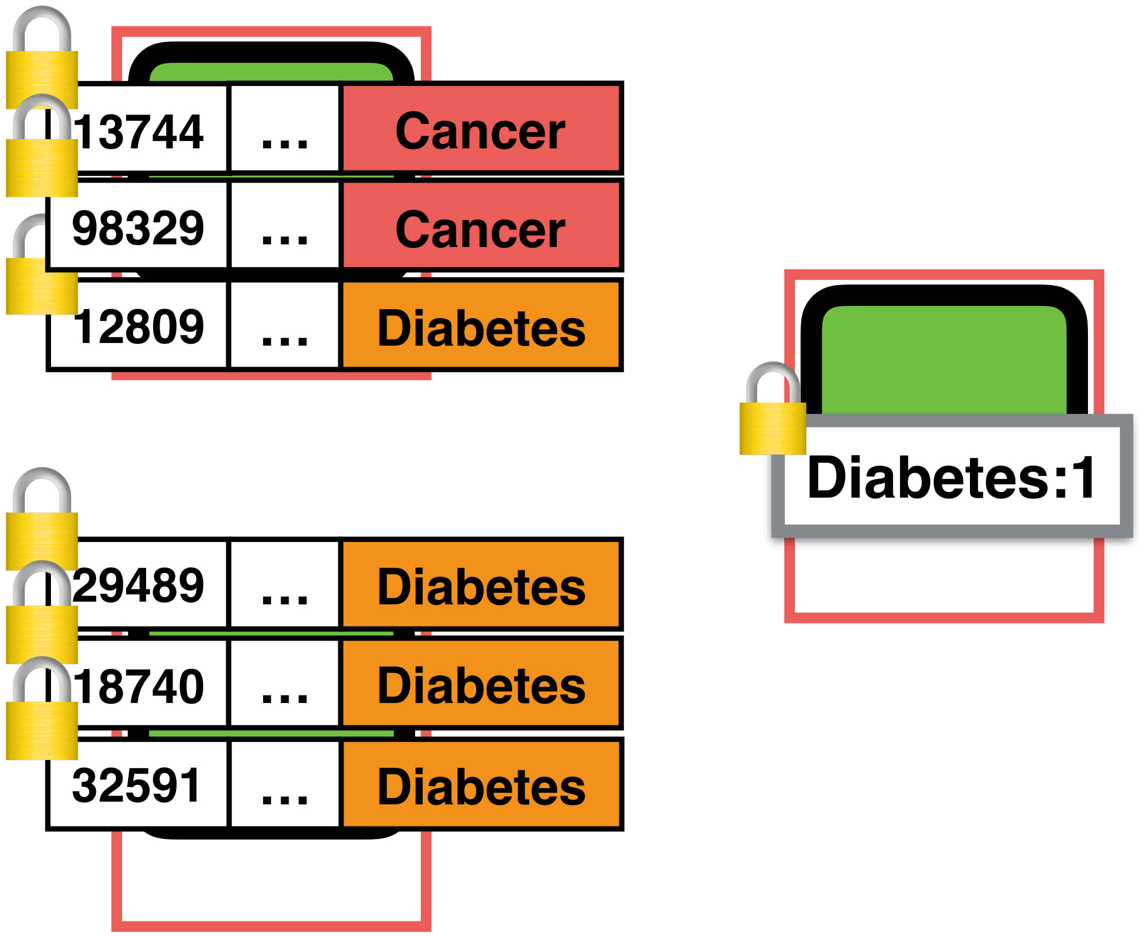
Diabetes:3

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

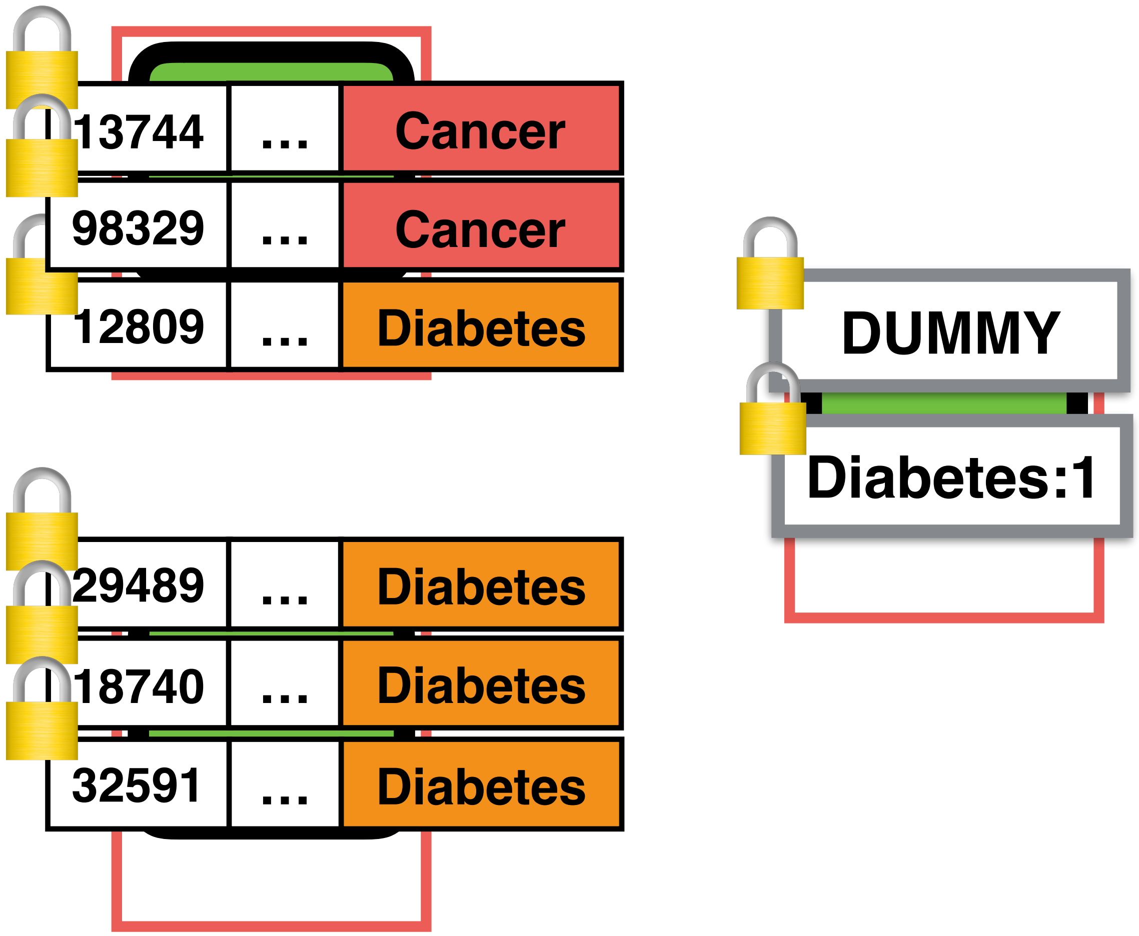
29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease

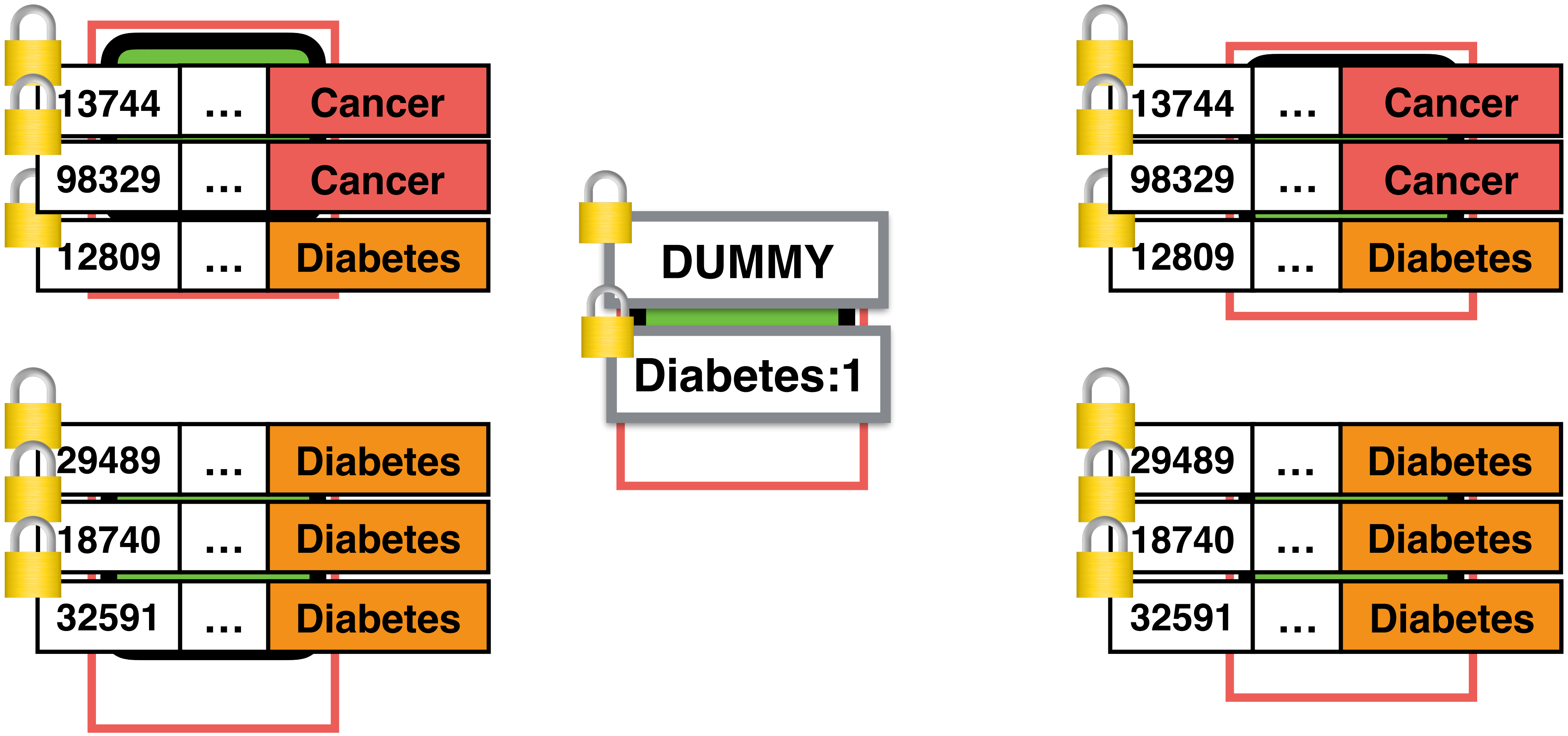


Scan

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
12809	…	Diabetes

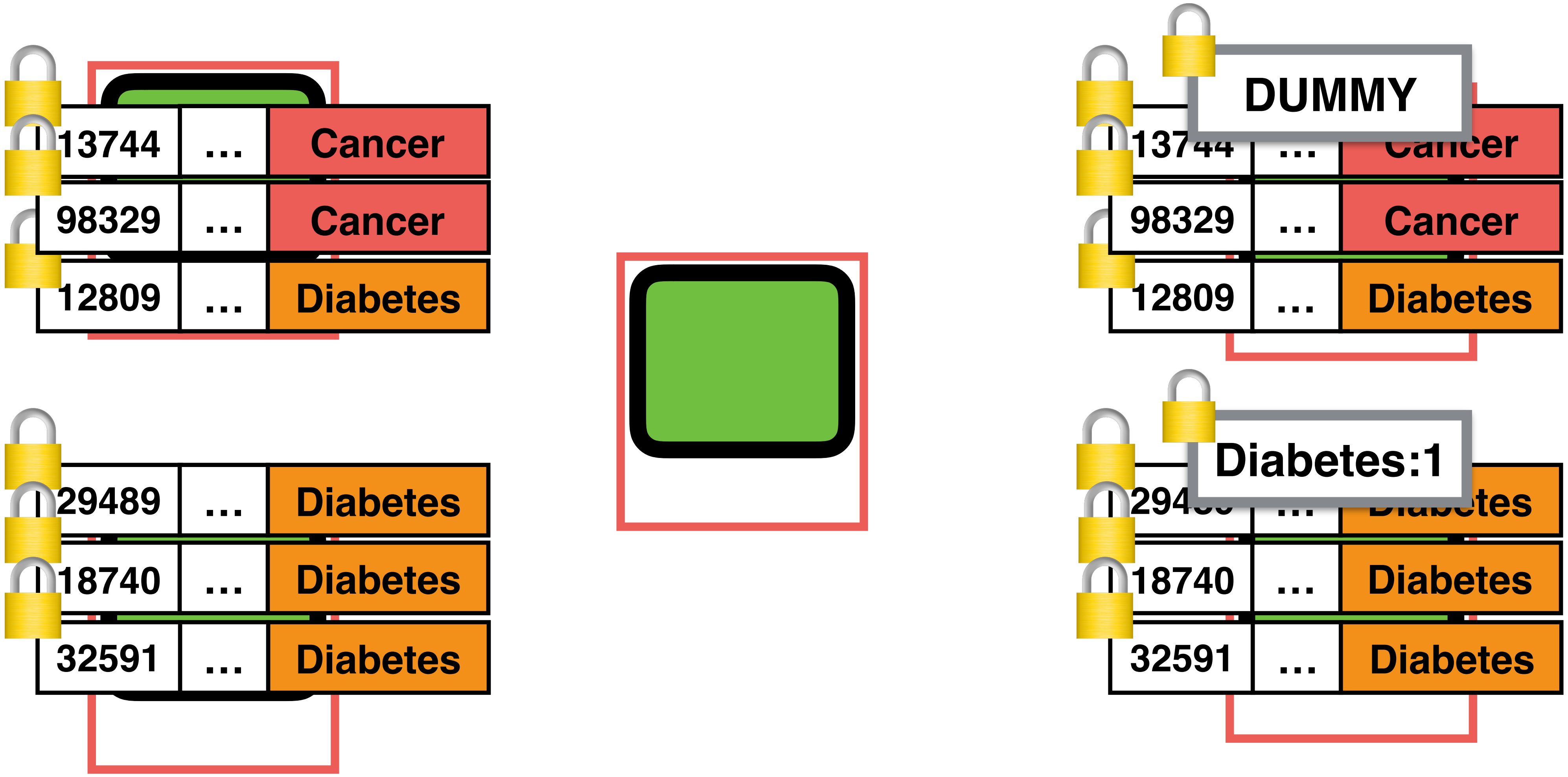
29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

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

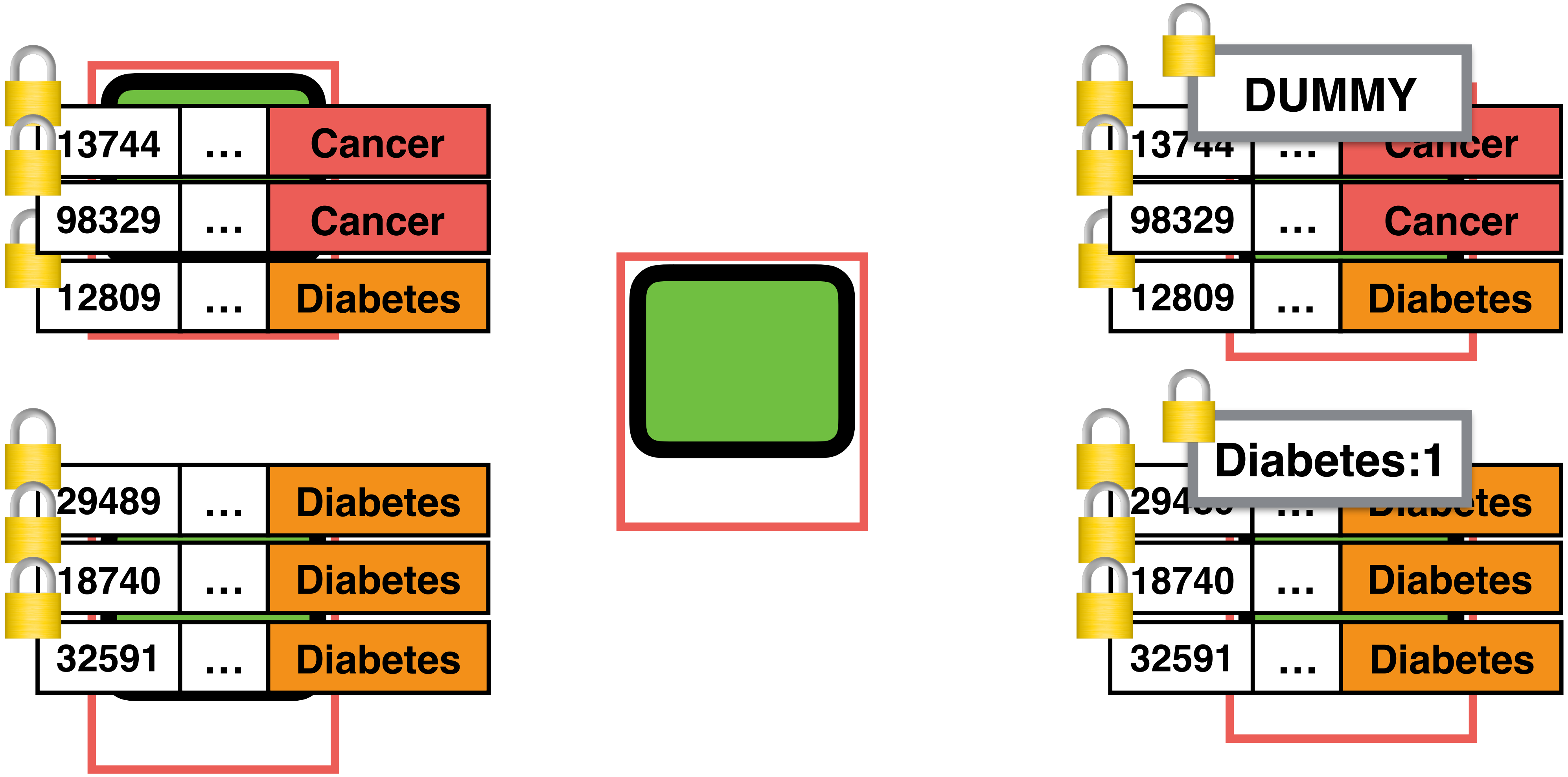
29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

Scan

Boundary processing

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



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

DUMMY

13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

Diabetes:1

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

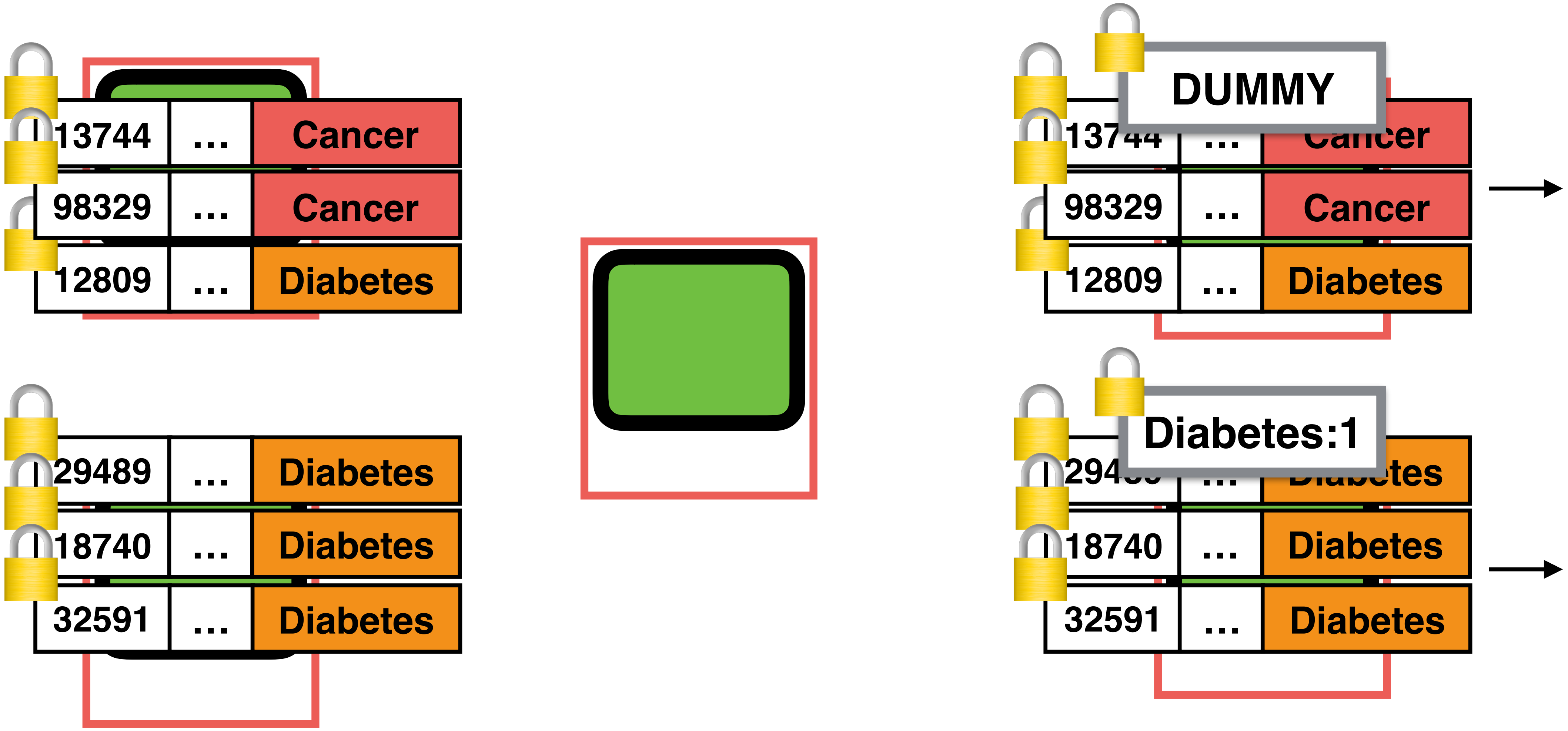
Scan

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

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

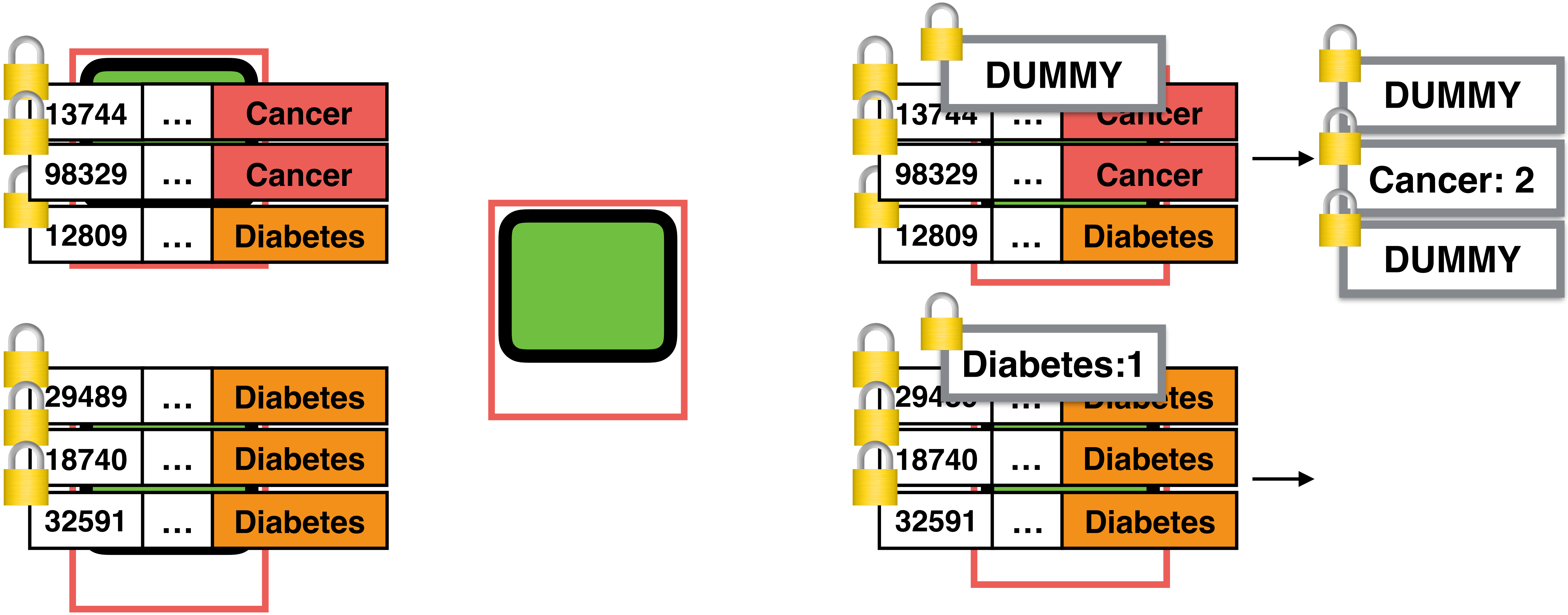
Scan

Boundary processing

Scan

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744	…	Cancer
98329	…	Cancer
12809	…	Diabetes

29489	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

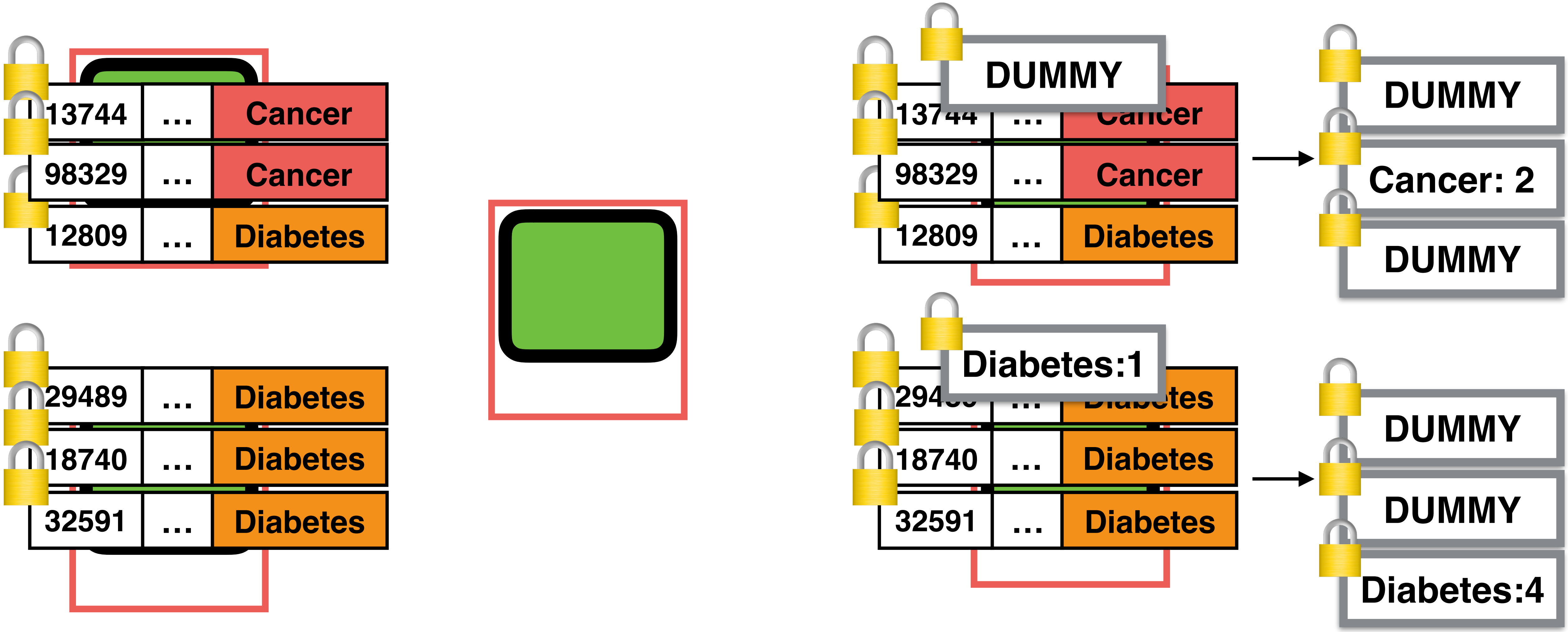
Scan

Boundary processing

Scan

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



13744 … Cancer

98329 … Cancer

12809 … Diabetes

29489 … Diabetes

18740 … Diabetes

32591 … Diabetes

DUMMY

13744 … Cancer

98329 … Cancer

12809 … Diabetes

DUMMY

Cancer: 2

DUMMY

Diabetes:1

29489 … Diabetes

18740 … Diabetes

32591 … Diabetes

DUMMY

DUMMY

Diabetes:4

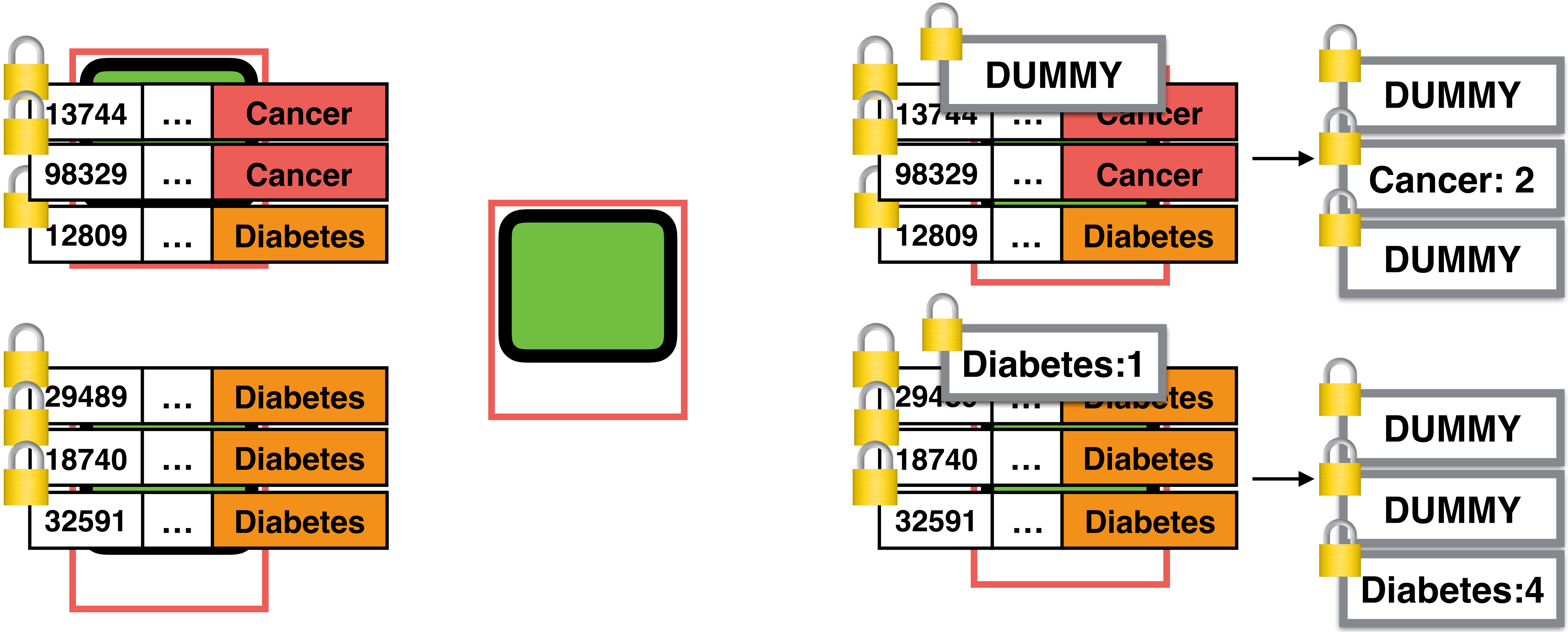
Scan

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

DUMMY
Cancer: 2
DUMMY

Diabetes:1

294	…	Diabetes
18740	…	Diabetes
32591	…	Diabetes

DUMMY
DUMMY
Diabetes:4

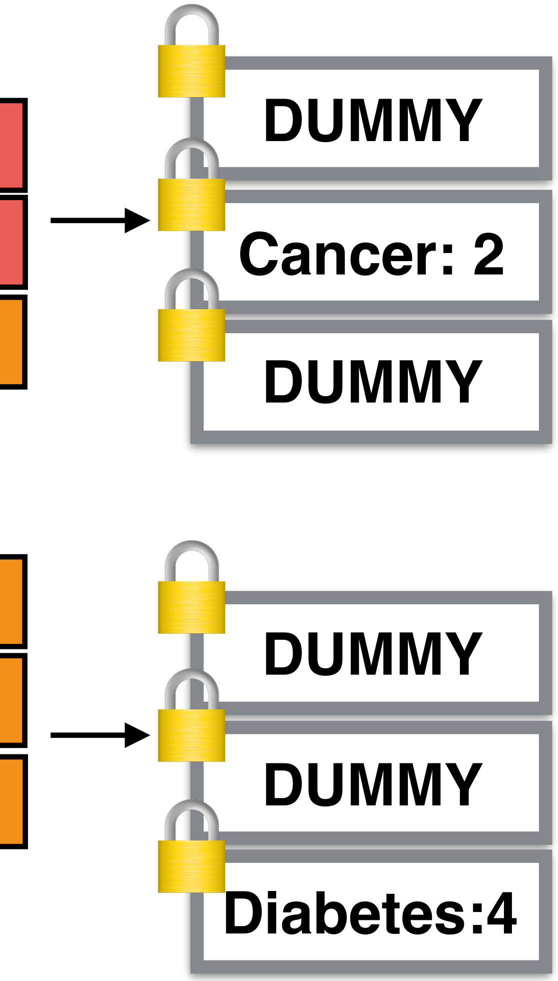
Scan

Boundary processing

Scan

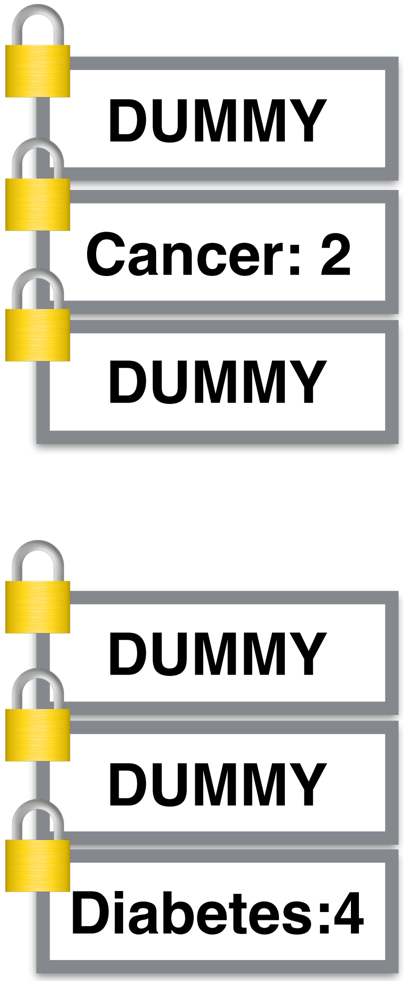
Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



DUMMY

Cancer: 2

DUMMY

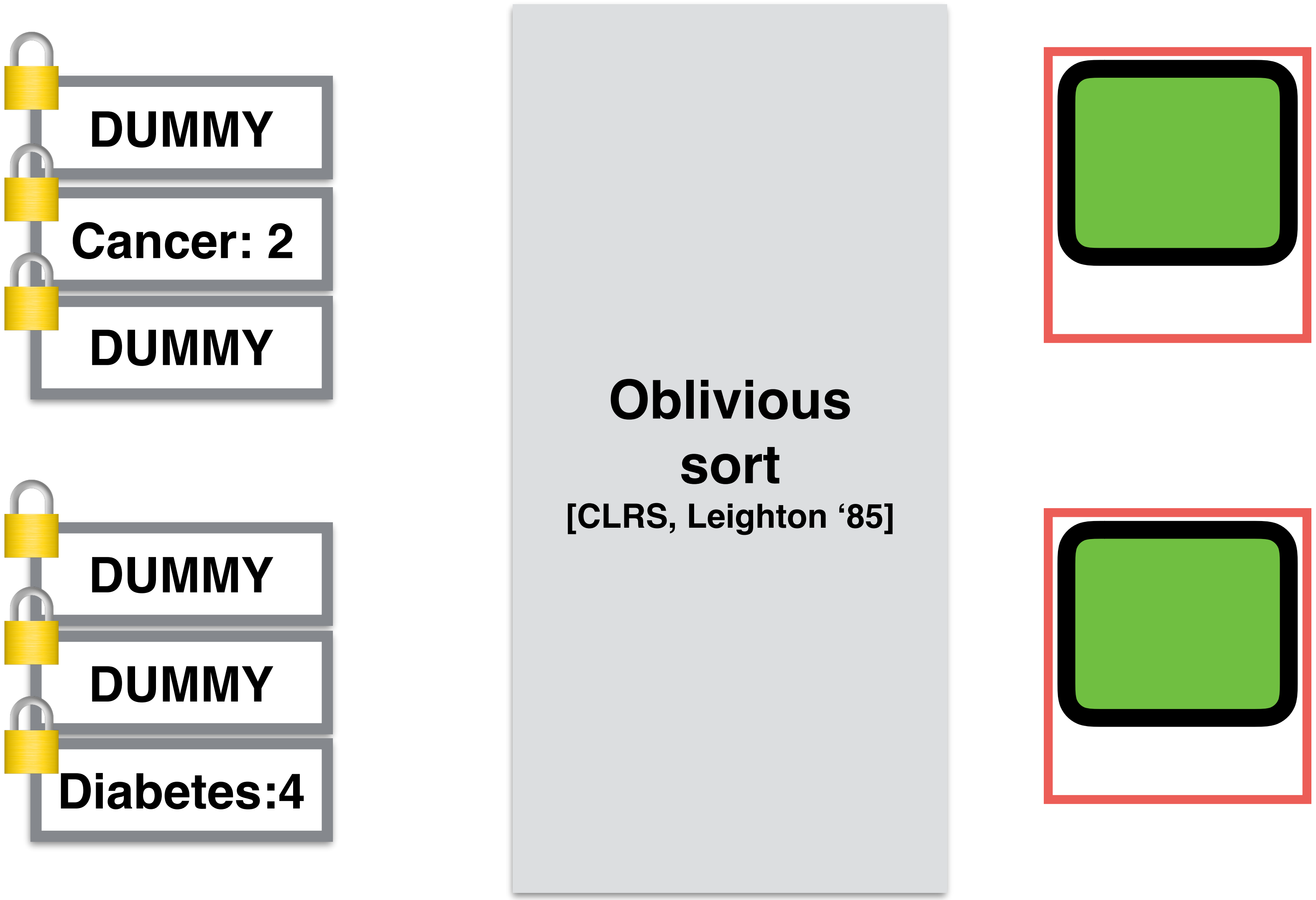
DUMMY

DUMMY

Diabetes:4

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



DUMMY

Cancer: 2

DUMMY

DUMMY

DUMMY

Diabetes:4

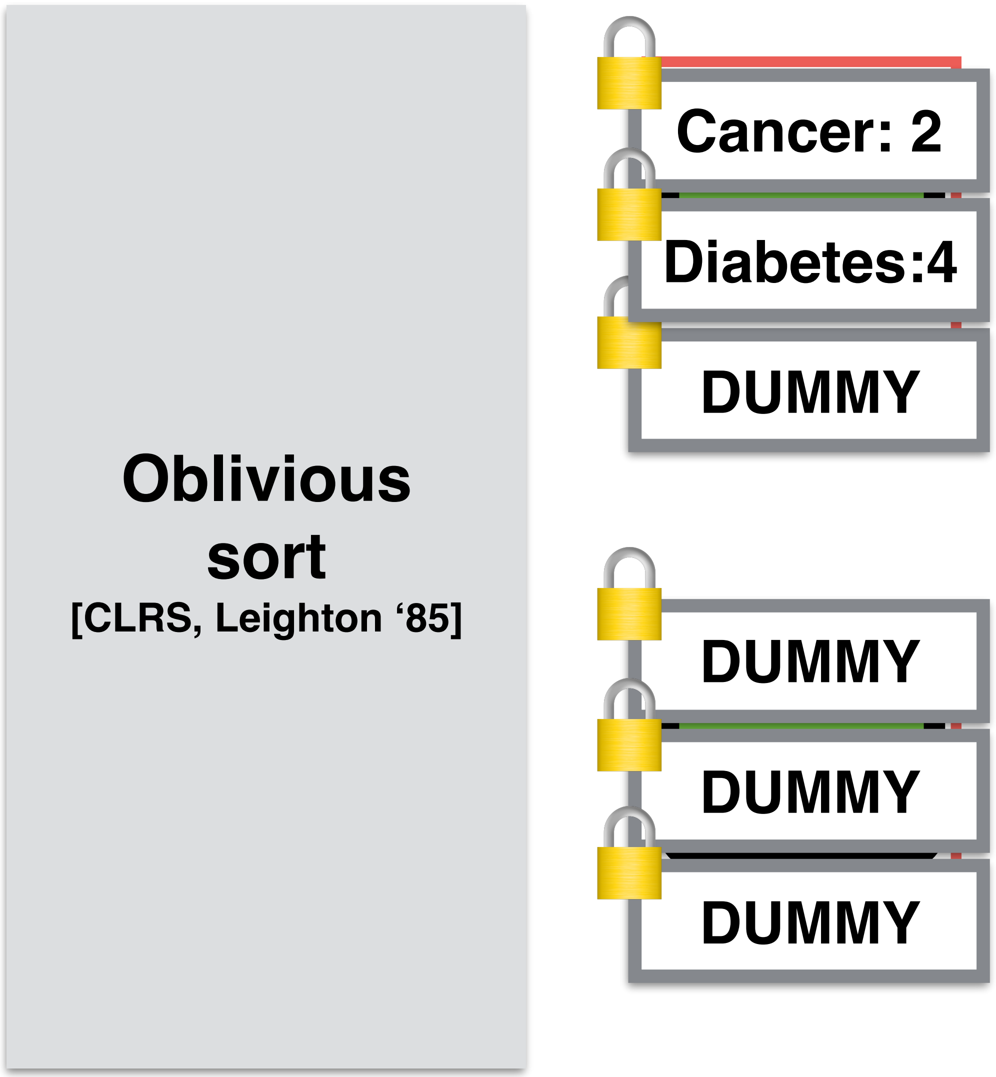
Oblivious sort

[CLRS, Leighton '85]

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious sort

[CLRS, Leighton ‘85]

Cancer: 2

Diabetes:4

DUMMY

DUMMY

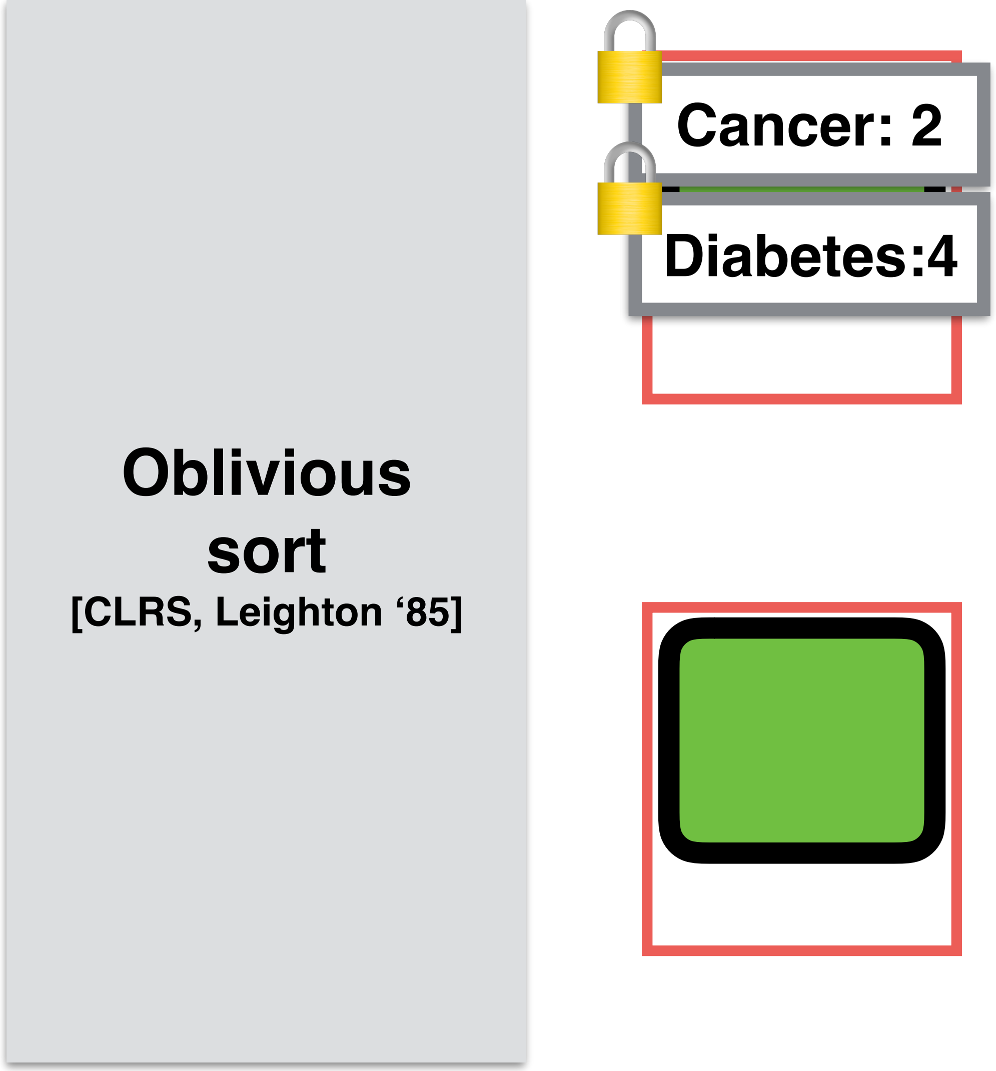
DUMMY

DUMMY

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious sort

[CLRS, Leighton '85]

