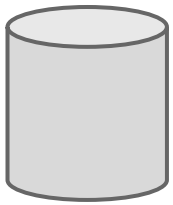
Parallelizing user-defined aggregations using symbolic execution

Veselin Raychev ETH Zurich
Madanlal Musuvathi Microsoft Research
Todd Mytkowicz Microsoft Research

Goal

Answer questions with Big Data

Example:
query logs



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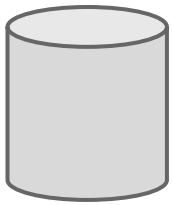

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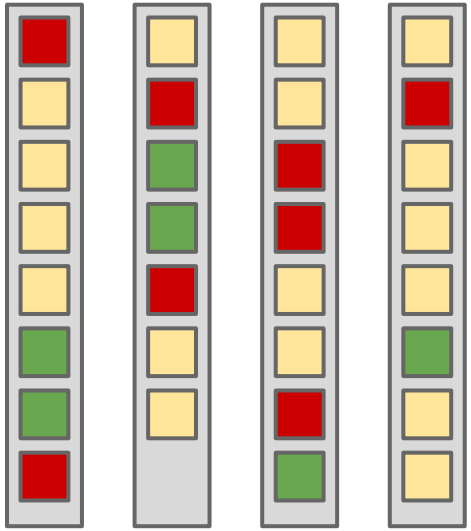

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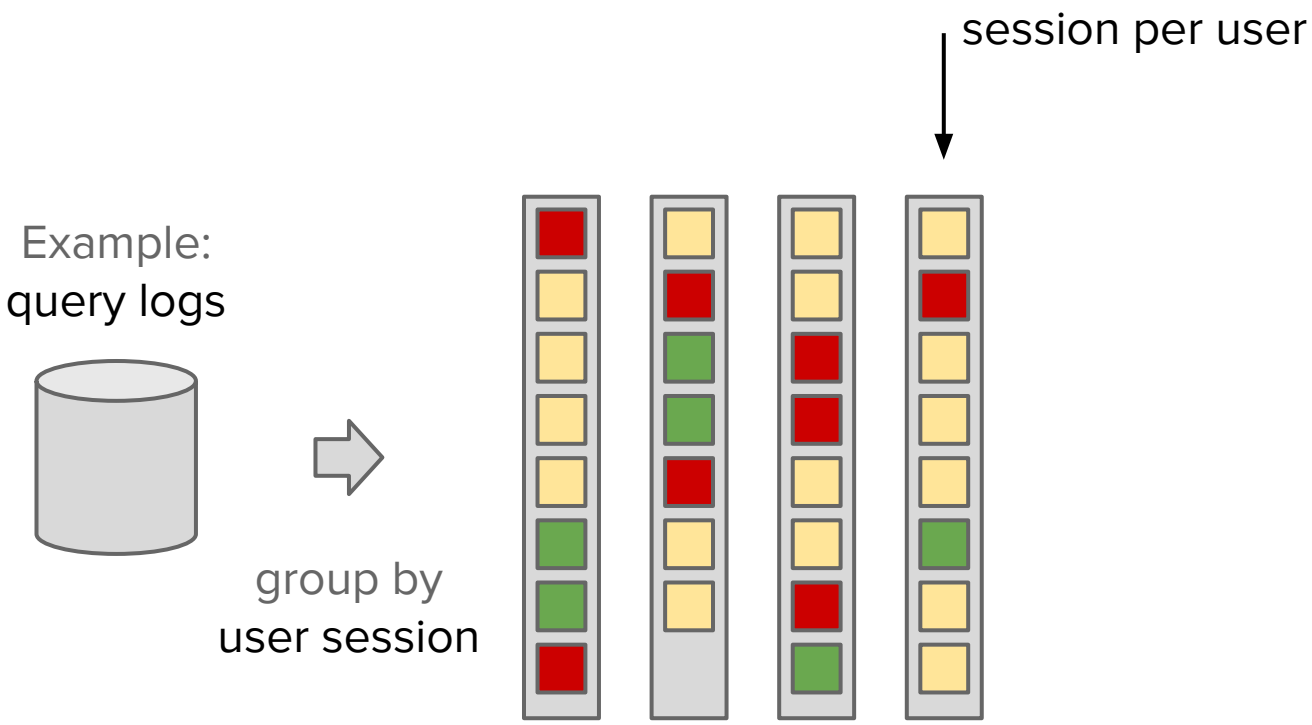

