Splinter: Practical Private Queries on Public Data

Frank Wang, Catherine Yun, Shafi Goldwasser, Vinod Vaikuntanathan (MIT CSAIL), and Matei Zaharia (Stanford)

Users regularly perform online searches

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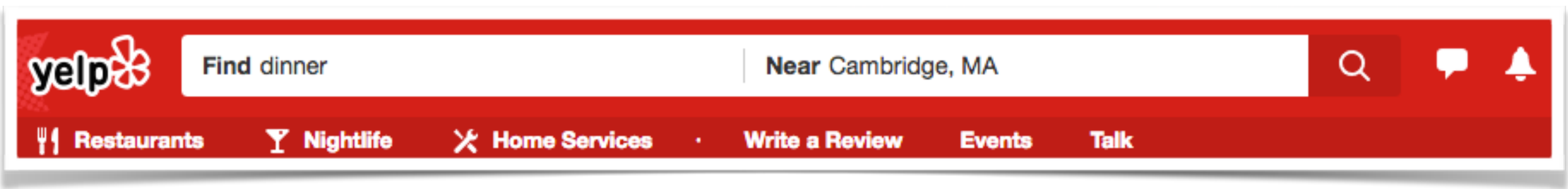

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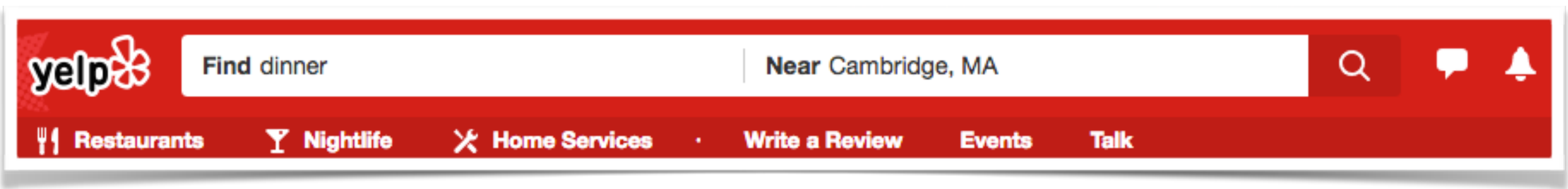

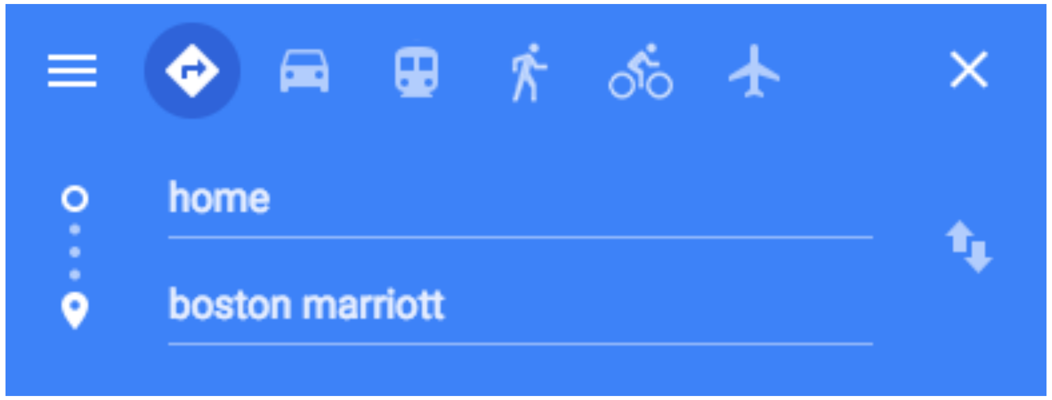

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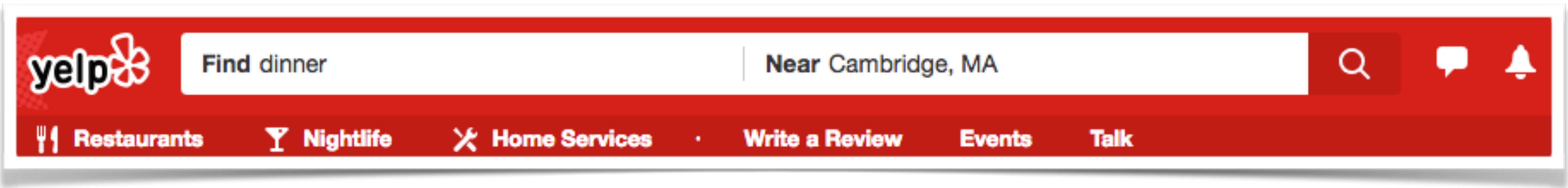