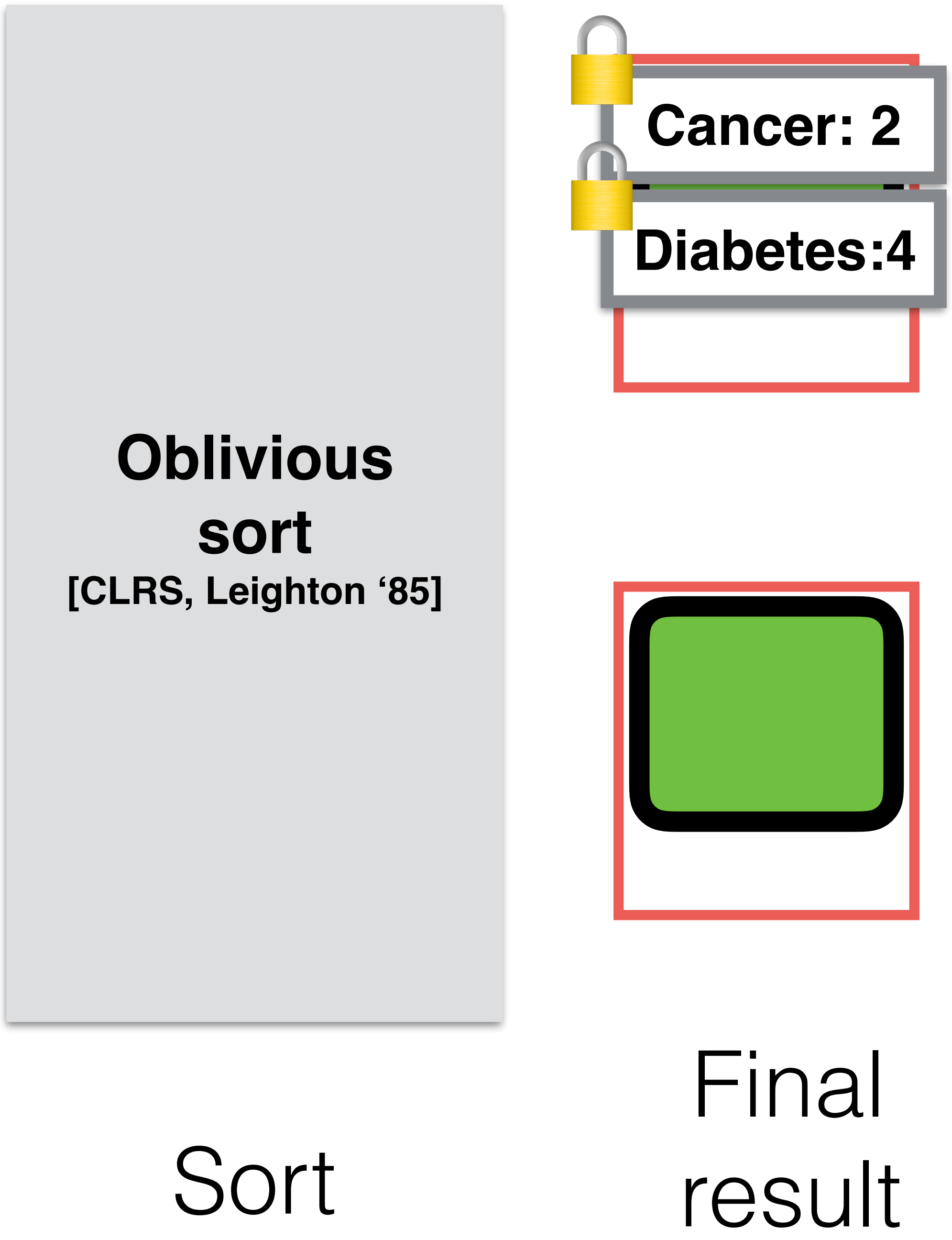
Cancer: 2

Diabetes:4

Sort

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



Oblivious sort
[CLRS, Leighton '85]

Cancer: 2

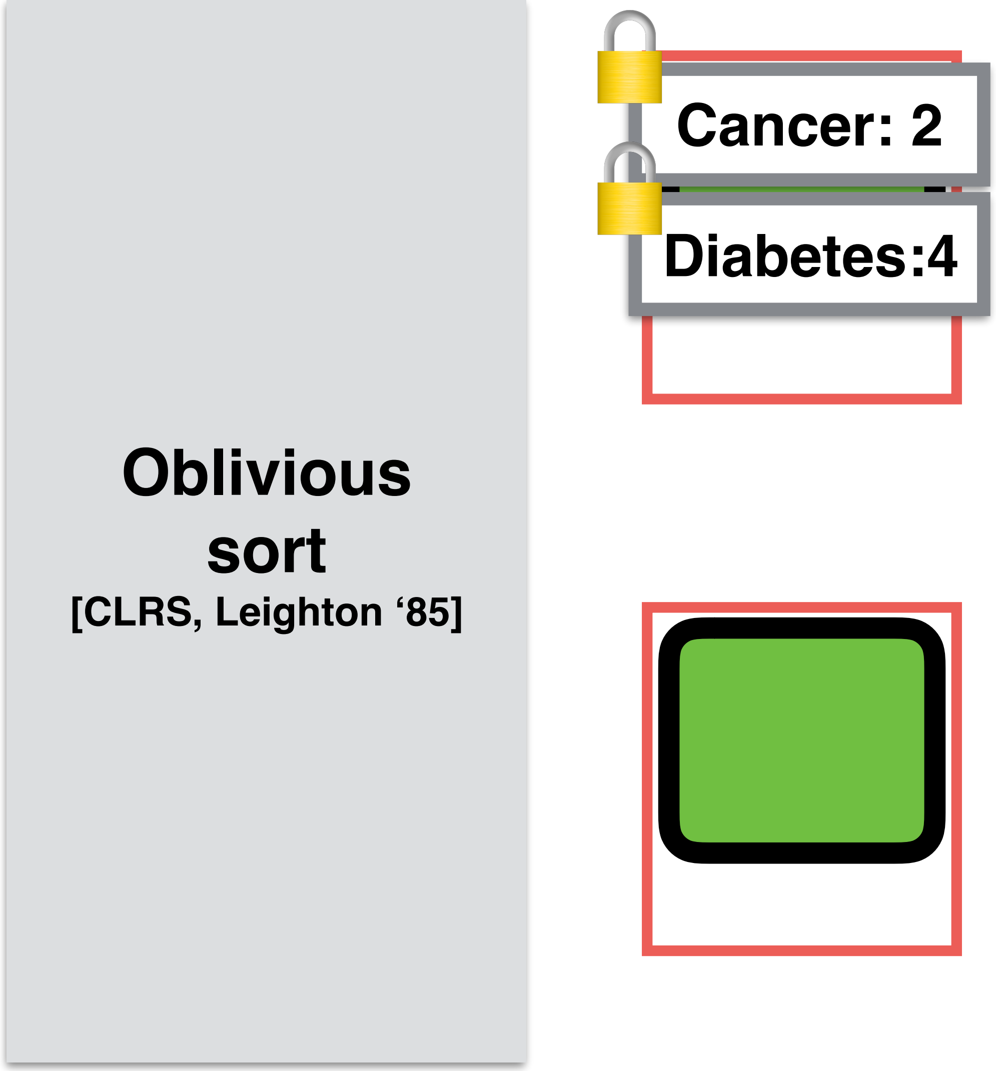
Diabetes:4

Sort

Final result

Oblivious aggregation

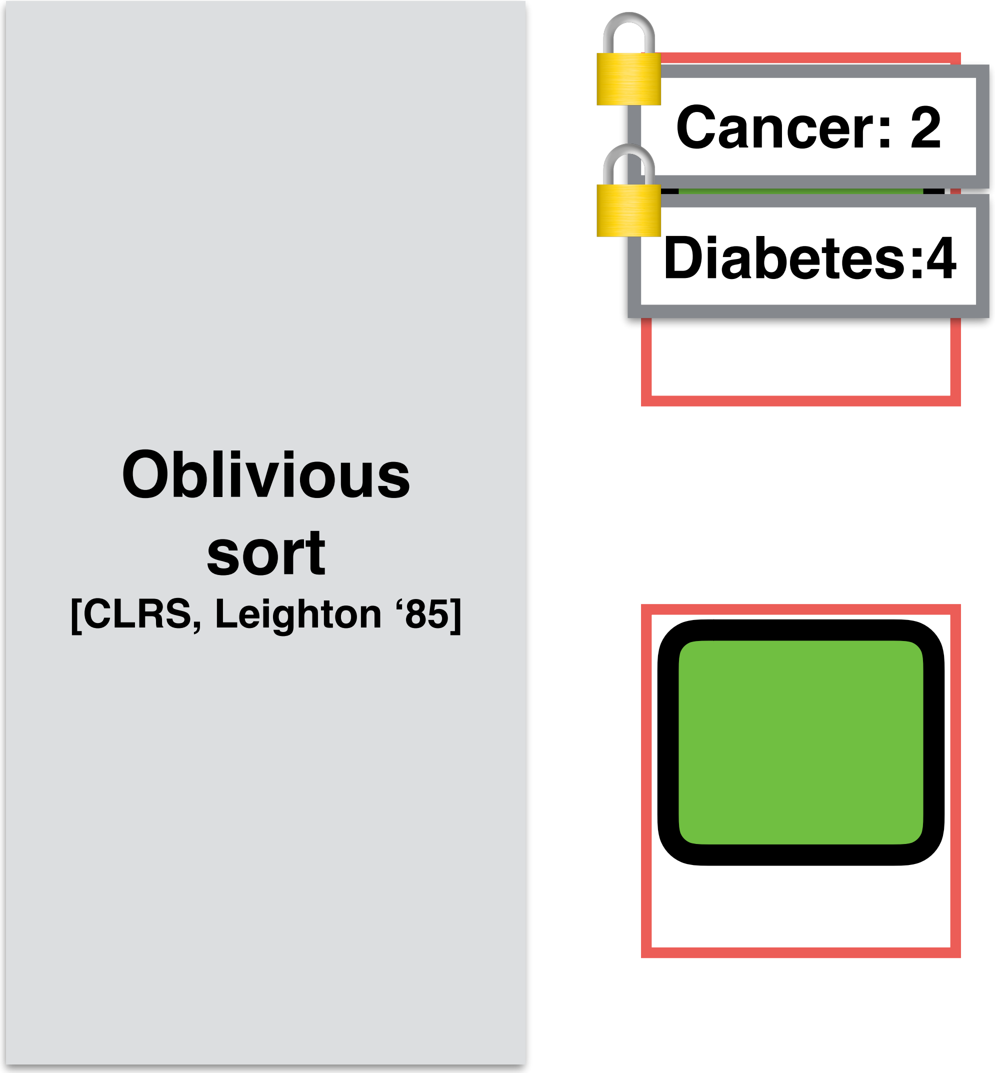
SELECT count(*) FROM medical GROUP BY disease