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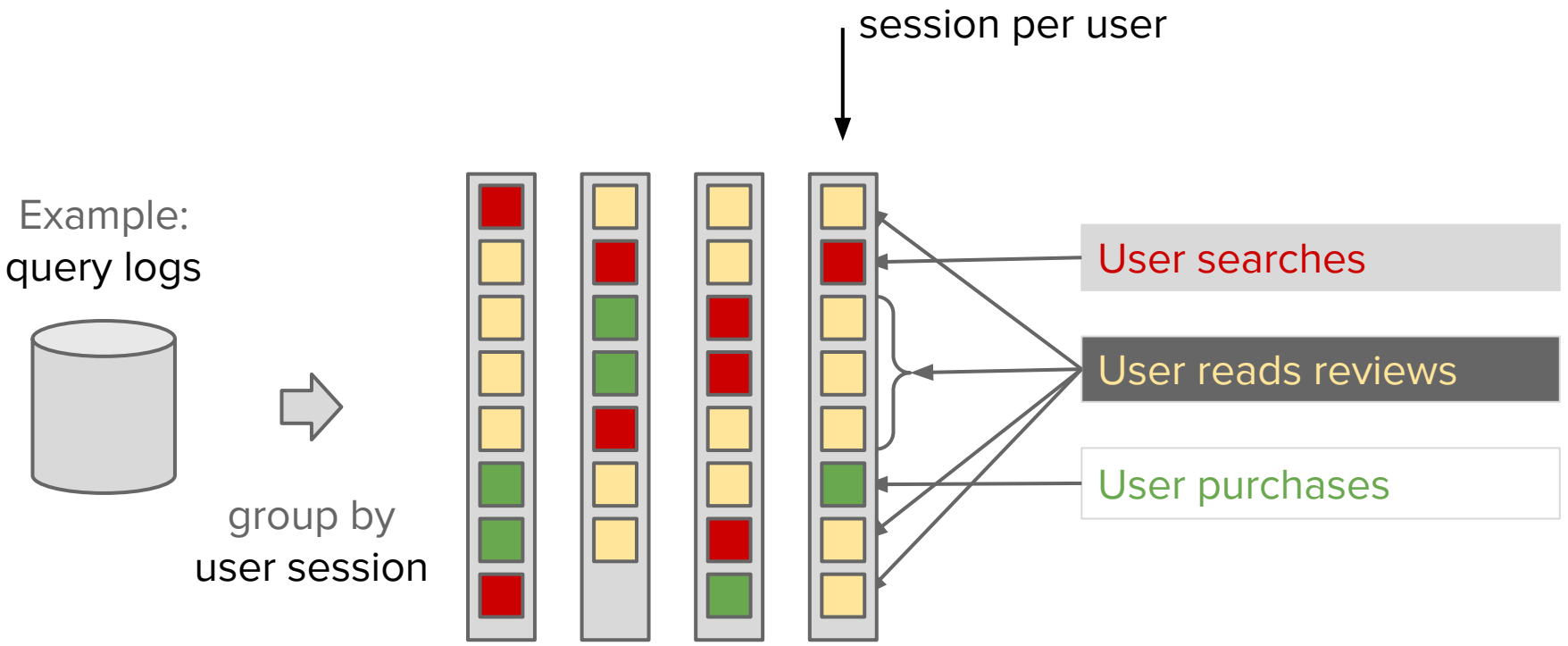

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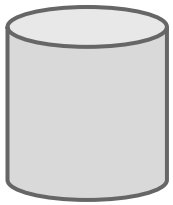

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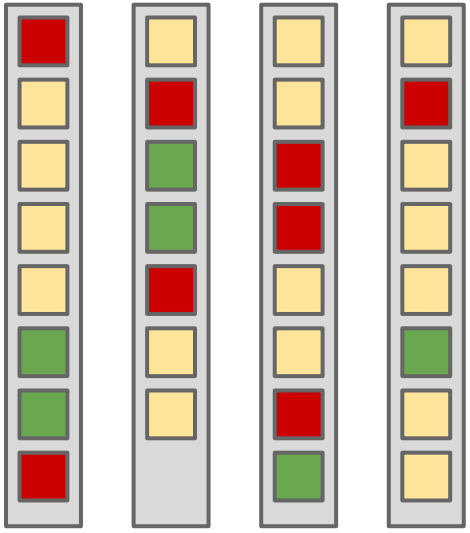

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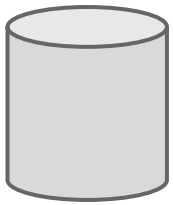