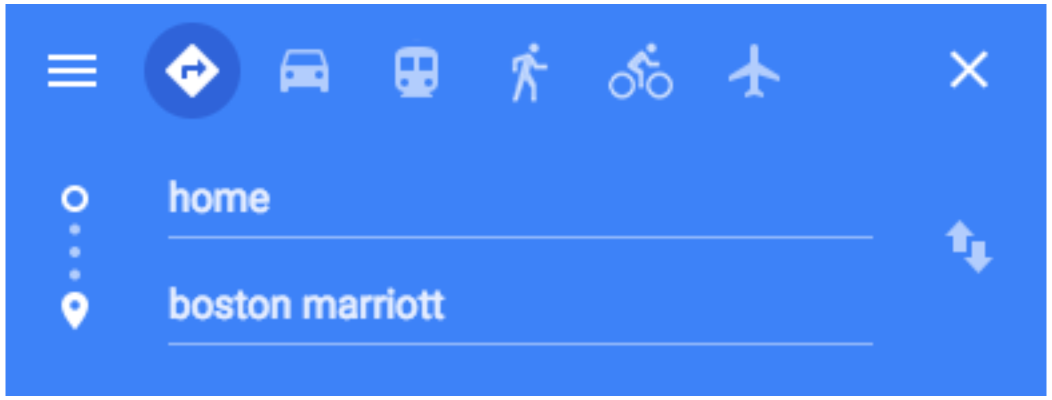

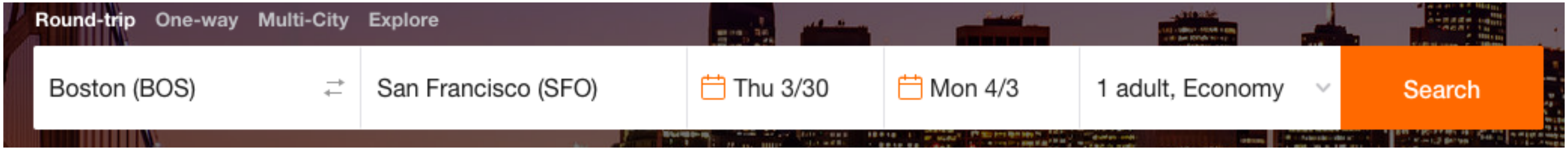

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by Drew Macomber | Jan 15, 2013 | 12 comments

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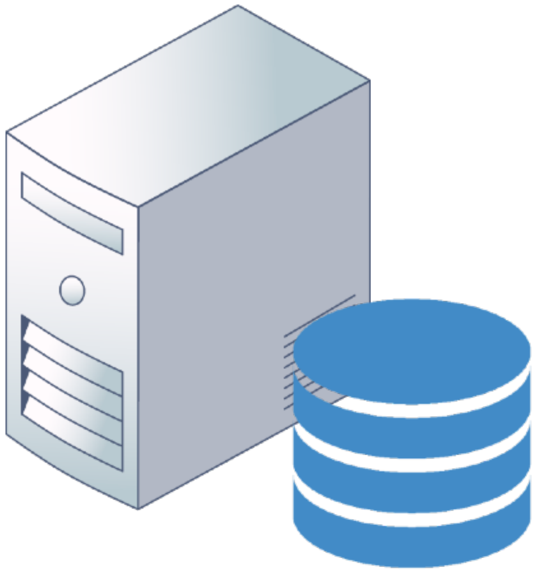
LILY HAY NEWMAN SECURITY 12.31.16 7:00 AM

THE YEAR'S BIGGEST HACKS, FROM YAHOO TO THE DNC

Naive Approach



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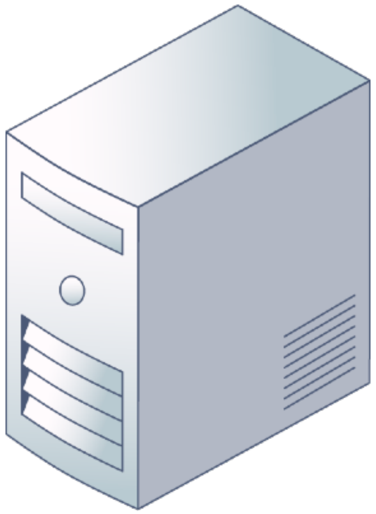

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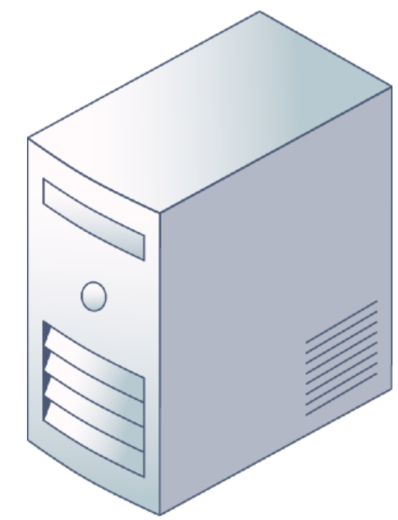

Problem: Large databases and user has to re-download on updates.

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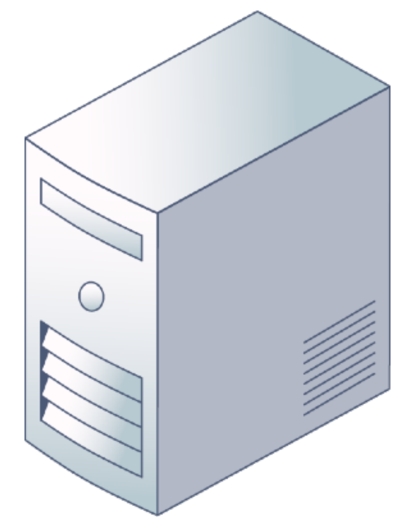


Problem: Large databases and user has to re-download on updates.