Aggregation has two sorts…

Oblivious aggregation

SELECT count(*) FROM medical GROUP BY disease



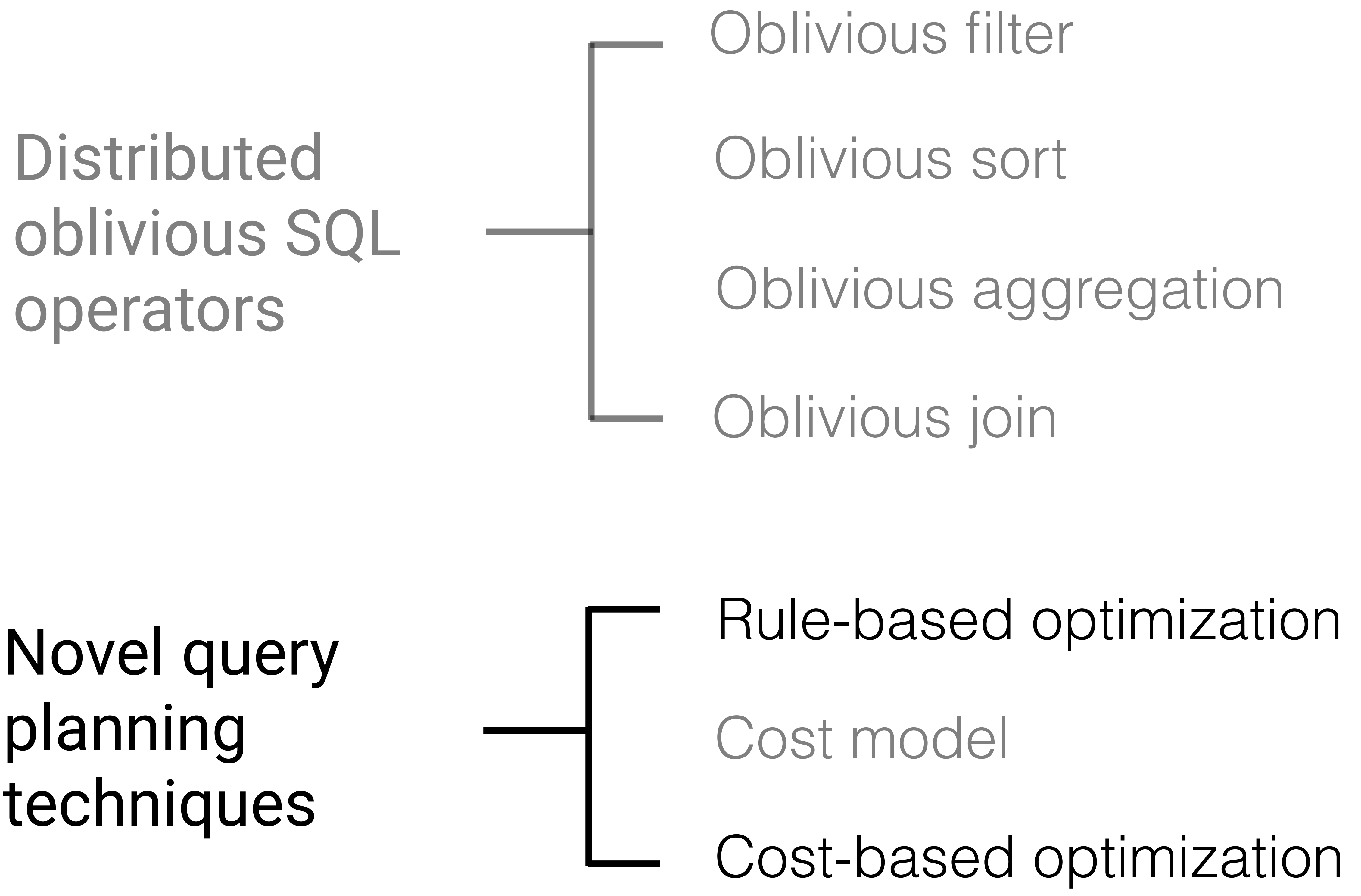
Sort

Final result

Aggregation has two 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

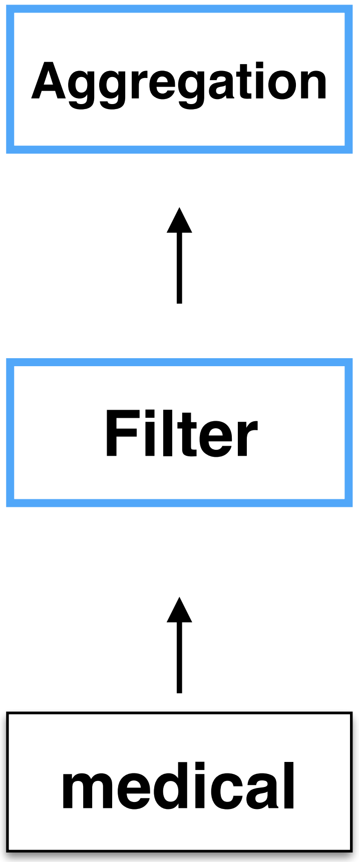
Rule-based optimization

```
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

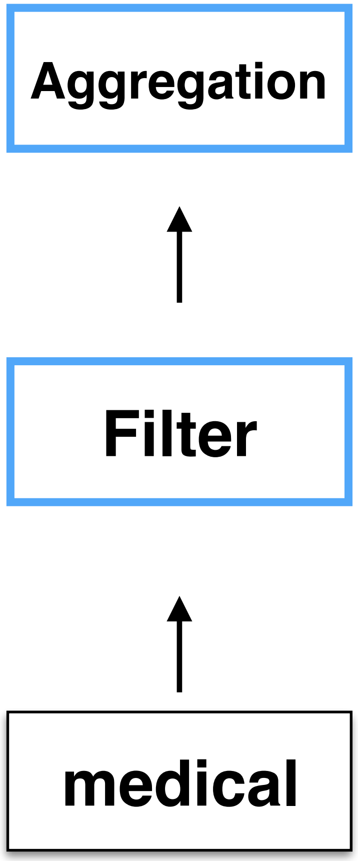
Insight 1

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

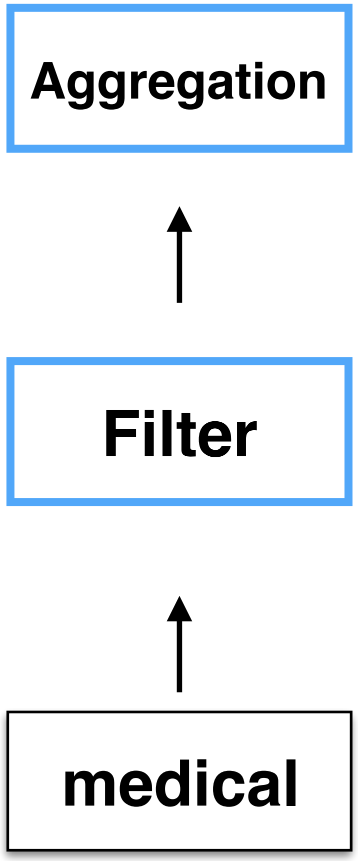
Logical op.



Rule-based optimization

Opaque op.

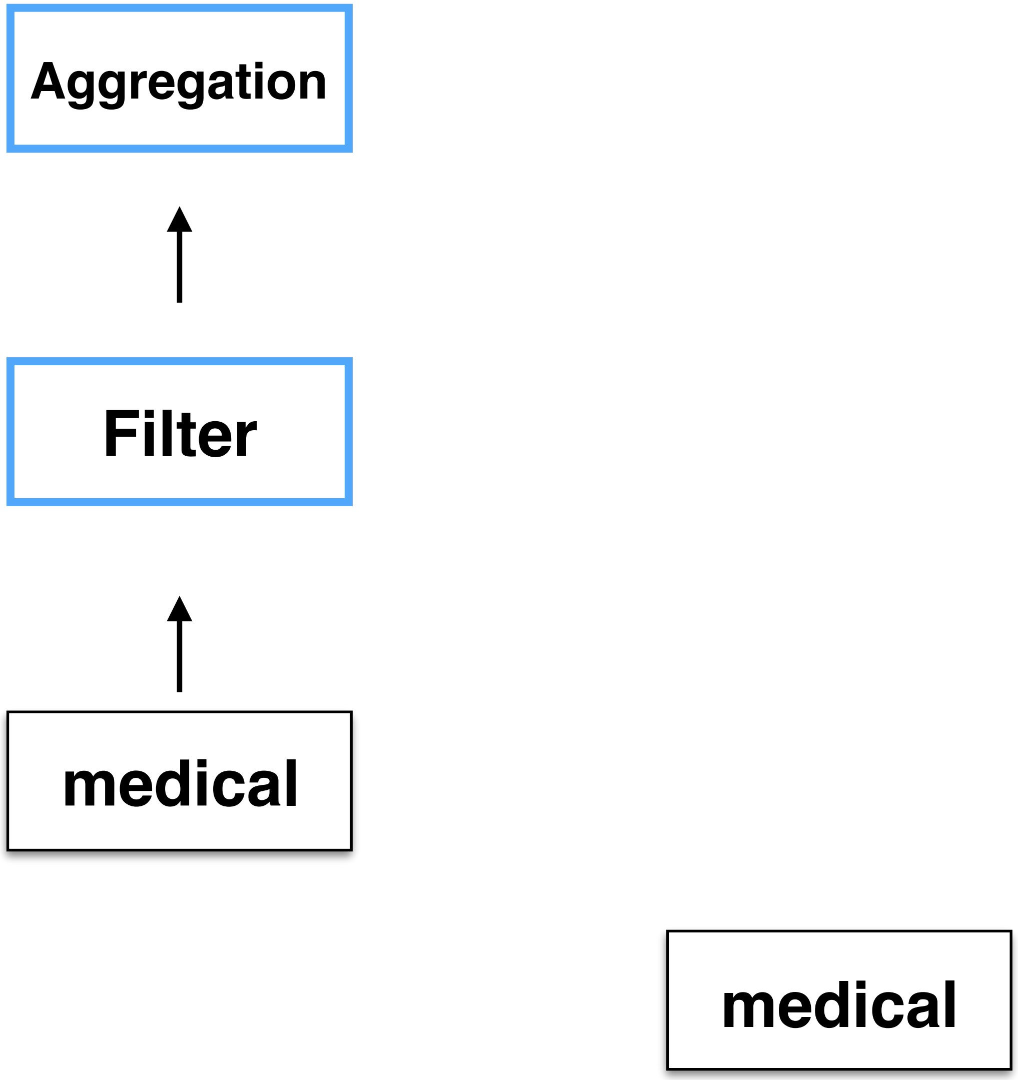
Logical op.



Rule-based optimization

Opaque op.

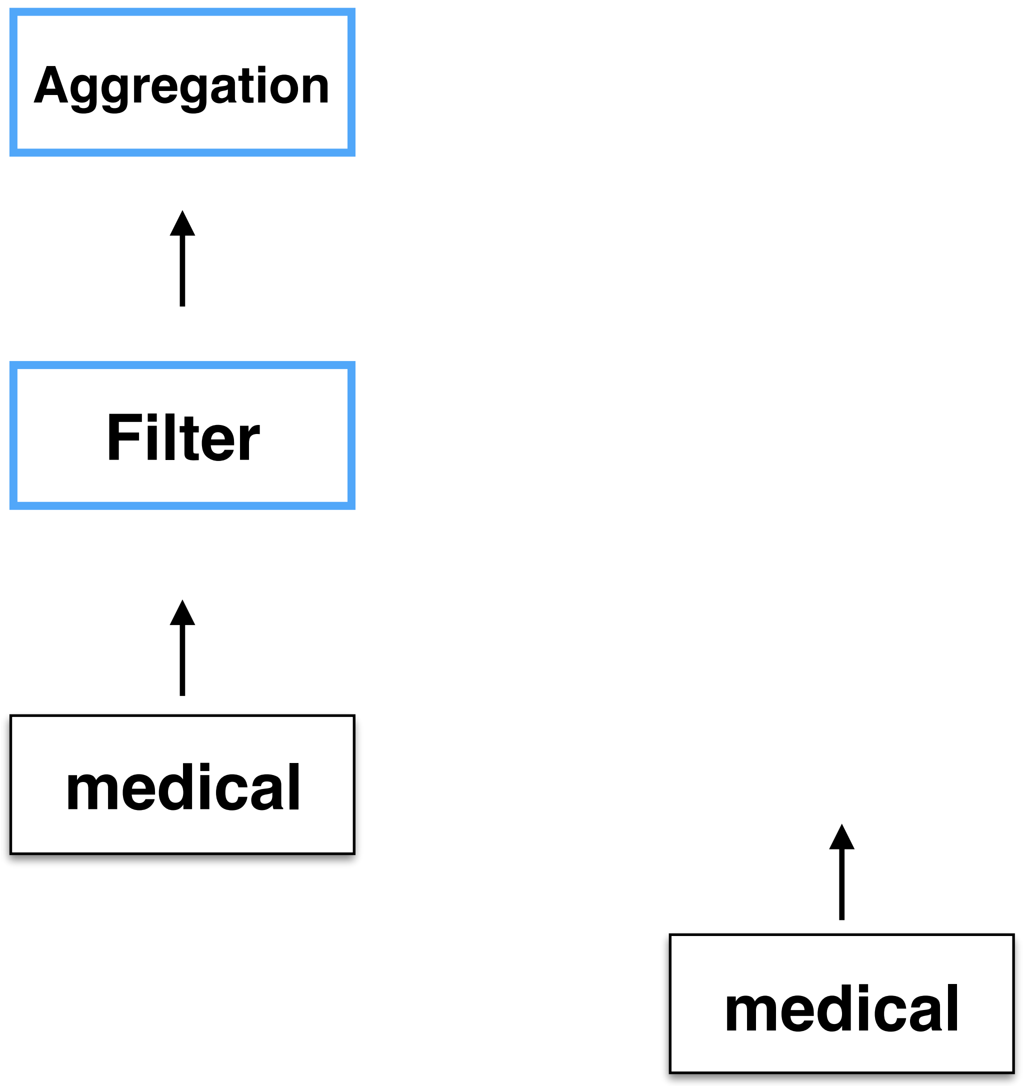
Logical op.



Rule-based optimization

Opaque op.

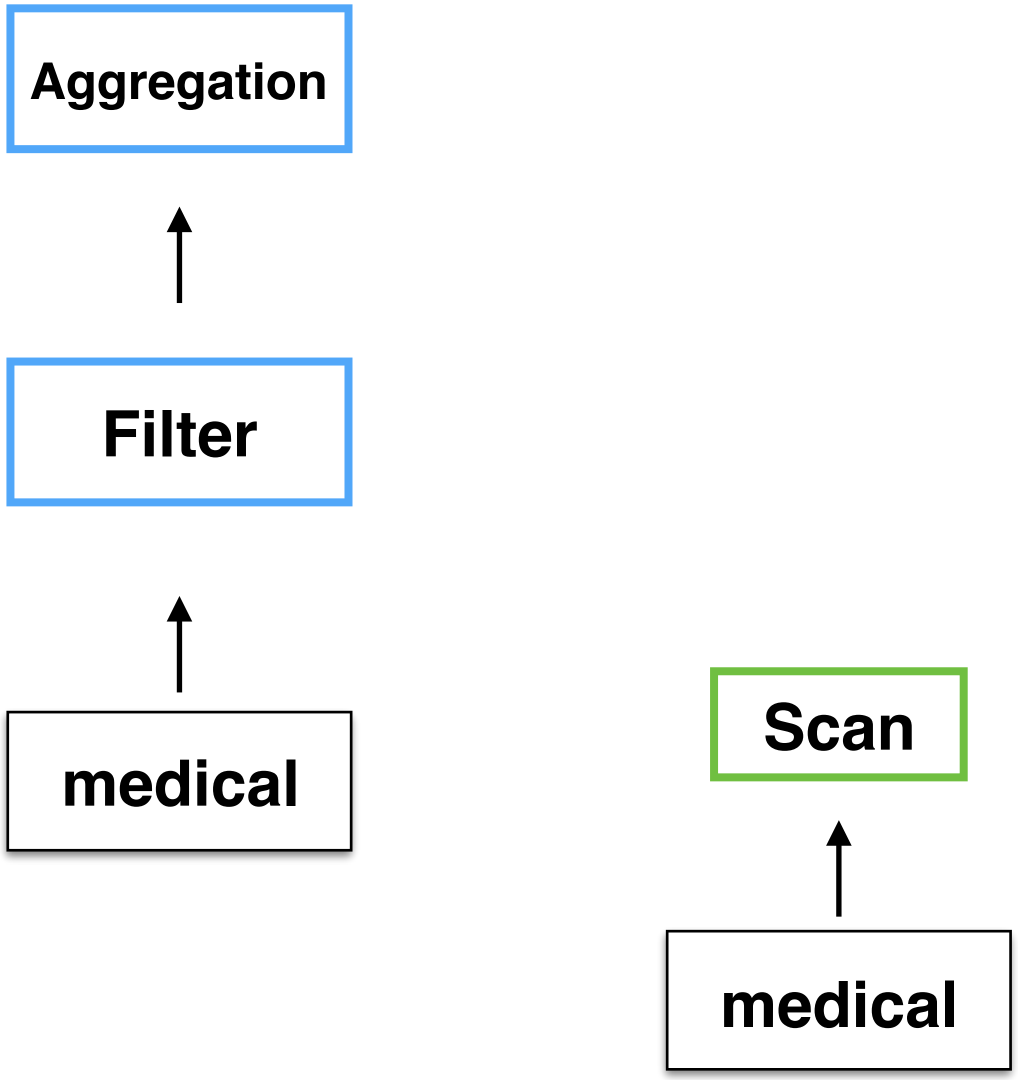
Logical op.



Rule-based optimization

Opaque op.

Logical op.



Aggregation

Filter

medical

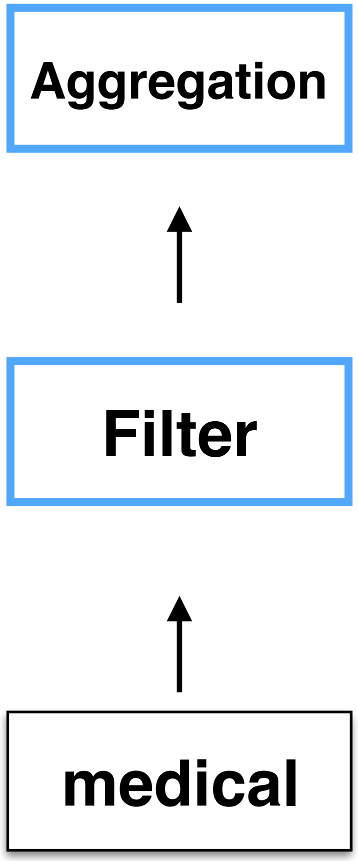
Scan

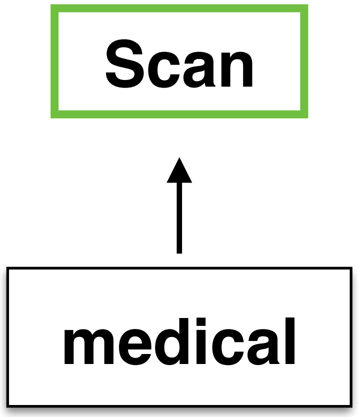
medical

Rule-based optimization

Opaque op.

Logical op.





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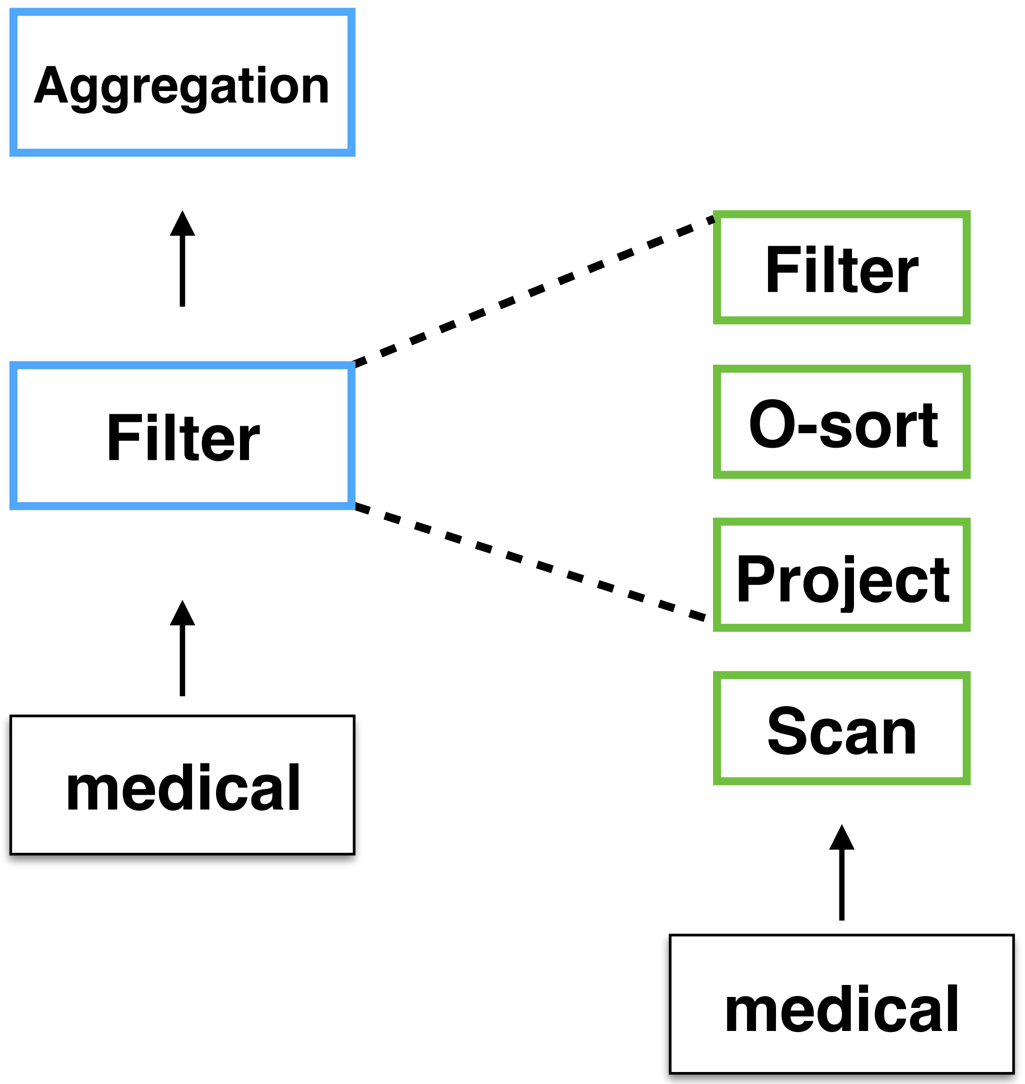
Rule-based optimization

Opaque op.

Logical op.



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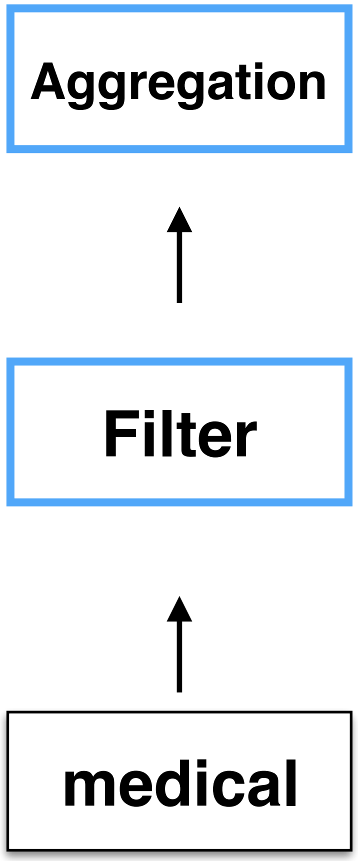
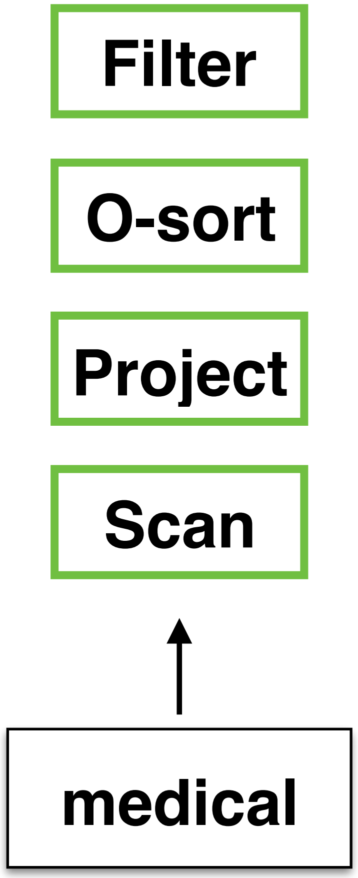
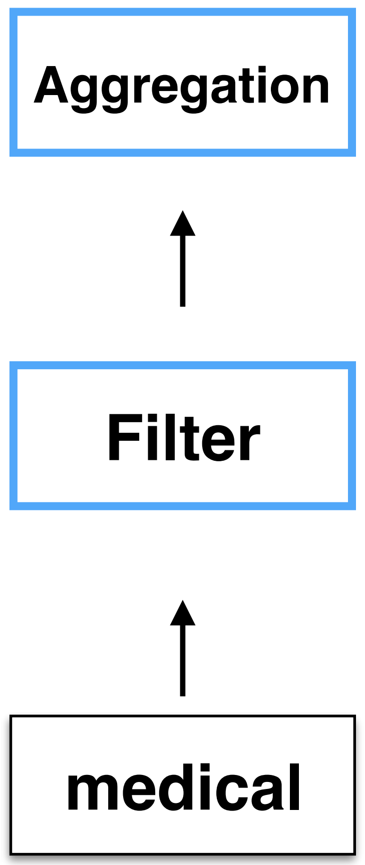


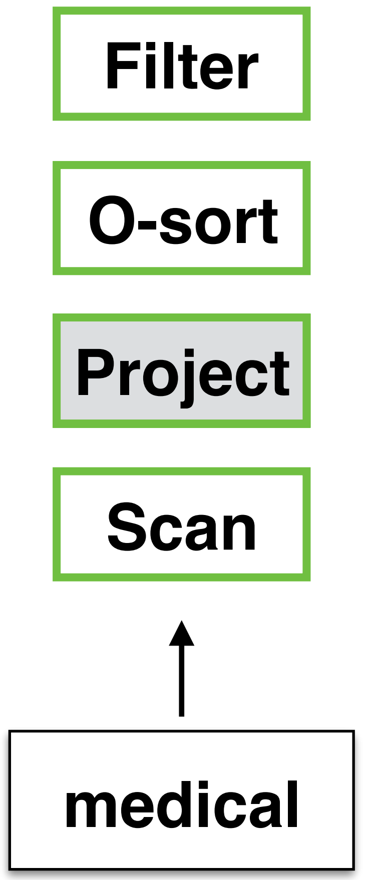


Rule-based optimization

Opaque op.

Logical op.





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Rule-based optimization

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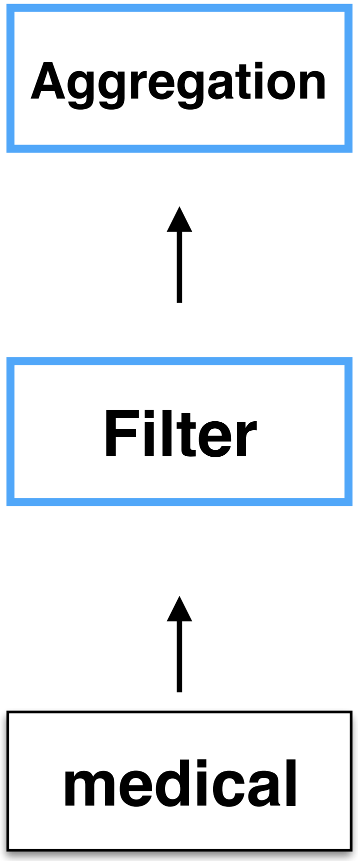
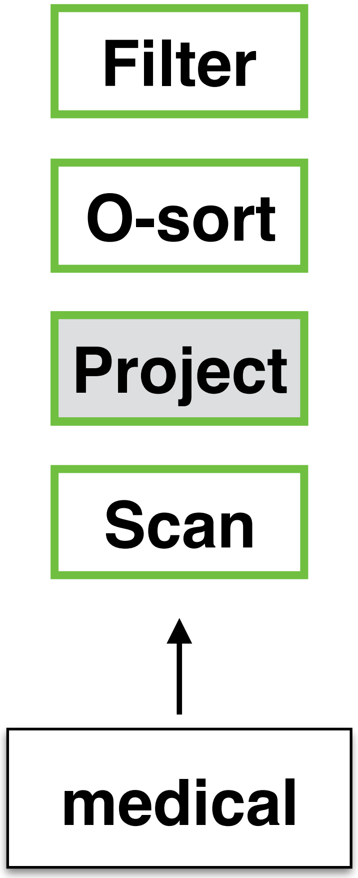
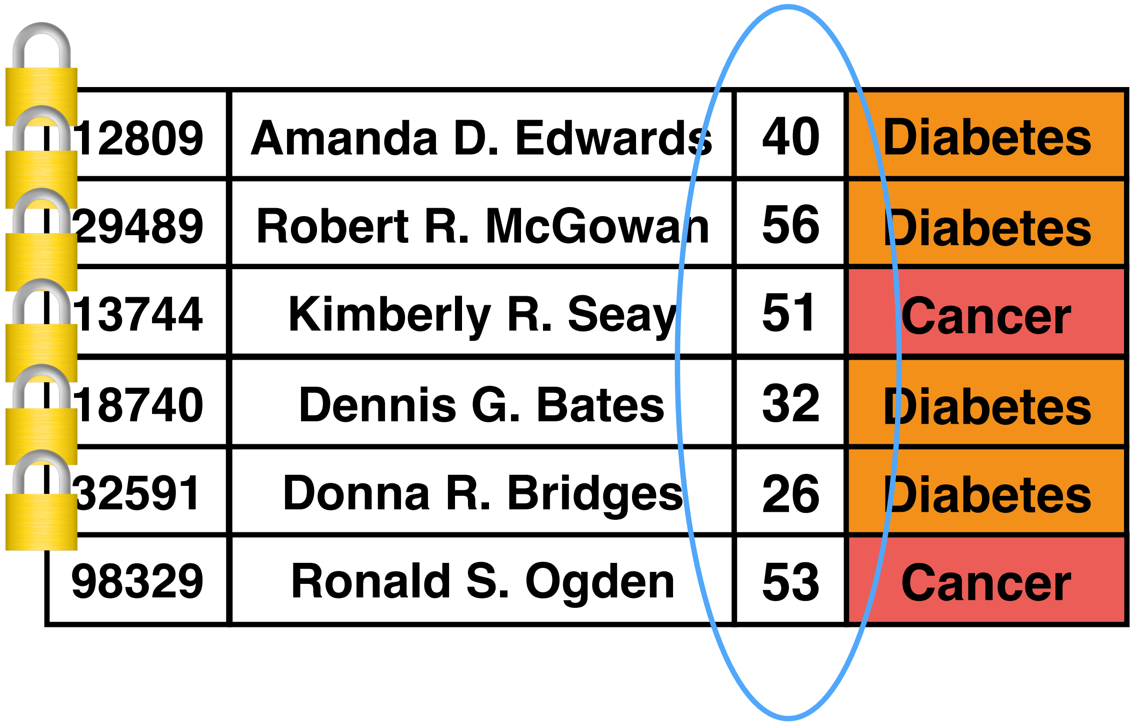


Opaque op.





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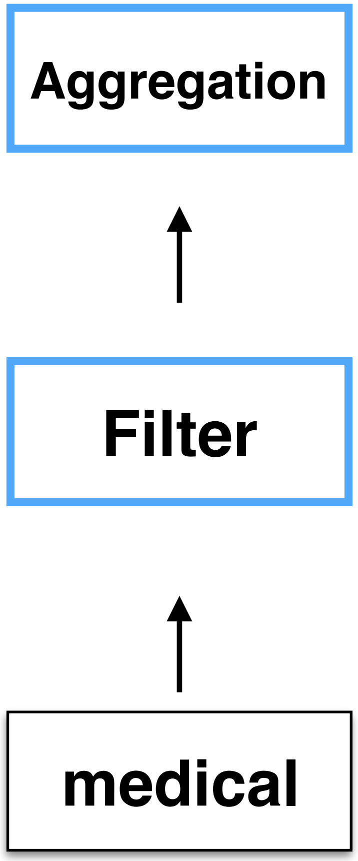

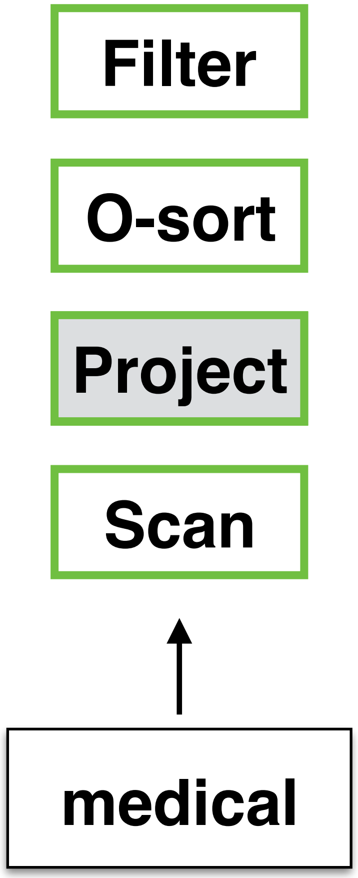

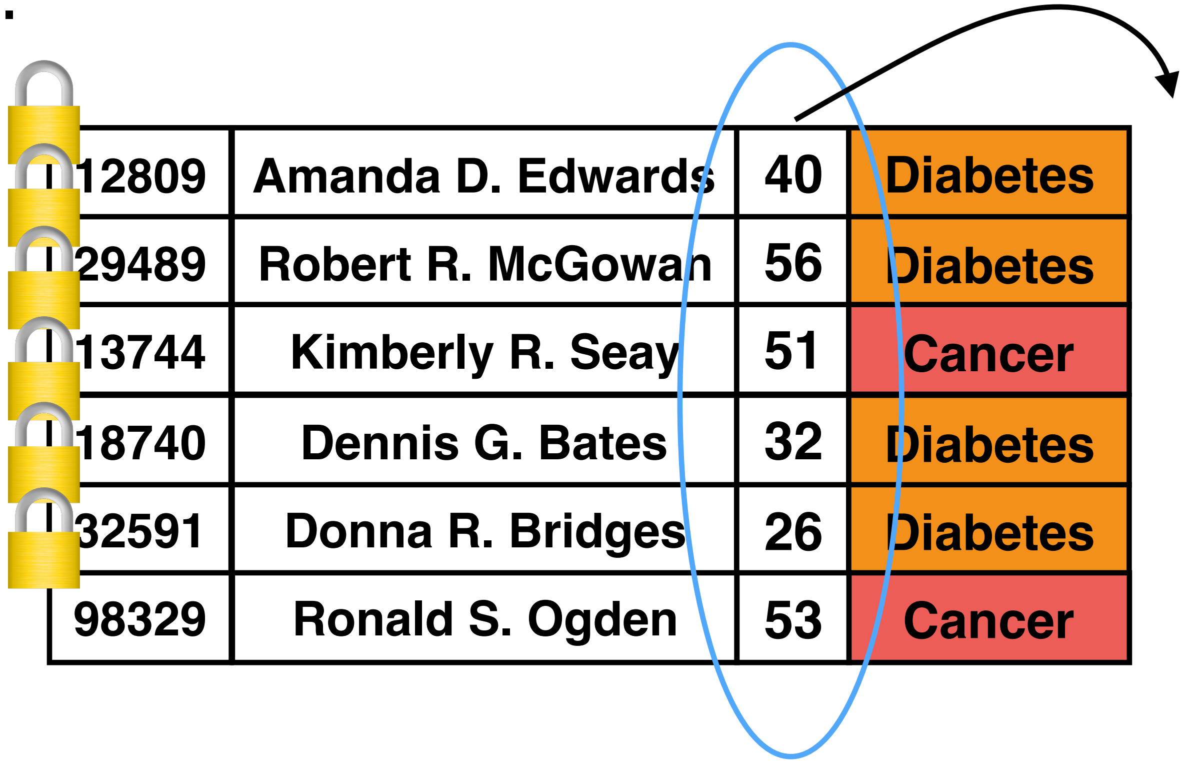

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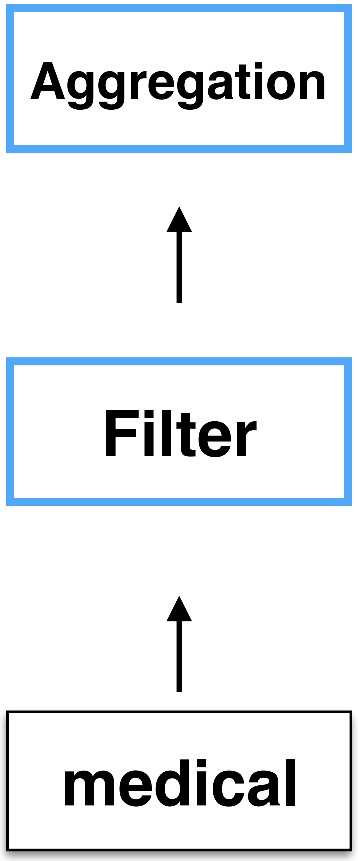

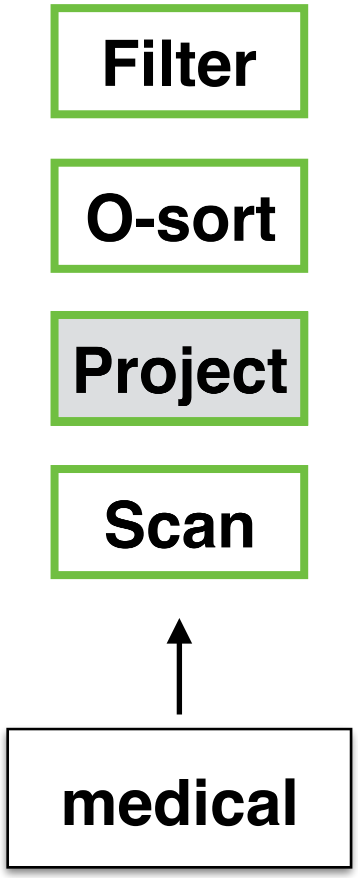

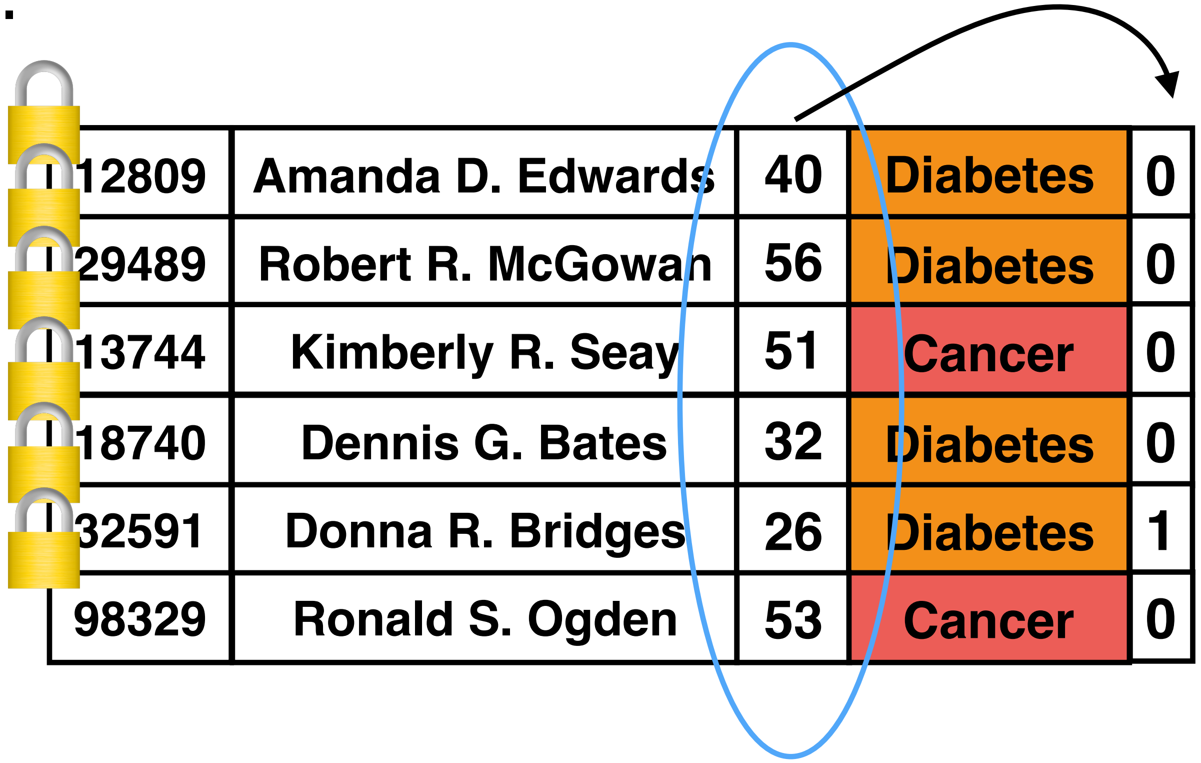

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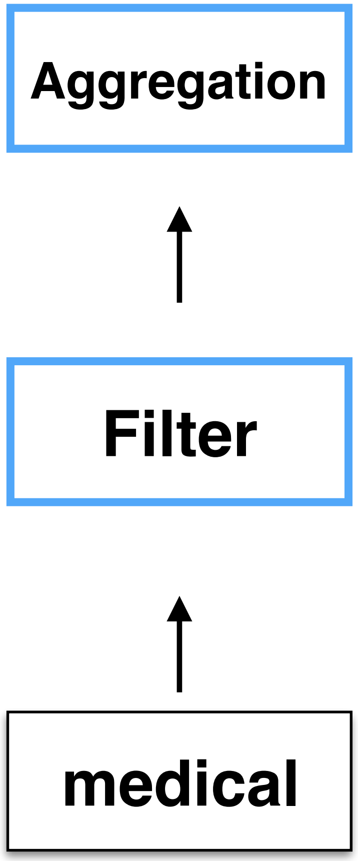
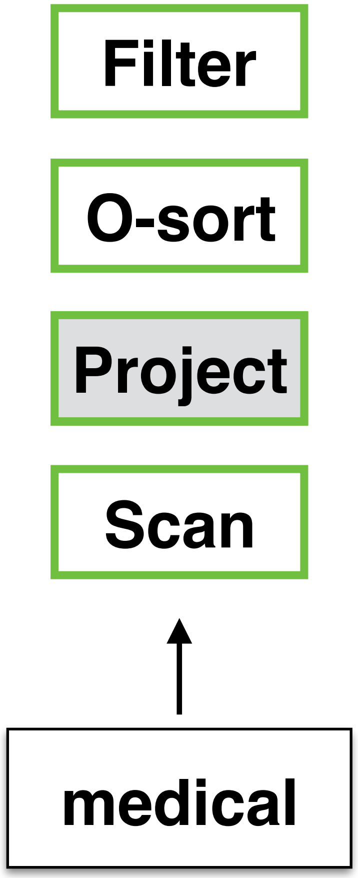
Rule-based optimization

Opaque op.

Logical op.





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Rule-based optimization

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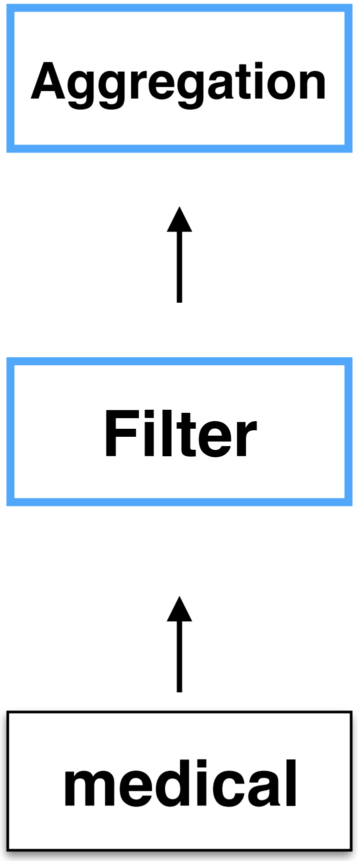

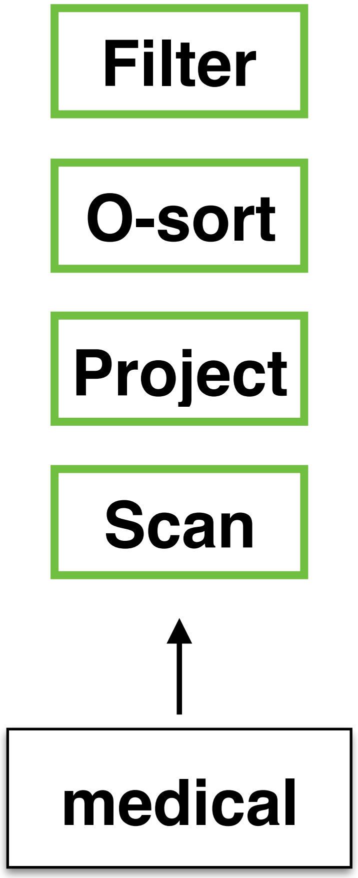