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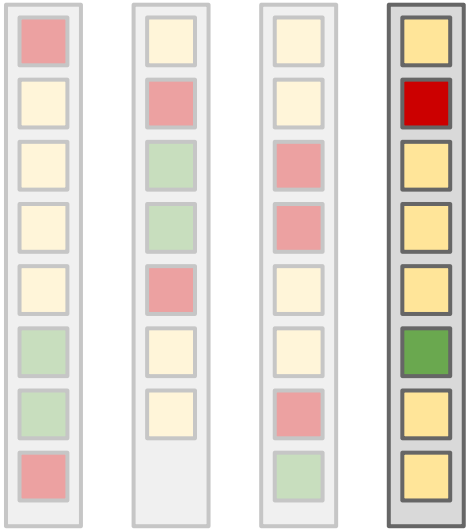

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Queries

1. Number of reviews per user session

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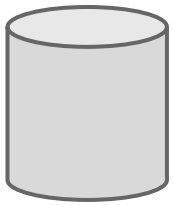

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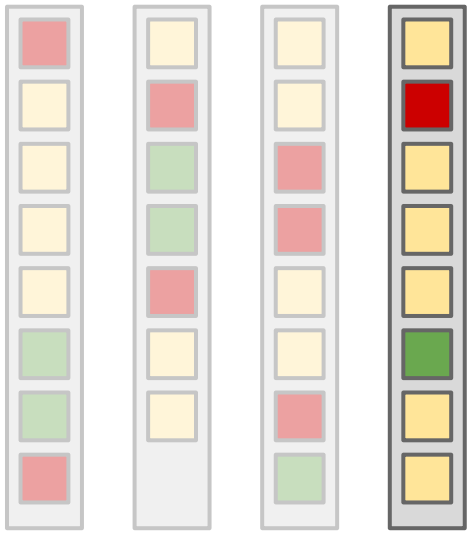

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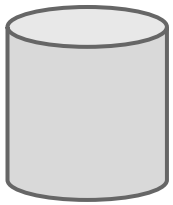

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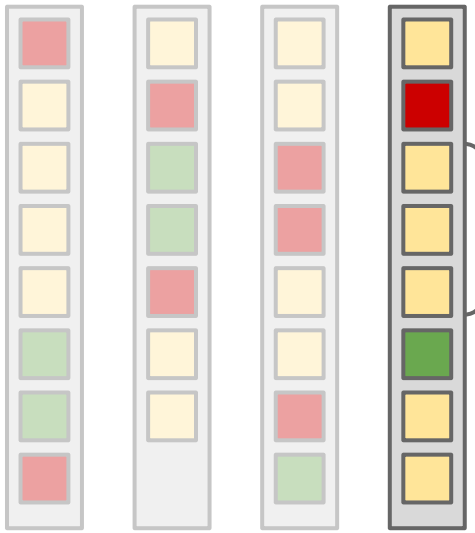

1. Number of reviews per user session

2. Number of reviews between a search and a purchase

Goal

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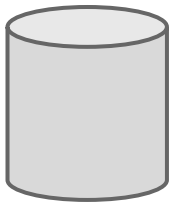

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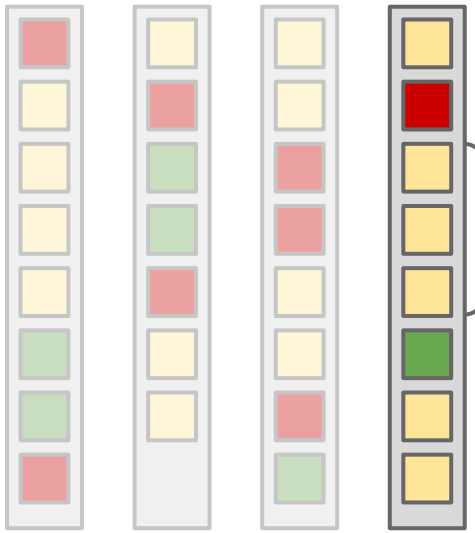

1. Number of reviews per user session
2. Number of reviews between a search and a purchase
3. Time between a search and a purchase
4. Searches not followed by a purchase

What we do?