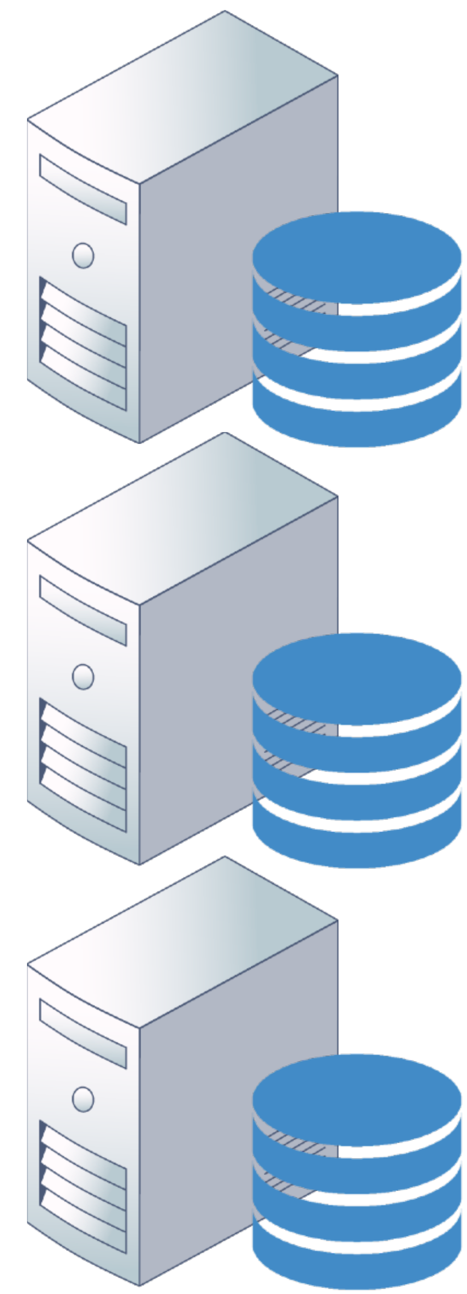
How do we build a practical system that keeps user queries private?

Splinter Design

Splinter Design

User

Providers



Splinter Design

Providers

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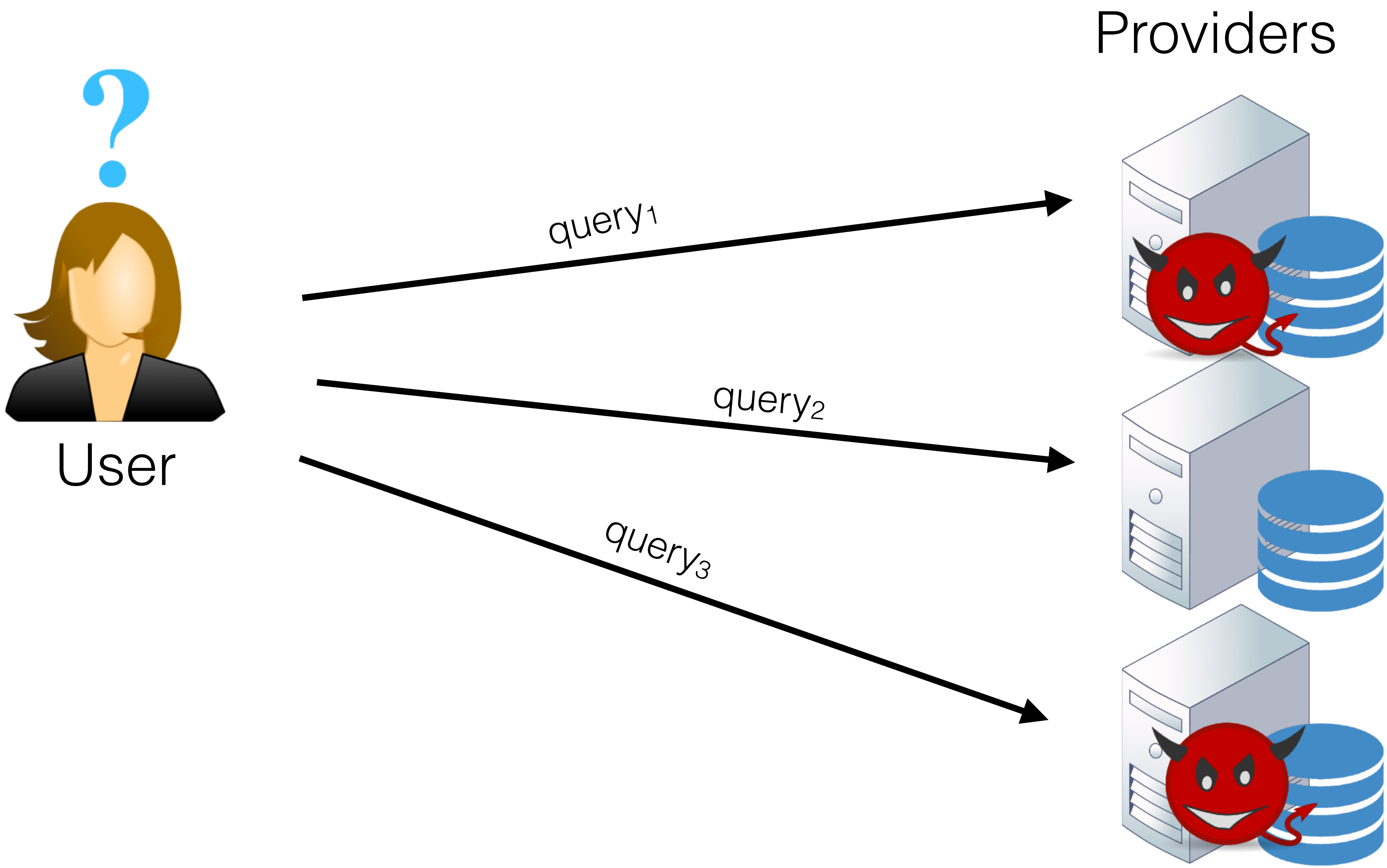