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Rule-based optimization

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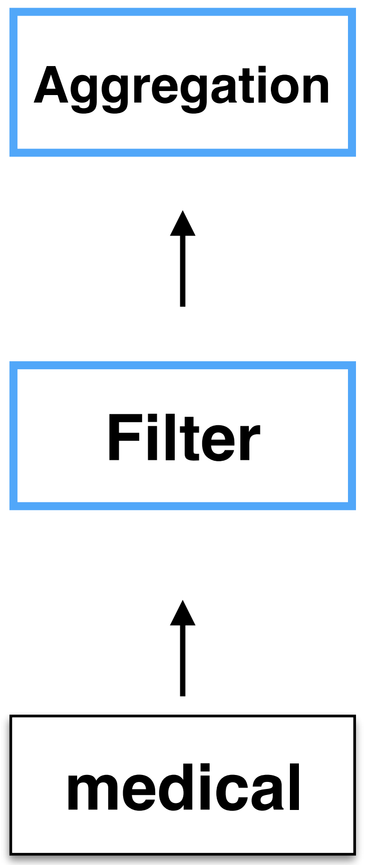

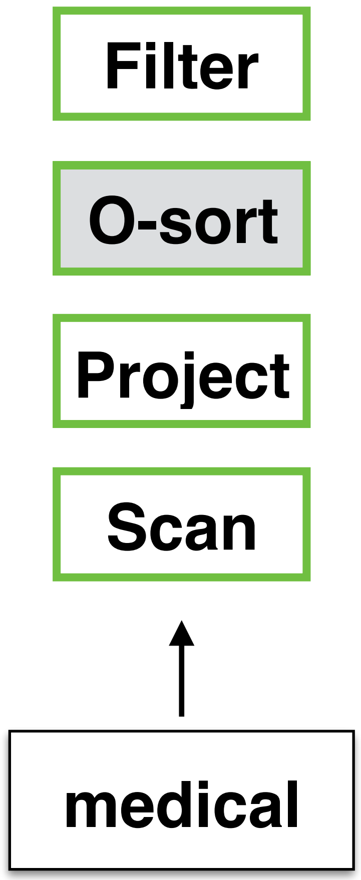

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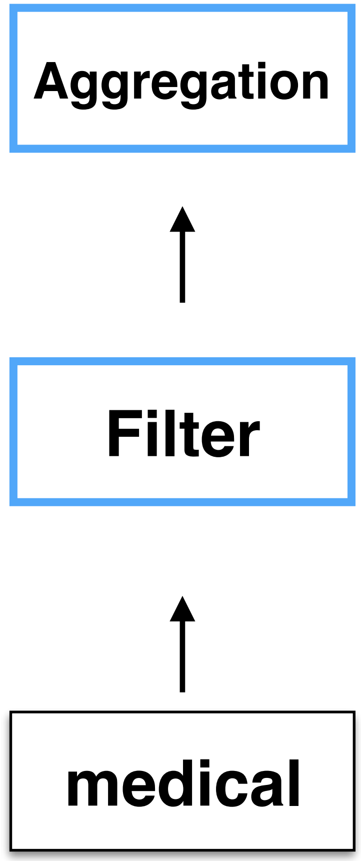
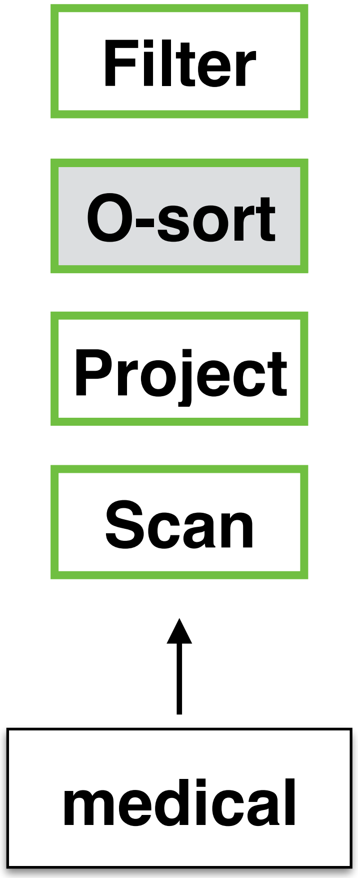
Rule-based optimization

Opaque op.

Logical op.





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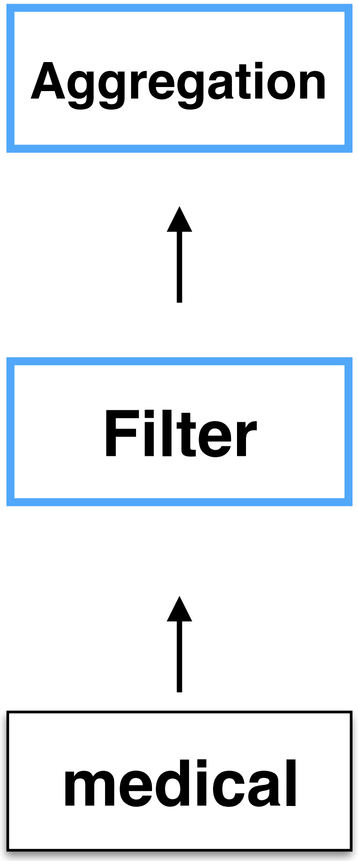
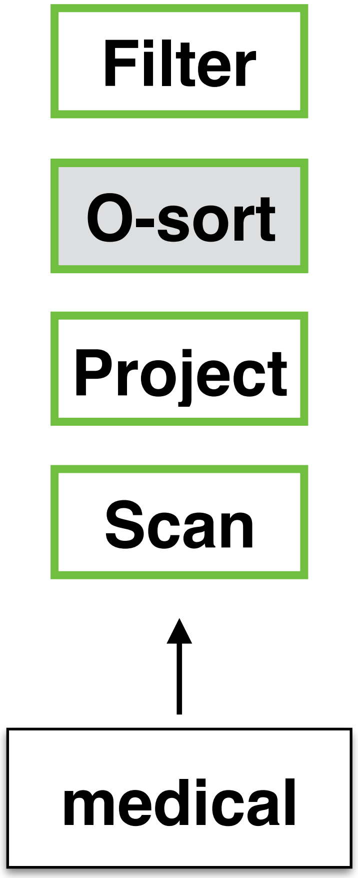
Rule-based optimization

Opaque op.

Logical op.





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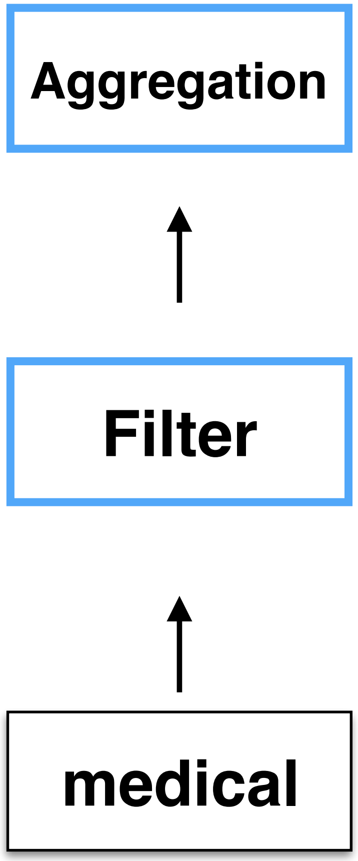
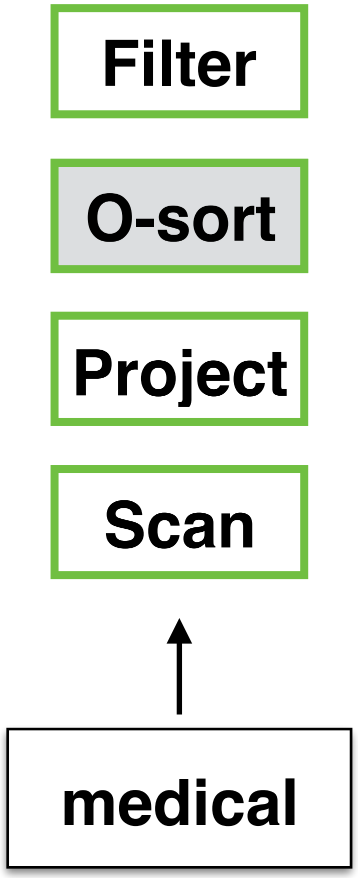
Rule-based optimization

Opaque op.

Logical op.





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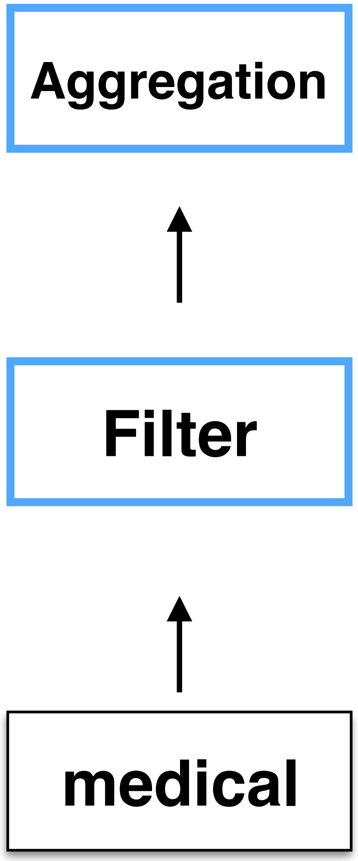
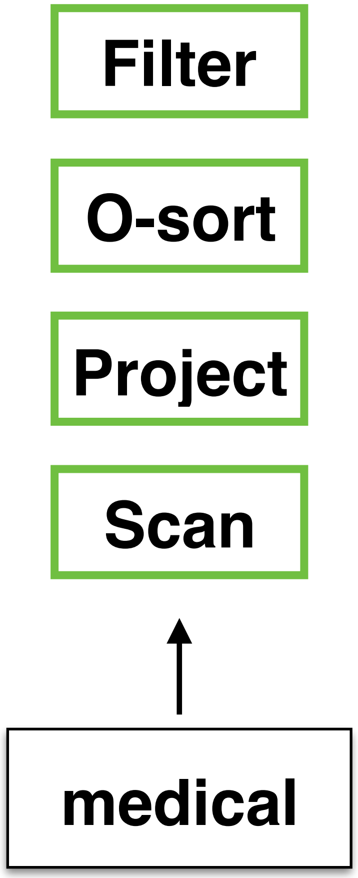
Rule-based optimization

Opaque op.

Logical op.





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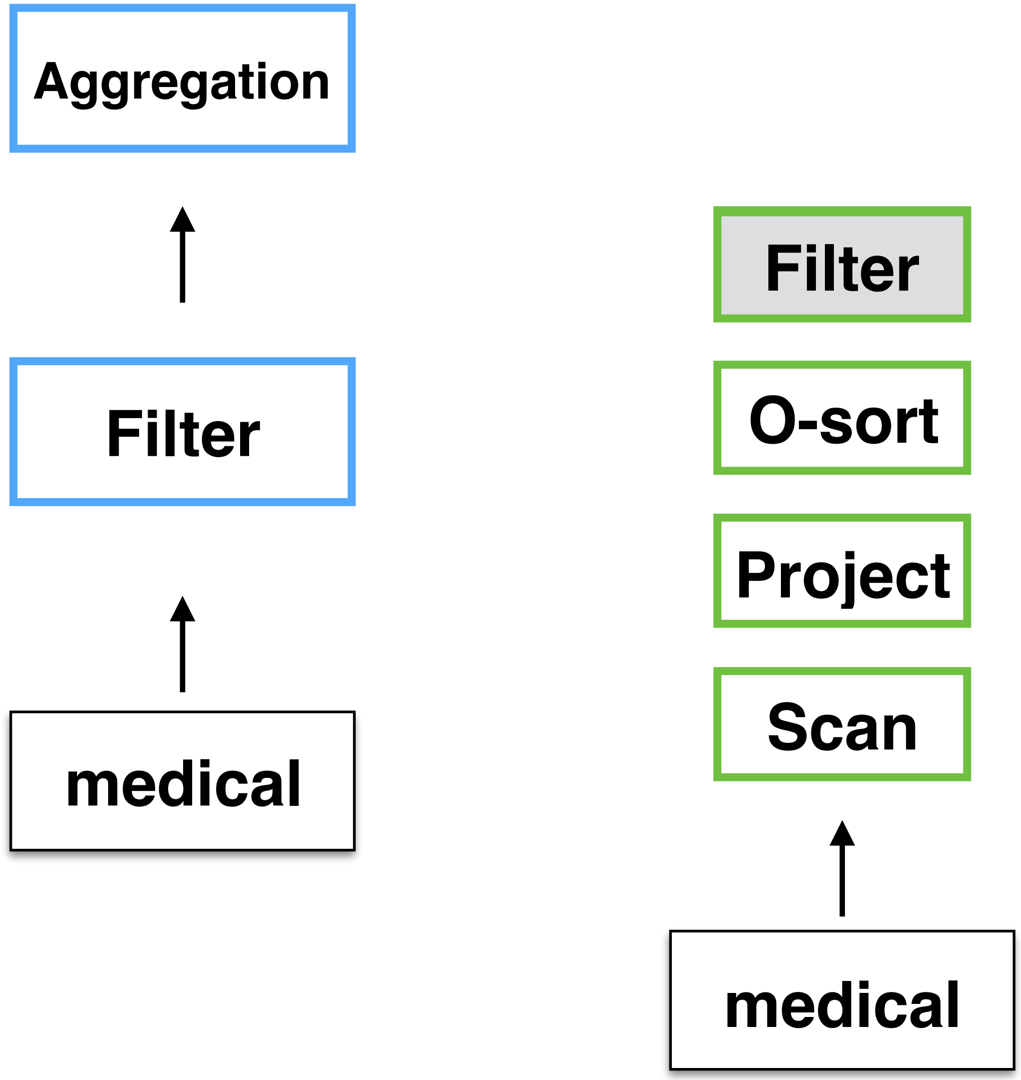
Rule-based optimization

Opaque op.

Logical op.



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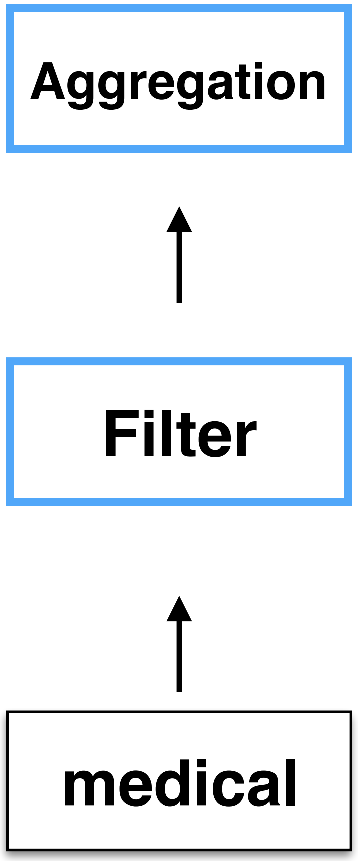
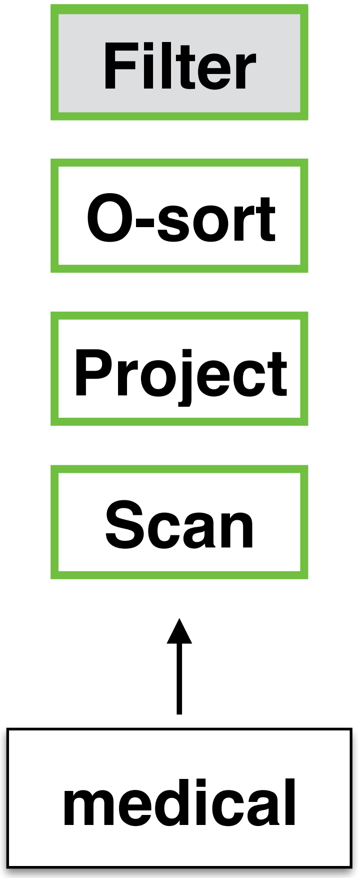
Rule-based optimization

Opaque op.

Logical op.





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Rule-based optimization

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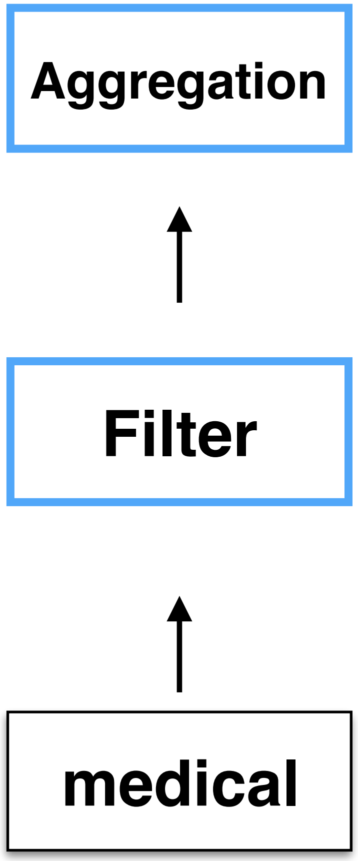

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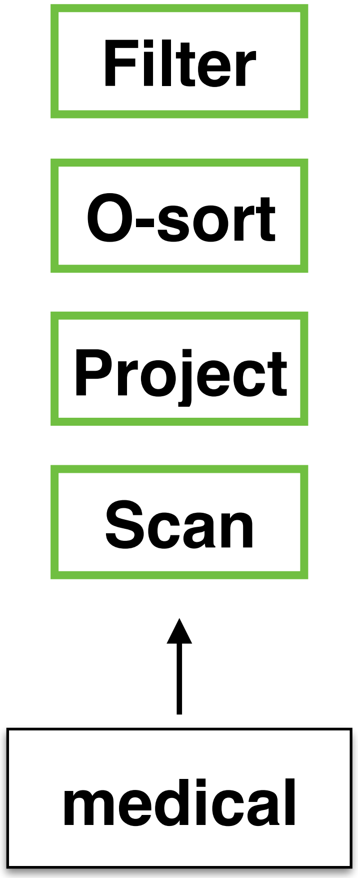

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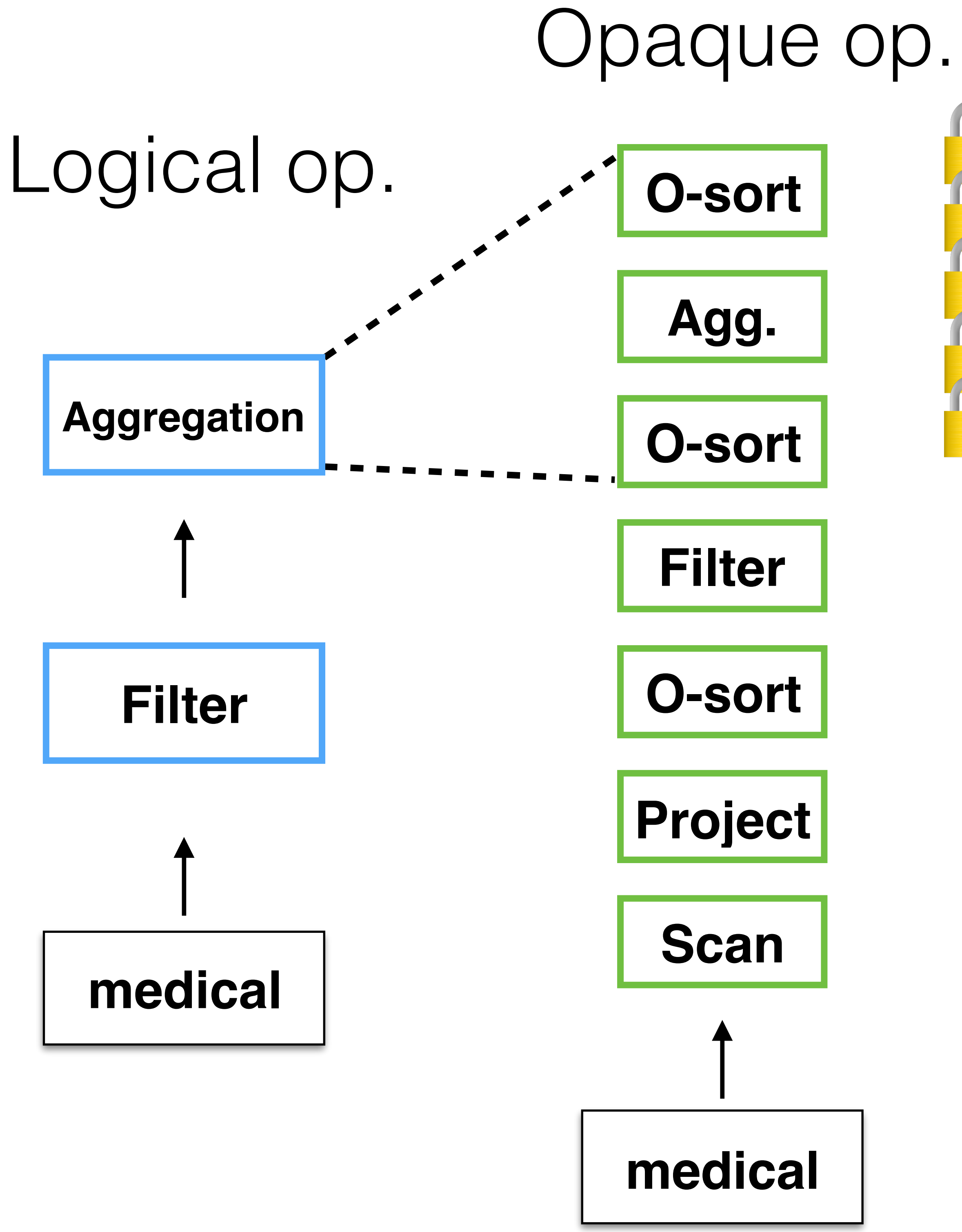

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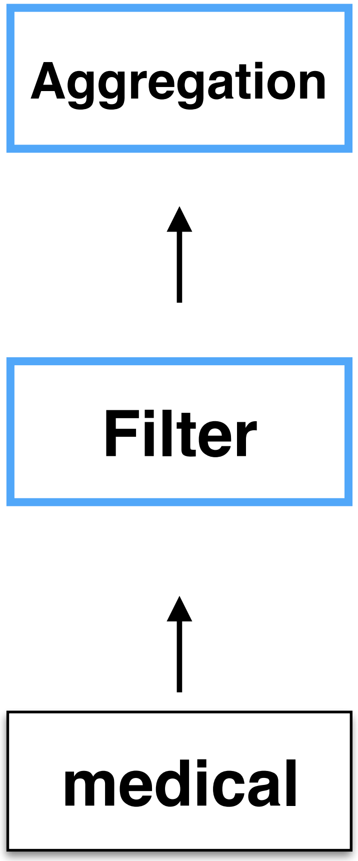

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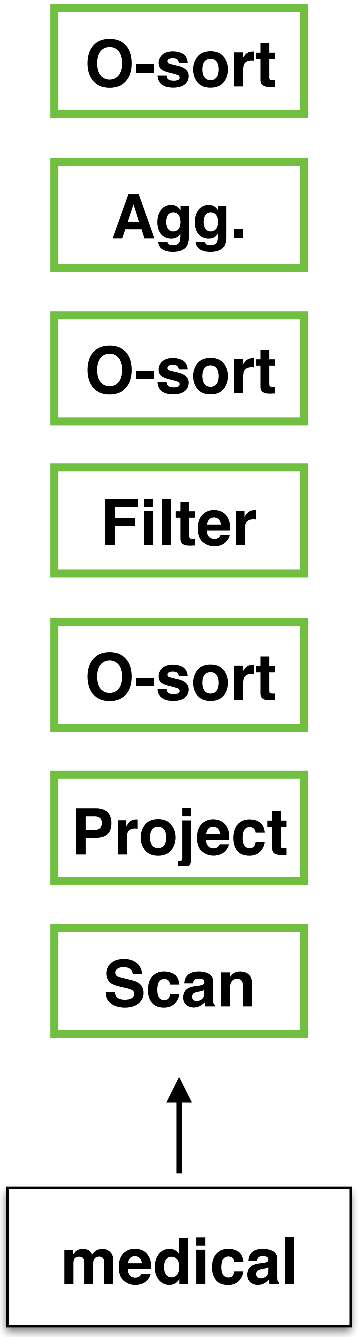

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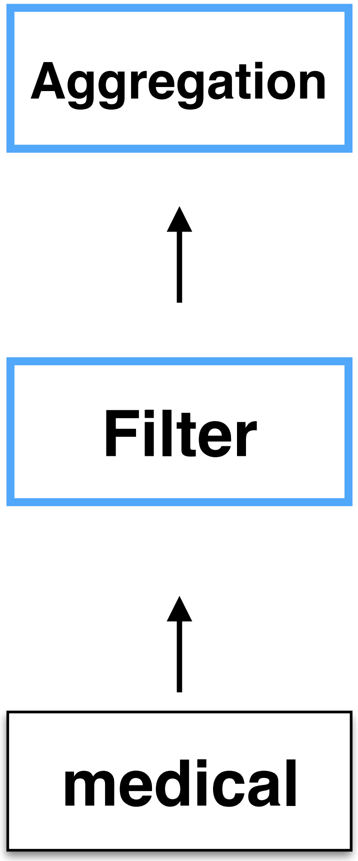

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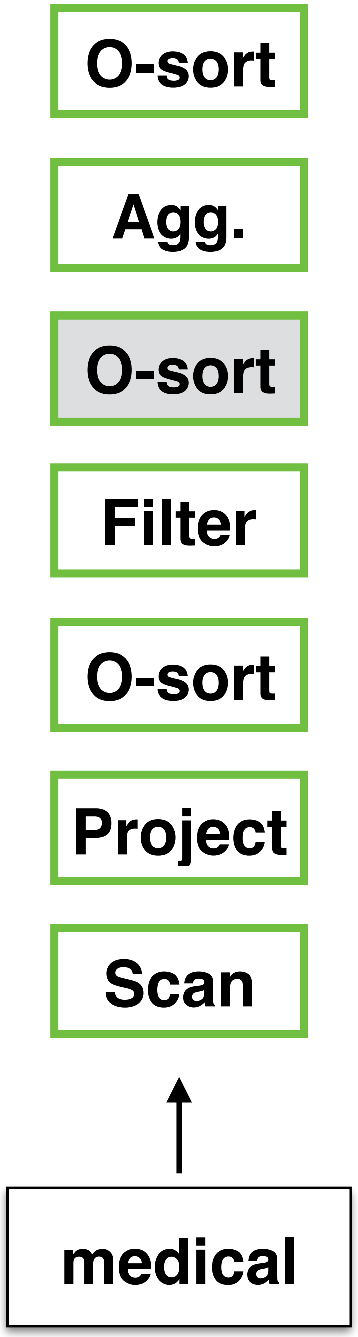

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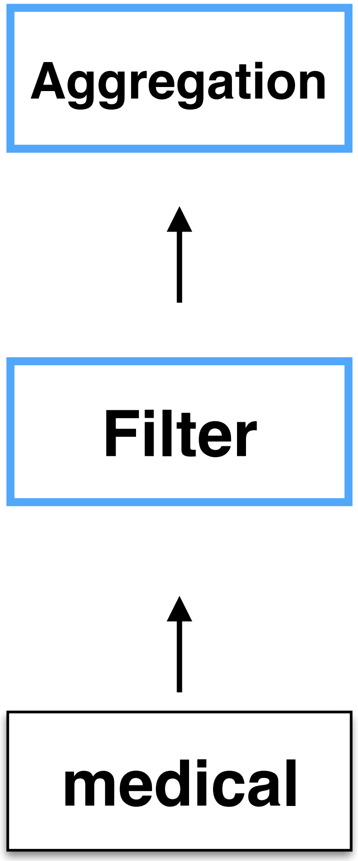
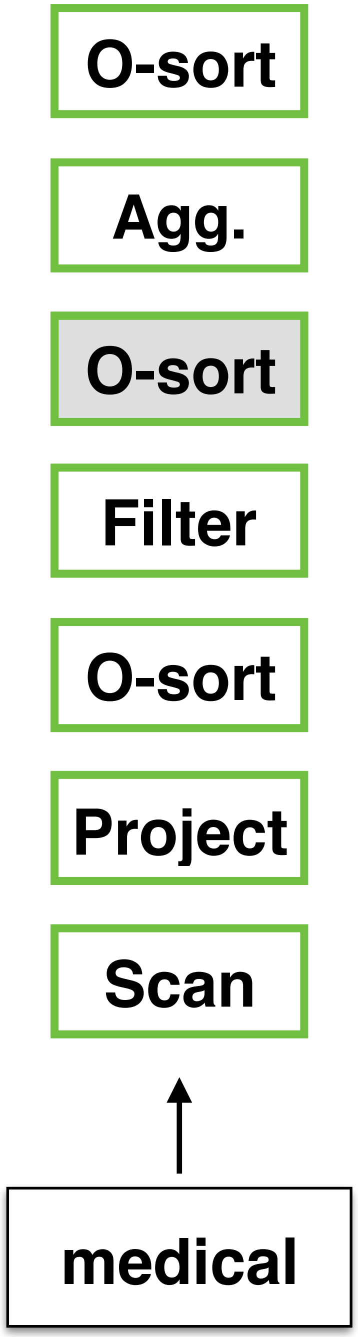
Rule-based optimization

Logical op.



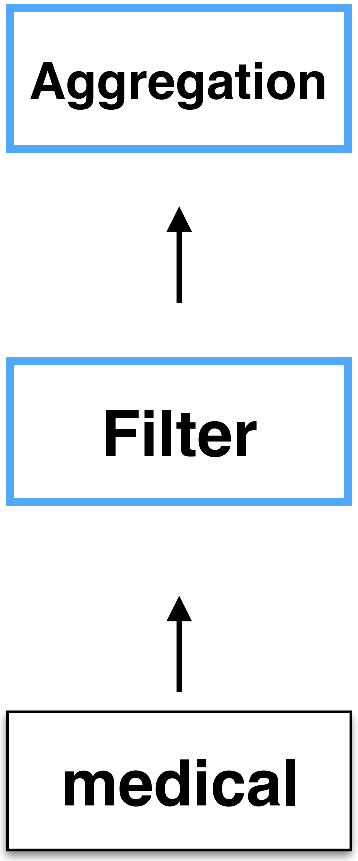
Opaque op.



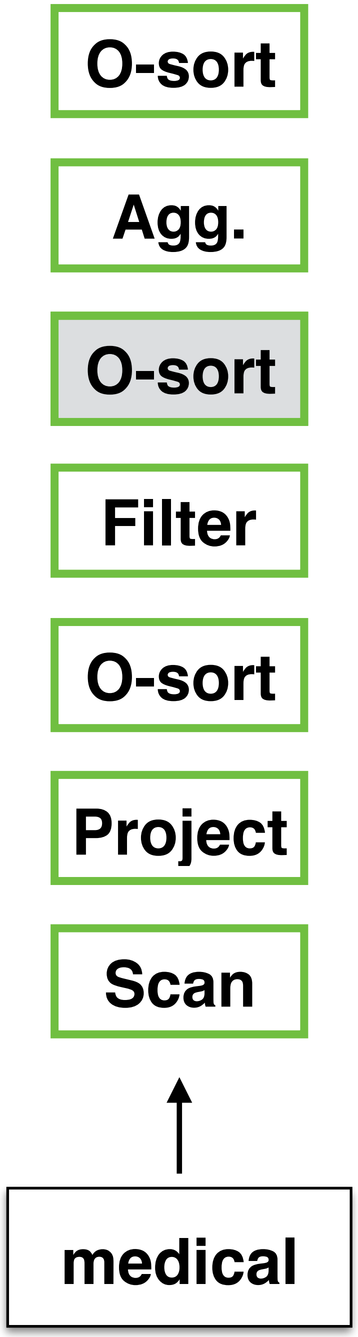
13744	Kimberly R. Seay	51	Cancer	0
98329	Ronald S. Ogden	53	Cancer	0
29489	Robert R. McGowan	56	Diabetes	0
18740	Dennis G. Bates	32	Diabetes	0
12809	Amanda D. Edwards	40	Diabetes	0