Parallelize such queries on

a sequence of records

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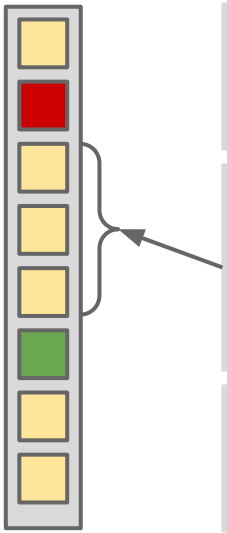
Queries



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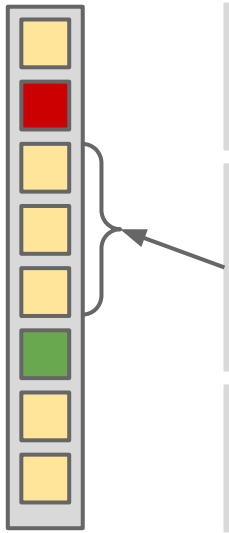

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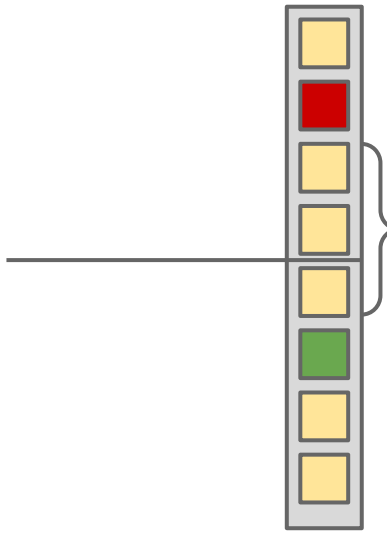

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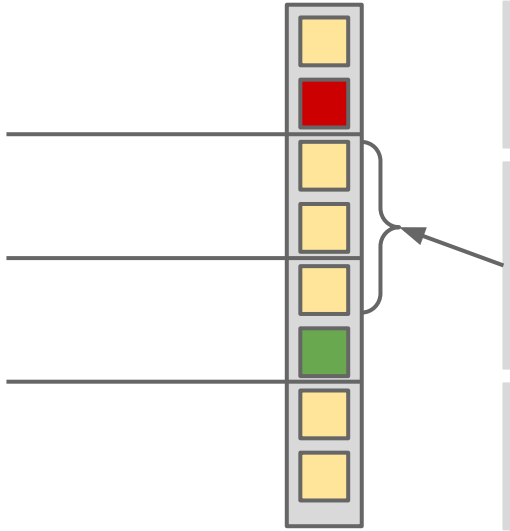

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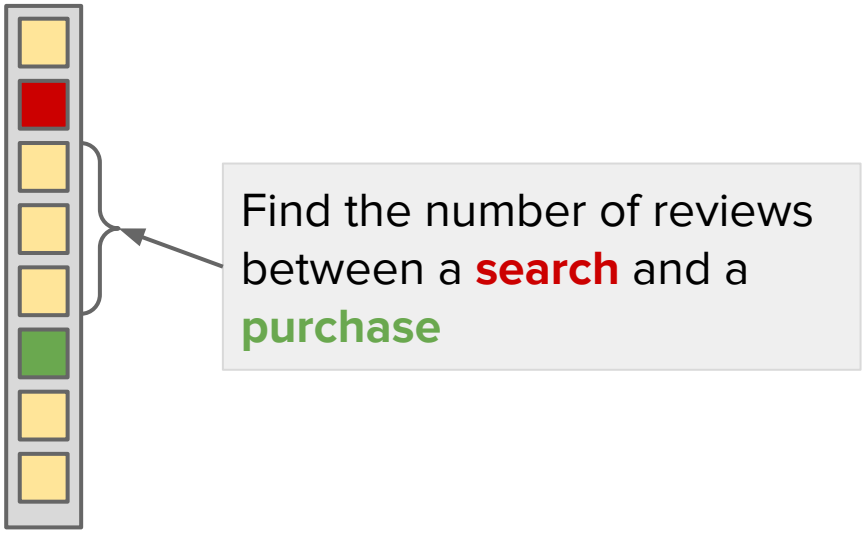
Using SYMPLE

Example query



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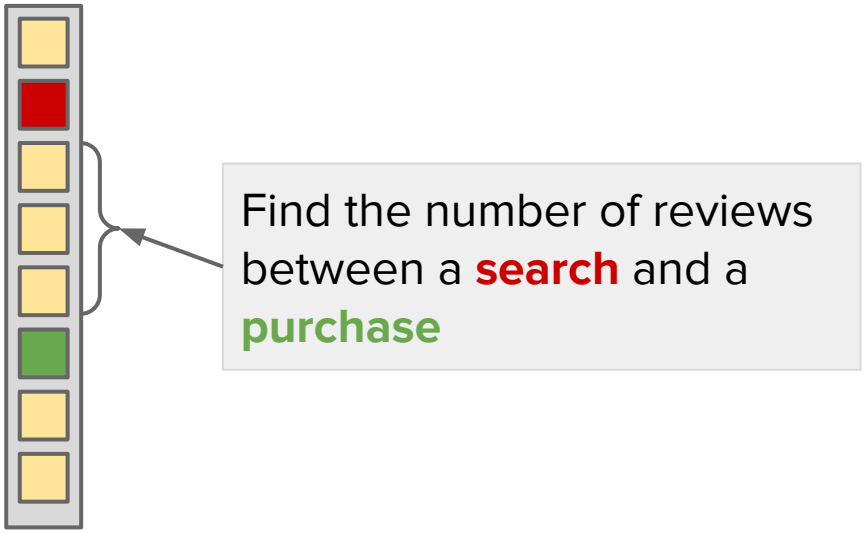


```
foreach record in user records:
    switch record.type:
        case SEARCH:
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        case PURCHASE:
```
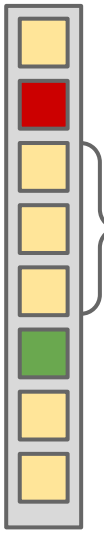