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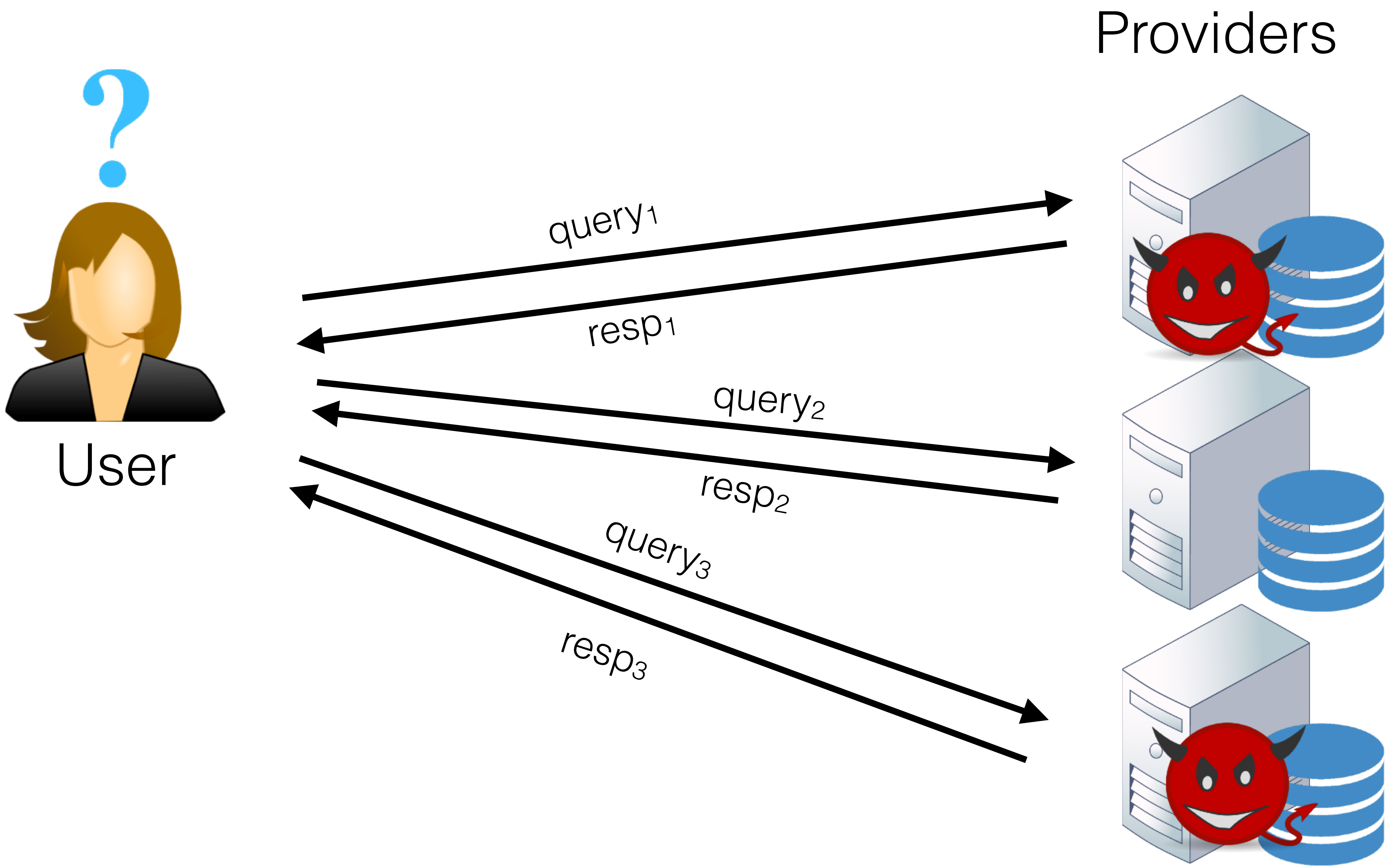

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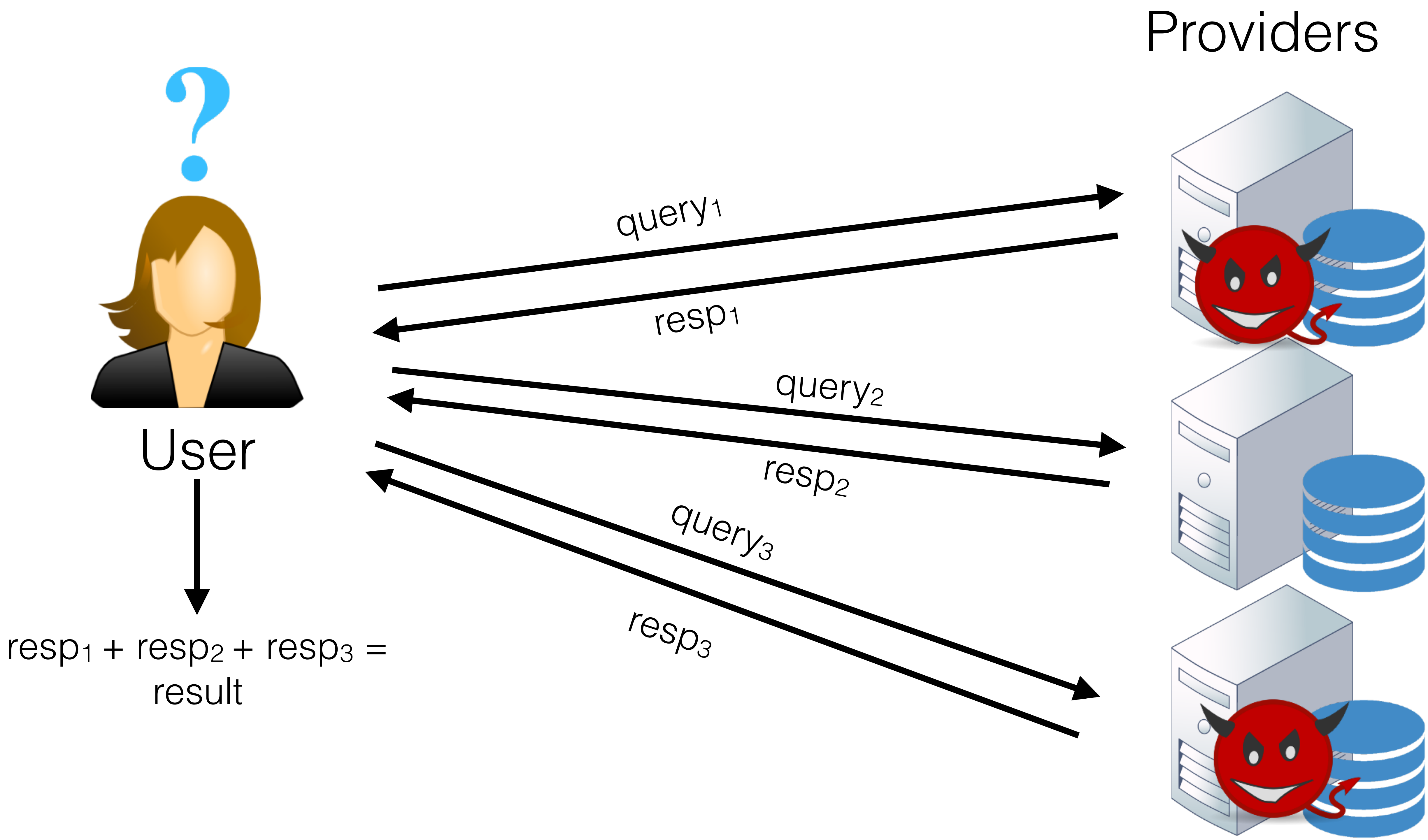