Rule-based optimization

Logical op.



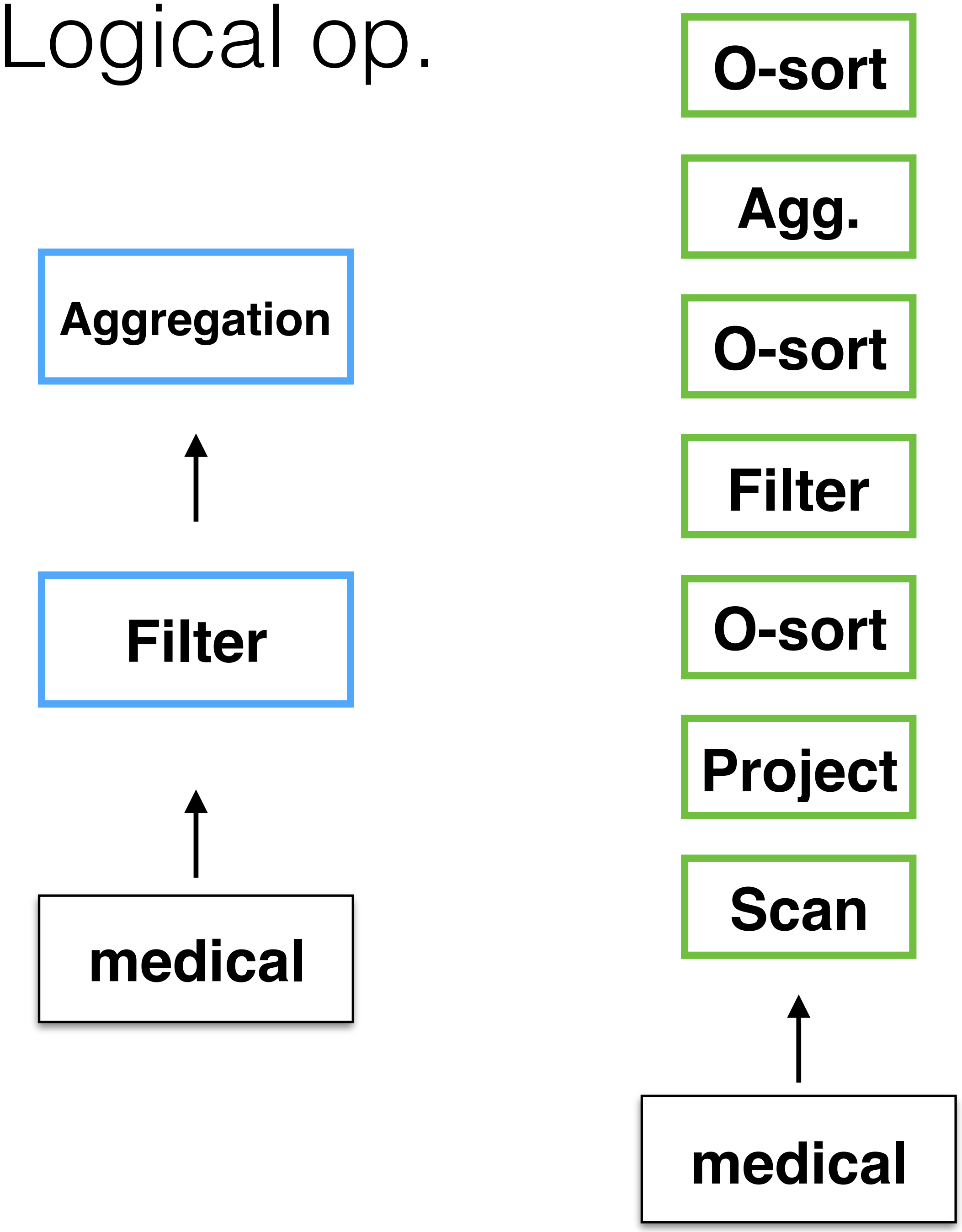
Opaque op.



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

Can we remove any sort?

Rule-based optimization



Logical op.

Aggregation

Filter

medical

Opaque op.

O-sort

Agg.

O-sort

Filter

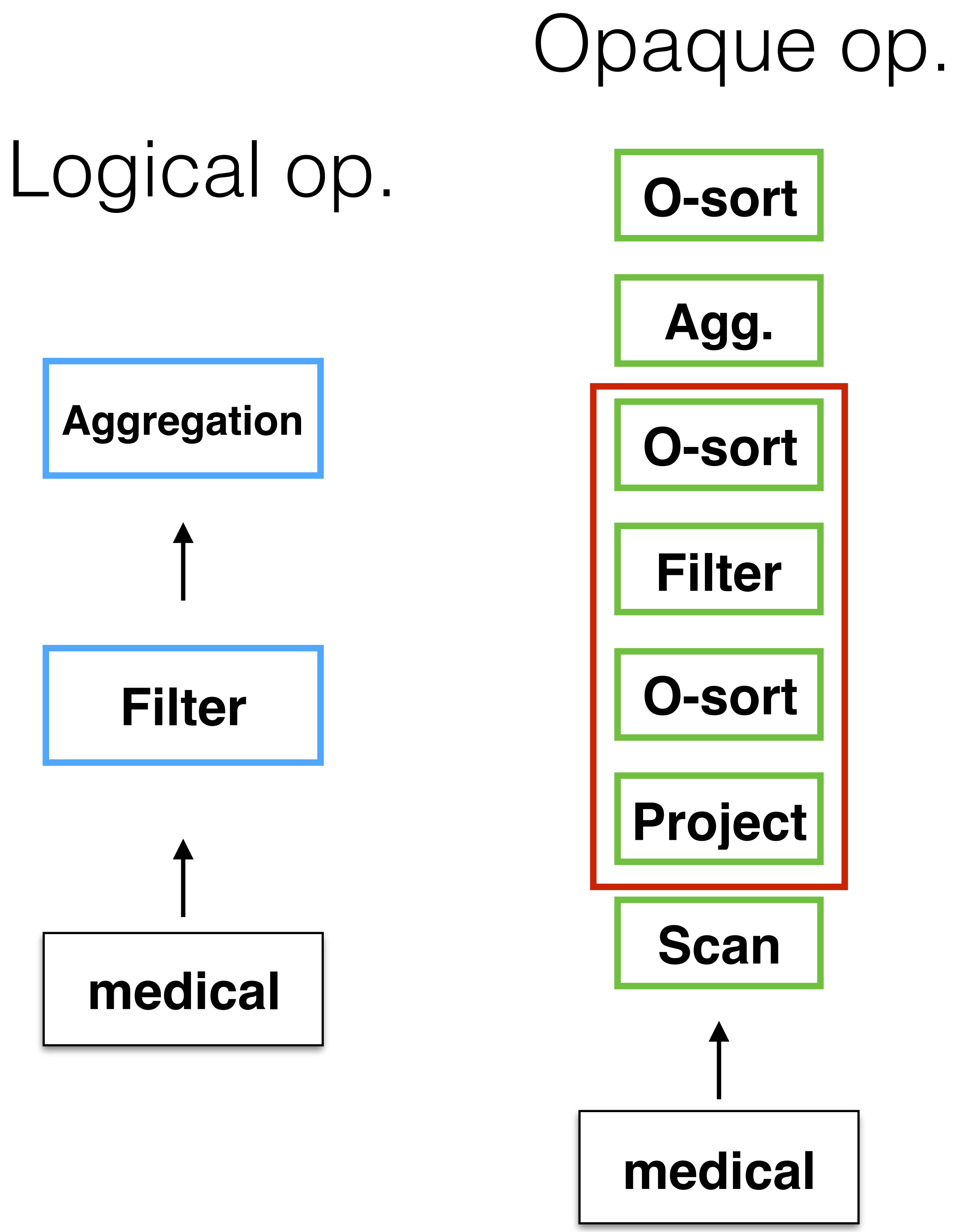
O-sort

Project

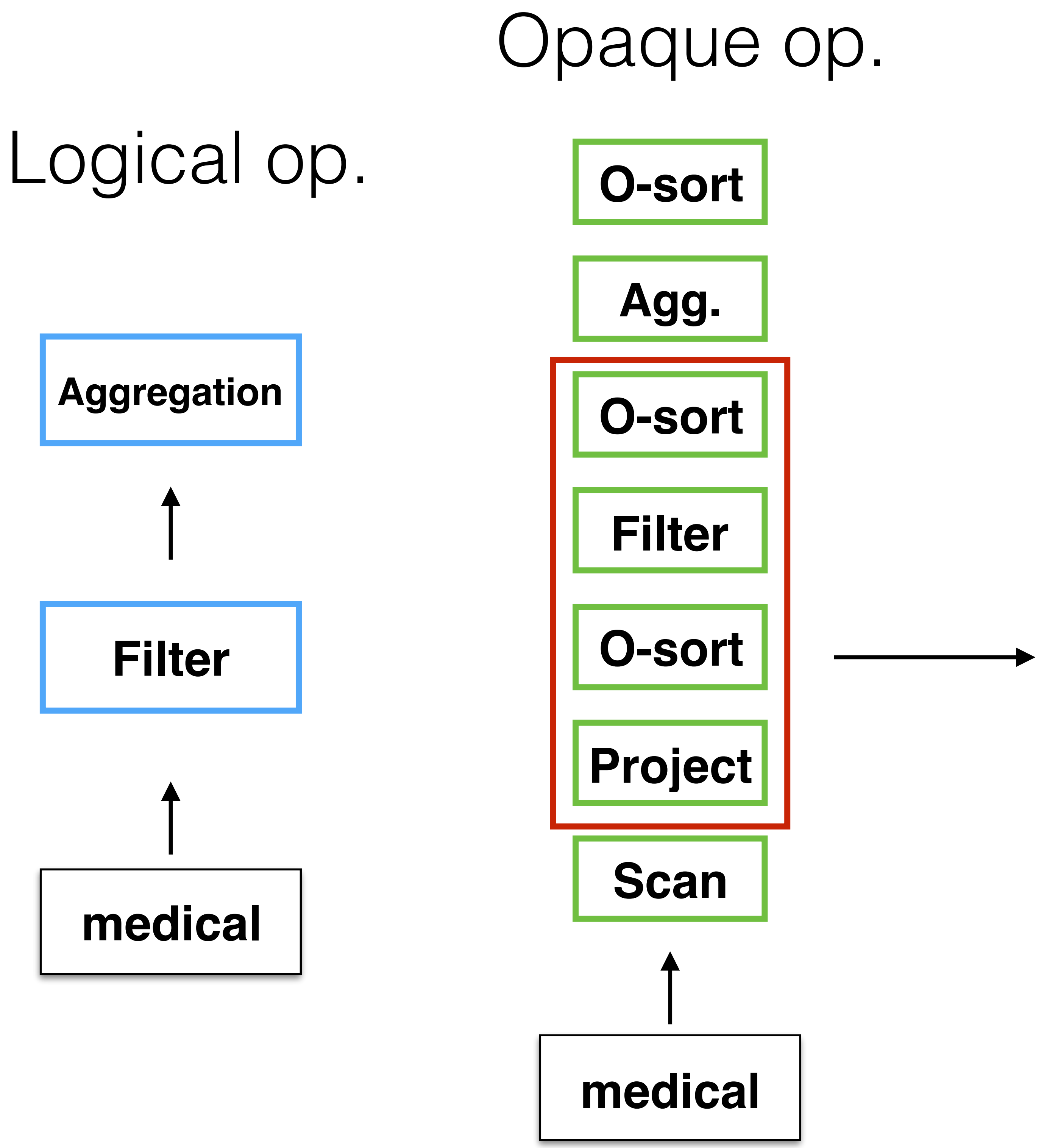
Scan

medical

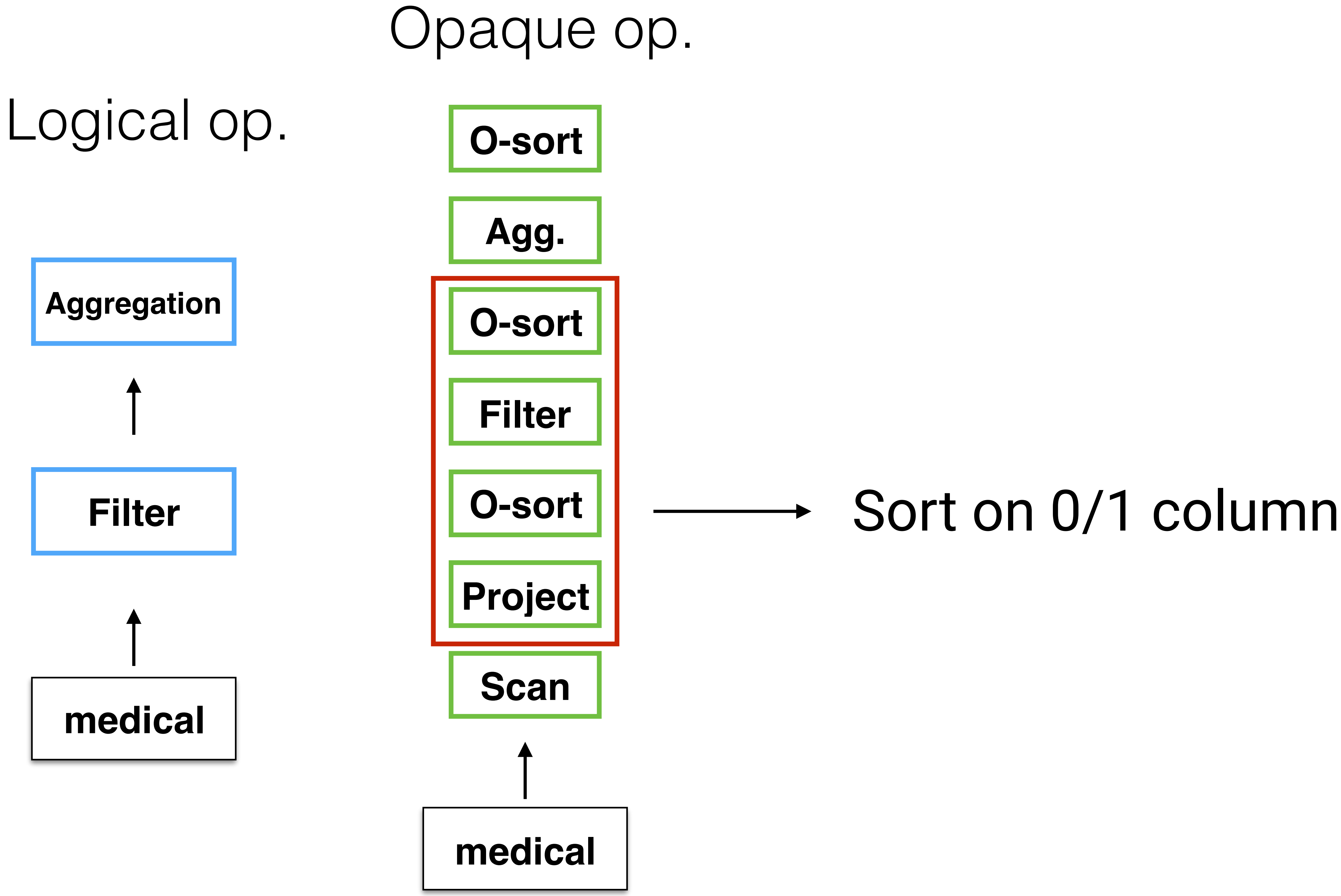
Rule-based optimization



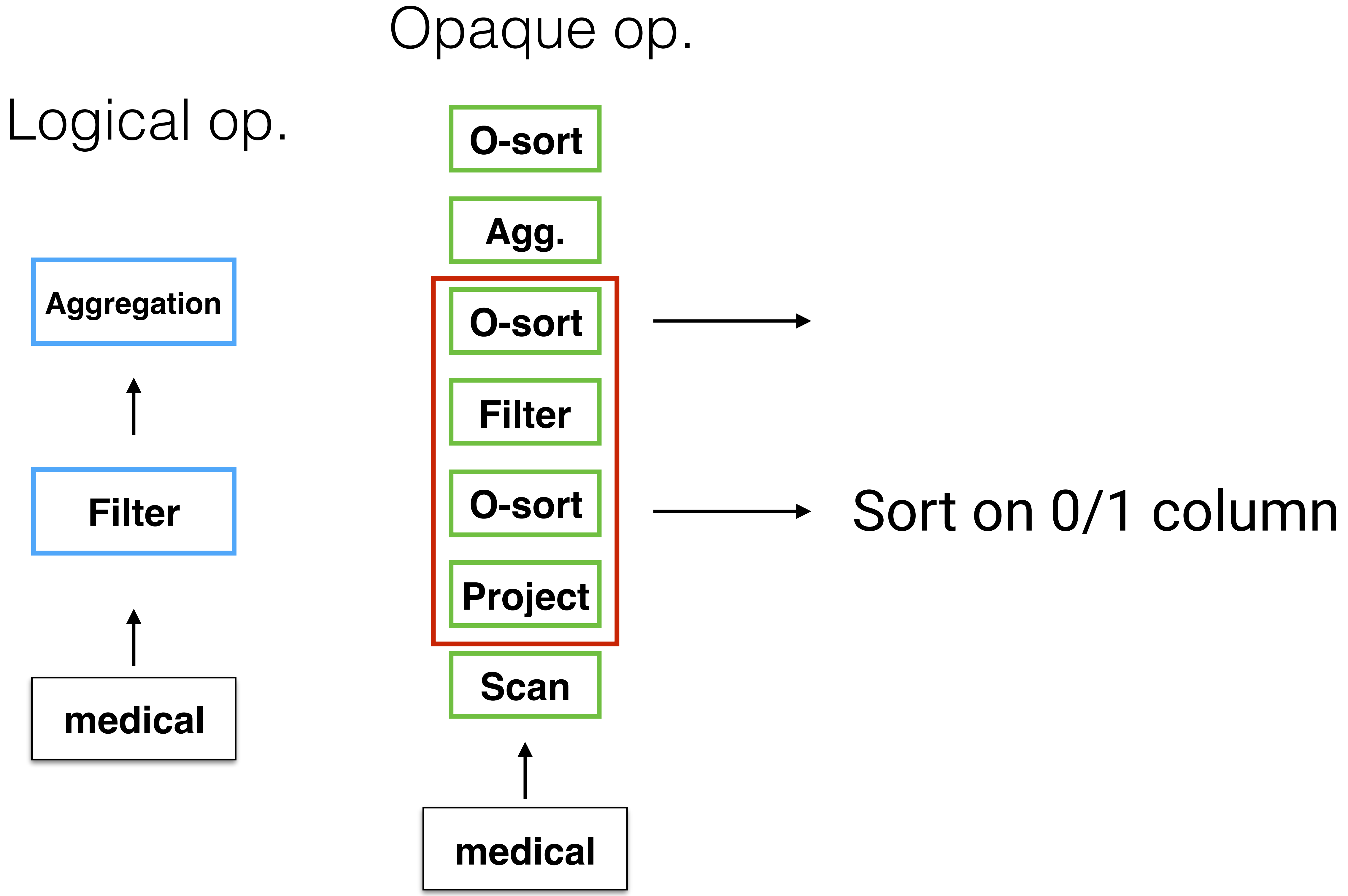
Rule-based optimization



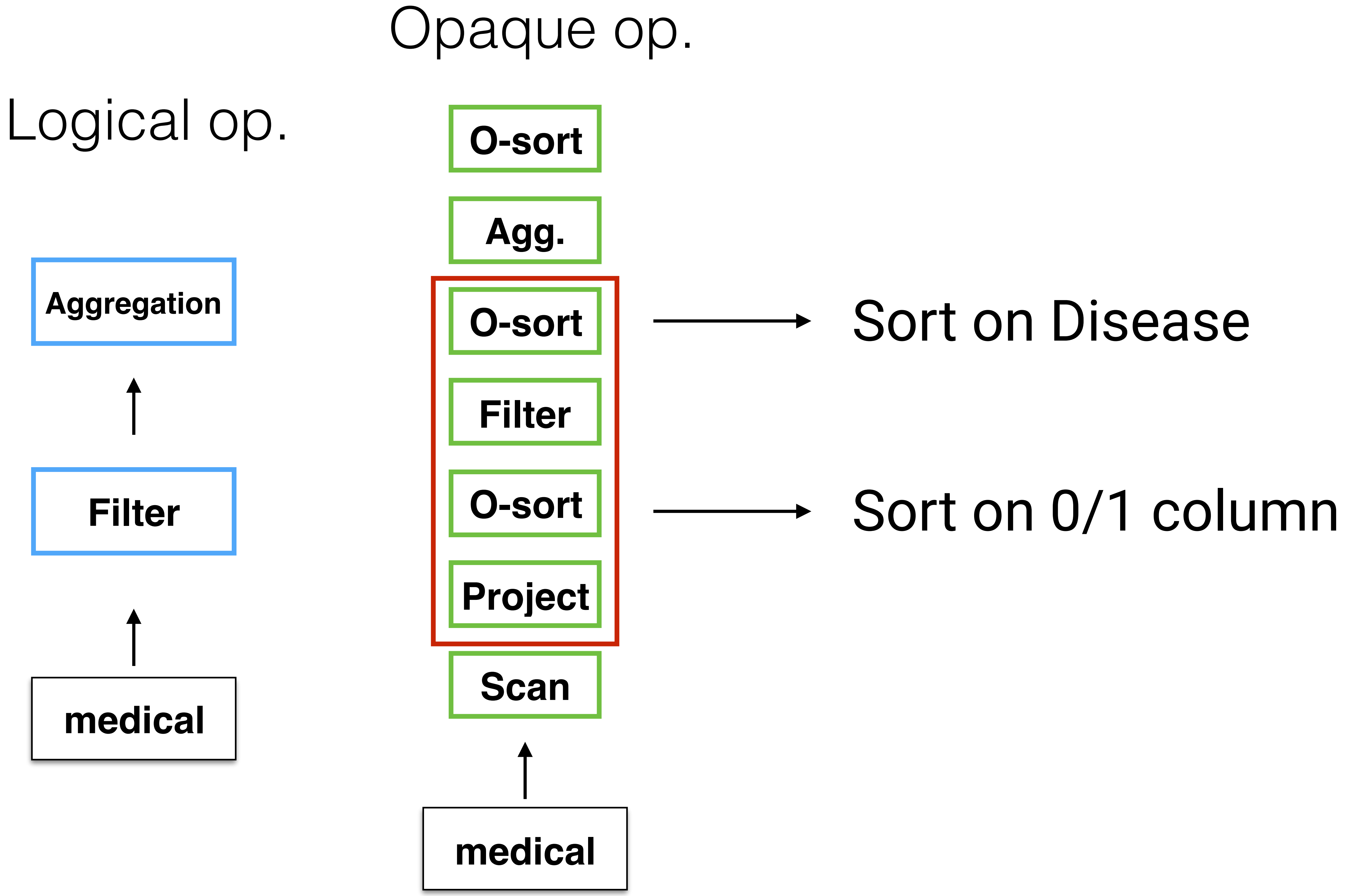
Rule-based optimization



Rule-based optimization



Rule-based optimization



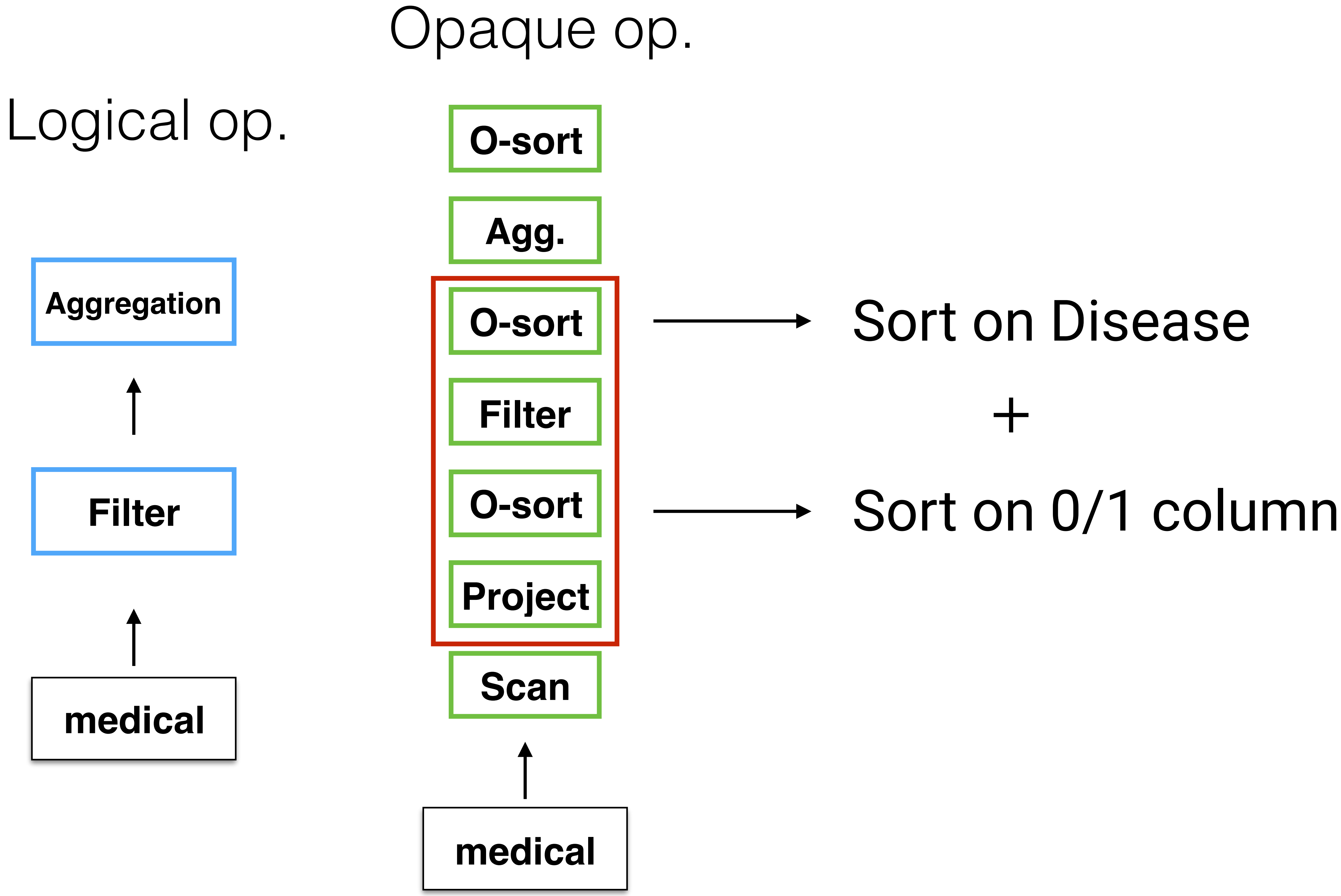
Opaque op.

Logical op.

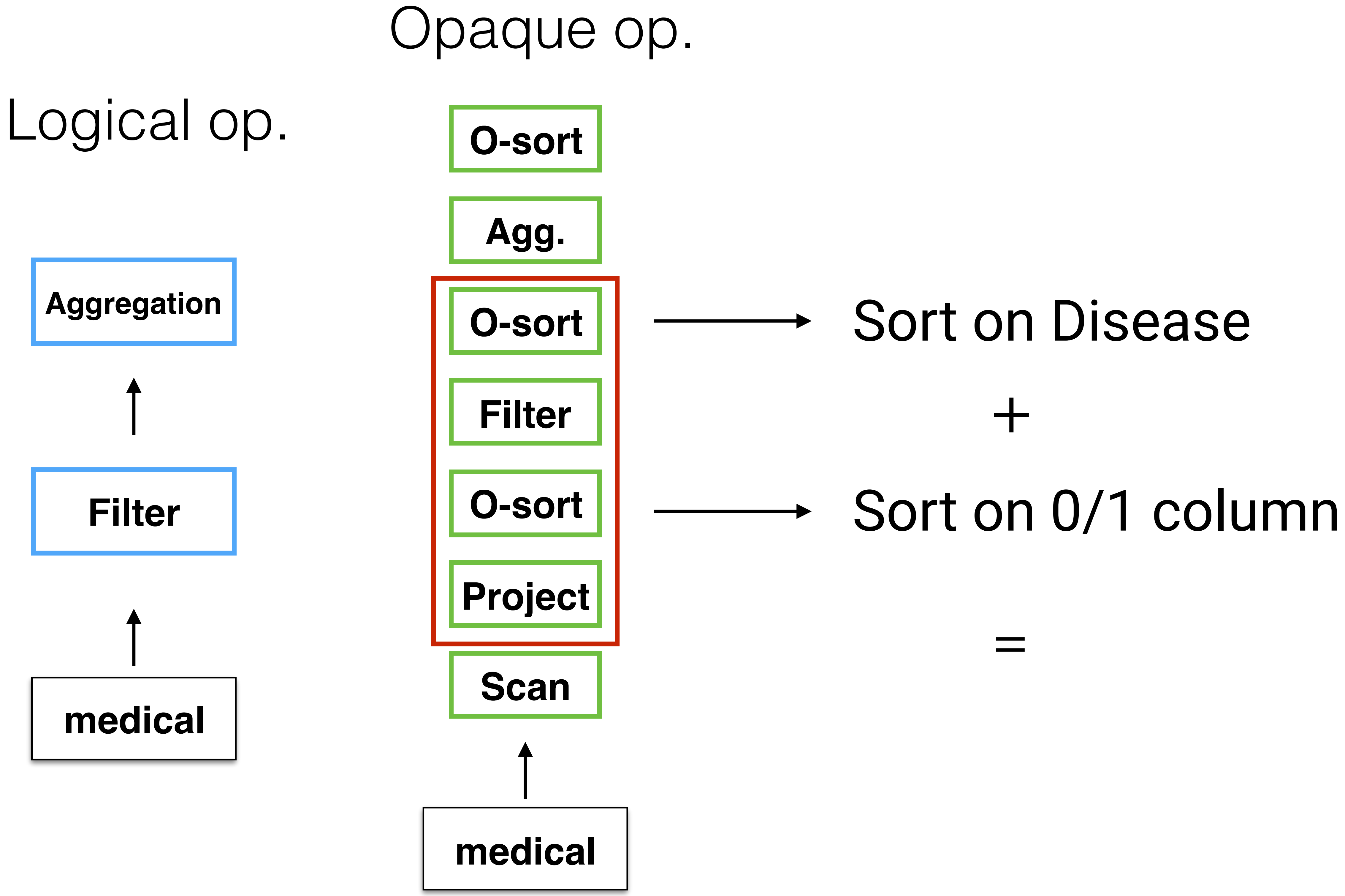
Sort on Disease

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

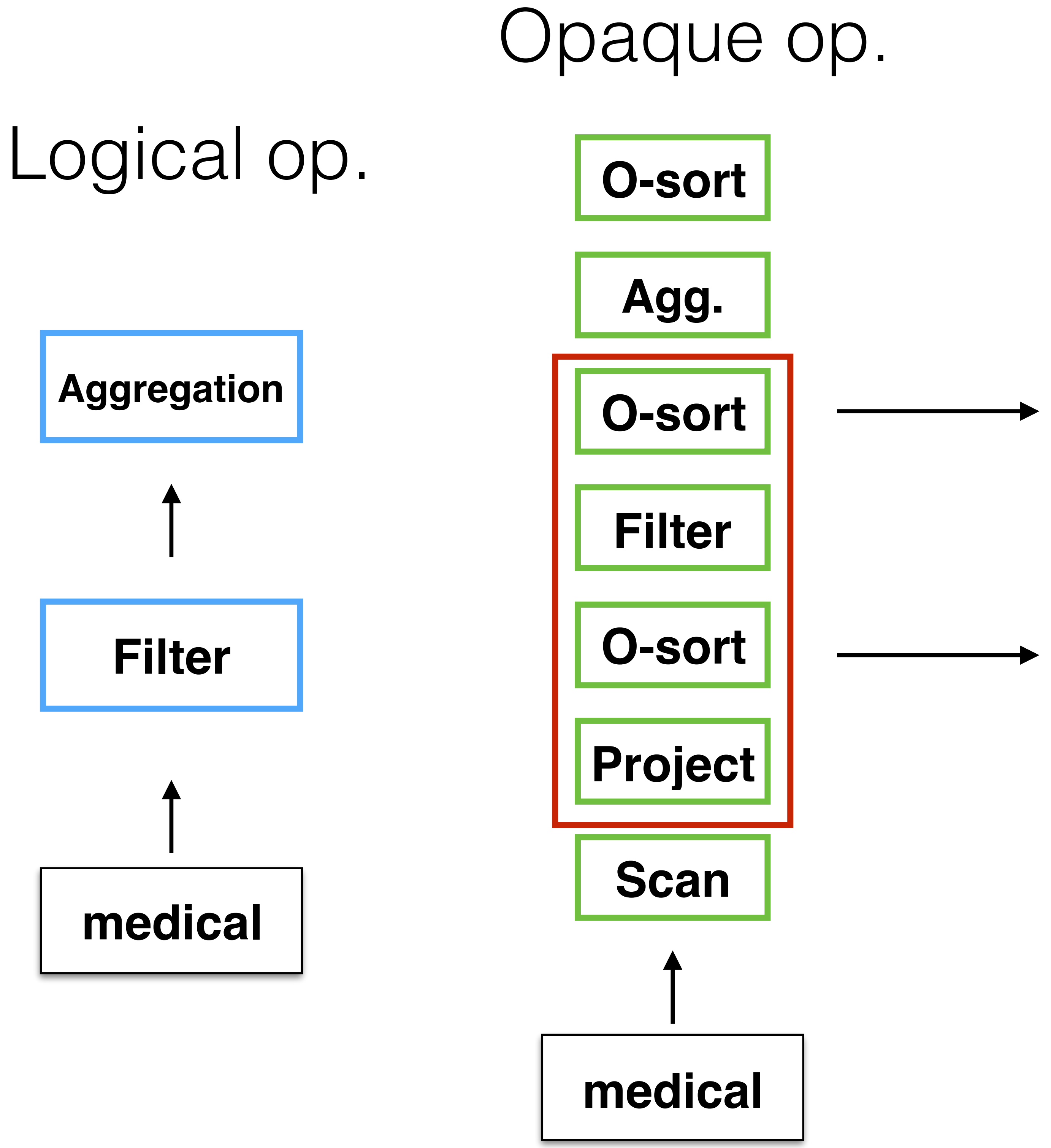
Sort on Disease

+

Sort on 0/1 column

=

Rule-based optimization



Sort on Disease

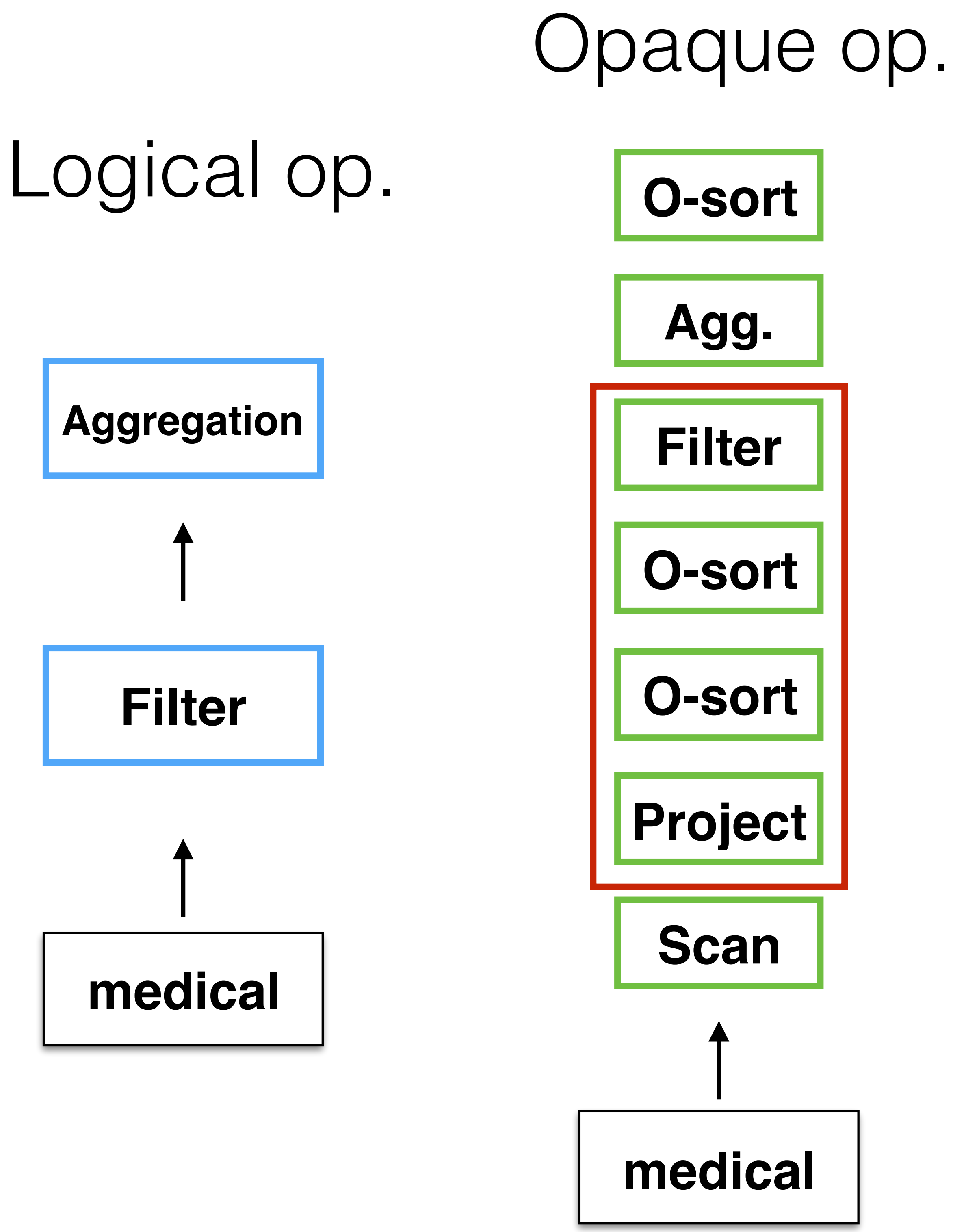
+

Sort on 0/1 column

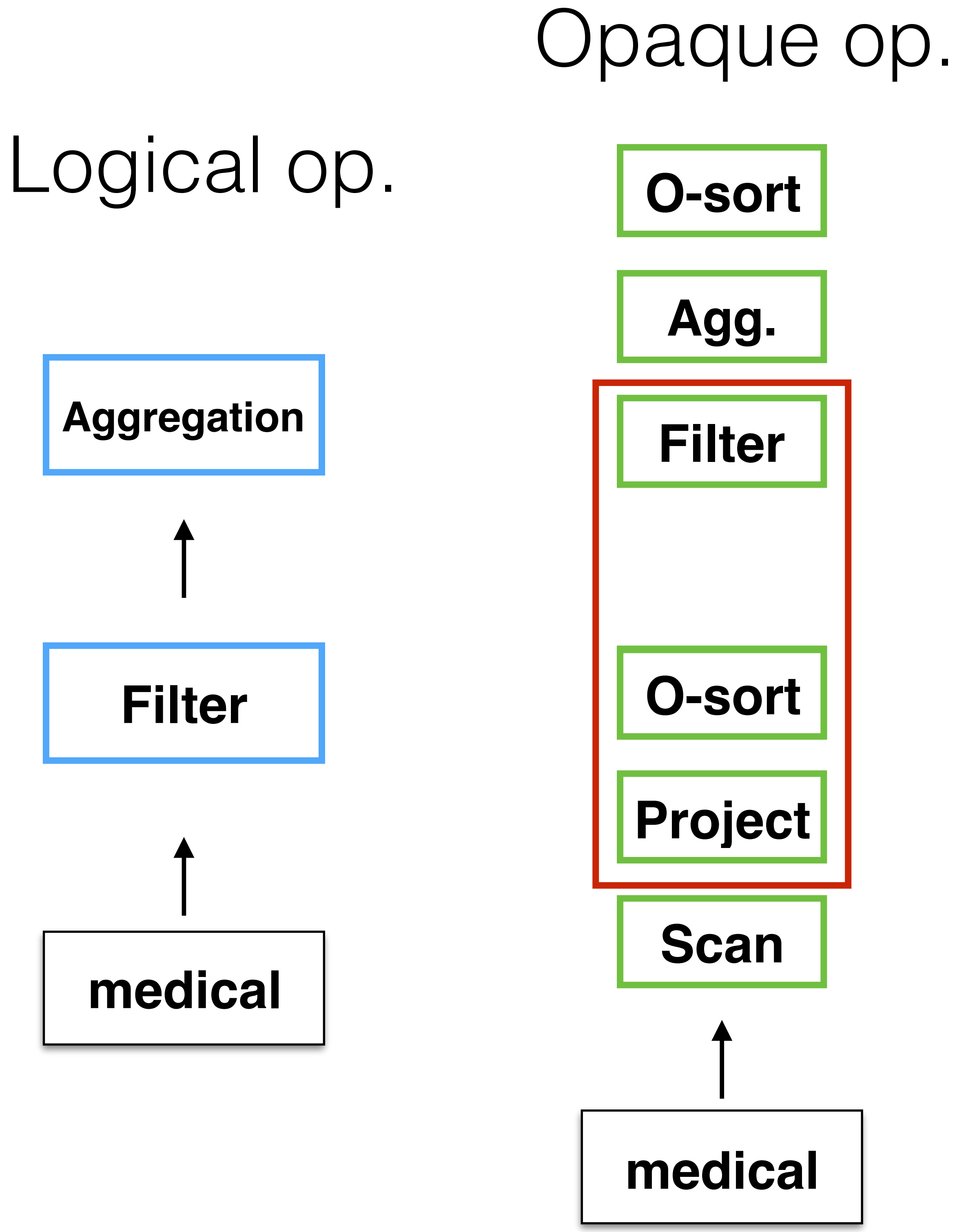
=

Sort on (0/1, Disease)

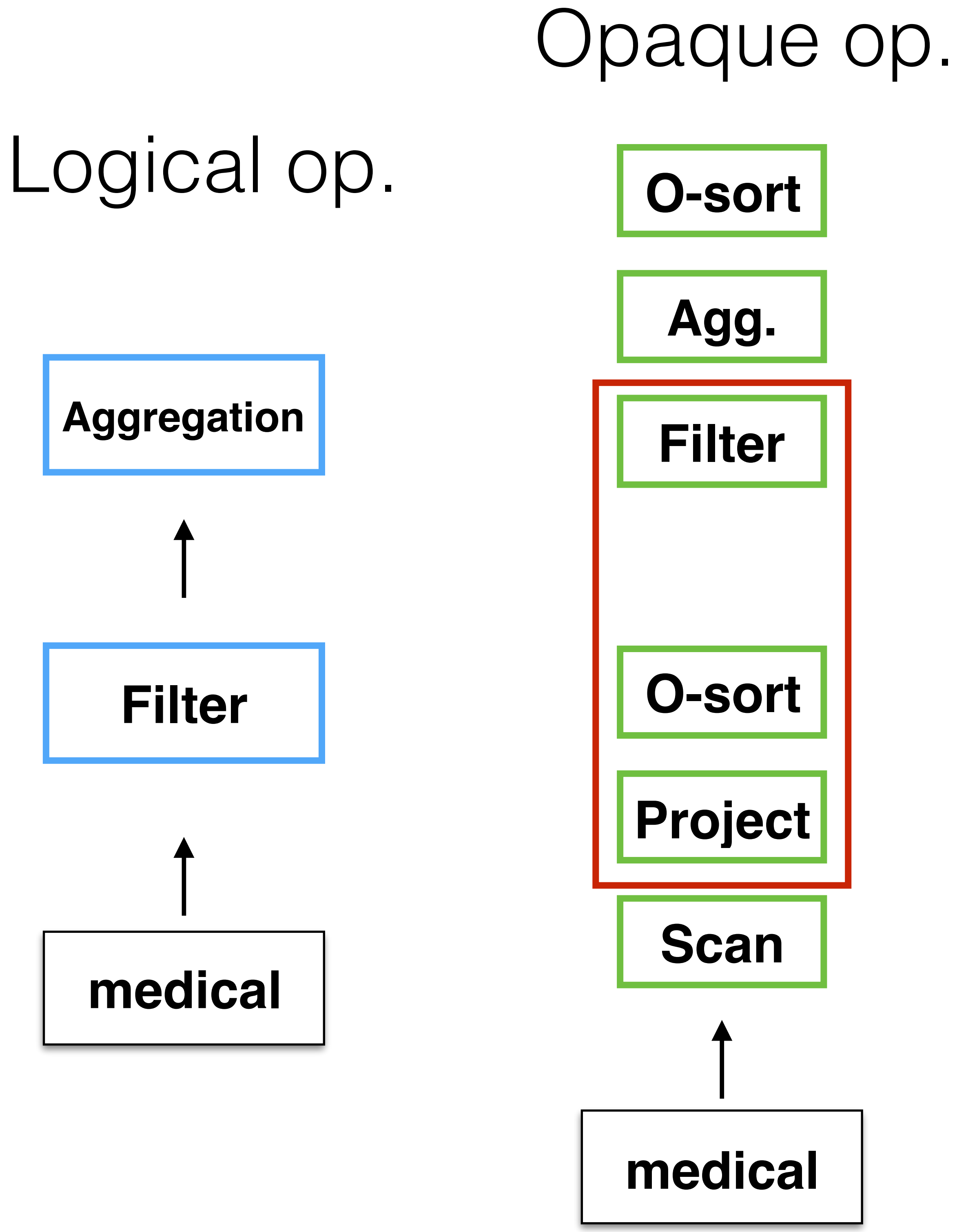
Rule-based optimization



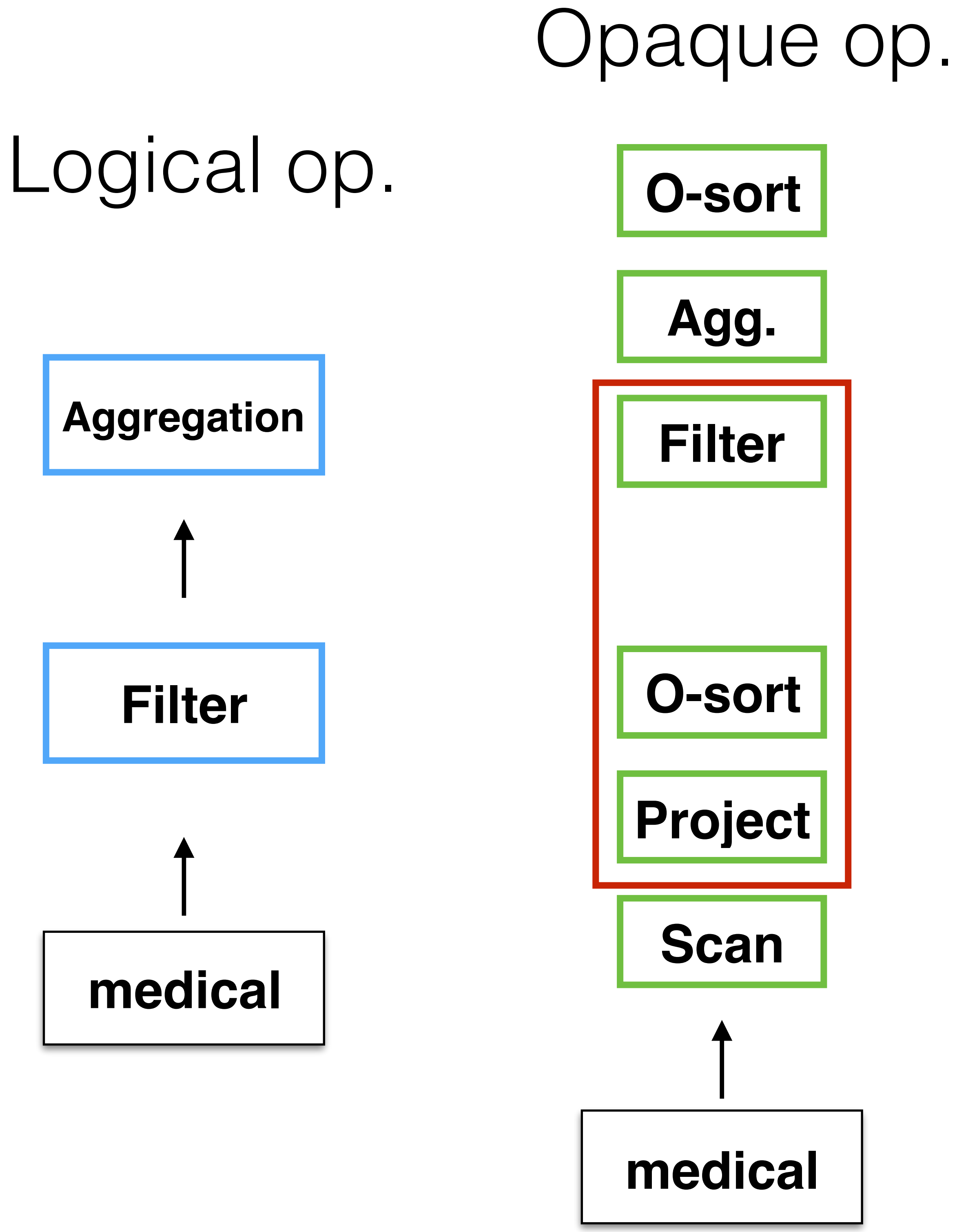
Rule-based optimization



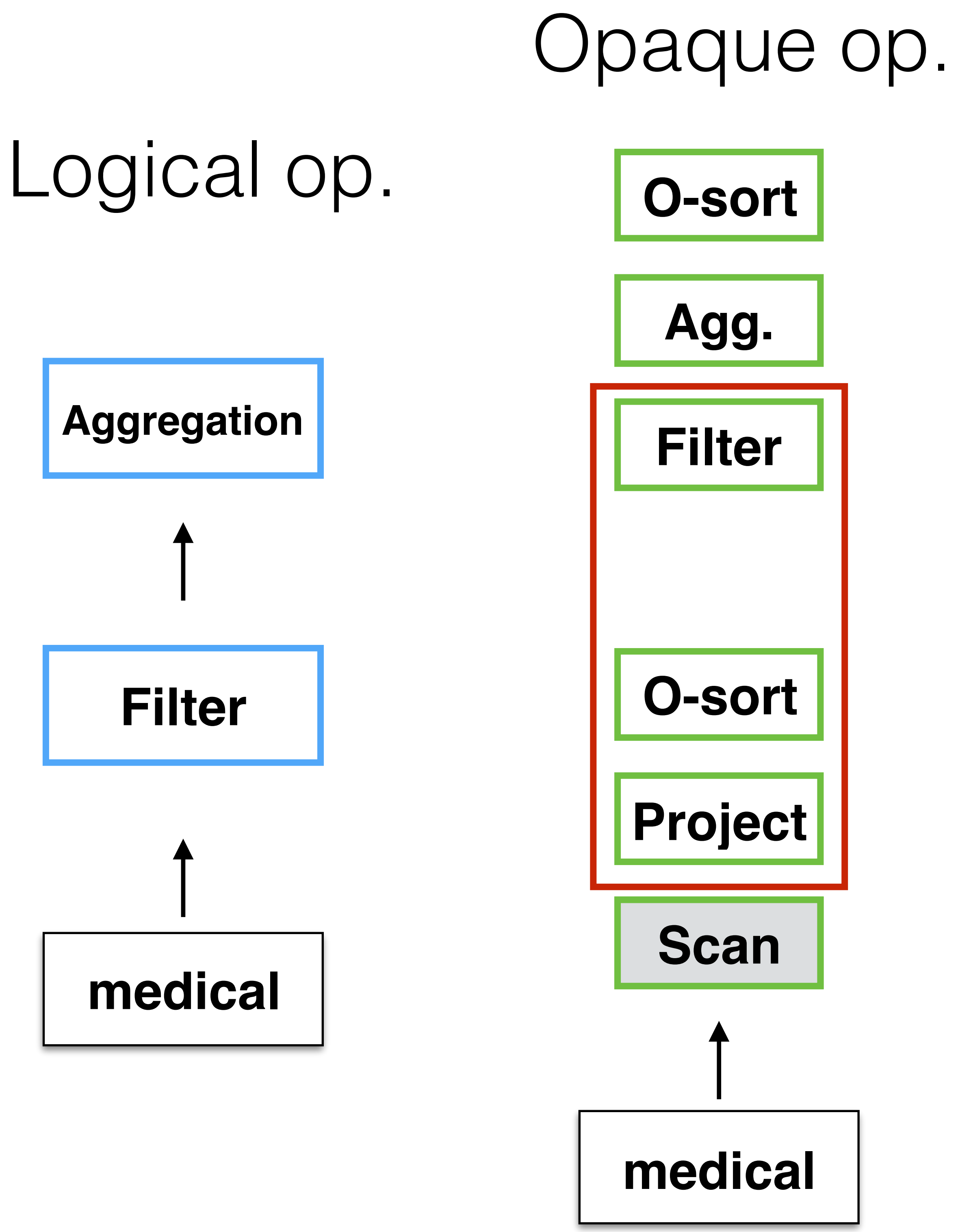
Rule-based optimization



Rule-based optimization



Rule-based optimization



Opaque op.

Logical op.

Aggregation

Filter

medical

O-sort

Agg.

Filter

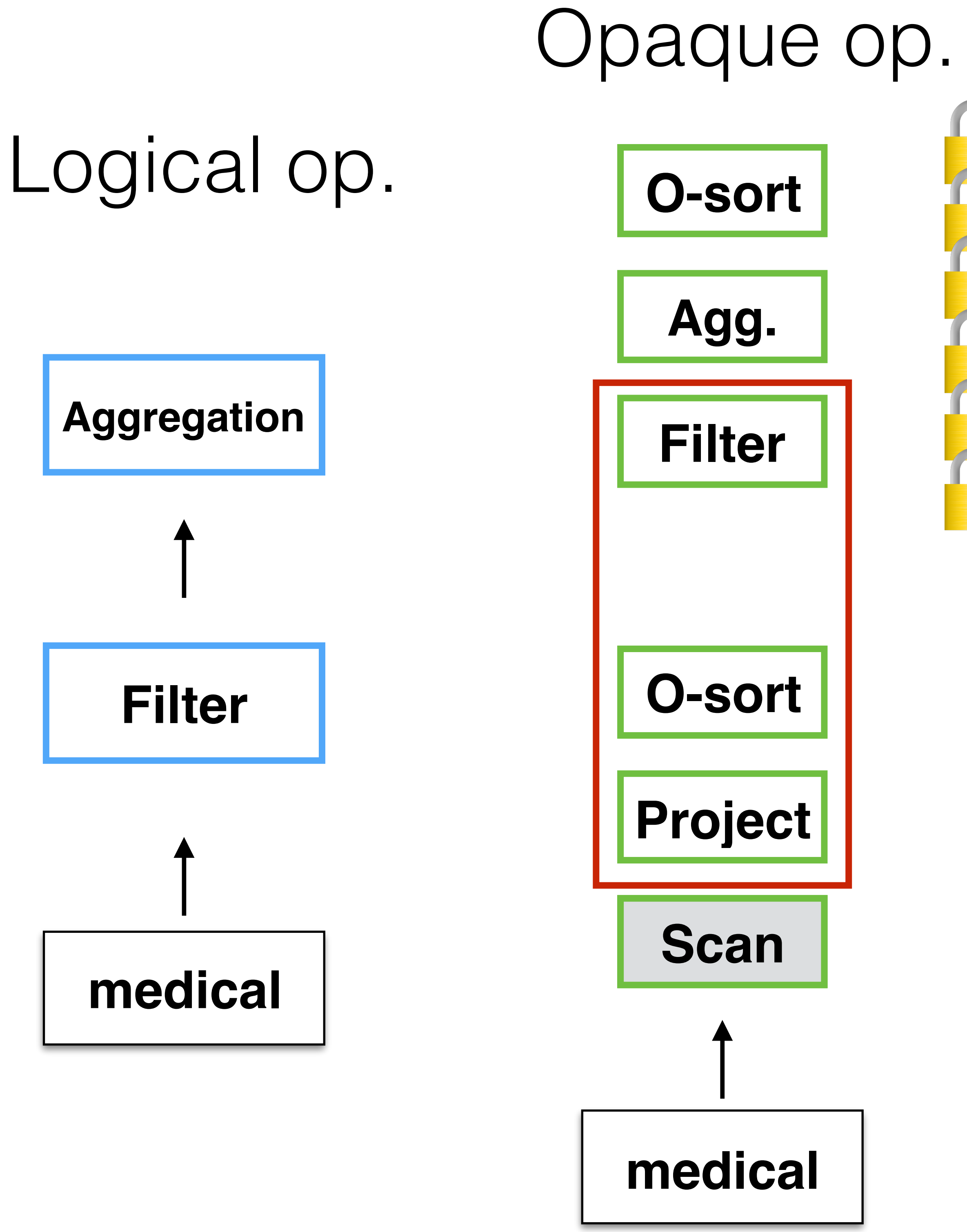
O-sort

Project

Scan

medical

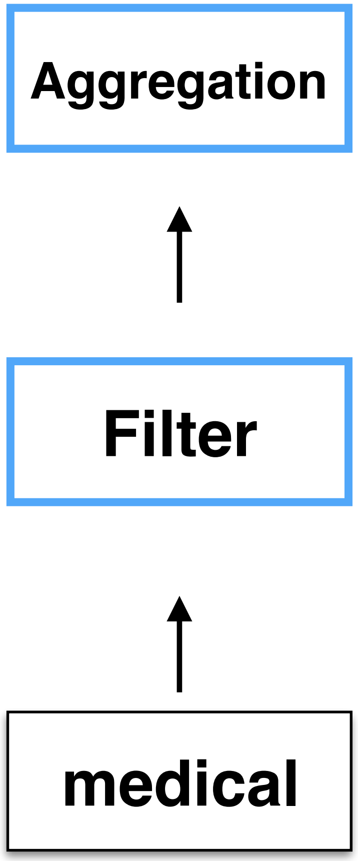
Rule-based optimization



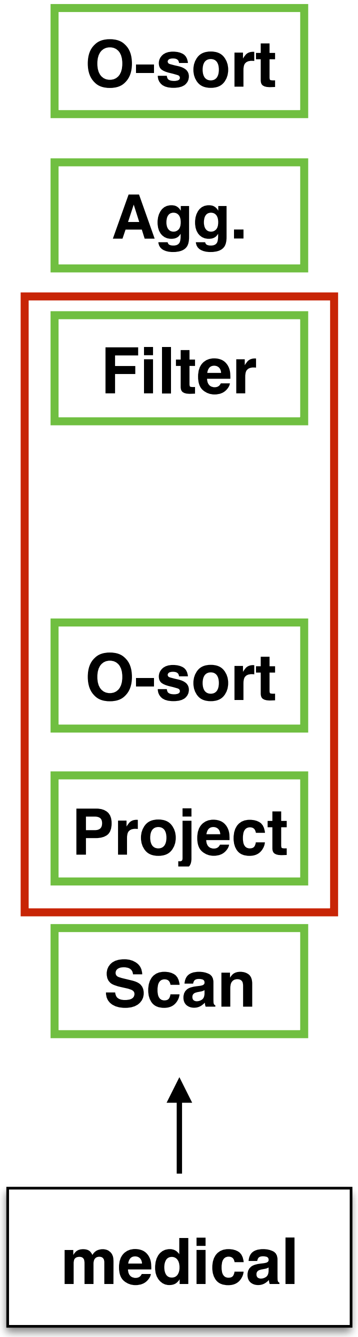
🔒 12809	Amanda D. Edwards	40	Diabetes
🔒 29489	Robert R. McGowan	56	Diabetes
🔒 13744	Kimberly R. Seay	51	Cancer
🔒 18740	Dennis G. Bates	32	Diabetes
🔒 32591	Donna R. Bridges	26	Diabetes
98329	Ronald S. Ogden	53	Cancer

Rule-based optimization

Logical op.



Opaque op.



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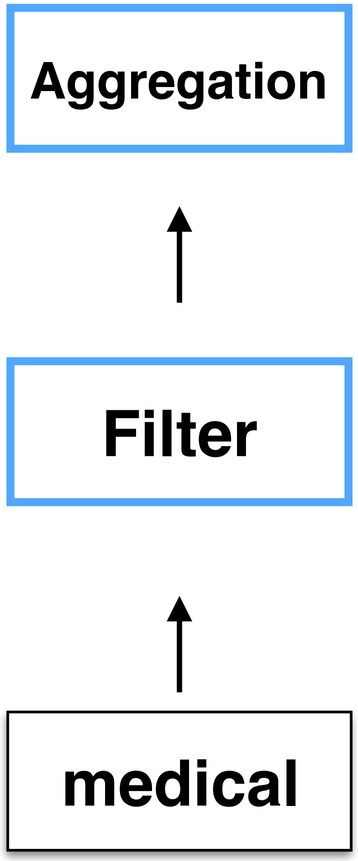
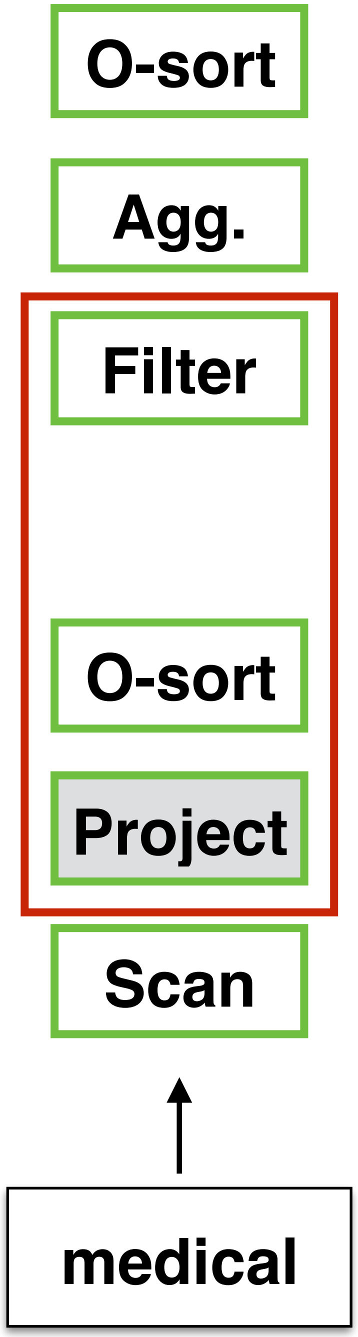
🔒 18740	Dennis G. Bates	32	Diabetes
🔒 32591	Donna R. Bridges	26	Diabetes
98329	Ronald S. Ogden	53	Cancer

Rule-based optimization

Logical op.



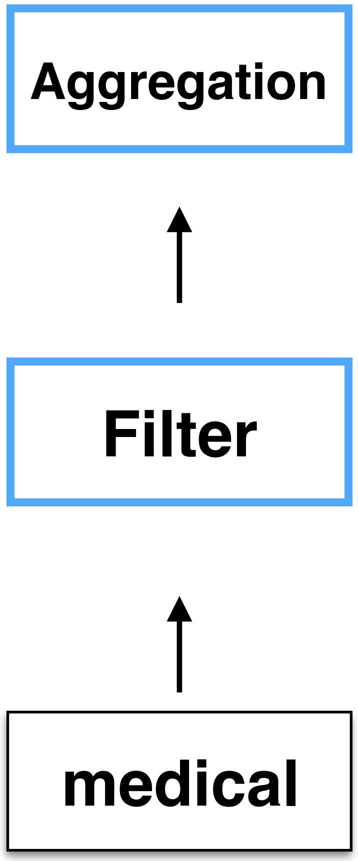
Opaque op.



🔒 12809	Amanda D. Edwards	40	Diabetes
🔒 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

Logical op.

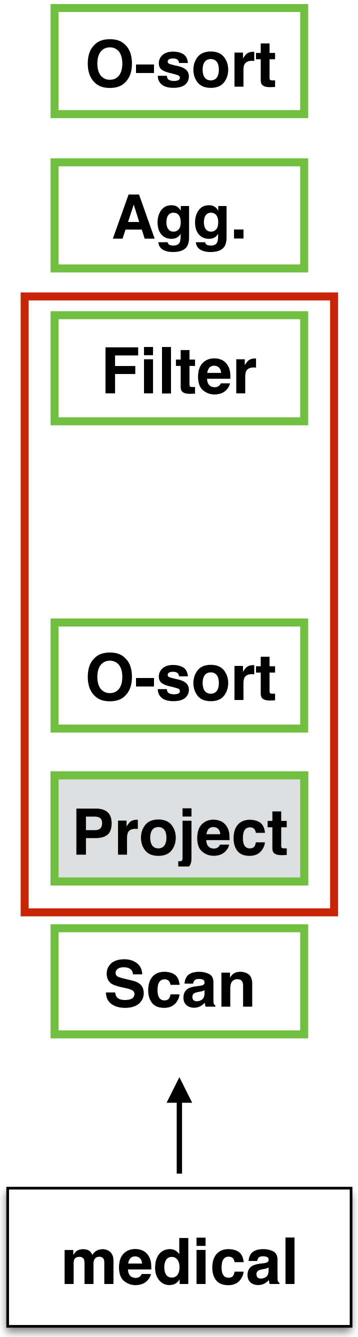


Aggregation

Filter

medical

Opaque op.



O-sort

Agg.

Filter

O-sort

Project

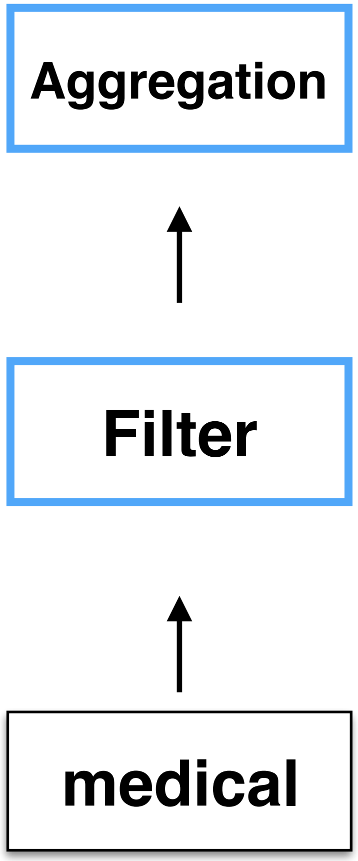