Using SYMPLE

Example query

```
int num_reviews = 0;
```



Find the number of reviews between a **search** and a **purchase**

```
foreach record in user records:
    switch record.type:
        case SEARCH:        num_reviews = 0;
        case REVIEW:        num_reviews++;
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Using SYMPLE

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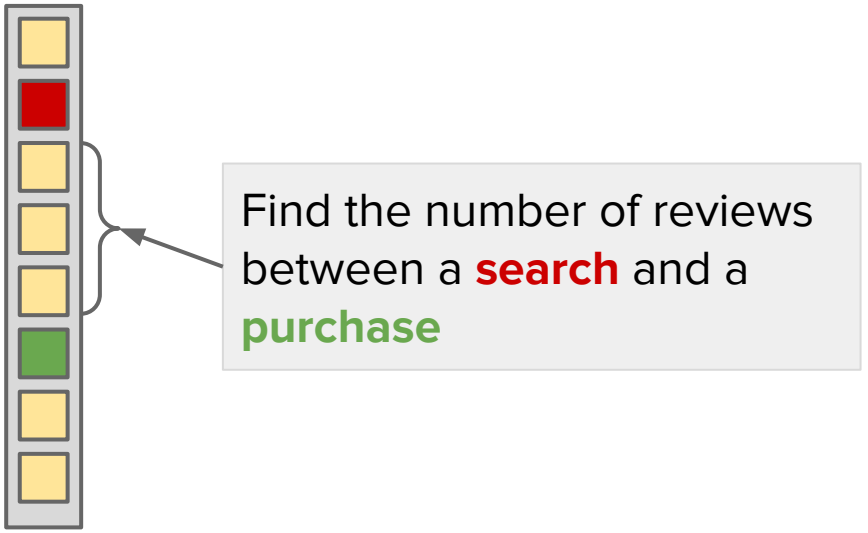


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int num_reviews = 0;
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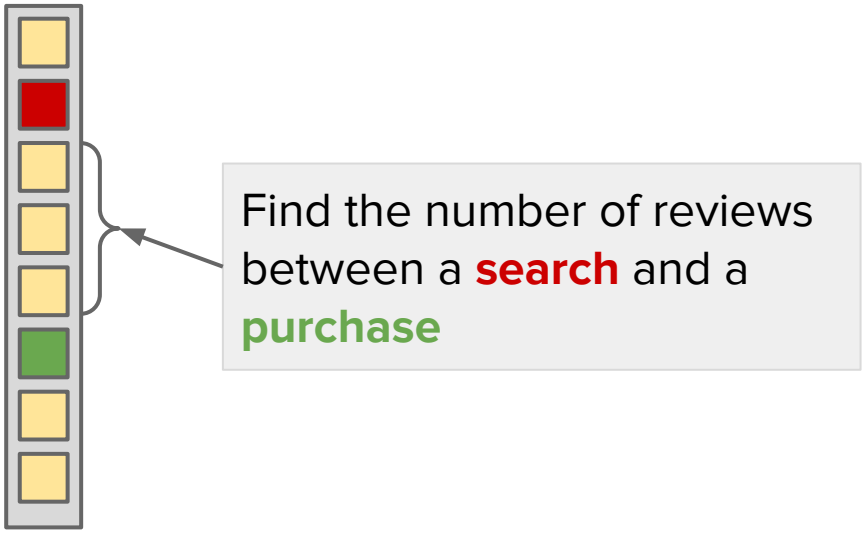


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int num_reviews = 0;
bool search_done = false;
vector<int> result;
```