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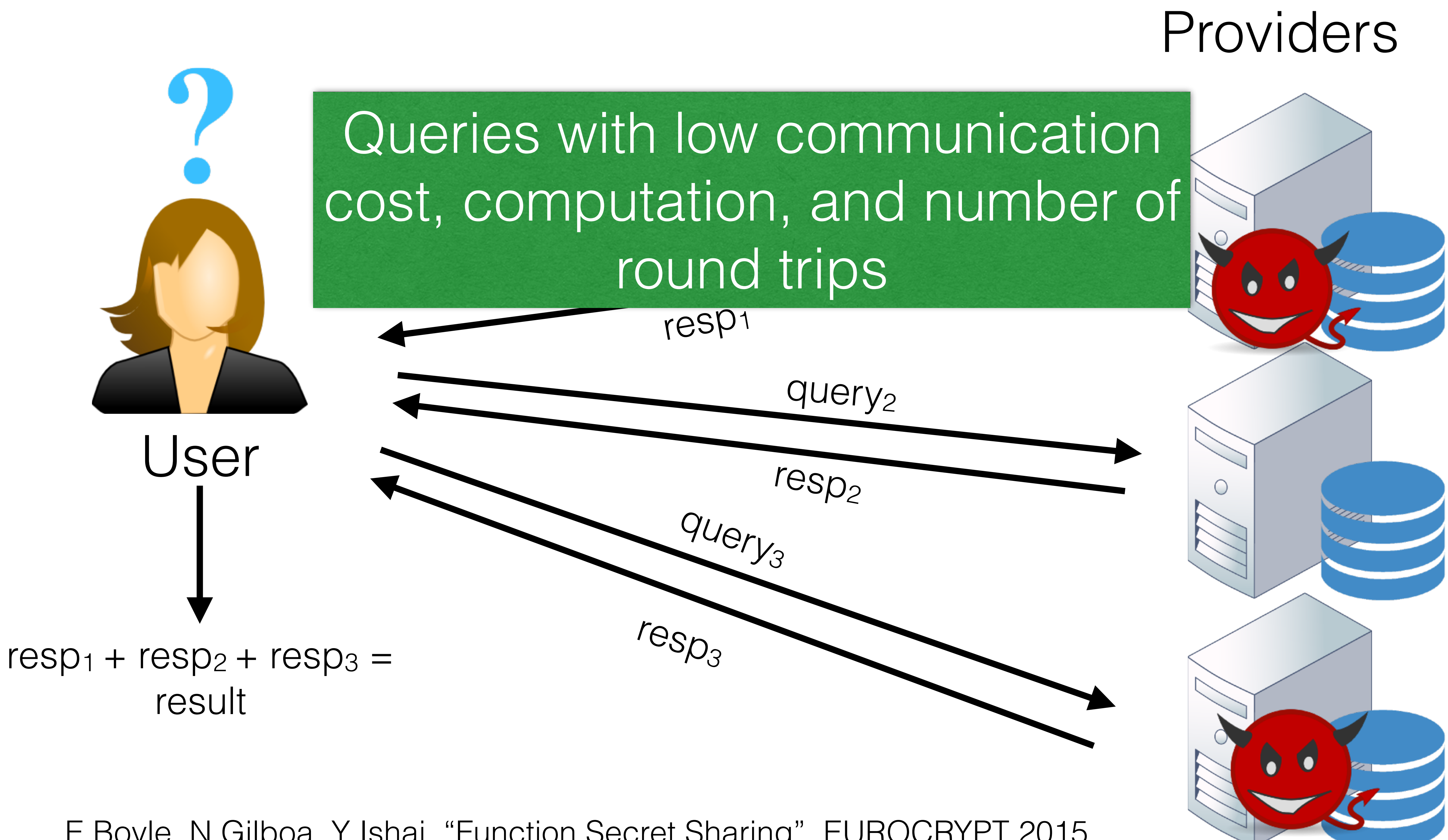

E Boyle, N Gilboa, Y Ishai. “Function Secret Sharing”. EUROCRYPT 2015

Threat Model

- Data on the providers not sensitive and in cleartext
- Providers are passive adversaries
    - Try to learn user's query
    - Cannot tamper with query or database
- At least one provider does not collude with others

Performance

- Response times of **< 1.6 seconds** for databases with millions of records (NYC map, US flights, etc.)
- Up to **10x fewer** round trips than prior systems that use PIR and garbled circuits