Scan

medical

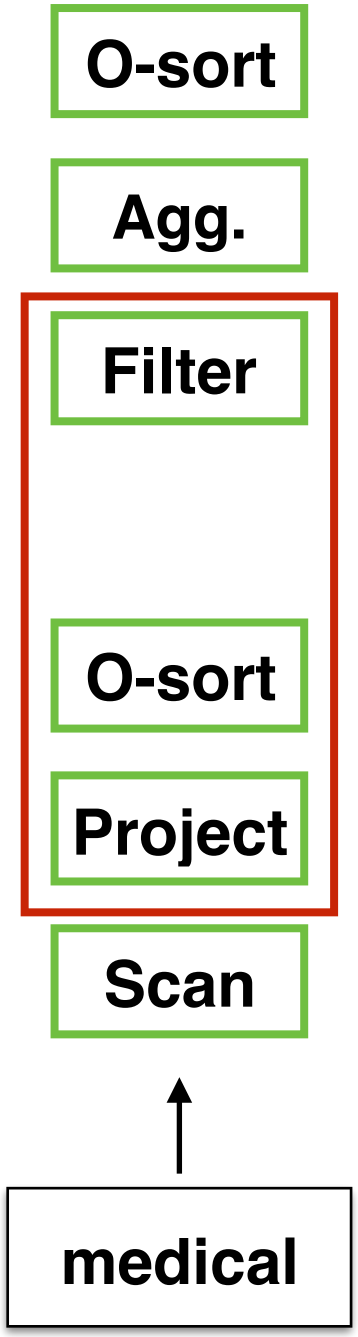
🔒 12809	Amanda D. Edwards	40	Diabetes	0
🔒 29489	Robert R. McGowan	56	Diabetes	0
🔒 13744	Kimberly R. Seay	51	Cancer	0
🔒 18740	Dennis G. Bates	32	Diabetes	0
🔒 32591	Donna R. Bridges	26	Diabetes	1
98329	Ronald S. Ogden	53	Cancer	0

Rule-based optimization

Logical op.



Opaque op.



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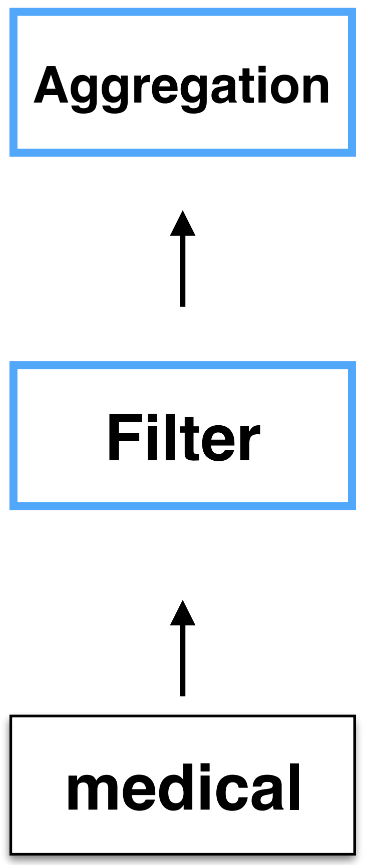
🔒 13744	Kimberly R. Seay	51	Cancer	0
🔒 18740	Dennis G. Bates	32	Diabetes	0
🔒 32591	Donna R. Bridges	26	Diabetes	1
98329	Ronald S. Ogden	53	Cancer	0

Rule-based optimization

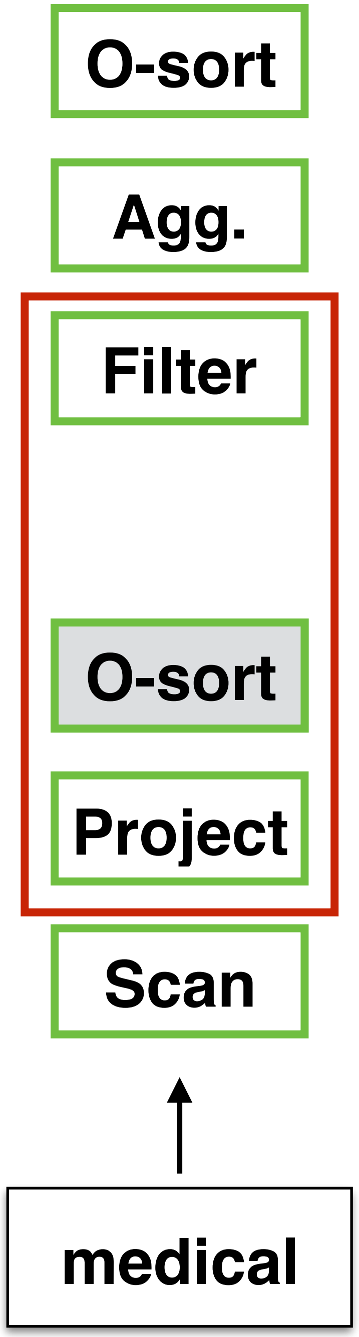
Opaque op.

Logical op.


Aggregation

Filter

medical


O-sort

Agg.

Filter

O-sort

Project

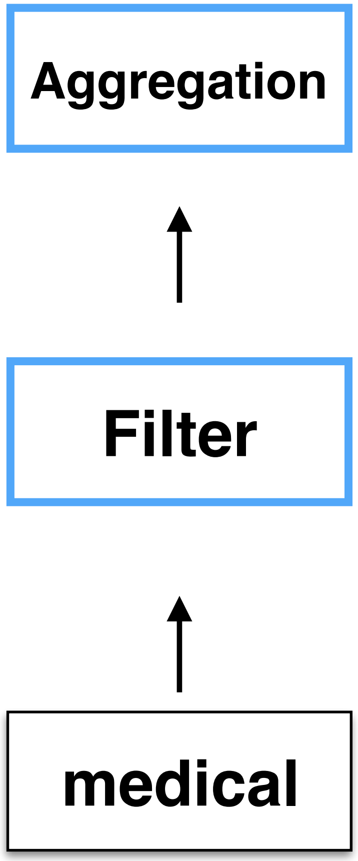
Scan

medical

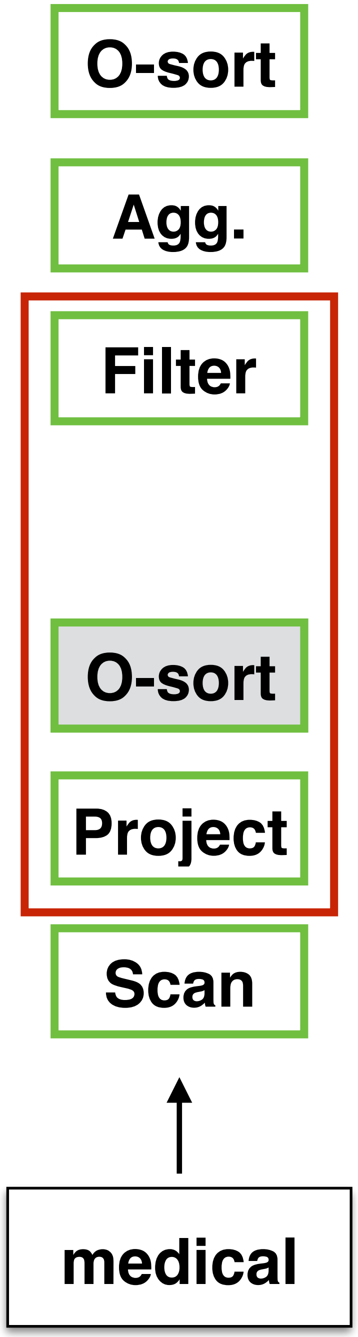
12809	Amanda D. Edwards	40	Diabetes	0
29489	Robert R. McGowan	56	Diabetes	0
13744	Kimberly R. Seay	51	Cancer	0
18740	Dennis G. Bates	32	Diabetes	0
32591	Donna R. Bridges	26	Diabetes	1
98329	Ronald S. Ogden	53	Cancer	0

Rule-based optimization

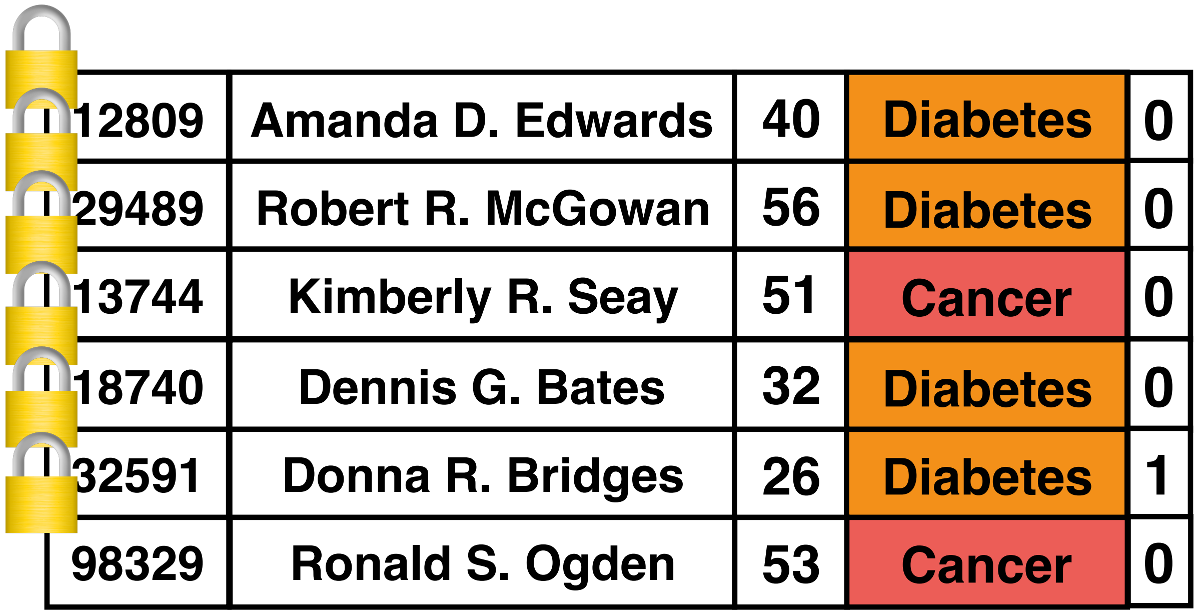
Logical op.



Opaque op.

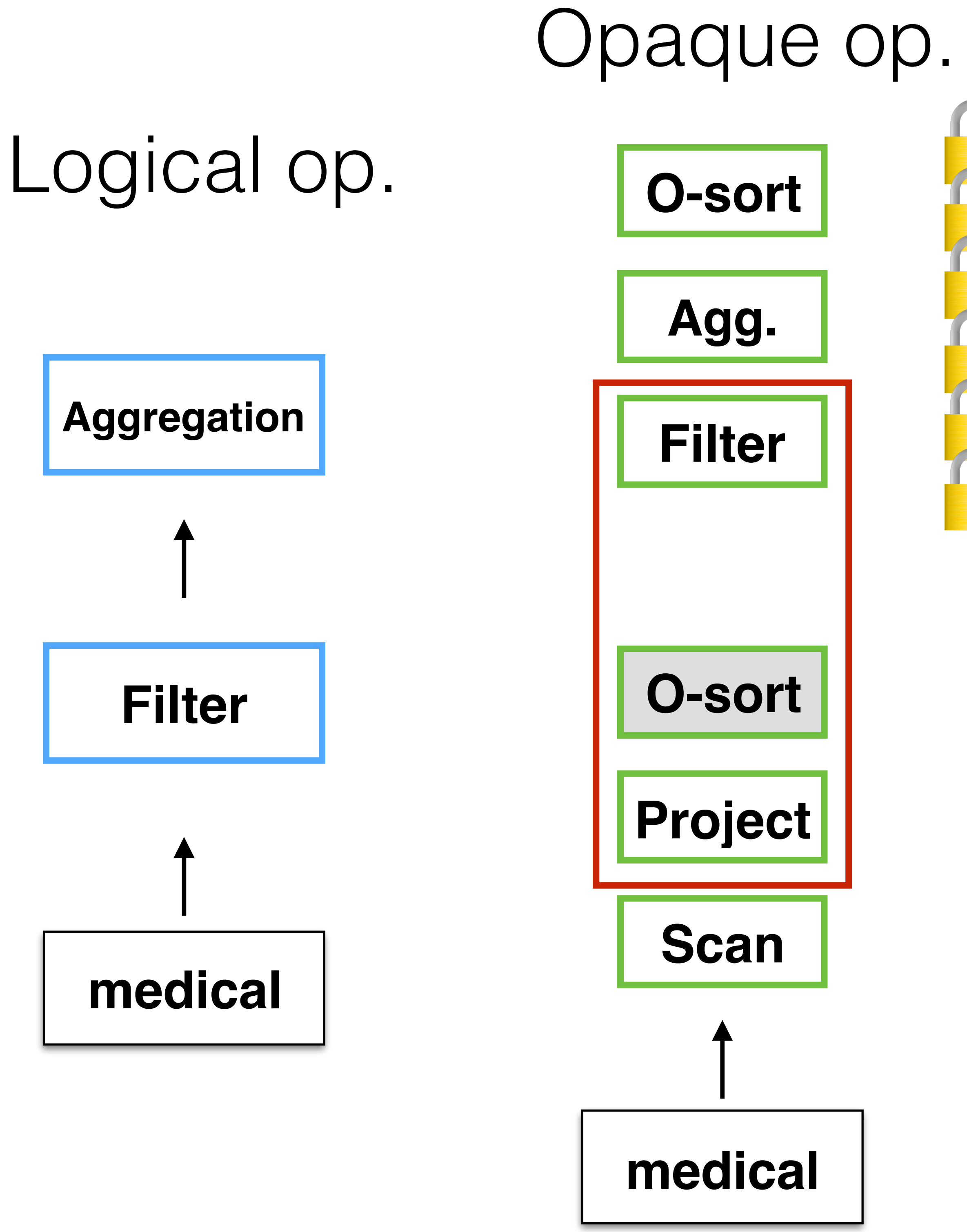


multi-column sort



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.

Aggregation

Filter

medical

Opaque op.

O-sort

Agg.

Filter

O-sort

Project

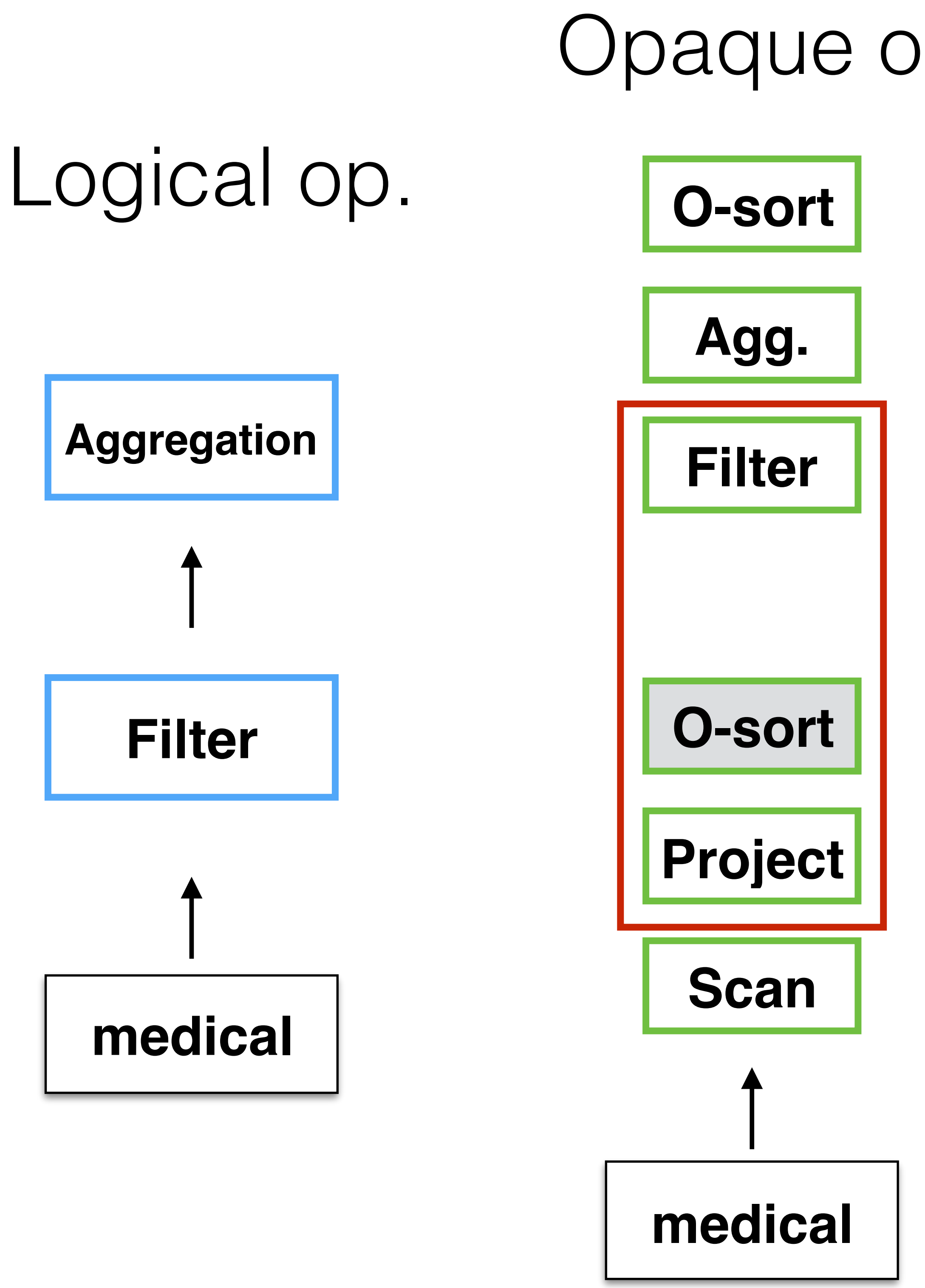
Scan

medical

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



multi-column sort

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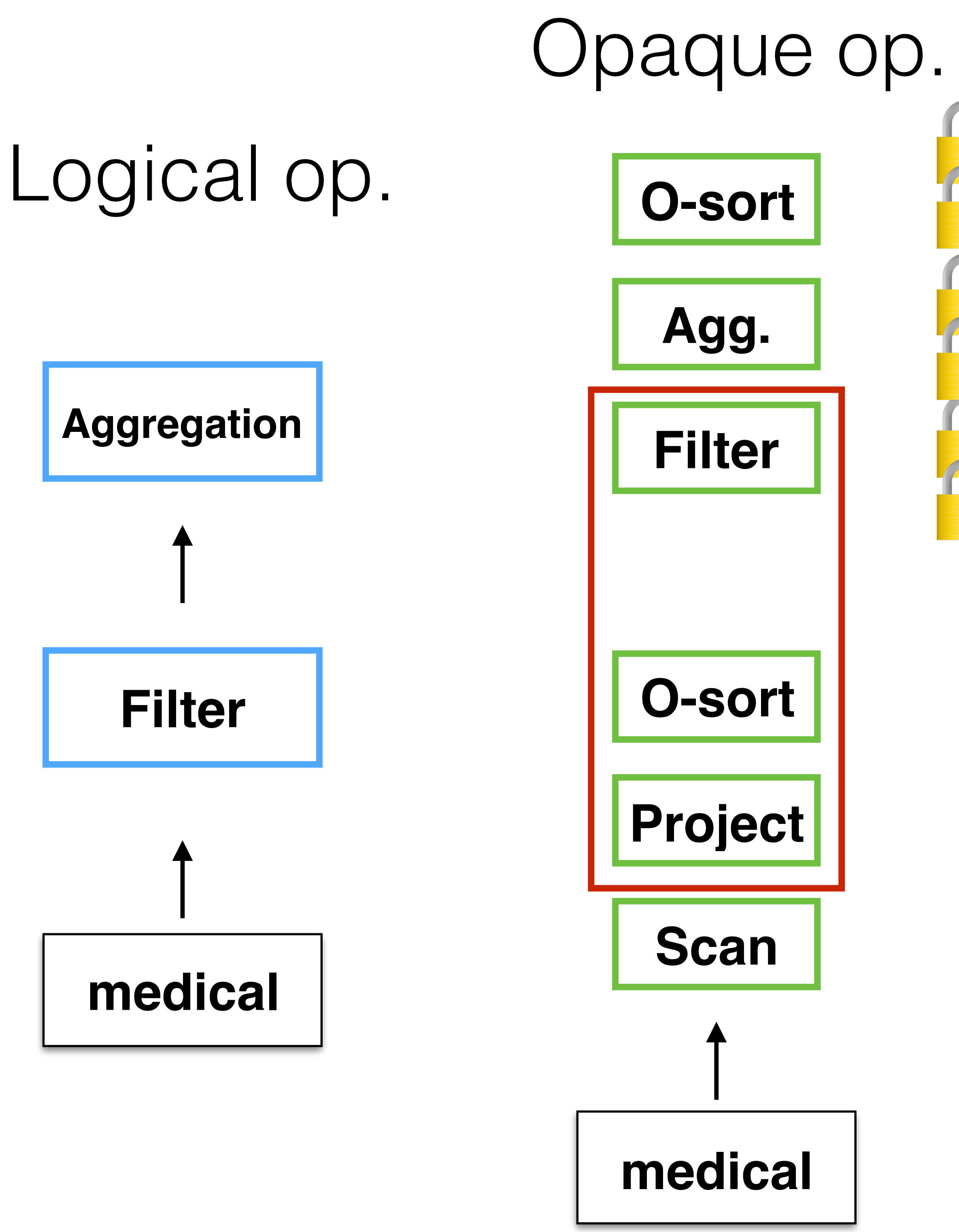
29489	Robert R. McGowan	56	Diabetes	0
32591	Donna R. Bridges	26	Diabetes	1

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
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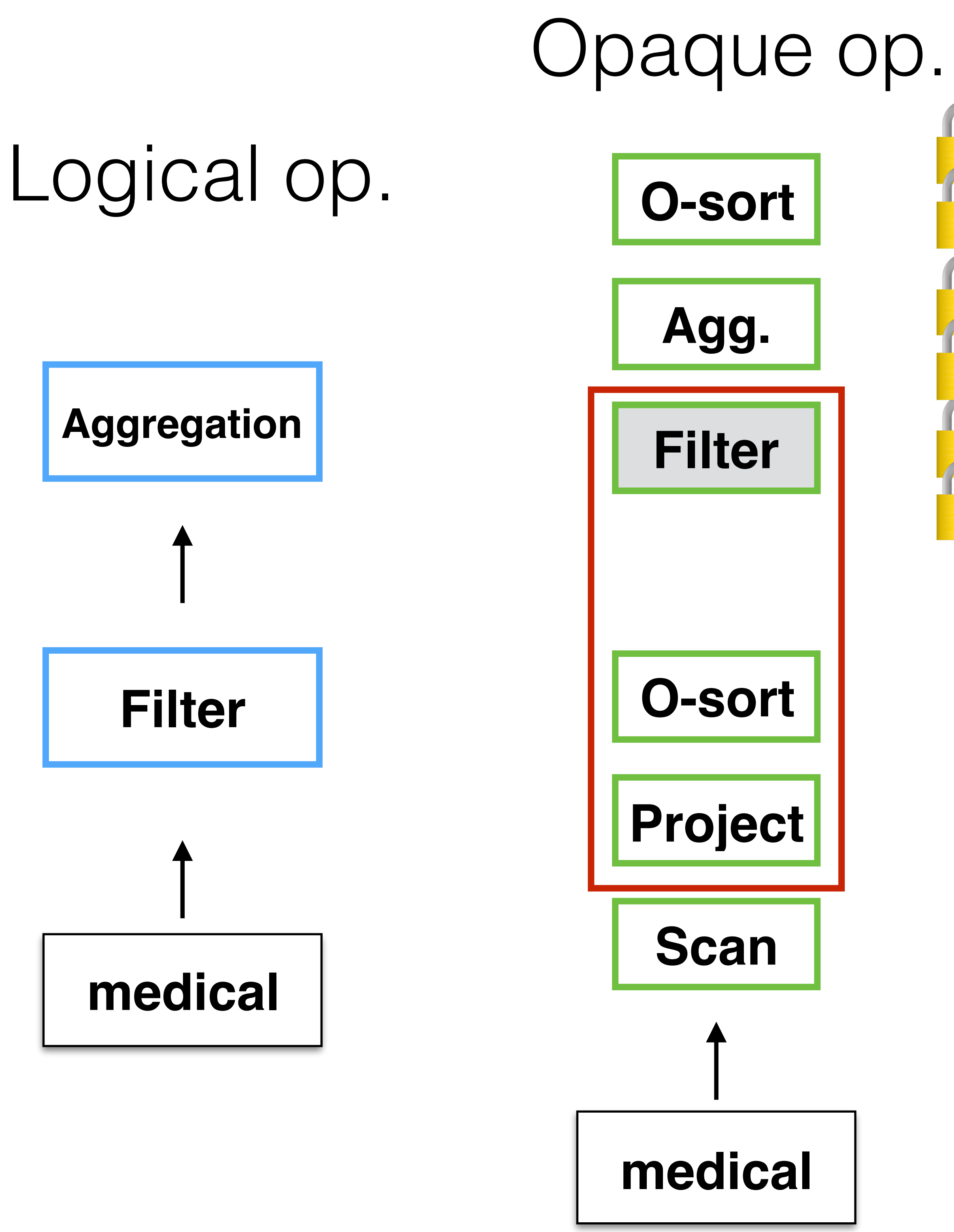
Rule-based optimization



multi-column sort

13744	Kimberly R. Seay	51	Cancer	0
98329	Ronald S. Ogden	53	Cancer	0
12809	Amanda D. Edwards	40	Diabetes	0
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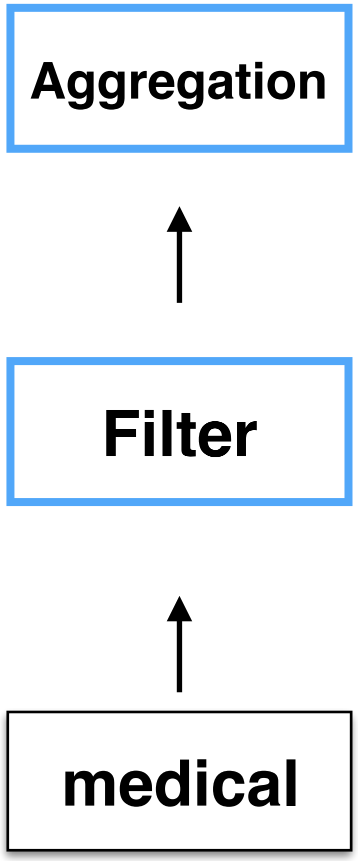
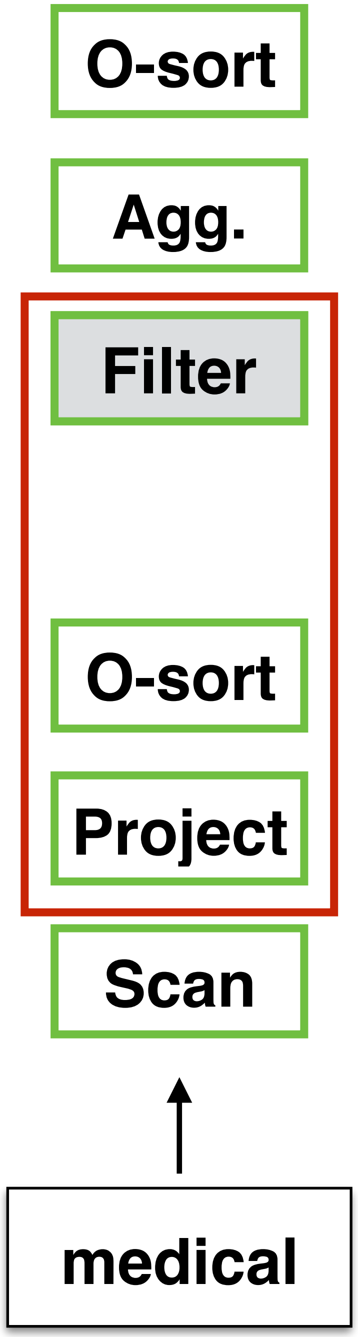
32591	Donna R. Bridges	26	Diabetes	1

Rule-based optimization

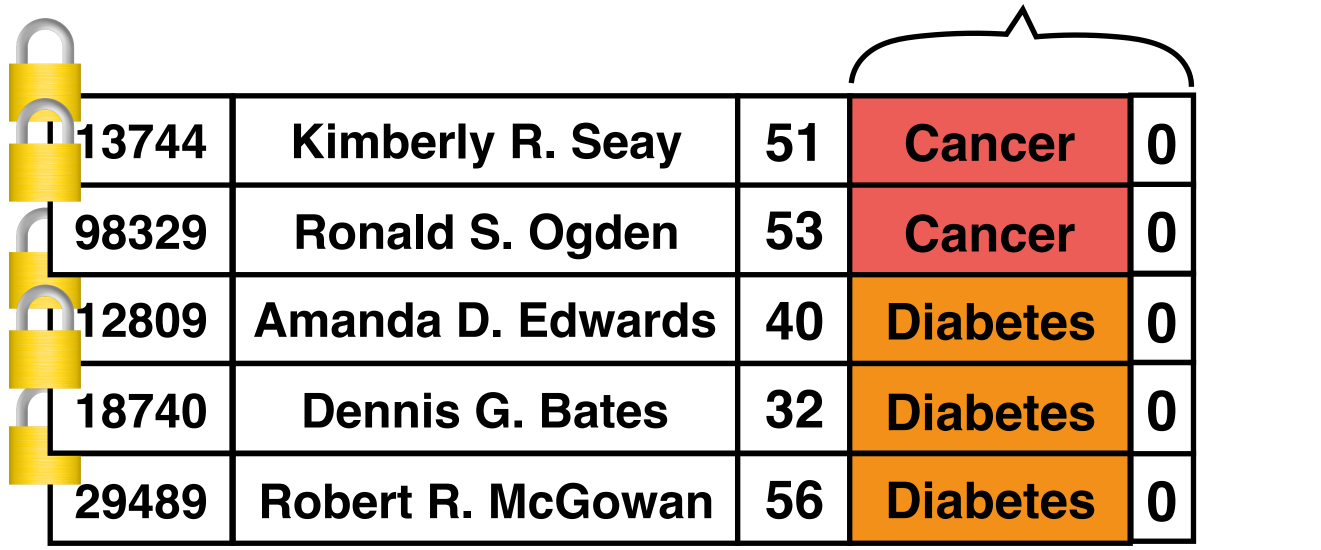
Logical op.



Opaque op.



multi-column sort



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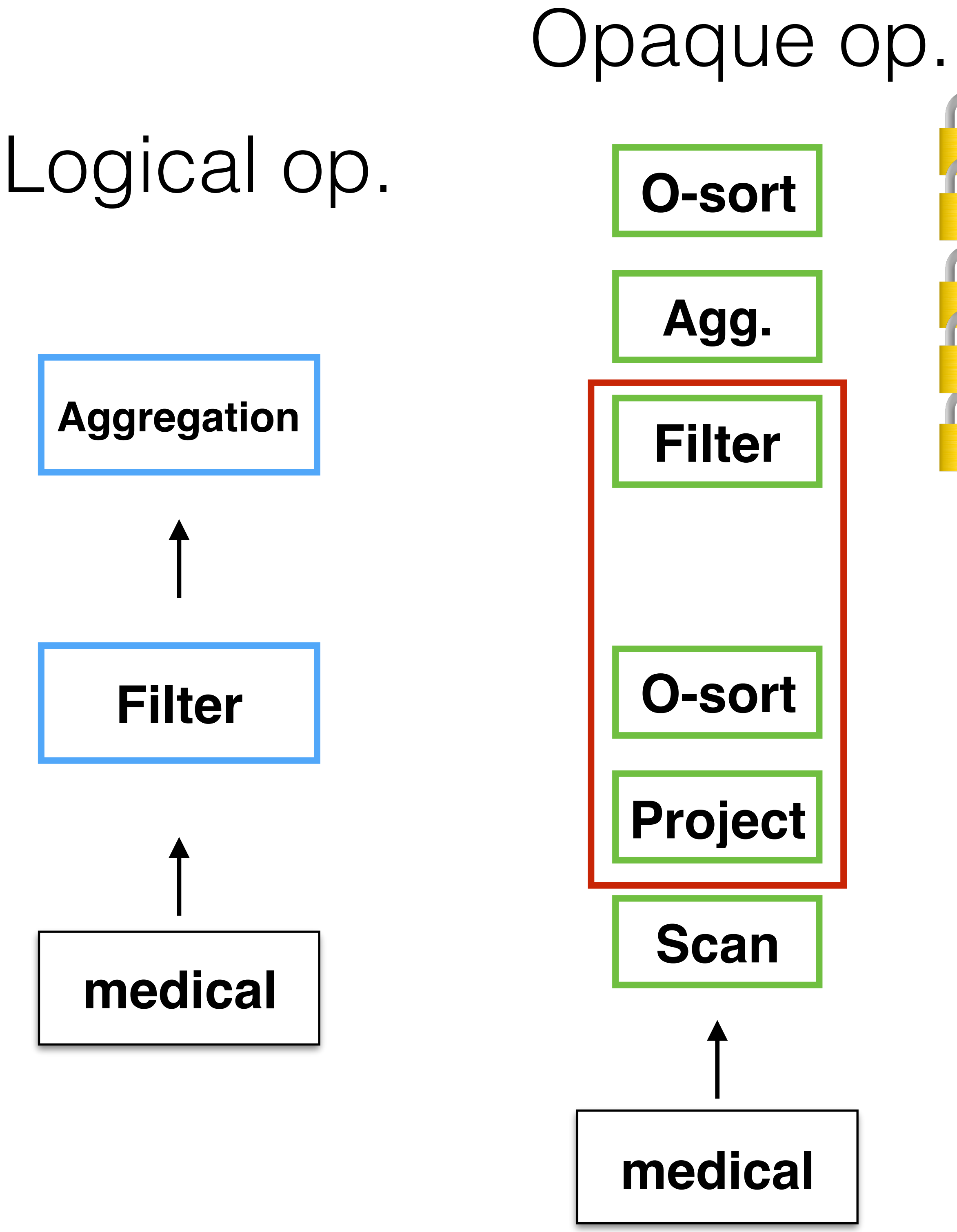
29489	Robert R. McGowan	56	Diabetes	0

Rule-based optimization



multi-column sort

13744	Kimberly R. Seay	51	Cancer	0