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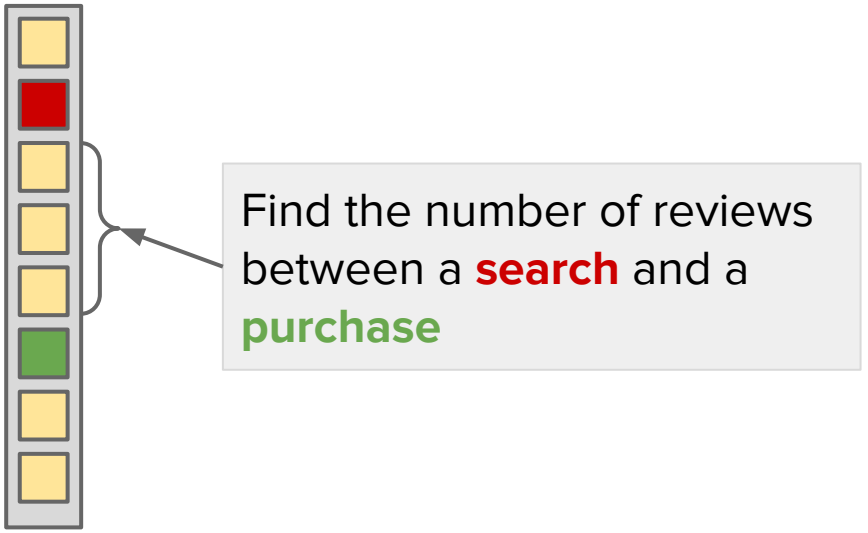

SymInt num_reviews = 0;

SymBool search_done = false;

SymVector<**SymInt**> result;

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Benefits:

- same code for sequential and parallel computation
- not introducing bugs
- easier maintenance

Outline

1. Symbolic parallelism

2. Data types

3. Evaluation

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Notation

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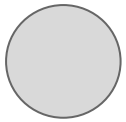

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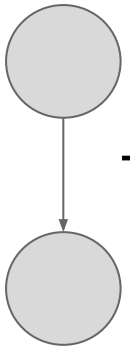

Transition for `record`

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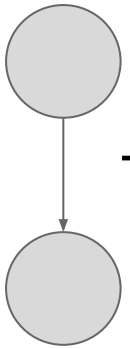

Transition for record

Next state: s′ = t(s)

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Why is this hard to parallelize?

Records

Initial state 

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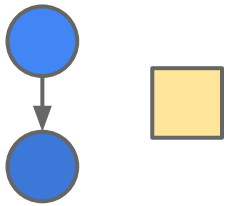

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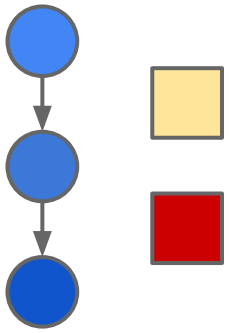

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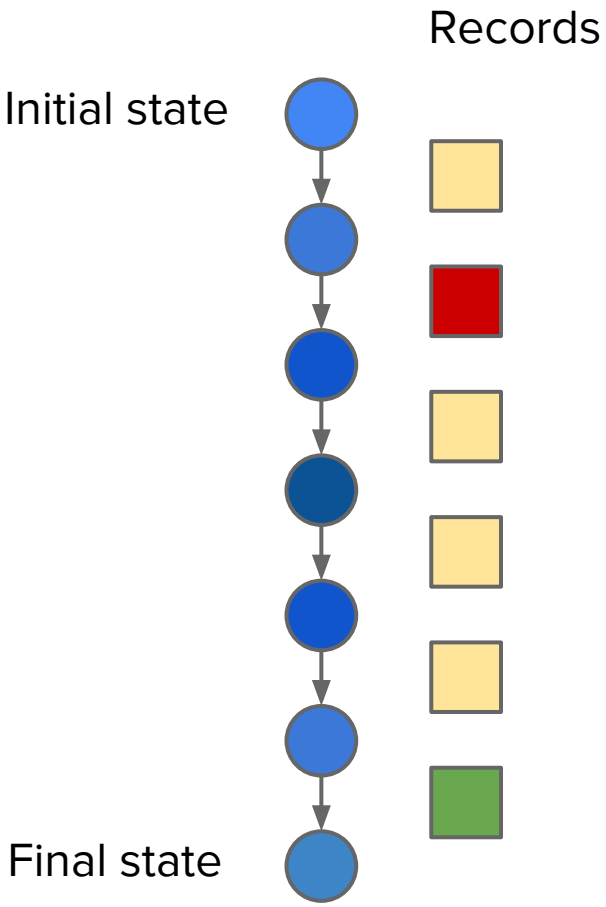