Key Contributions

Splinter builds on Function Secret Sharing (FSS) to divide queries into opaque shares

- **New protocols** to run complex queries, such as MAX, TOPK, and disjunctions, over FSS
- **Optimized implementation** of FSS protocol using AES-NI instruction

Outline

- Splinter Queries
- Implementation
- Evaluation

Query Format

- Splinter supports a subset of SQL: projections, limiting filters, aggregates, no joins

```
SELECT aggregate1, aggregate2, … | projections
FROM table
WHERE condition
[GROUP BY expr1, expr2, …]
[ORDER BY expr1, expr2, …]
[LIMIT k]
```

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Supported conditions

- Splinter query algorithm for aggregates depends on condition type

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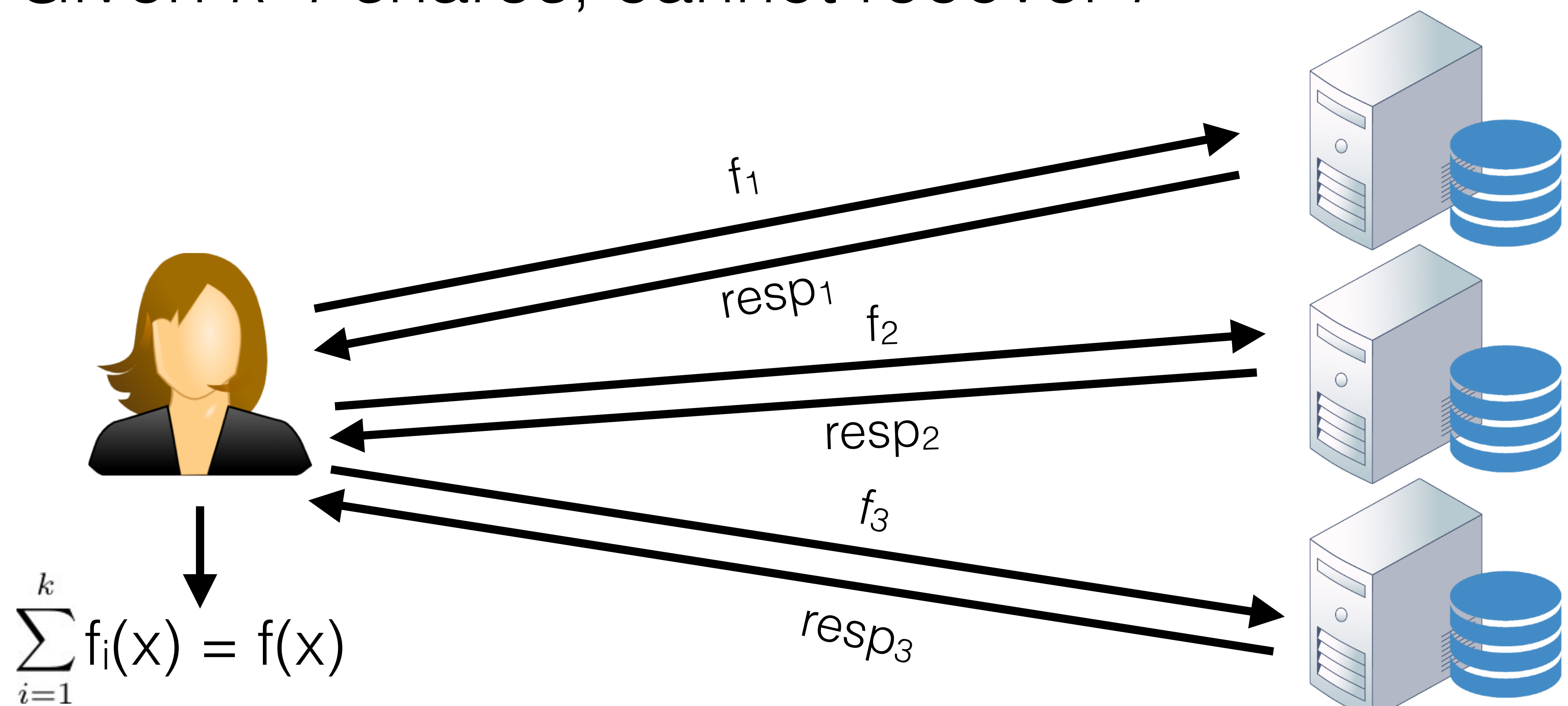
Condition	Form
Equality-only	e_1 = $secret_1$ AND … AND e_n = $secret_n$
Intervals	$secret_1 \leq e_1 \leq secret_2$
Disjoint ORs	c_1 OR … OR c_n (c_i can be equality or interval condition)

FSS Properties

- Divides a function f into k shares, f_i, such that:
  - f_i can be evaluated quickly
  - $\sum_{i=1}^{k} f_i(x) = f(x)$
  - Given k-1 shares, cannot recover f



FSS Properties

- Efficient constructions exist for two cases:
  - Point functions: **f(x) = 1** if x = a, **0** otherwise
  - Interval functions: **f(x) = 1** if a ≤ x ≤ b, **0** otherwise

COUNT Query

COUNT Query

route	price
5	8
2	8
5	9
3	4
2	7

COUNT Query

```
SELECT COUNT(*) where route = 5
```

route	price
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COUNT Query

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function shares: $\mathbf{f_1}$, $\mathbf{f_2}$

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$f_1(x) + f_2(x) = f(x)$

route	price
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Having either f_1 or f_2 does **not** reveal any information about f

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`SELECT COUNT(*) where route =` $\boxed{?}$

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route	**price**	f_1(route)	f_2(route)
5	8	10	-9
2	8	-3	3
5	9	10	-9
3	4	7	-7
2	7	-3	3