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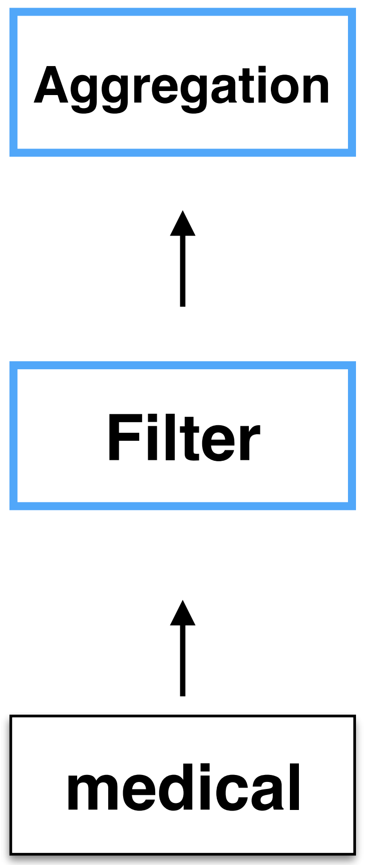
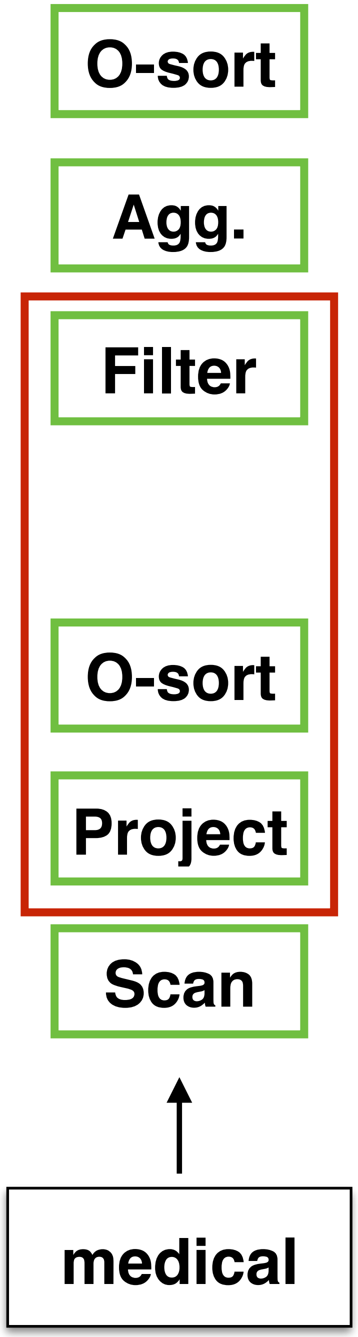
Rule-based optimization

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

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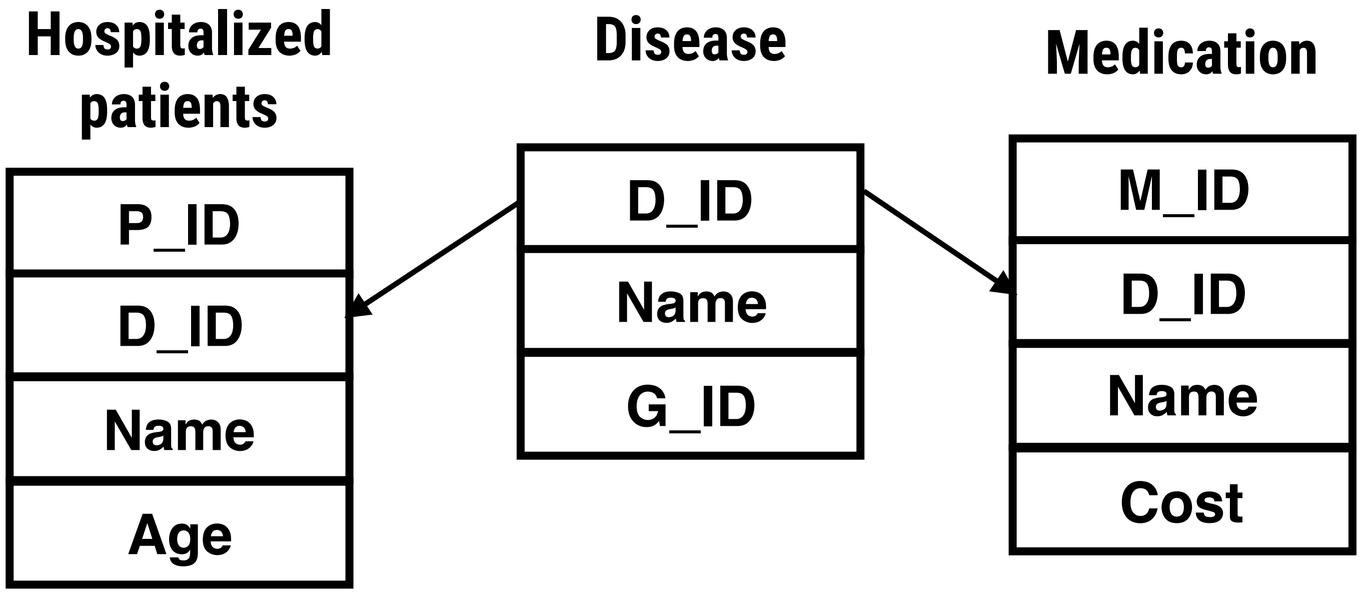


Hospitalized patients

P_ID

D_ID

Name

Age

Disease

D_ID

Name

G_ID

Medication

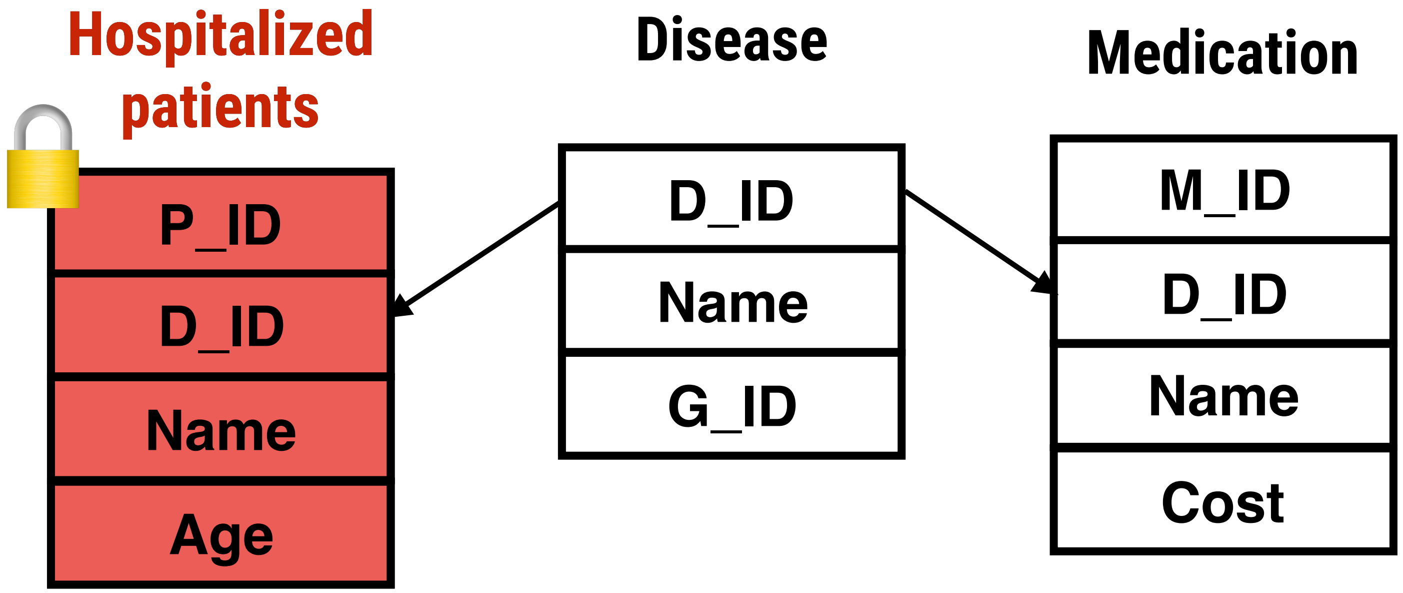
M_ID

D_ID

Name

Cost

Observation: not all tables are sensitive



Hospitalized patients

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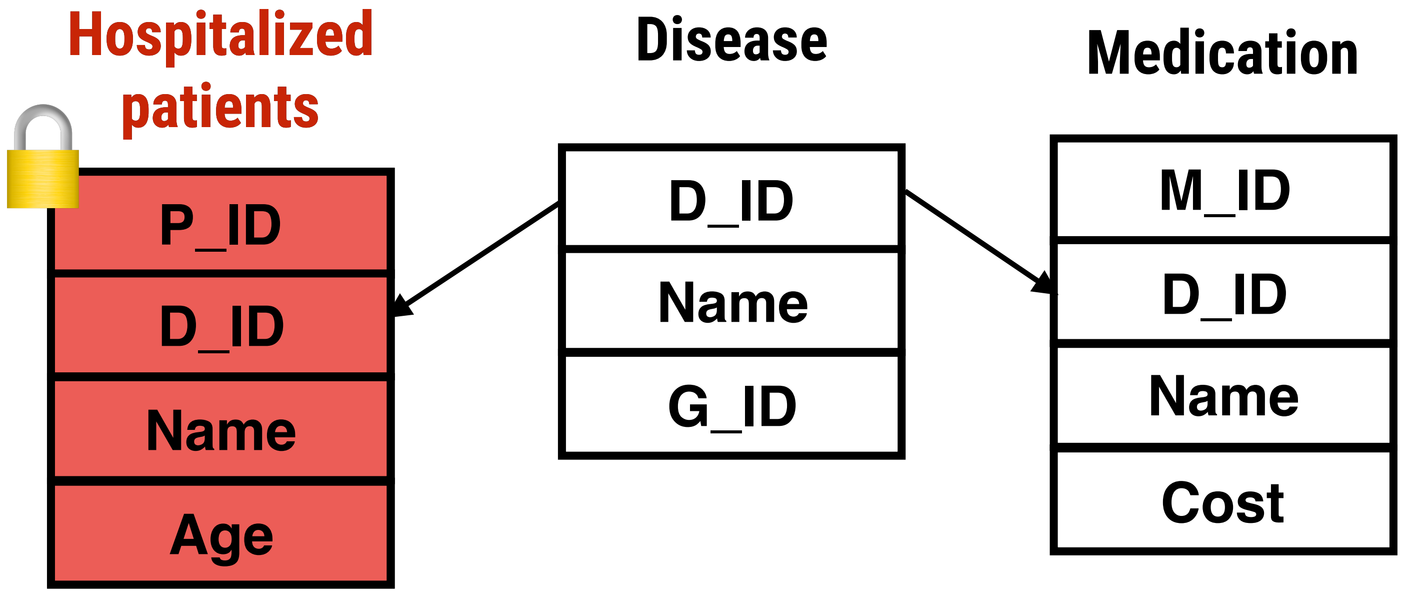
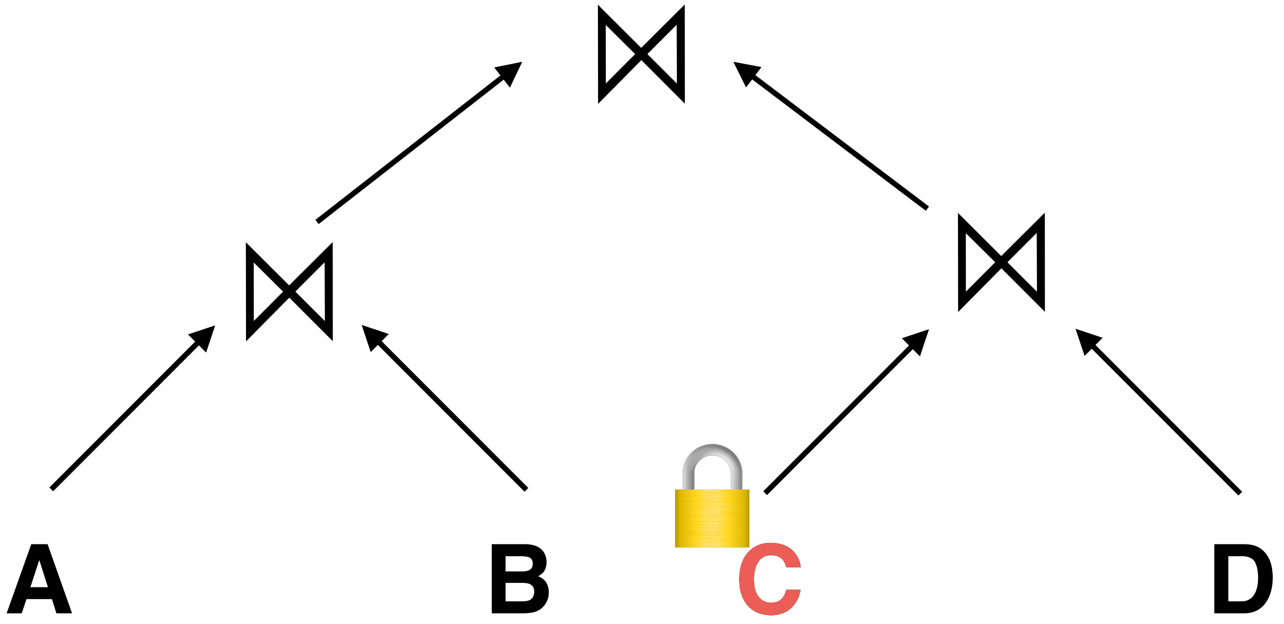
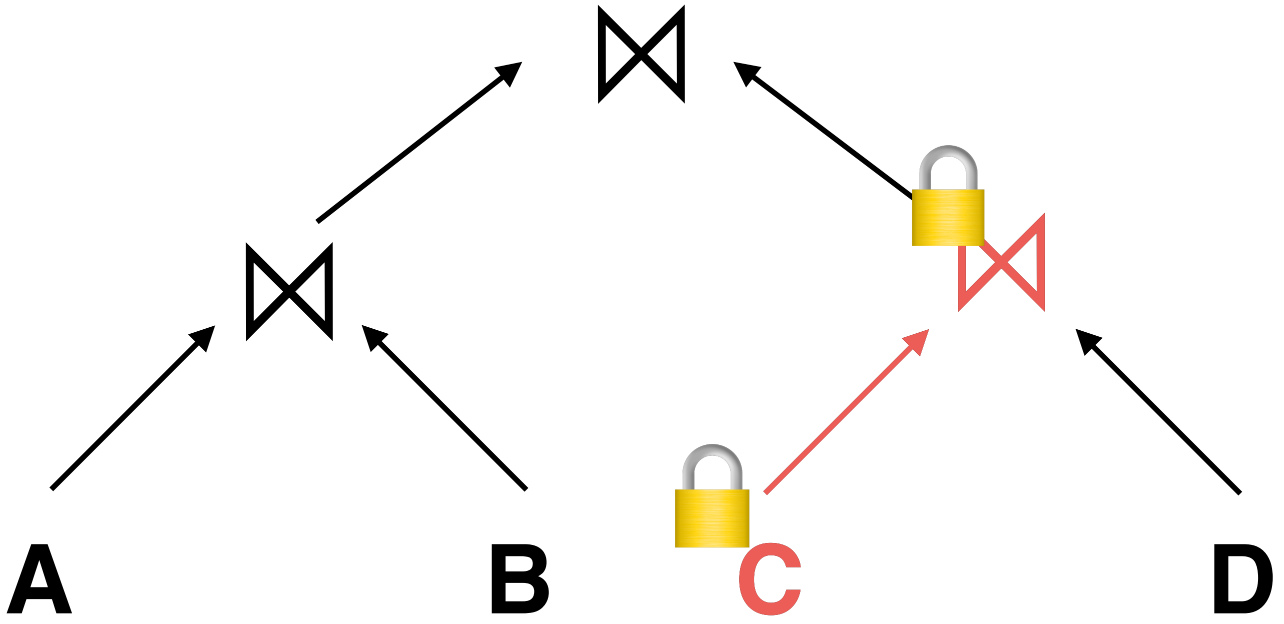


Opaque can operate in *mixed sensitivity*:
sensitive tables are run with oblivious operators

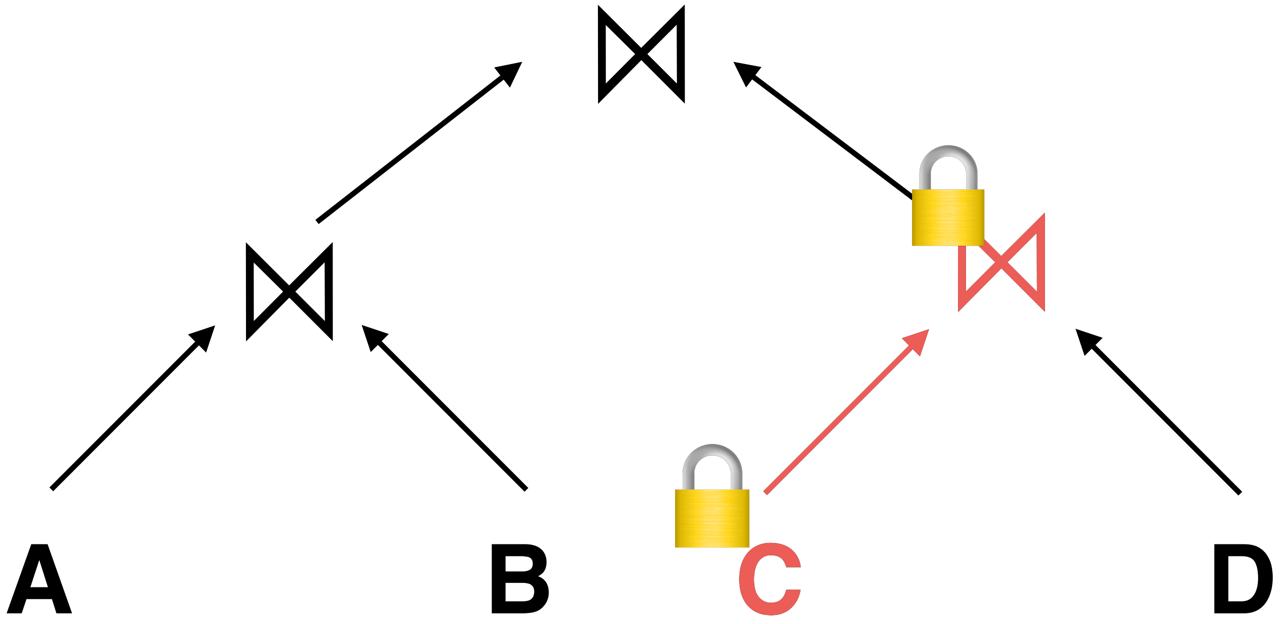
Observation: not all tables are sensitive



Observation: not all tables are sensitive

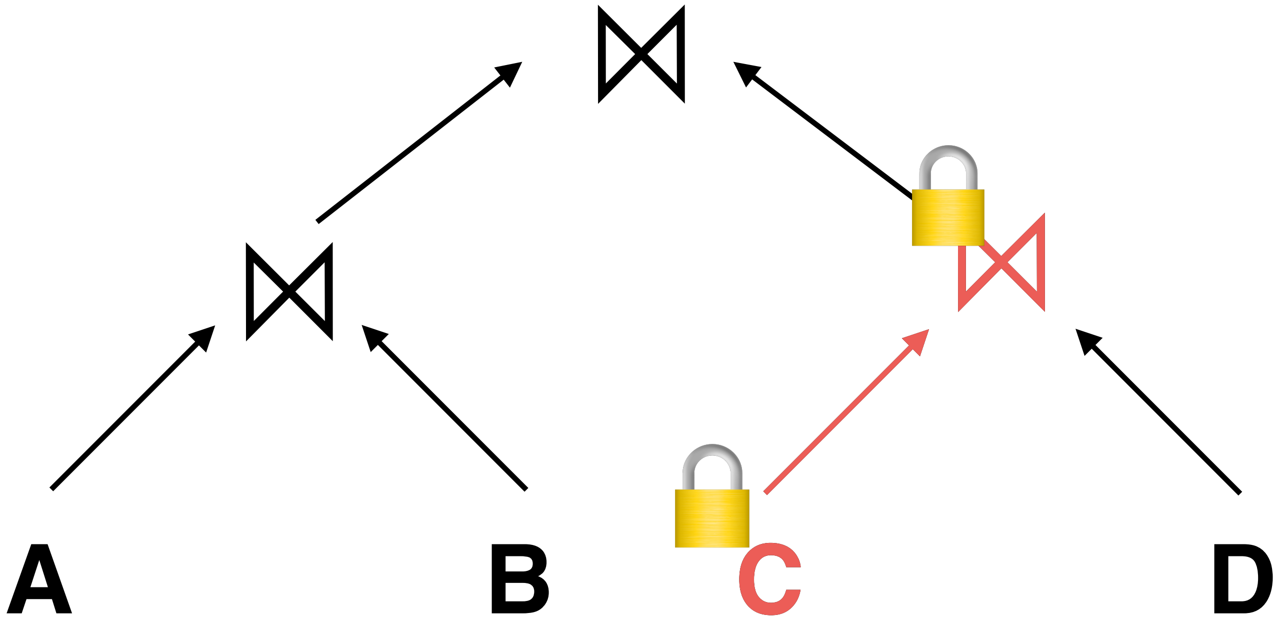


Observation: not all tables are sensitive

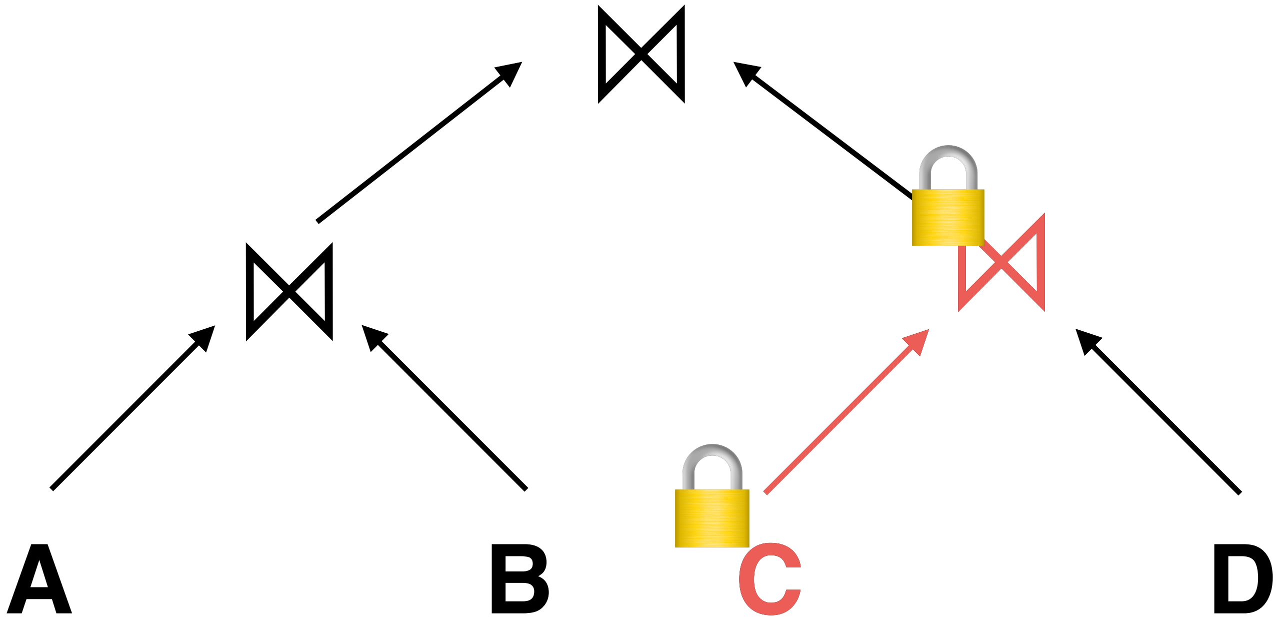


Not oblivious!

Observation: not all tables are sensitive

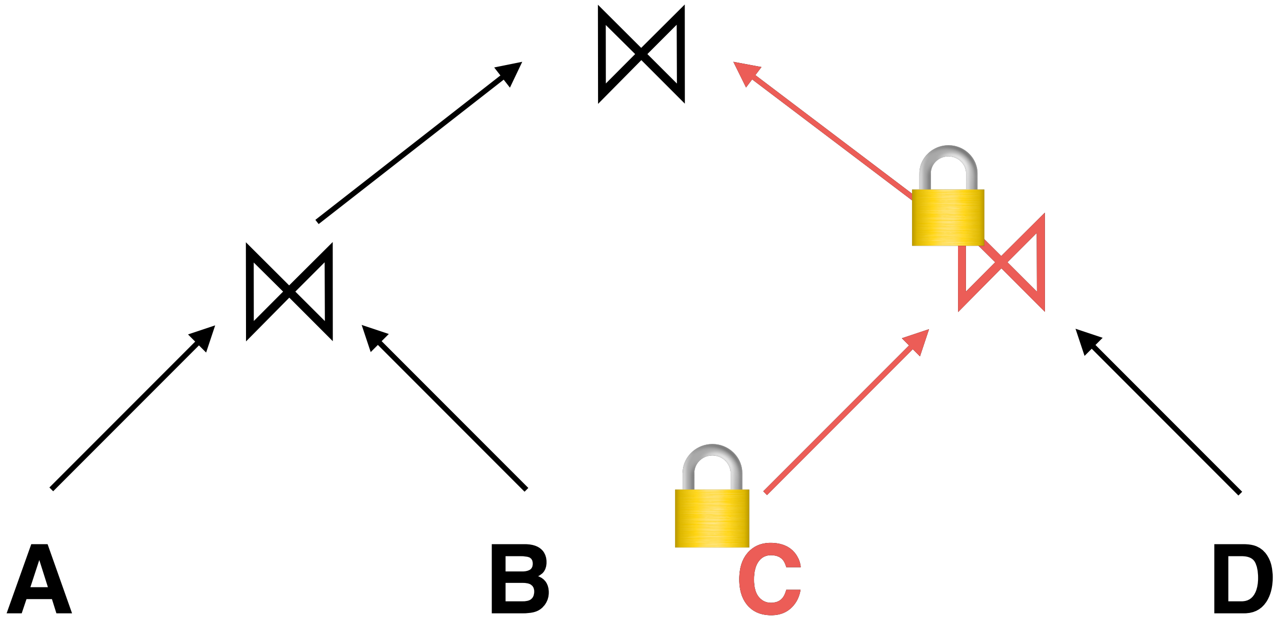


Observation: not all tables are sensitive



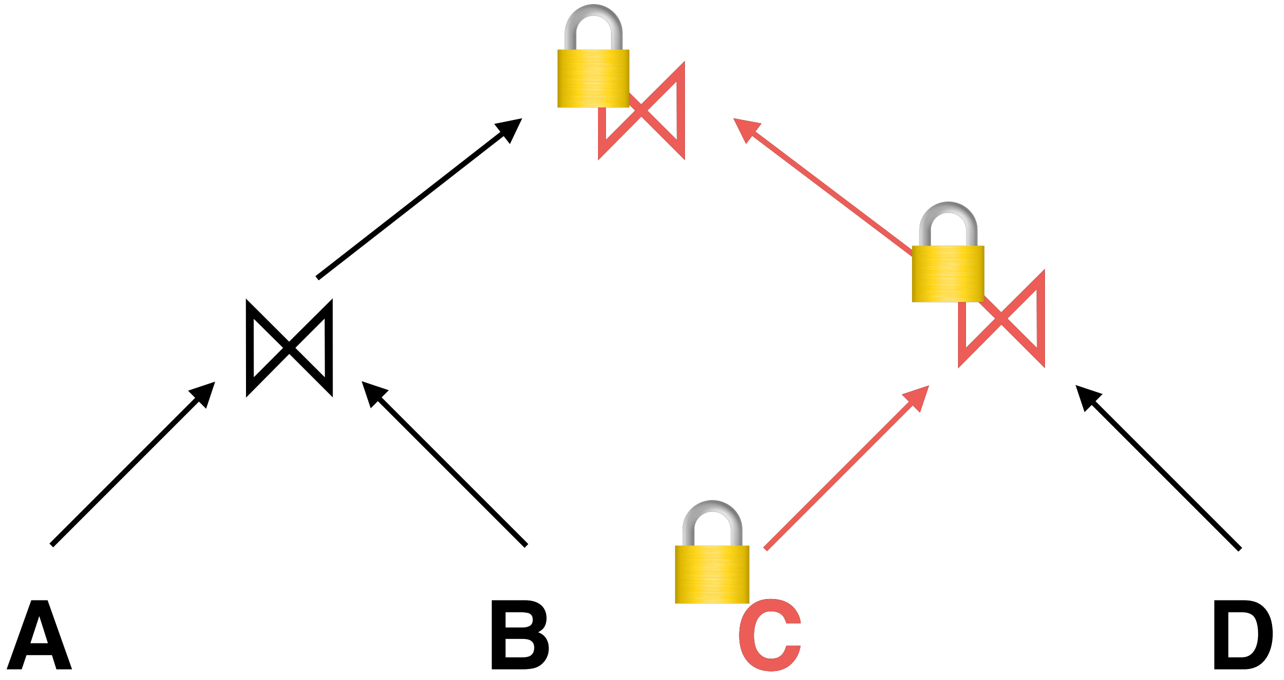
Sensitivity propagation: propagate obliviousness from leaf to root

Observation: not all tables are sensitive



Sensitivity propagation: propagate obliviousness from leaf to root

Observation: not all tables are sensitive

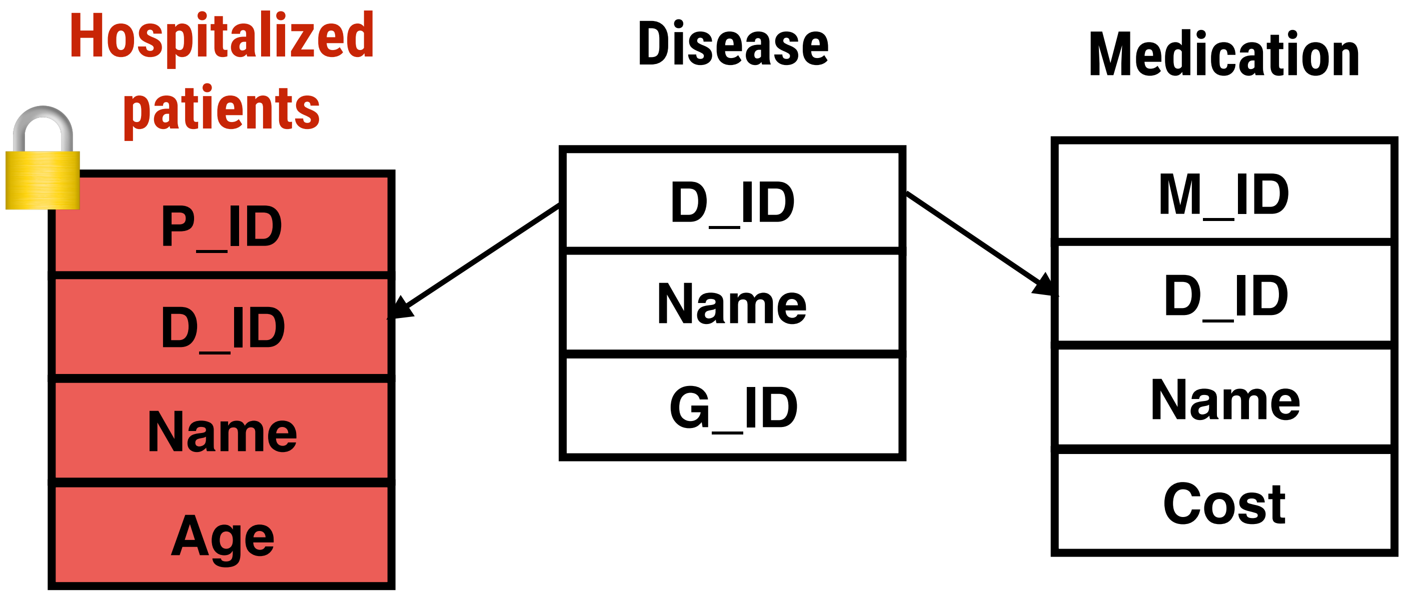


Sensitivity propagation: propagate obliviousness from leaf to root

Insight 2

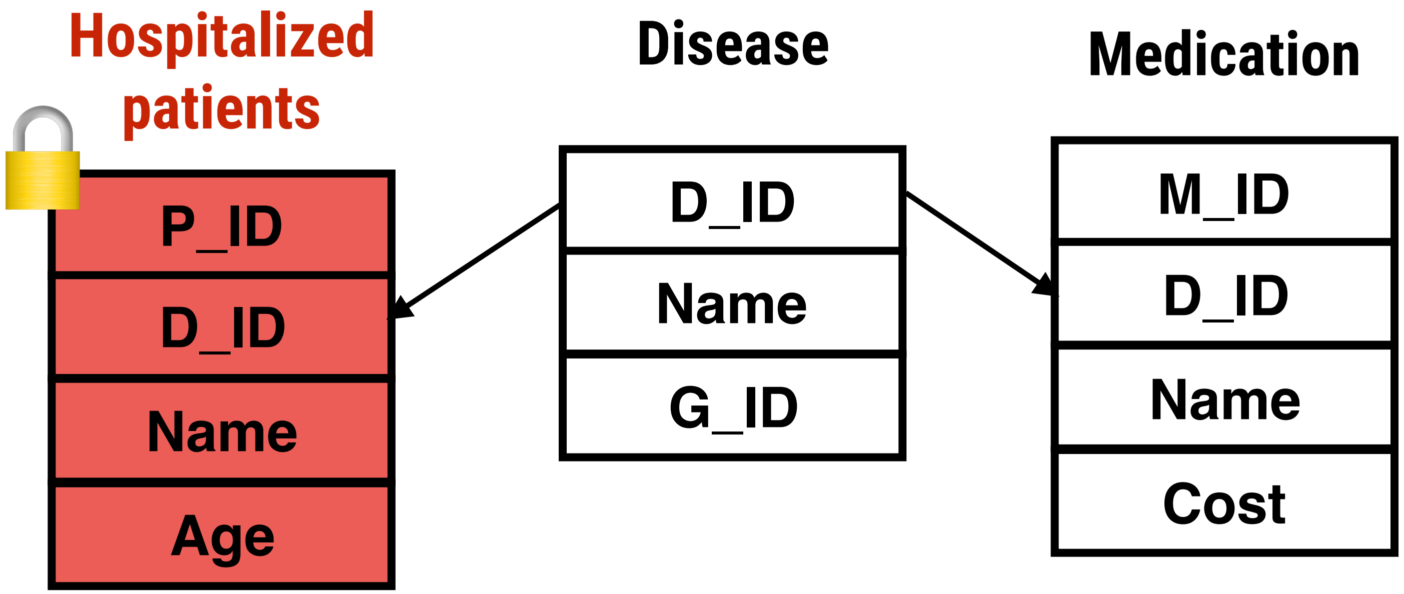
Sensitivity propagation
introduces a new dimension to
query optimization

Cost-based optimization



Find the least costly medication for each patient

Cost-based optimization



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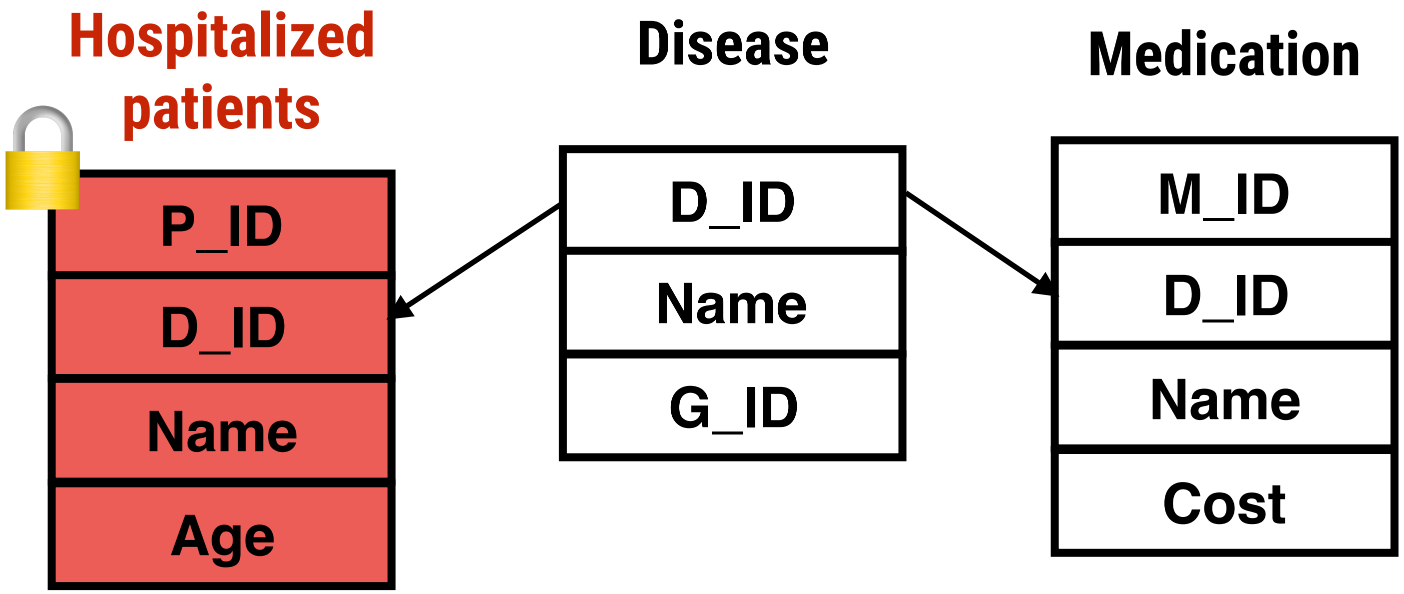

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FROM patient, disease,
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        GROUP BY d_id) AS med
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      AND disease.d_id = med.d_id
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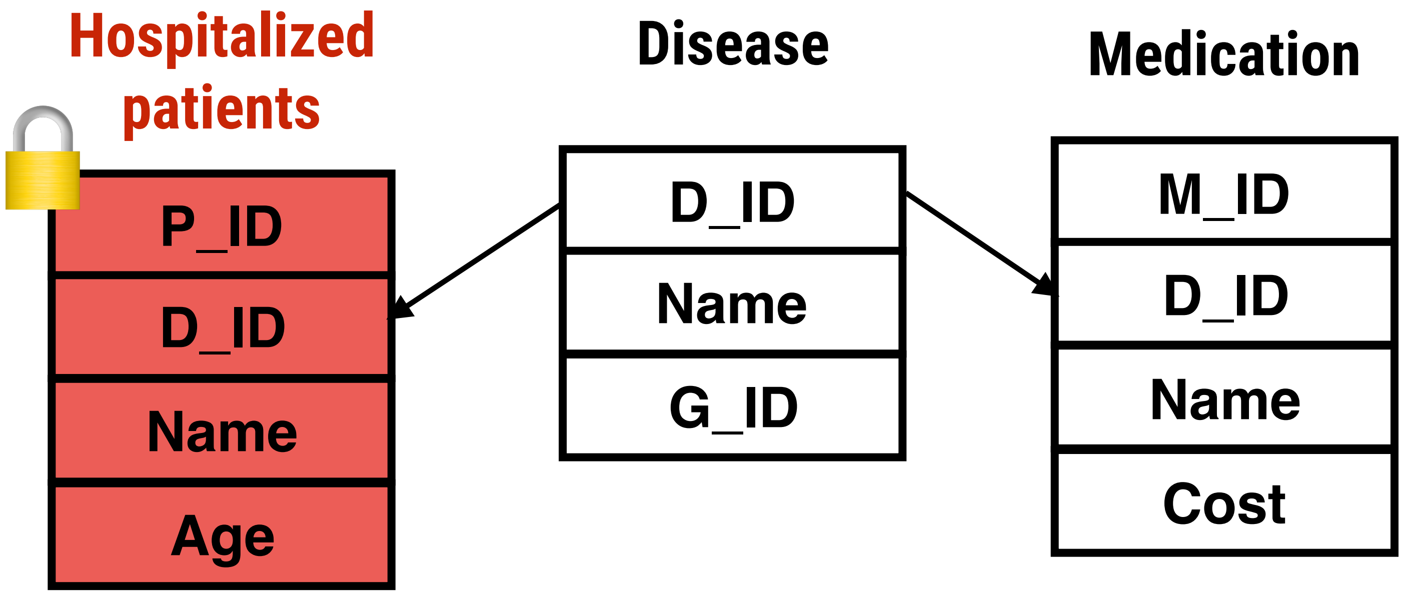

Hospitalized patients

P_ID

D_ID

Name

Age

Disease

D_ID

Name

G_ID

Medication

M_ID

D_ID

Name

Cost

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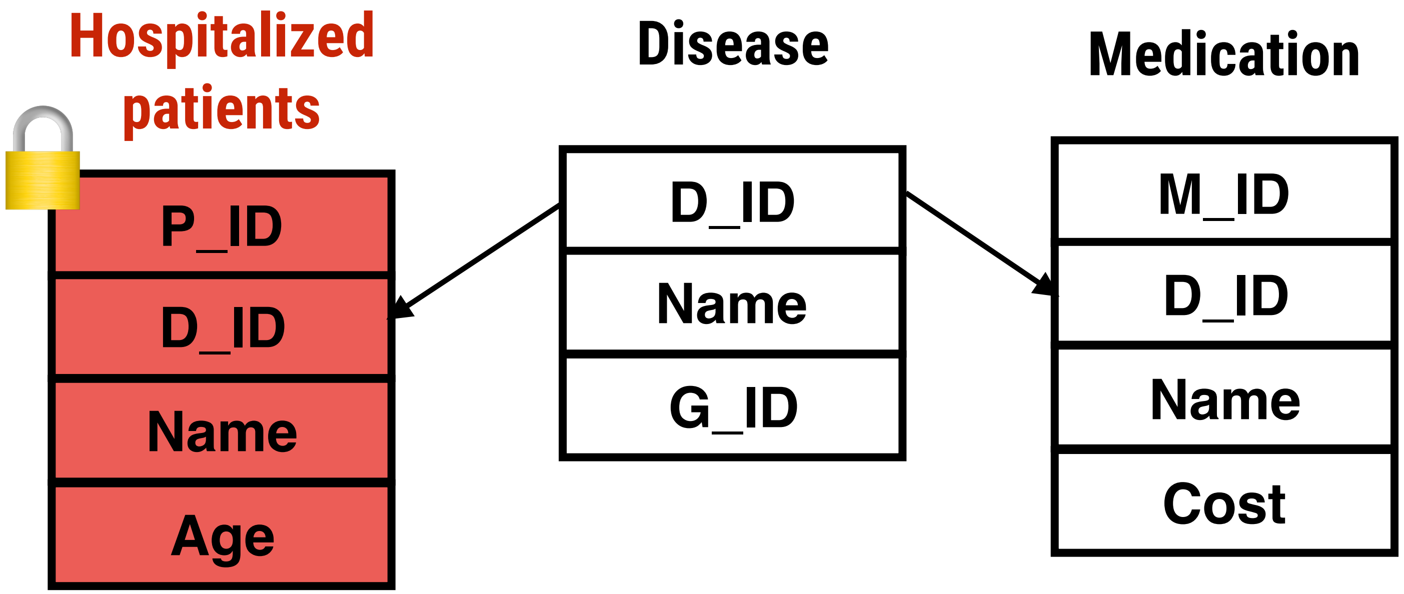

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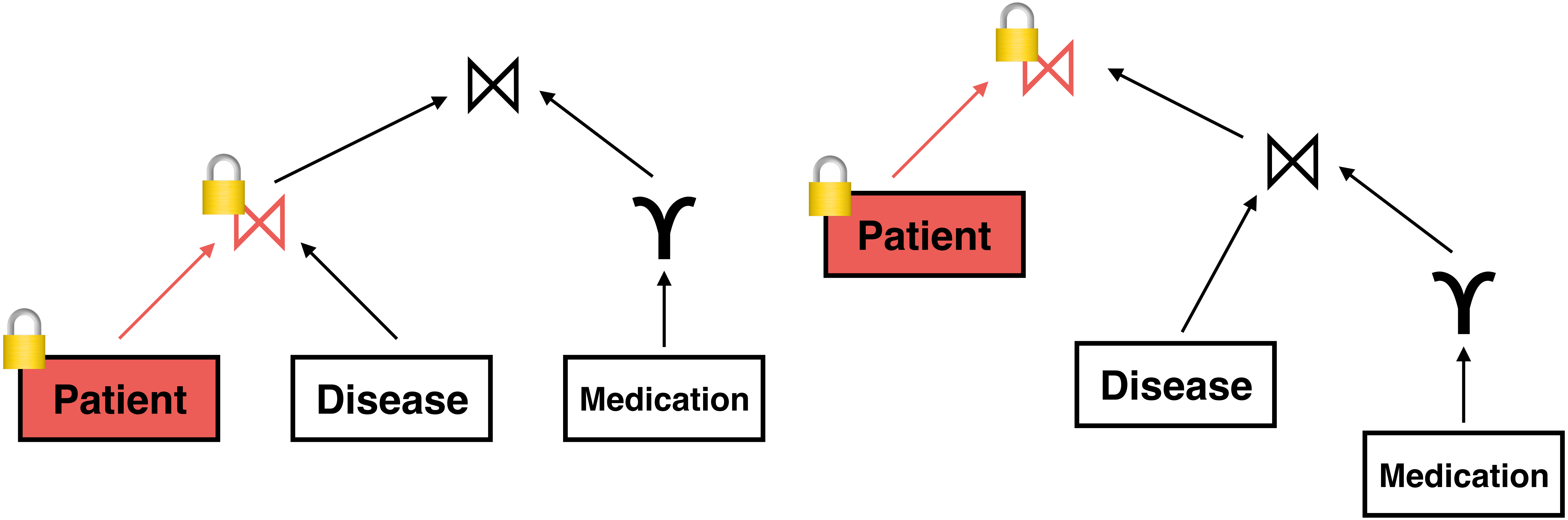