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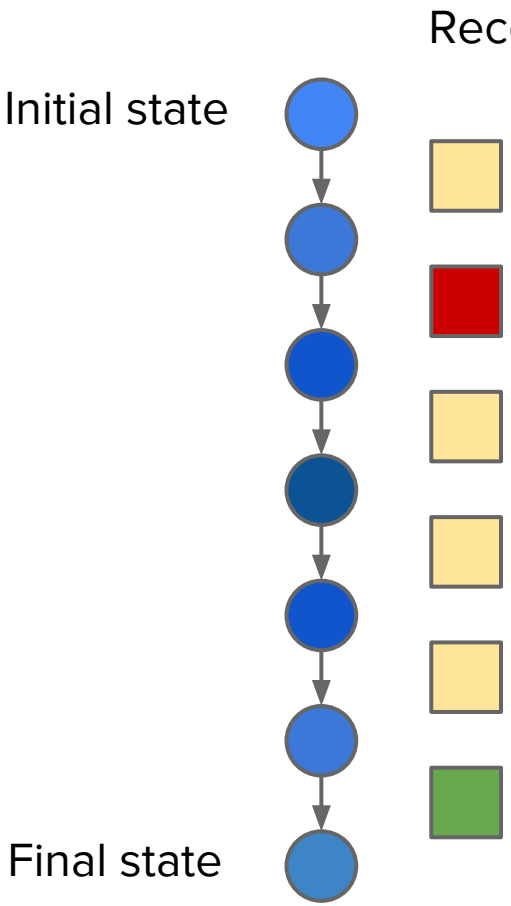

Data dependencies

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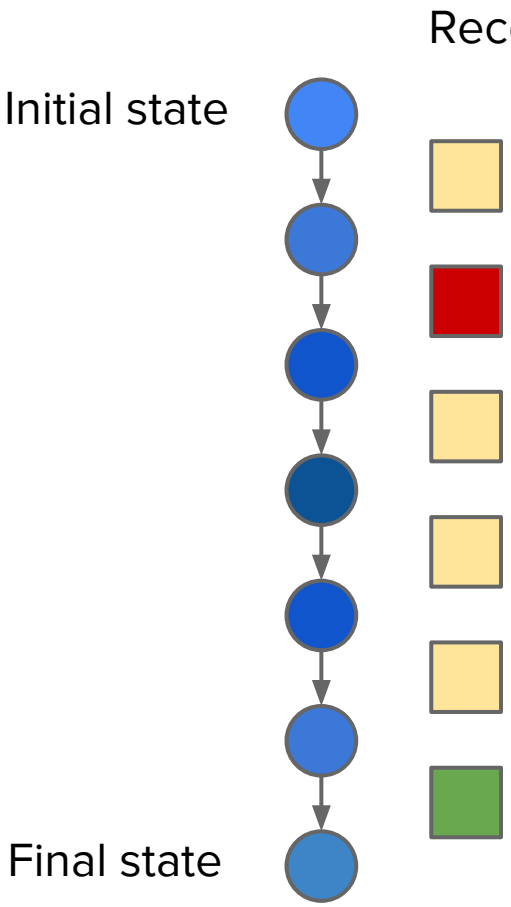
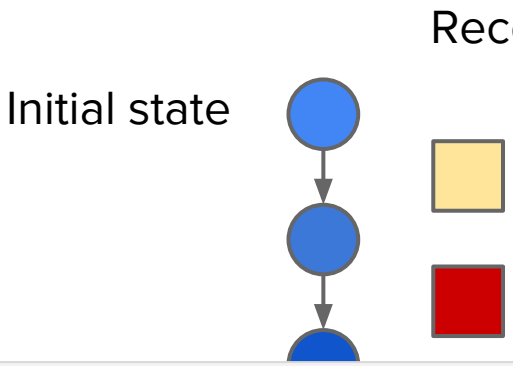


Data dependencies

Some systems include built-in aggregates that parallelize (`sum`, `max`)

Different computation based on **commutativity** and/or **associativity**

Why is this hard to parallelize?