Having either f_1 or f_2 does **not** reveal any information about f

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route	**price**	f_1(route)	f_2(route)
5	8	10	-9
2	8	-3	3
5	9	10	-9
3	4	7	-7
2	7	-3	3
		21	-19

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2	7	-3	3

21 + -19 = 2

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route	**price**	f_1(route)	f_2(route)	
5	8	10	-9	= 1
2	8	-3	3	
5	9	10	-9	= 1
3	4	7	-7	
2	7	-3	3	
		21	+ -19	= 2

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route	**price**	f_1(route)	f_2(route)	
5	8	10	-9	
2	8	-3	3	= 0
5	9	10	-9	
3	4	7	-7	= 0
2	7	-3	3	= 0
		21	+ -19	= 2

Having either f_1 or f_2 does **not** reveal any information about f

SUM Query

```
SELECT SUM(price) where route = ?
```

FSS

$\mathbf{f(x) = 1}$ if $x = 5$ and $\mathbf{0}$ otherwise

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```

FSS

f(x) = 1 if x = 5 and **0** otherwise

→ function shares: $\mathbf{f_1}$, $\mathbf{f_2}$

route	**price**	f_1(route)***price**	f_2(route)***price**
5	8	80	-72
2	8	-24	24
5	9	90	-81
3	4	28	-28
2	7	-21	21

SUM Query

```
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```

FSS

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Scale matching records by price

route	**price**	f_1(route)***price**	f_2(route)***price**
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2	7	-21	21
		153	+ -136 = 17

MIN Query for Equality-Only

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route	price
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```
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MIN Query for Equality-Only

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→ function shares: $\mathbf{f_1}$, $\mathbf{f_2}$

```
SELECT MIN(price)
GROUP BY route
```

Intermediate table

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5	8
2	8
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MIN Query for Equality-Only

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5	8
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→

Intermediate table

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SELECT MIN(price) where route = ?
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```
SELECT MIN(price)
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```

route	price
5	8
2	8
5	9
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Intermediate table

route	MIN(price)	
5	8	$f_i(route_1)$ * $MIN(price)_1$
2	7	$f_i(route_2)$ * $MIN(price)_2$
3	4	$f_i(route_3)$ * $MIN(price)_3$

MIN Query for Equality-Only

```
SELECT MIN(price) where route = ?
```

FSS

f(x) = 1 if x = 5 and **0** otherwise

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SELECT MIN(price)
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```

route	price
5	8
2	8
5	9
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Intermediate table

route	MIN(price)
5	8
2	7
3	4

$f_i(\text{route}_1) * \text{MIN(price)}_1$

$+$

$f_i(\text{route}_2) * \text{MIN(price)}_2$

$+$

$f_i(\text{route}_3) * \text{MIN(price)}_3$

MIN Query for Intervals

```
SELECT MIN(price) where 2 ≤ route ≤ 6
```

MIN Query for Intervals

```
SELECT MIN(price) where ? ≤ route ≤ ?
```

MIN Query for Intervals

```
SELECT MIN(price) where [?] ≤ route ≤ [?]
```

1. Each provider computes a sorted table T:

```
SELECT route, price ORDER BY route
```

MIN Query for Intervals

`SELECT MIN(price) where ? ≤ route ≤ ?`

1. Each provider computes a sorted table T:

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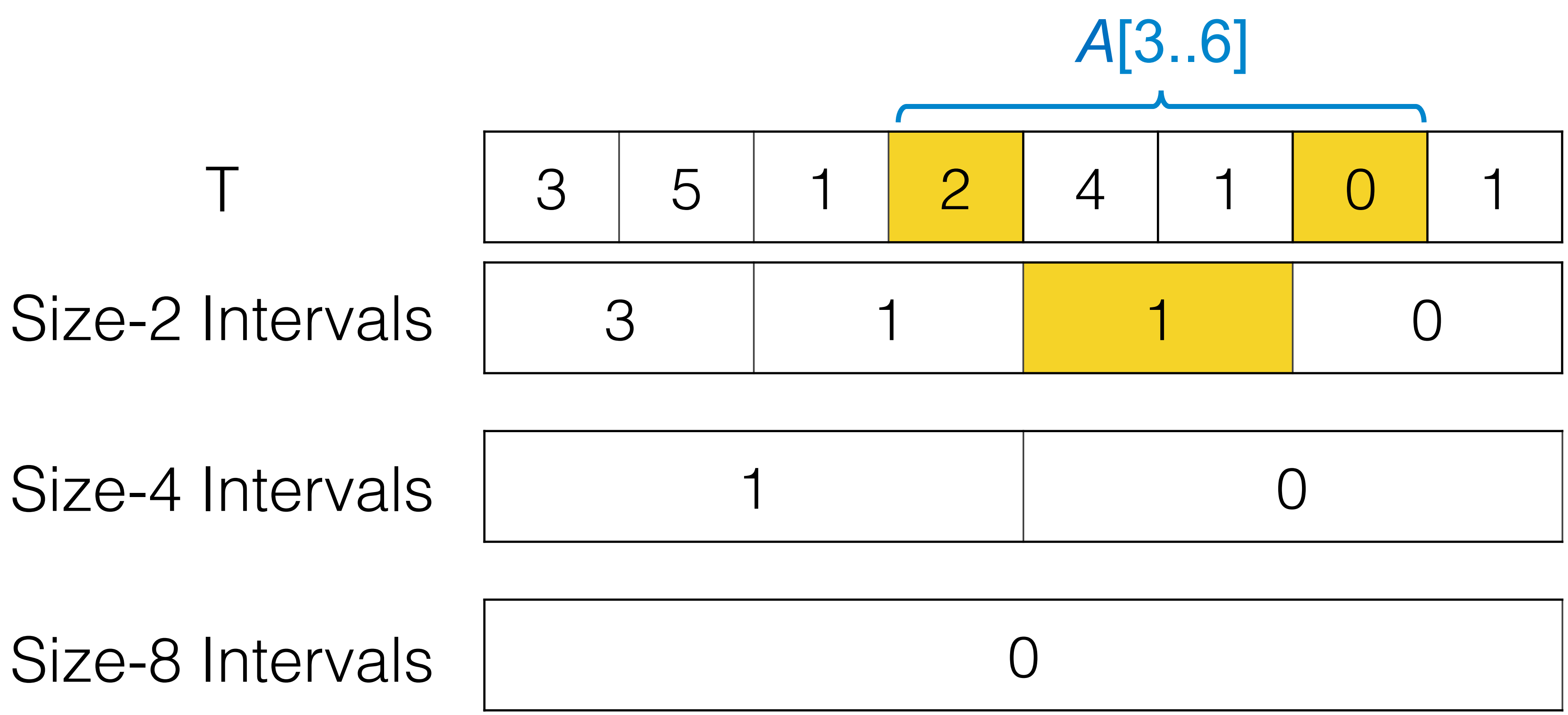
2. Providers find MIN on power-of-2 intervals:

<table>
<tr><td>T</td><td>3</td><td>5</td><td>1</td><td>2</td><td>4</td><td>1</td><td>0</td><td>1</td></tr>
<tr><td>Size-2 Intervals</td><td colspan="2">3</td><td colspan="2">1</td><td colspan="2">1</td><td colspan="2">0</td></tr>
<tr><td>Size-4 Intervals</td><td colspan="4">1</td><td colspan="4">0</td></tr>
<tr><td>Size-8 Intervals</td><td colspan="8">0</td></tr>
</table>

MIN Query for Intervals

3. Round 1: Find minimum and maximum indices where $3 \leq$ route ≤ 6. (2 point funcs)

4. Round 2: Select at most 2 intervals of each size to cover target interval (e.g. [3,6]). (log n point funcs)



Other algorithms

Algorithms	Supported queries
FSS	additive aggregates for all conditions (COUNT, SUM, AVG, STDEV, HISTOGRAM)
FSS + intermediate table	MAX, MIN, TOPK for equality-only
FSS + Fenwick tree-like data structure	MAX, MIN, TOPK for intervals
FSS + private binary search	MAX, MIN for disjoint ORs
FSS + private binary search + sampling	TOPK for disjoint ORs

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Complexity of Splinter algorithms

Aggregate	Condition	Computation	Round Trips	Bandwidth
Sum-based	any	O(n)	1	O(1)
MAX/MIN	equality-only	O(n)	1	O(1)
MAX/MIN	intervals	O(n log n)	2	O(log n)
MAX/MIN	disjoint ORs	O(n log n)	O(log n)	O(log n)
TOPK	equality-only	O(n)	1	O(1)
TOPK	intervals	O(n log n)	2	O(log n)
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TOPK	disjoint ORs	O(n log n)	O(log n)	O(log n)

Computation time is O(n log n) for all queries and communication costs much smaller than the database

Implementation

- Optimized FSS C++ library: 2000 LoC
- General Query Library: 1500 LoC
- Applications
  - Yelp clone, Flight search, Map routing

https://github.com/frankw2/libfss

Case Studies

Application	# of rows	Size (MB)
Yelp clone	225,000	23
Flight search	6,100,000	225
NYC Map Routing	260,000 nodes 733,000 edges	300

Providers: 64-core x1 Amazon EC2 instance
Client: 2 GHz Intel Core i7 machine
Network latency: 14 ms

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All case studies based on real datasets

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Case Study Queries

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Yelp clone	• `SELECT COUNT(*) WHERE category="Thai"` • `SELECT TOP 10 restaurant WHERE category="Mexican" AND hex2mi in (1, 2, 3) ORDER BY stars` • `SELECT restaurant, MAX(stars) WHERE category in ("Mexican", "Chinese", "Indian", "Greek", "Thai", "Japanese") GROUP BY category`

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Flight search	• `SELECT AVG(price) WHERE month=3 AND route = 5` • `SELECT TOP 10 flight_no WHERE route = 5 ORDER BY price`
Map routing	• `SELECT grid_nodes WHERE grid_no = 5` • `SELECT path WHERE src = 4 and dst = 10`

Performance

Query	Dataset	Providers	Round Trips	Communication	Response Time
Count of Thai Restaurants	Yelp	2 3	1	3 KB 30 KB	57 ms 52 ms
Top 10 Mexican restaurants	Yelp	2 3	1	24 KB 2 MB	150 ms 542 ms
Best rated restaurant in category subset	Yelp	2 3	11	245 KB 1.2 MB	1.3 s 1.6 s
AVG monthly price	Flights	2 3	1	9 KB 450 KB	1.0 s 1.2 s
Top 10 cheapest flights	Flights	2 3	1	4 KB 20 KB	30 ms 39 ms
NYC Routing	Maps	2 3	2	45 KB 725 KB	1.2 s 1.0 s

Splinter has lower response times and fewer rounds trips compared to Olumofin et al.

System	Round Trips	Response Times
Olumofin et al.	log n (all queries)	2-18 seconds
Splinter	constant (most queries) log n (select queries)	50 ms - 1.6 seconds

Other related work:

- PIR systems (Readon et al., Popcorn)
- Garbled circuits (Wu et al., Embark)

Conclusion

- Splinter is the first practical system that protects users' queries on real datasets
- We develop new protocols to execute complex queries over FSS and have fewer round trips and lower response times than prior systems