3-way join

Cost-based optimization

SQL optimizer with new cost:



Cost-based optimization

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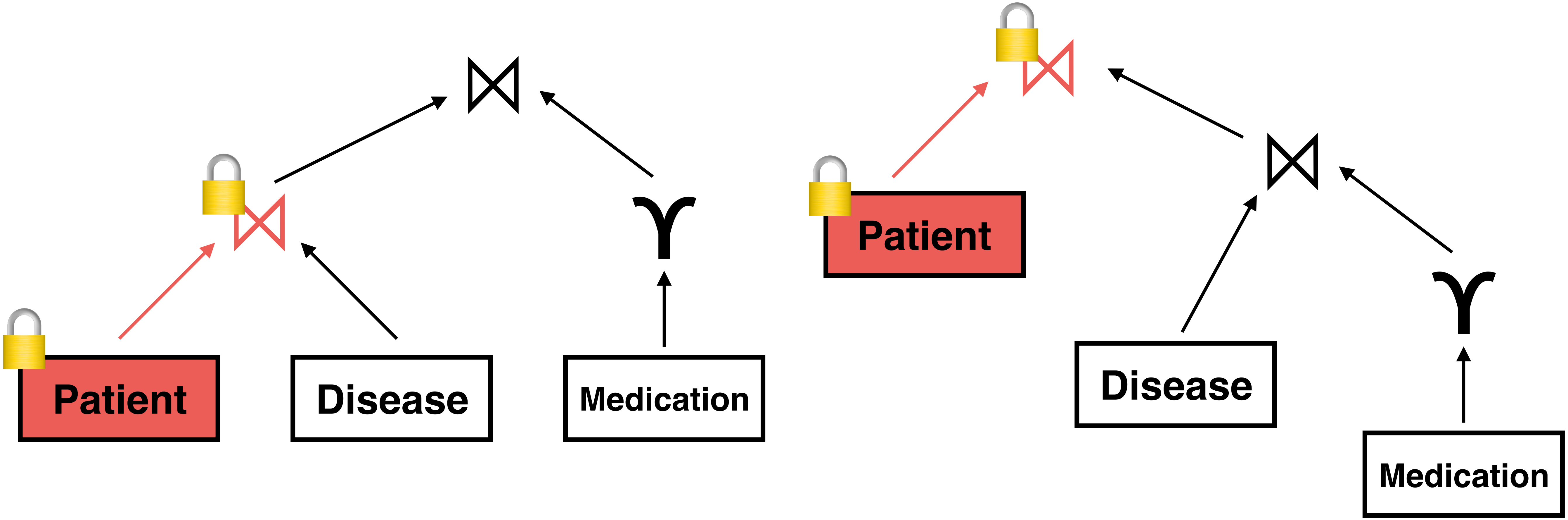

More selective
non-oblivious join

Cost-based optimization

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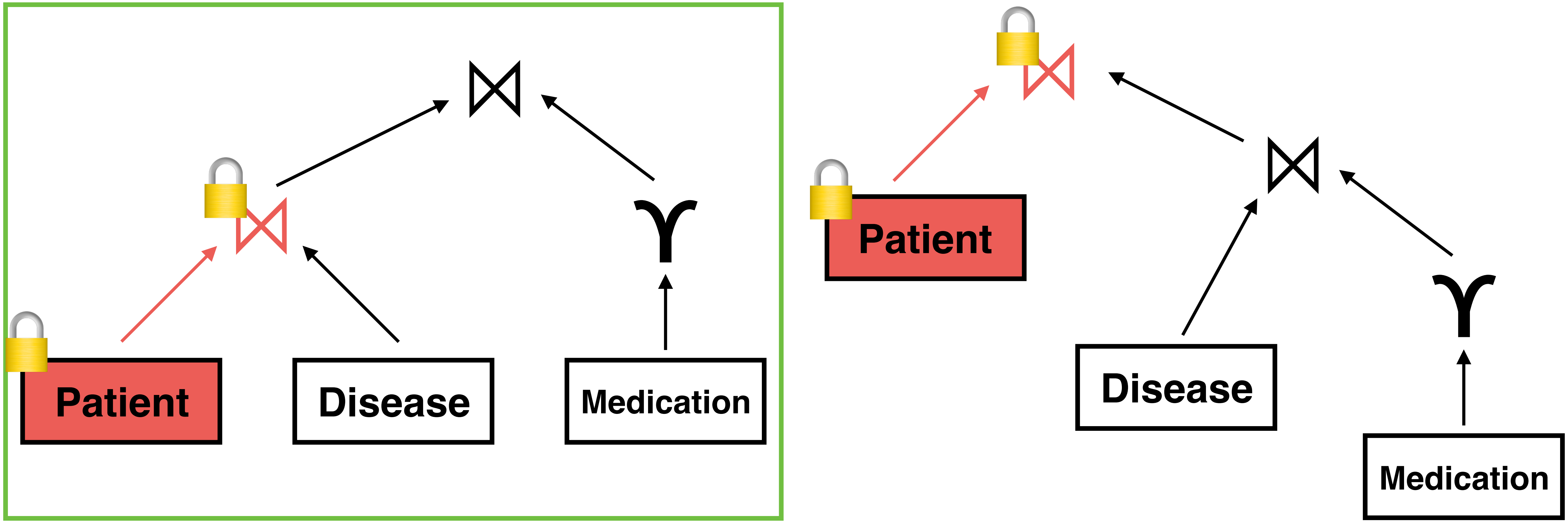

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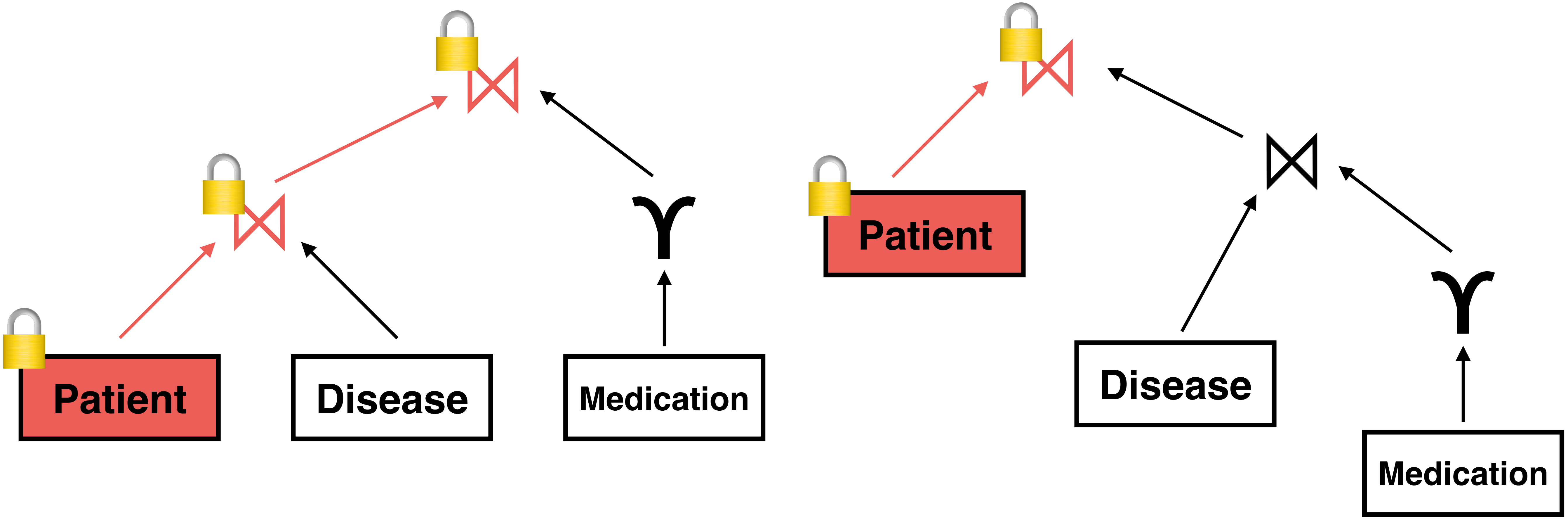
SQL optimizer with new cost and **sensitivity propagation**:



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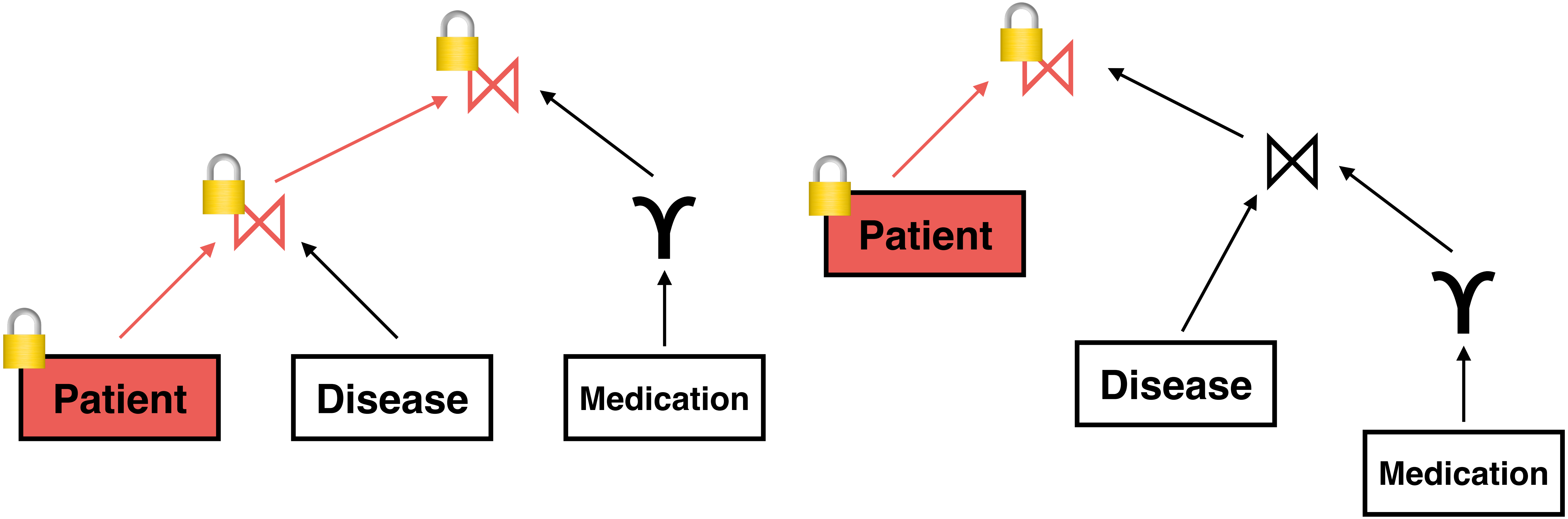

Fewer oblivious joins

Cost-based optimization

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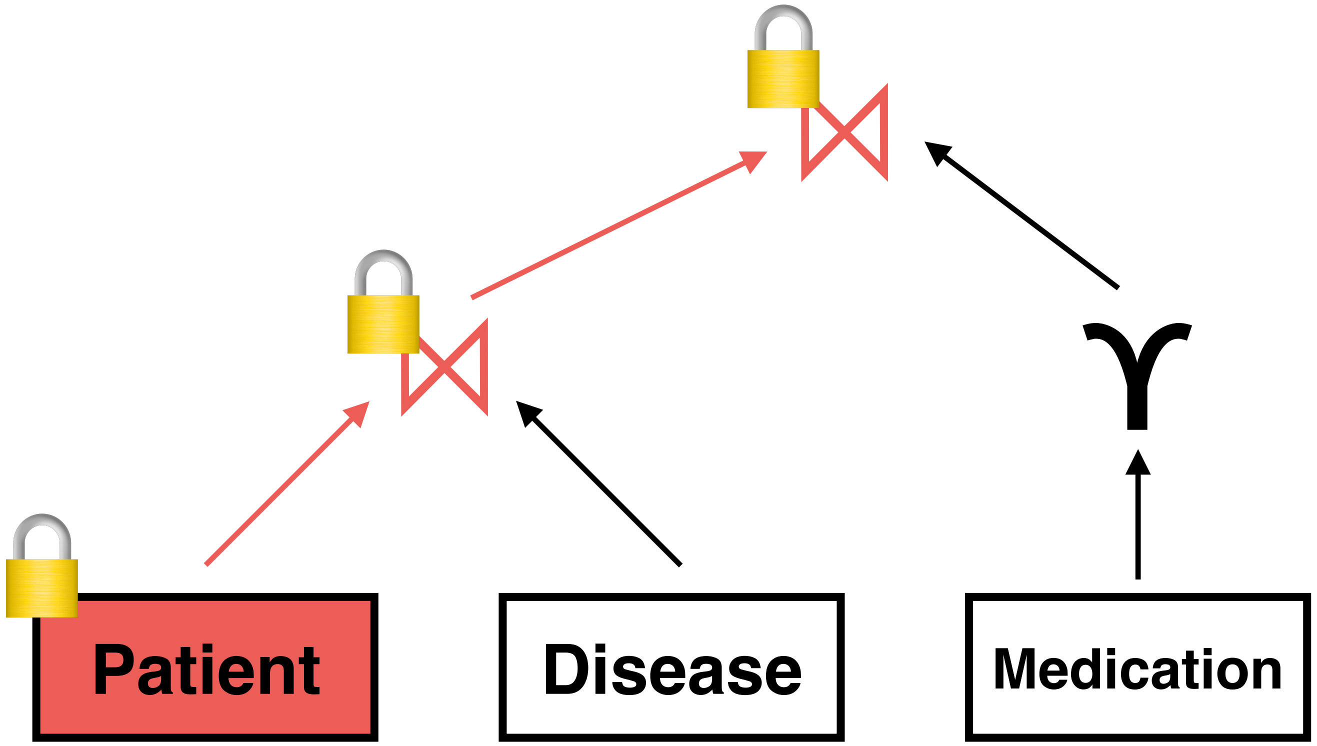

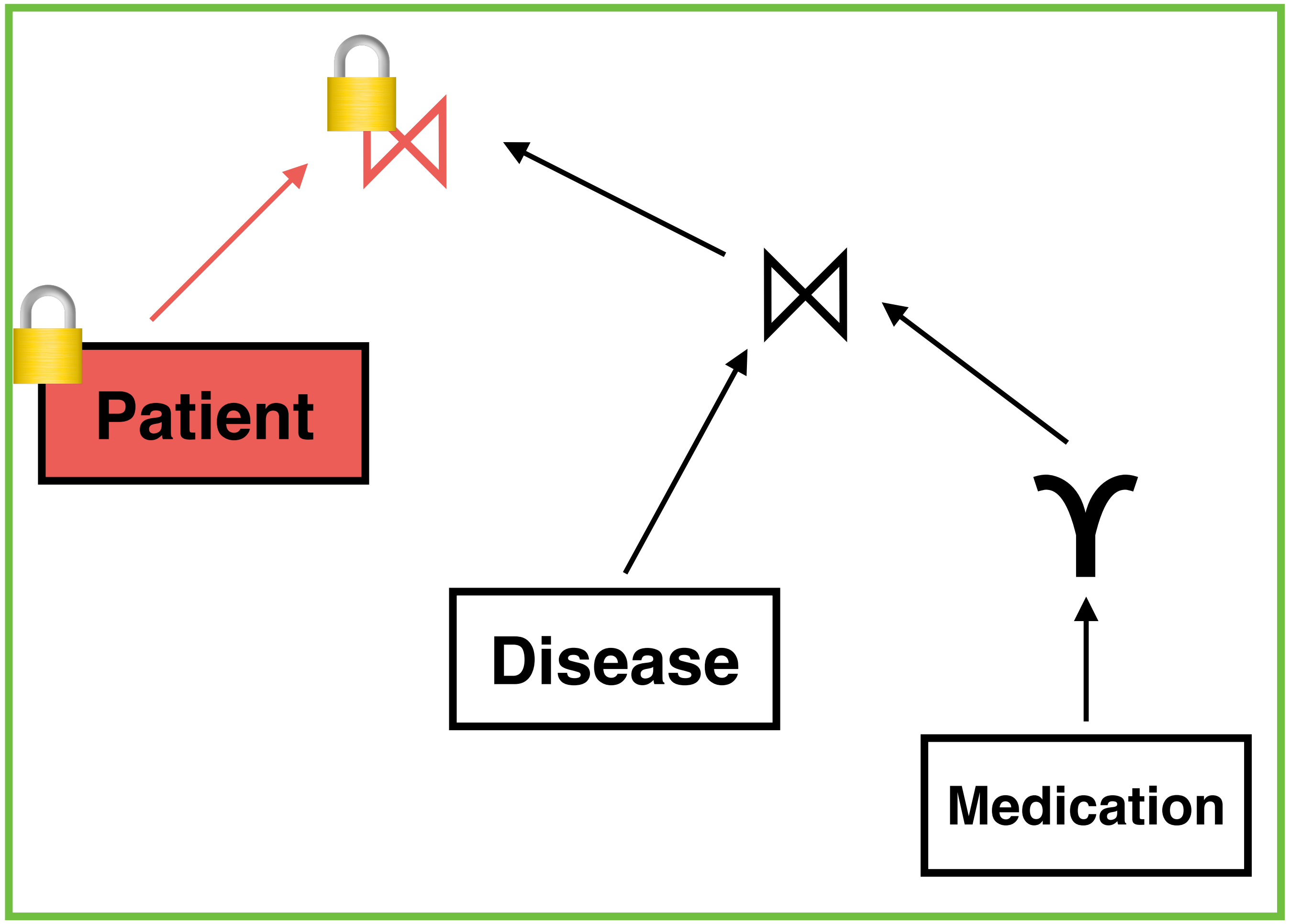

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    - A cluster of 5 SGX machines

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Data encryption, authentication, computation verification

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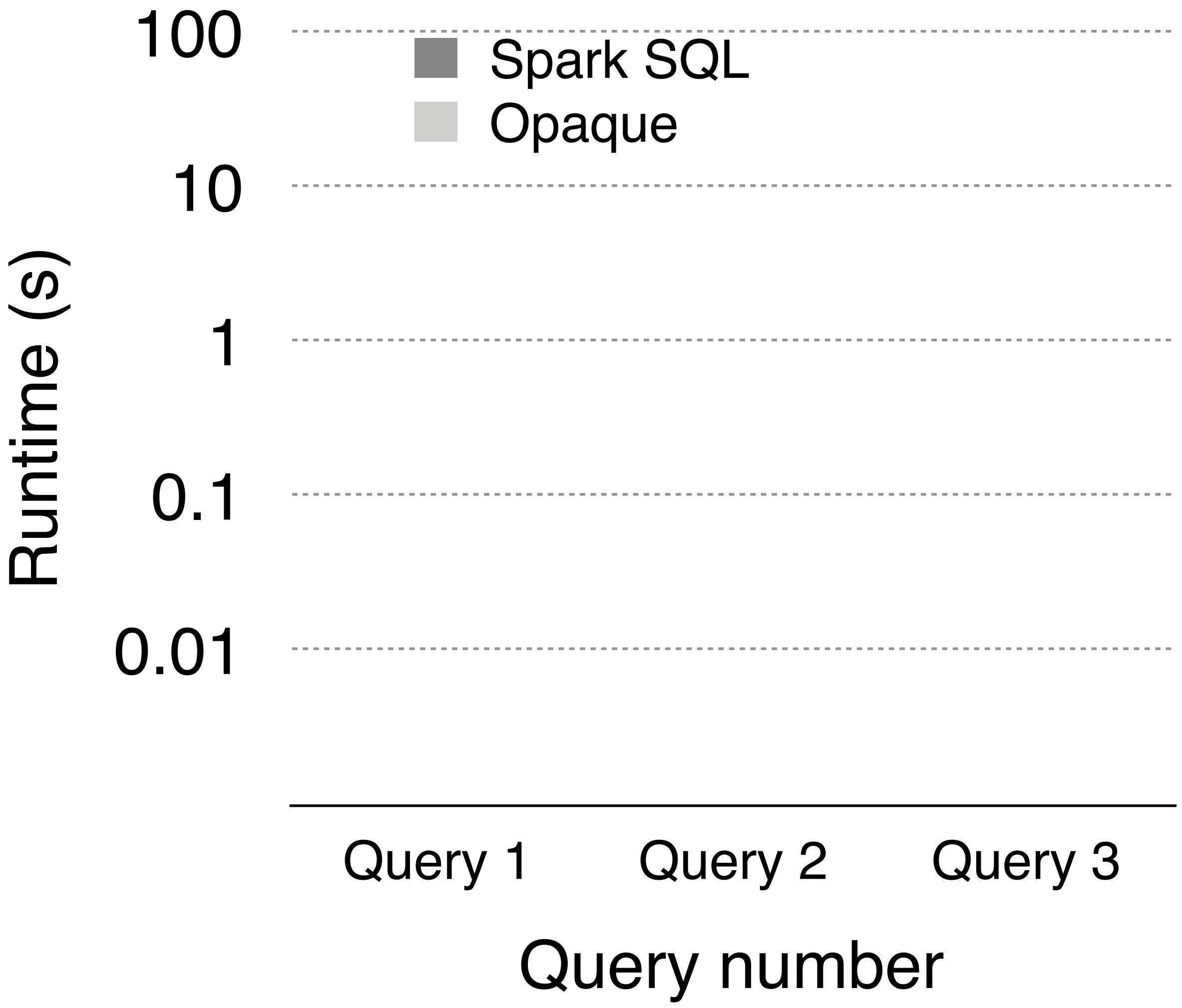

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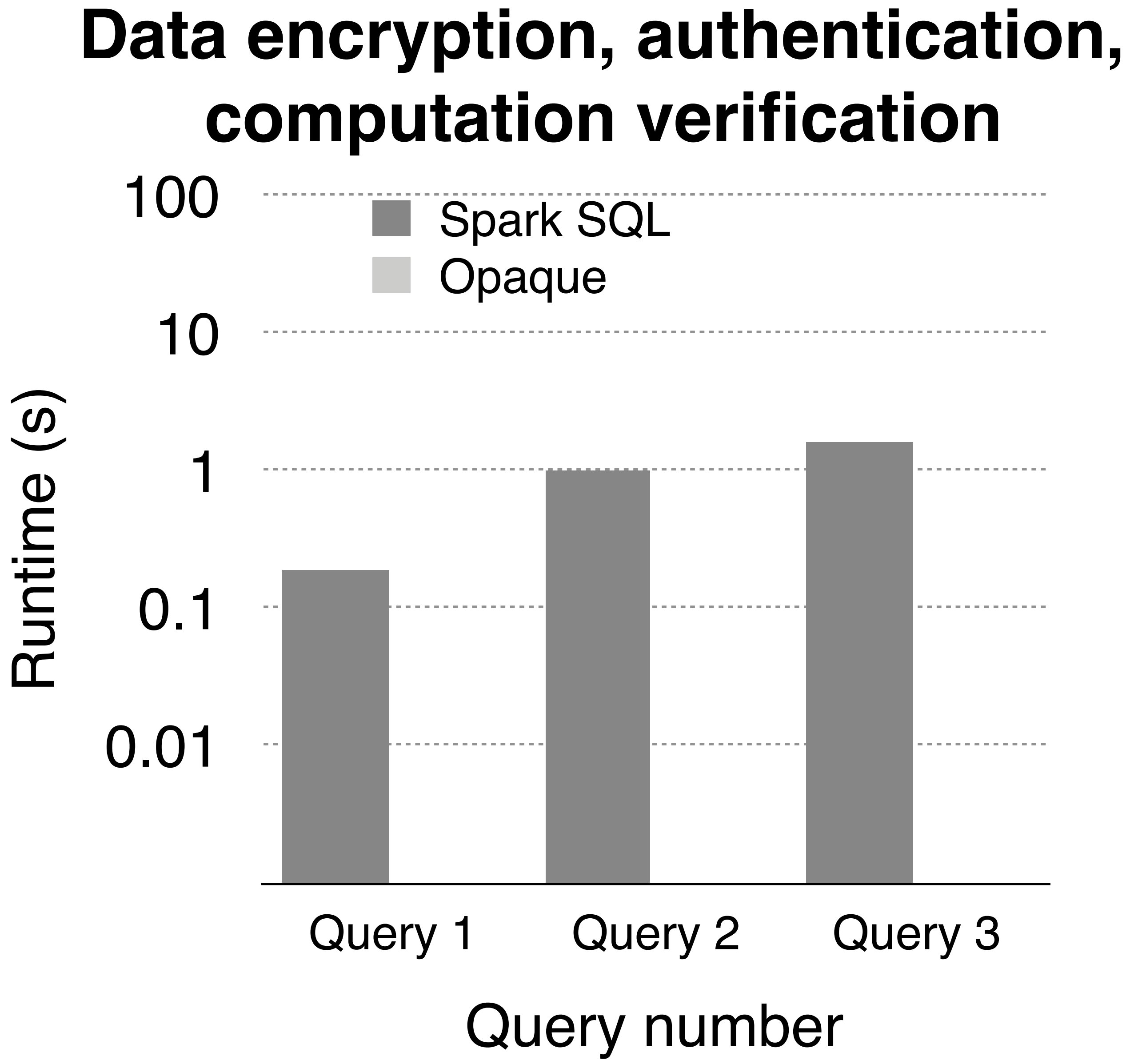

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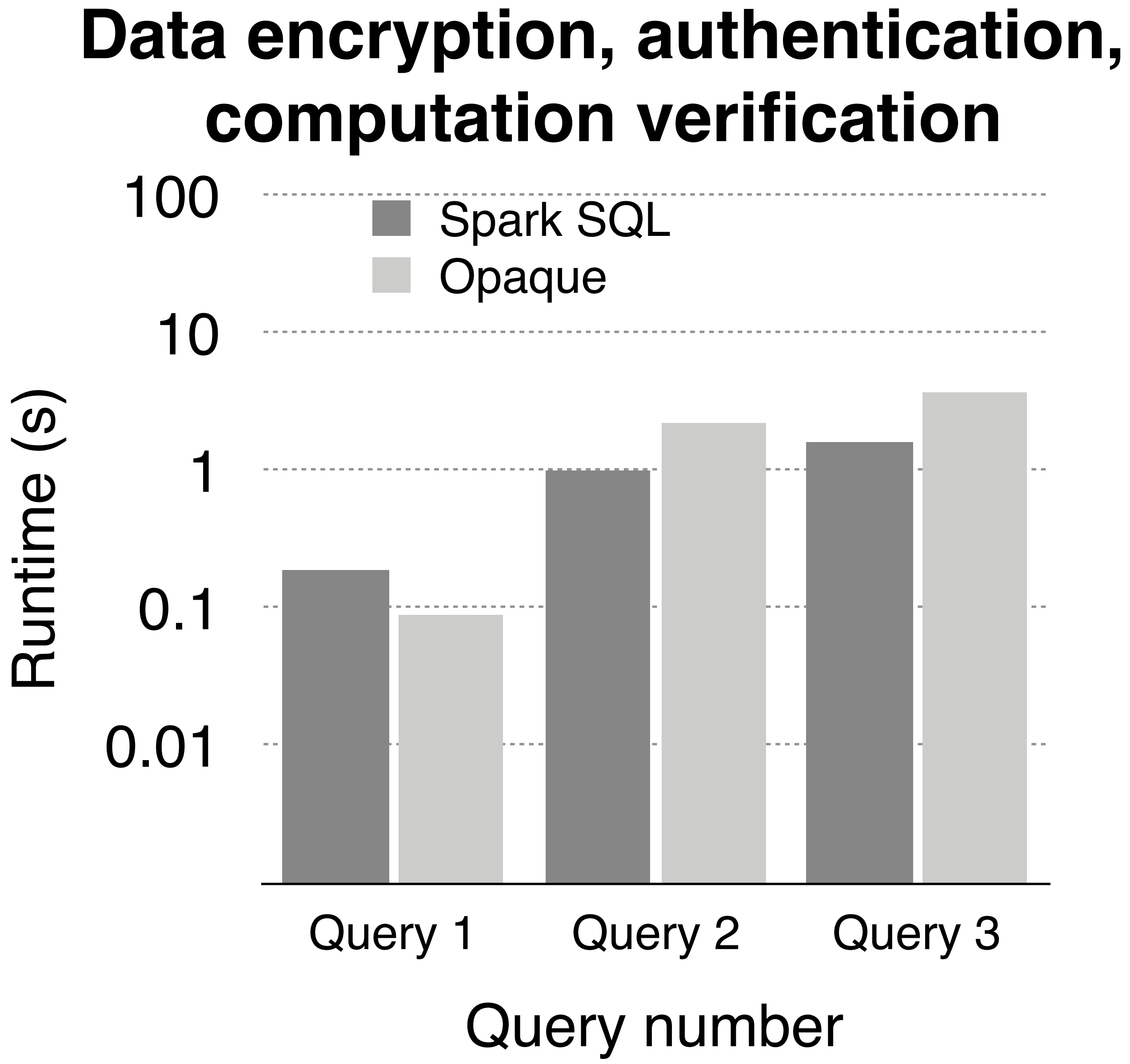

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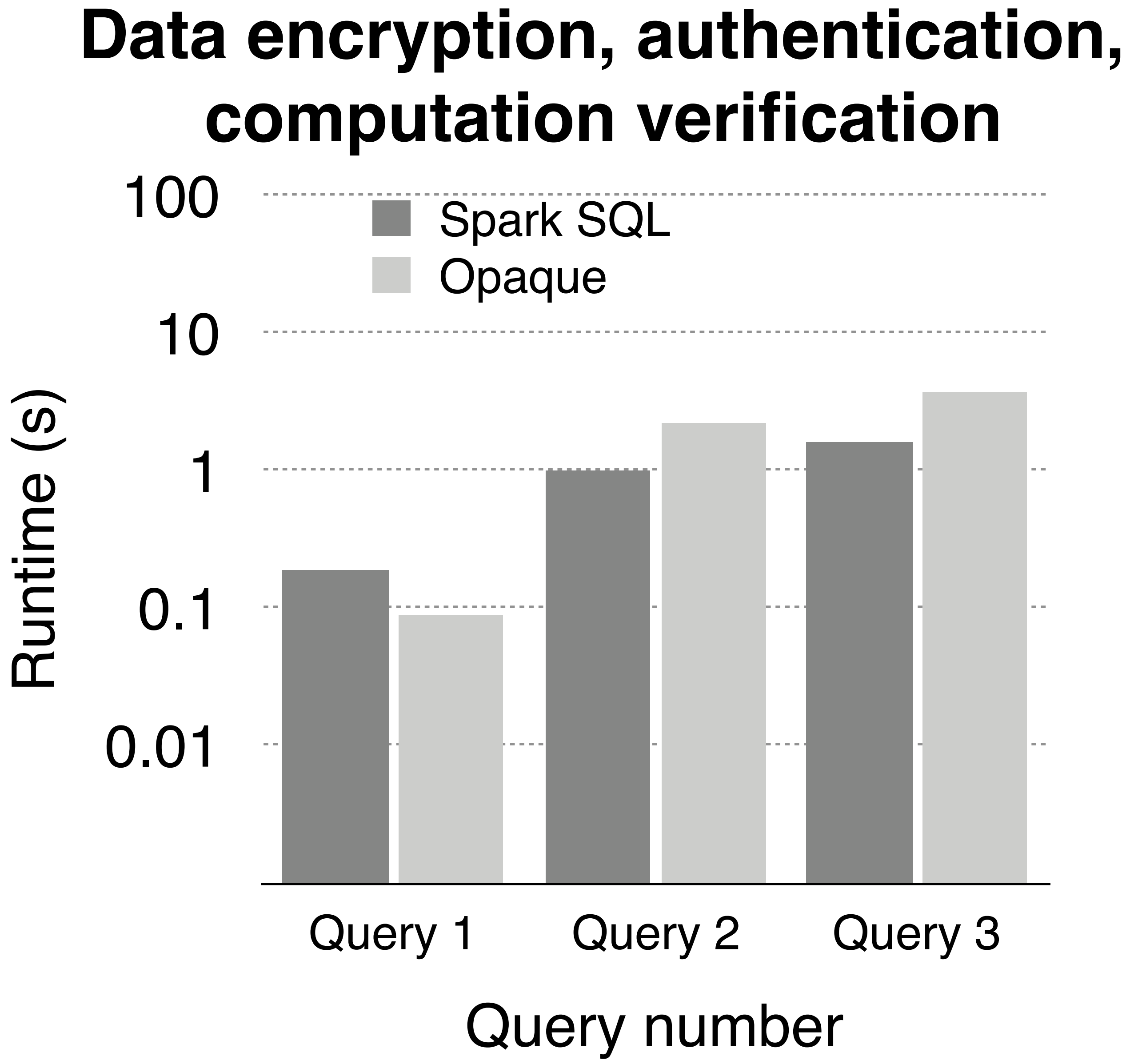

Overhead: 0.47x to 2.3x

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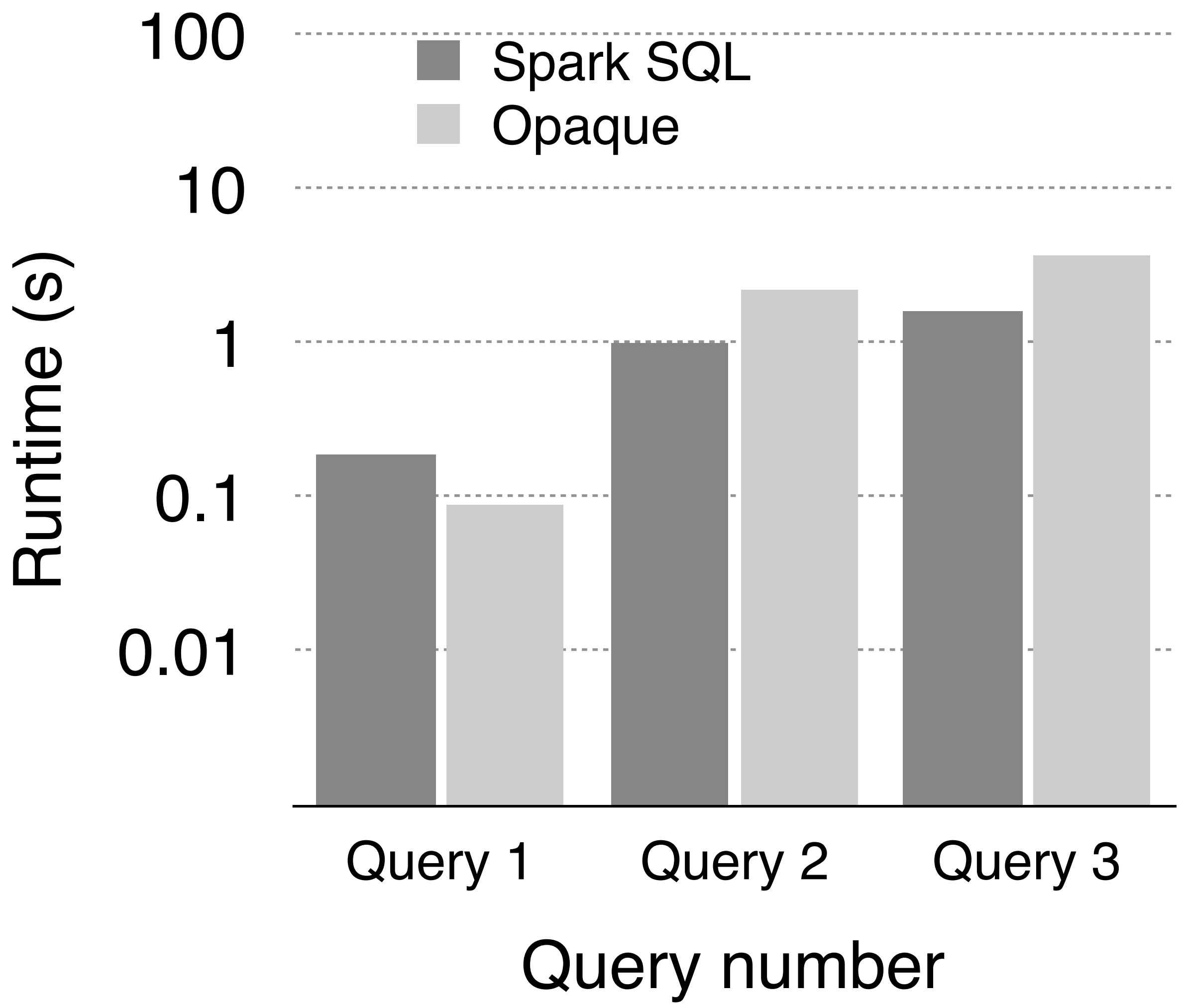

+ Obliviousness

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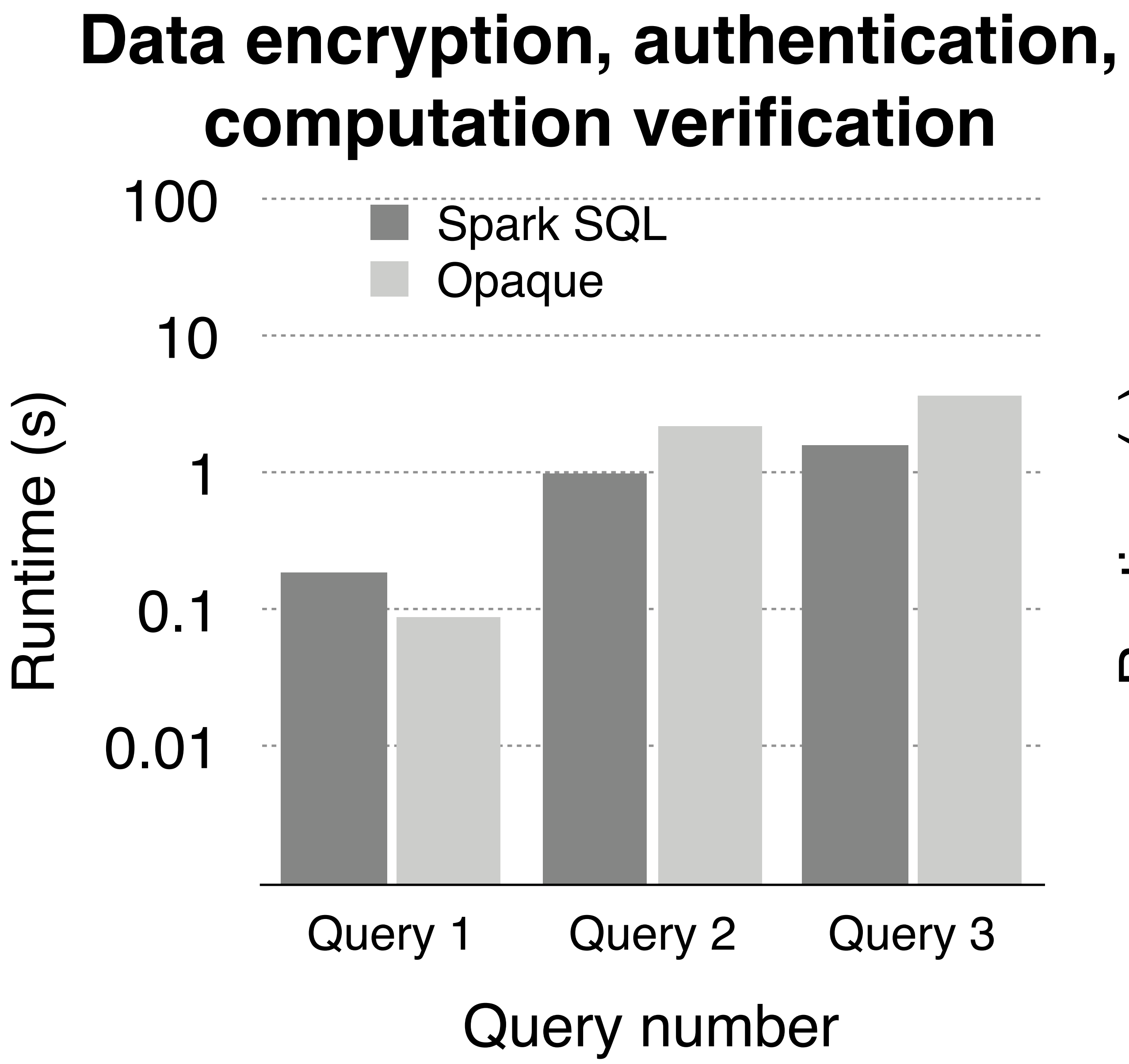

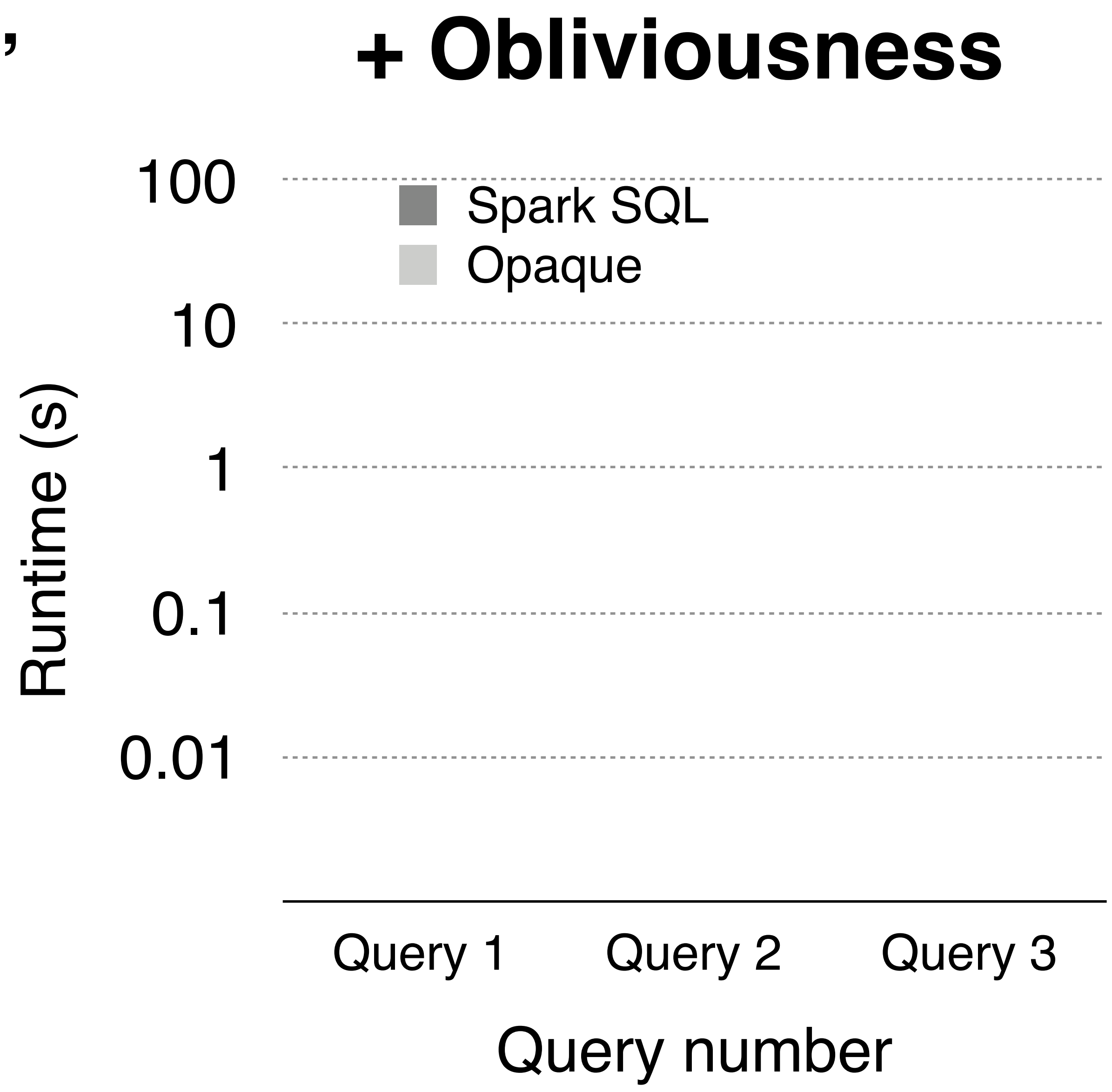

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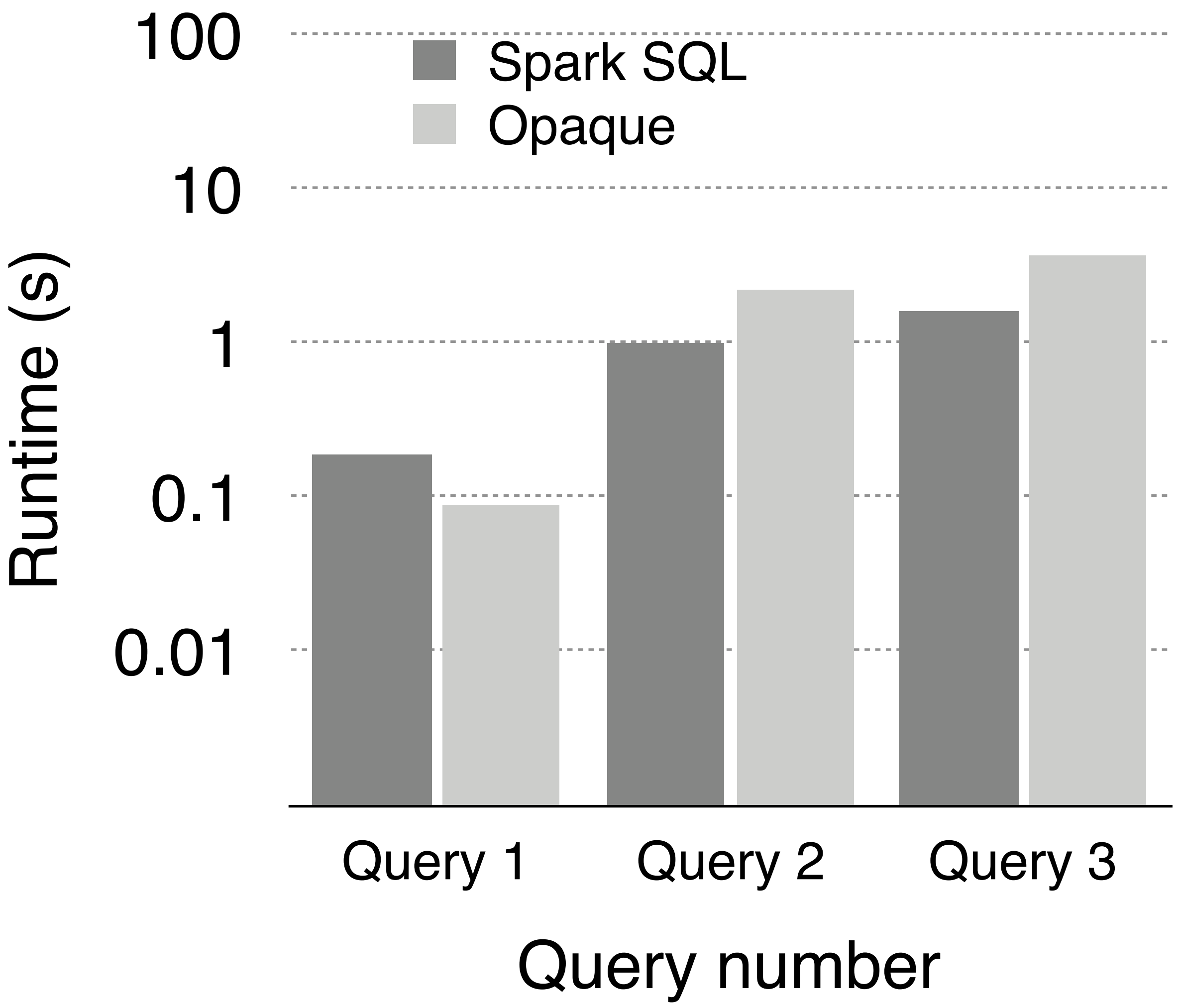

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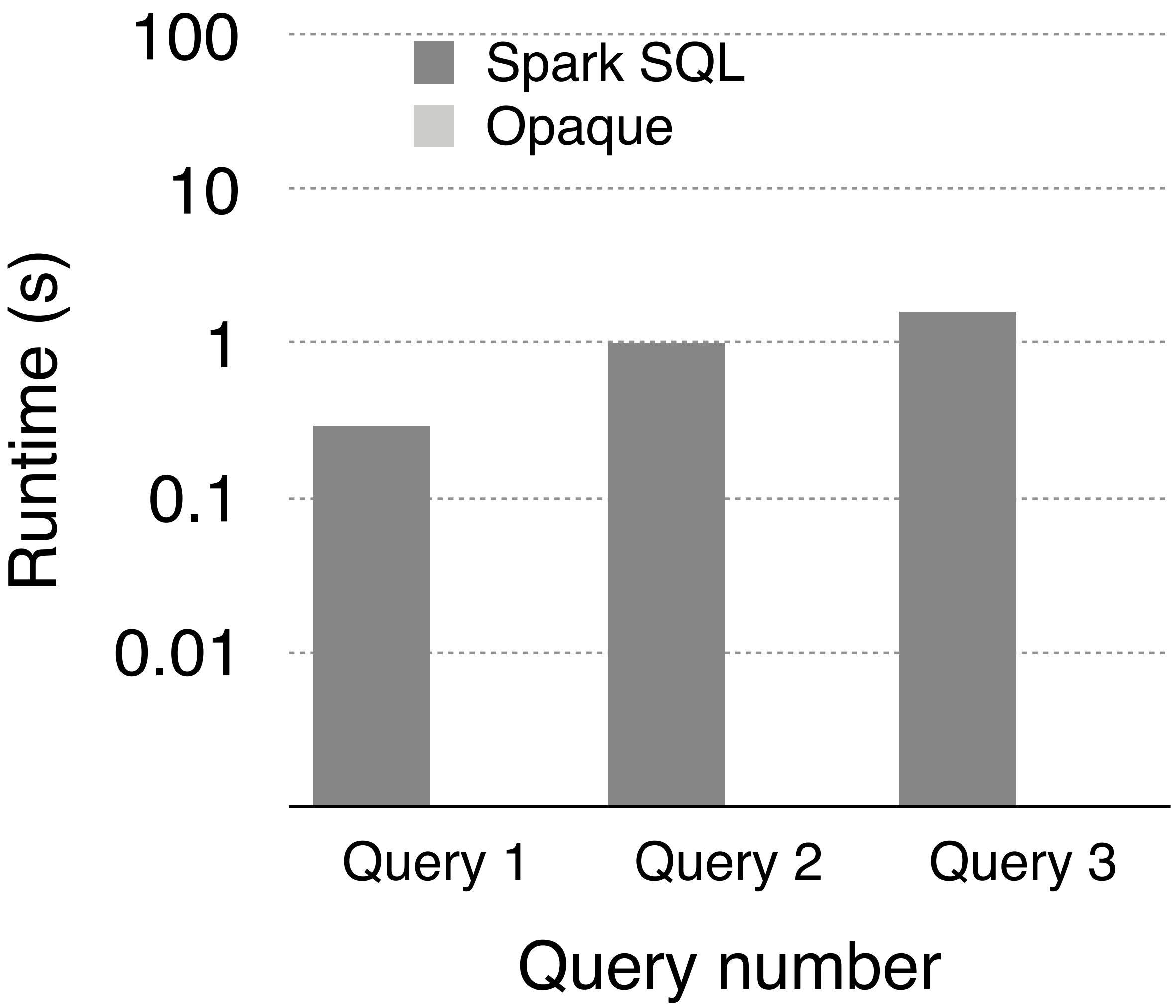

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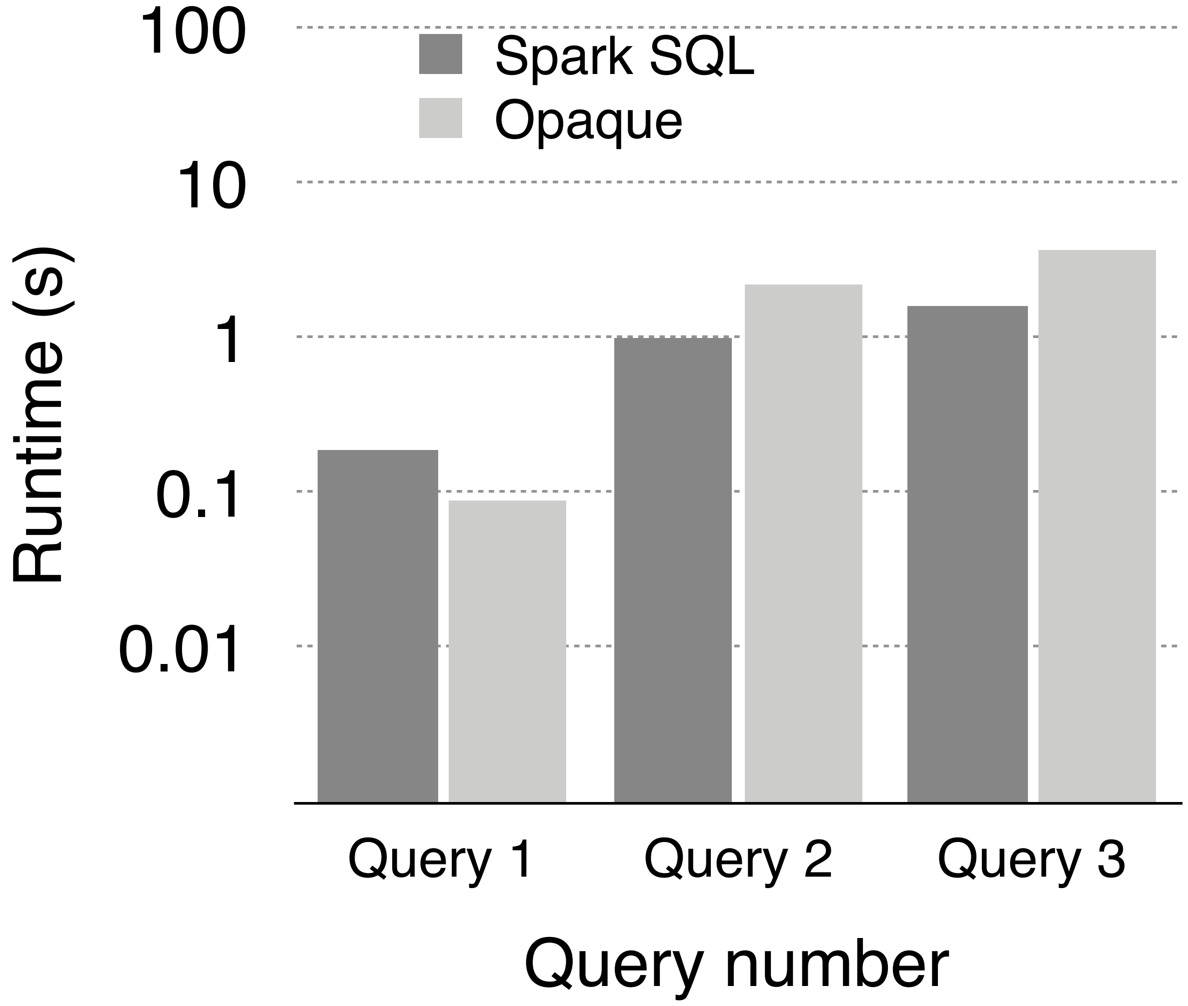

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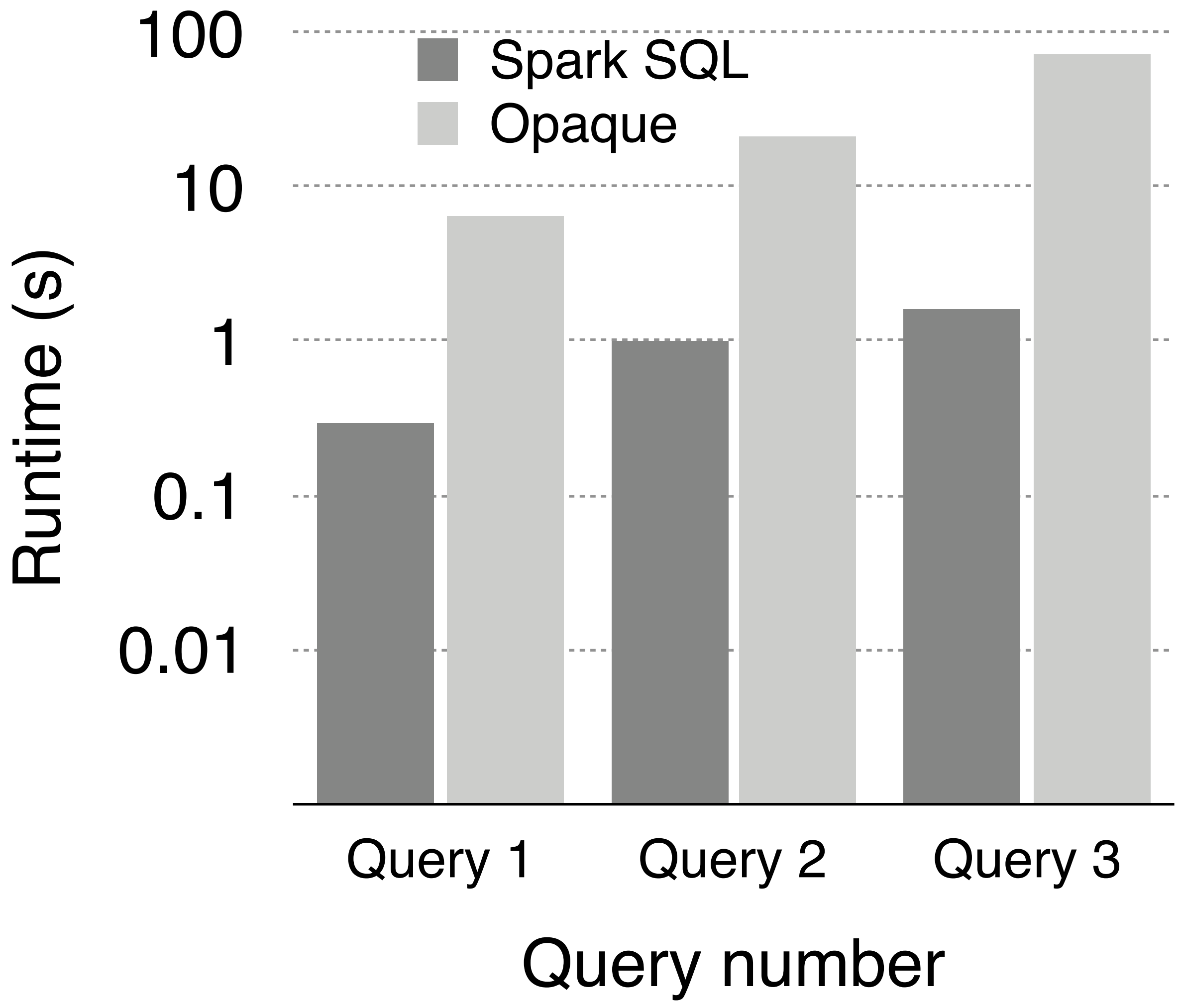

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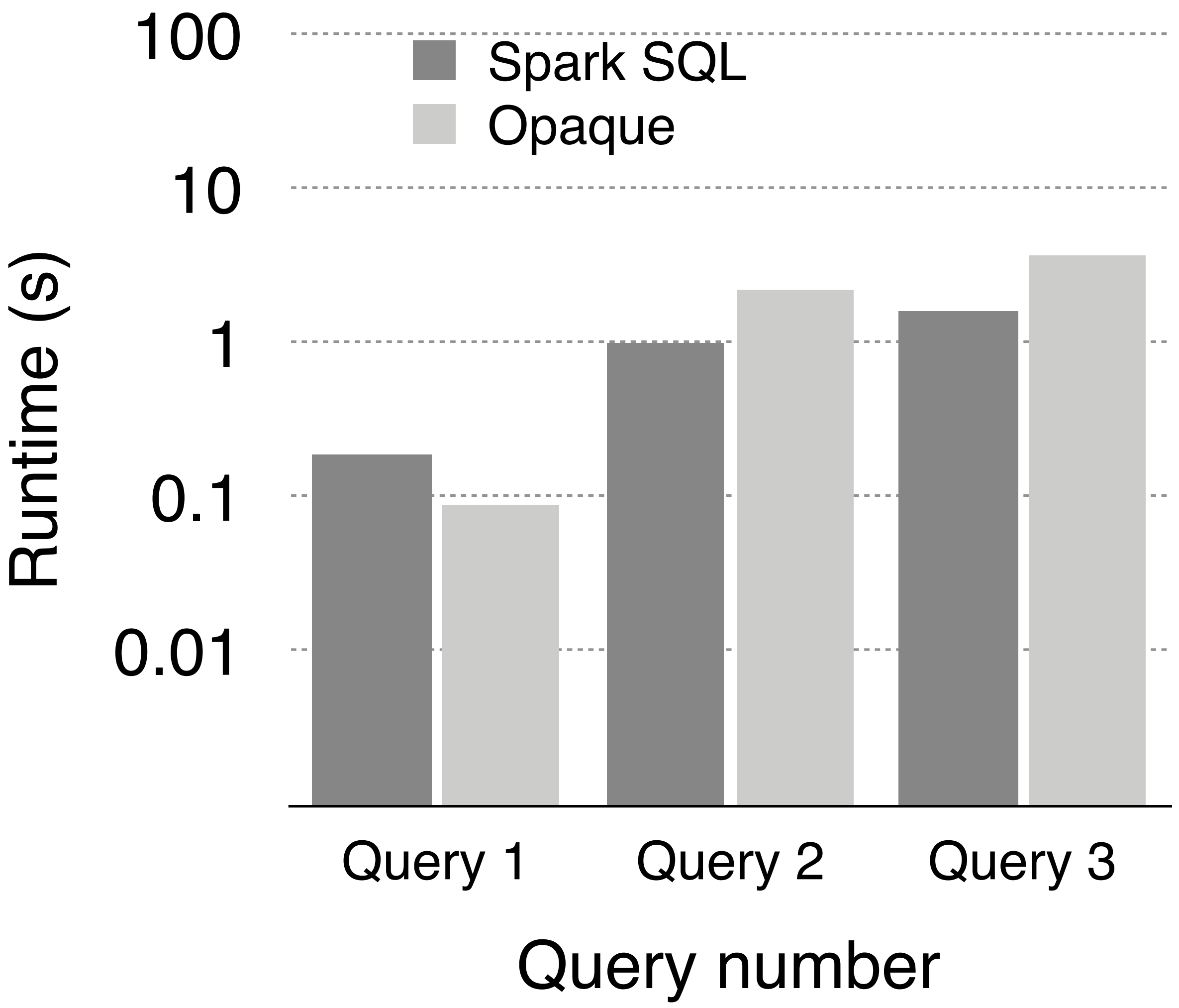

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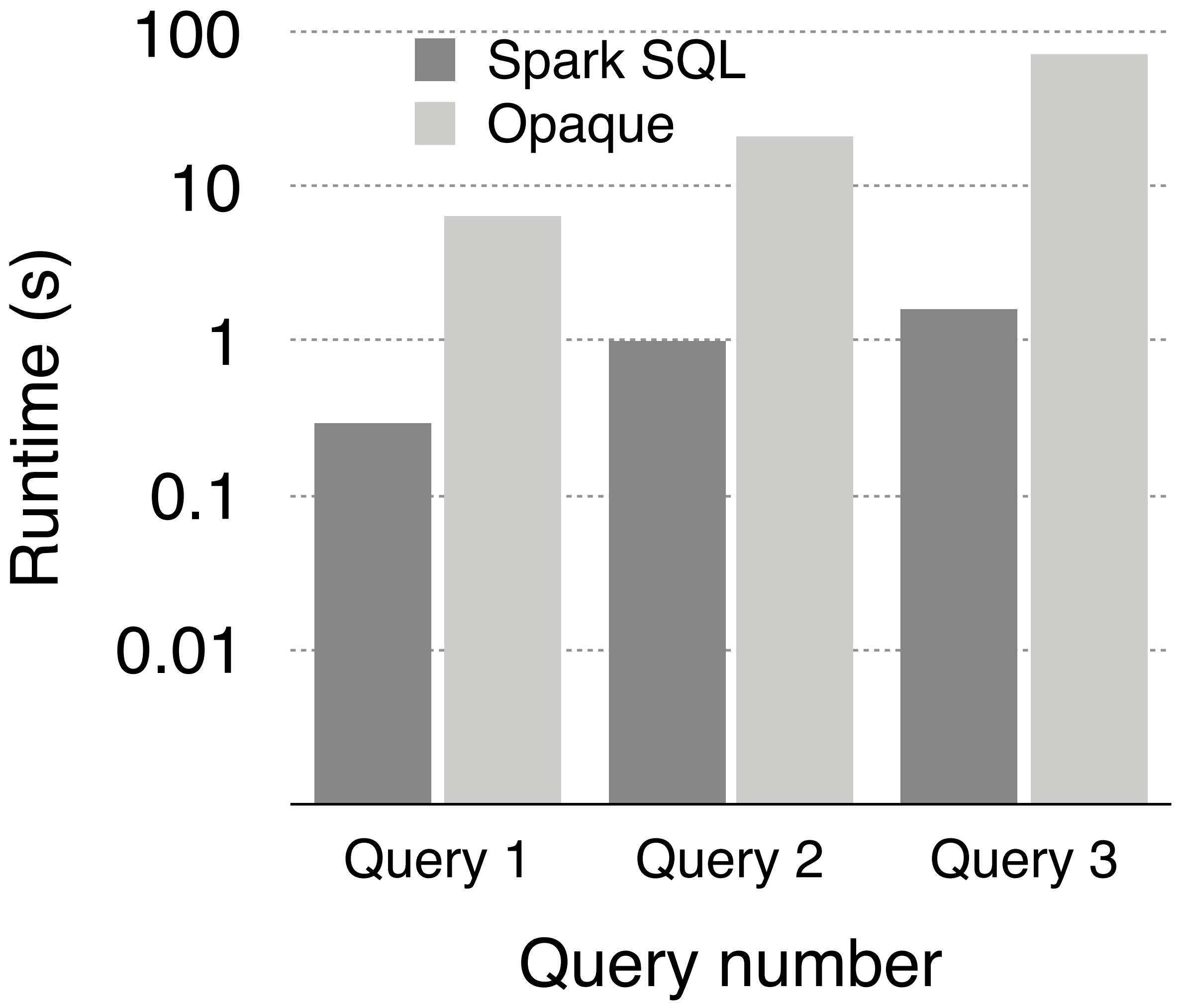
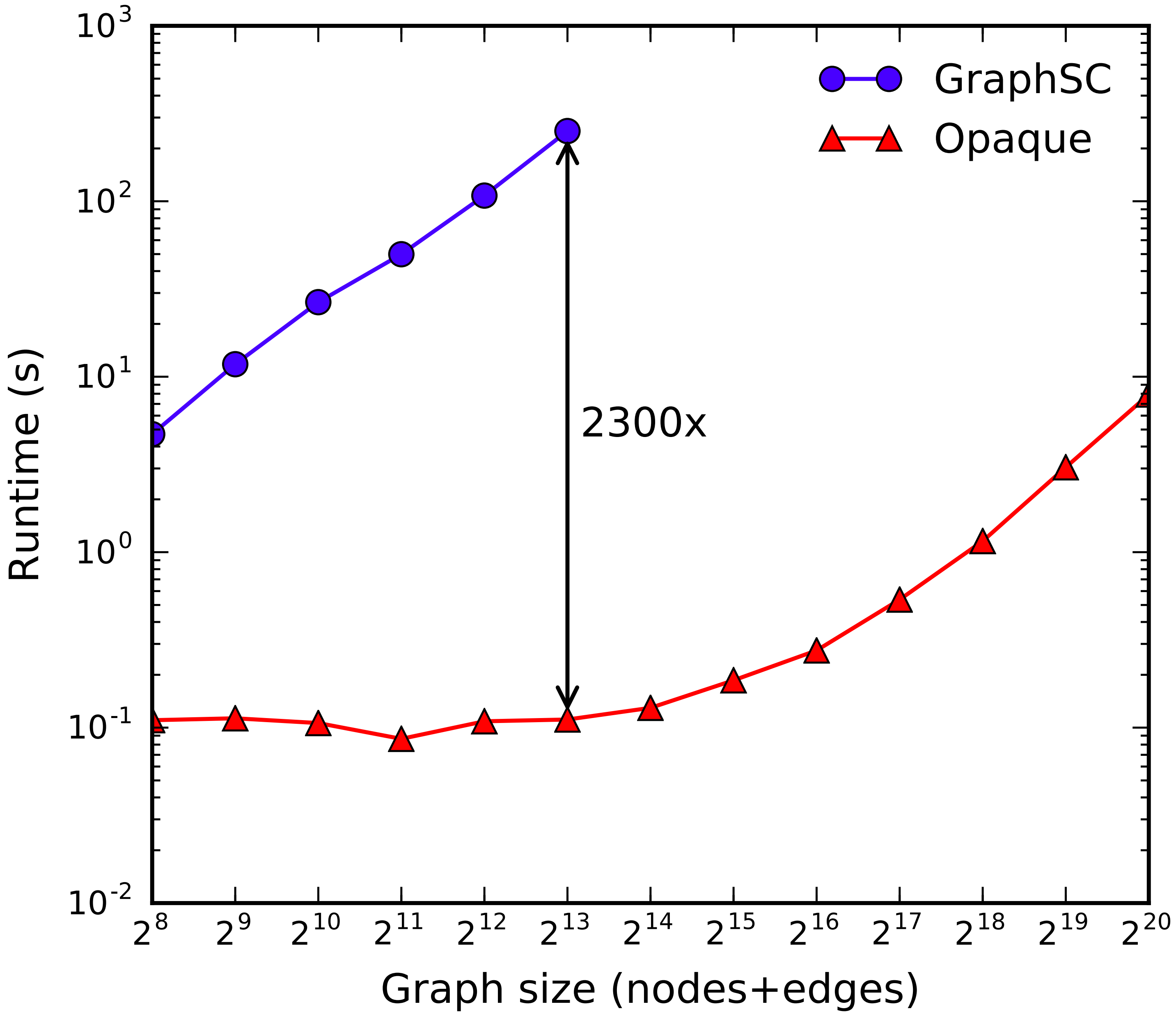


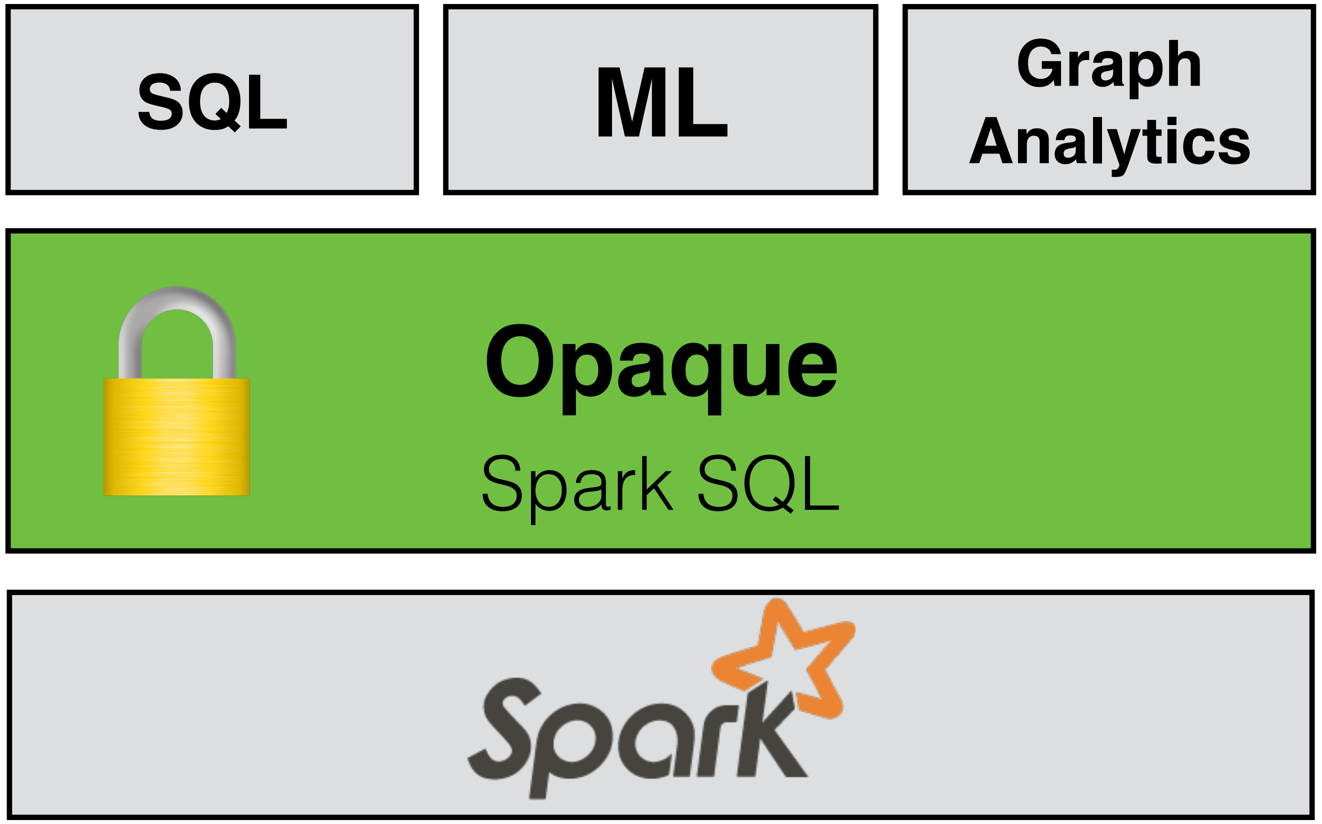
Overhead: 21x to 45x

PageRank: comparison with GraphSC (single machine)



Conclusion

Opaque is an oblivious and encrypted distributed analytics platform



Open source: github.com/ucbrise/opaque