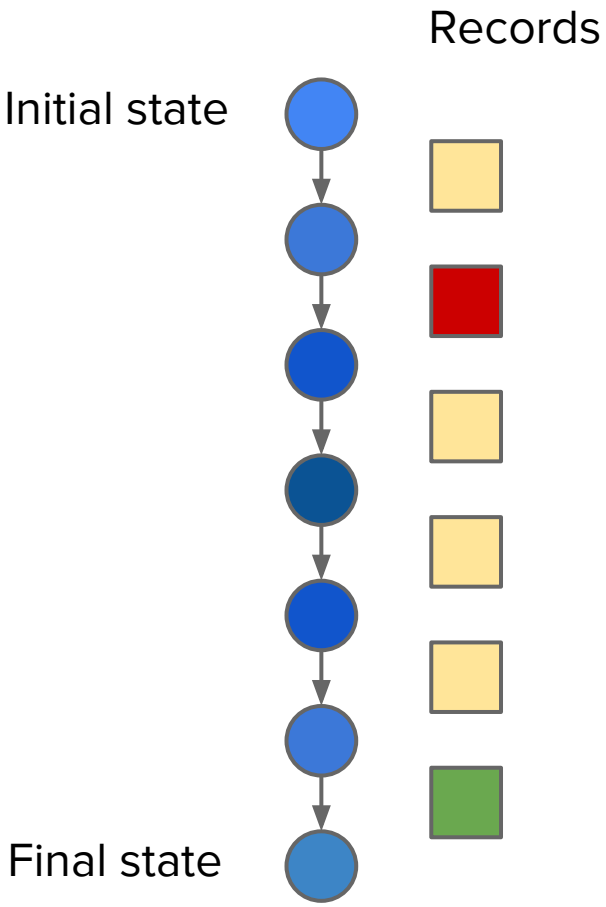
Data dependencies

But complex queries are
neither commutative, **nor associative**

Introducing symbolic parallelism

Reorganize computation to break dependencies

Introducing symbolic parallelism



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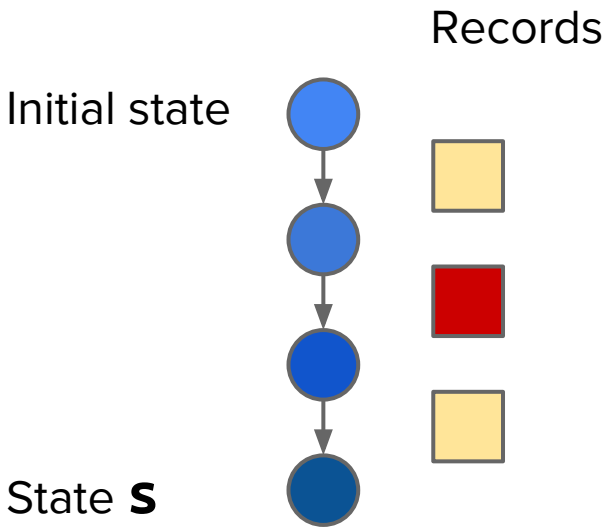

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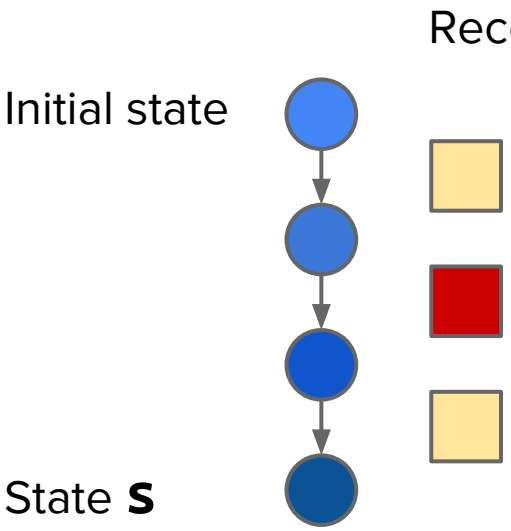

In parallel:

(Symbolic)
Unknown state **x**

Introducing symbolic parallelism

Records

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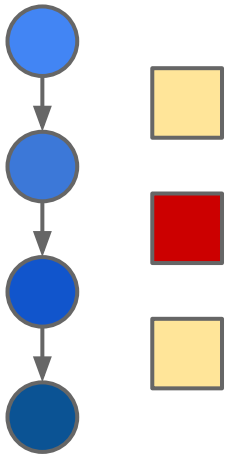

State **s**

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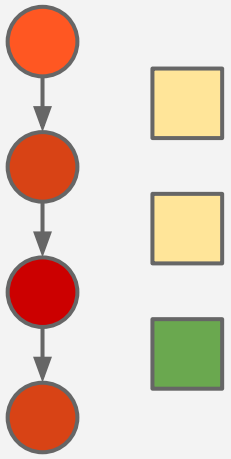

Introducing symbolic parallelism

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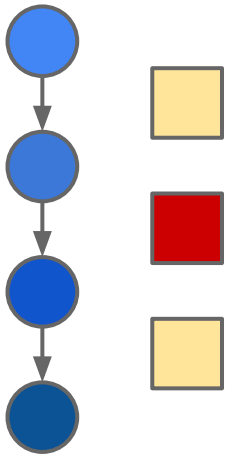

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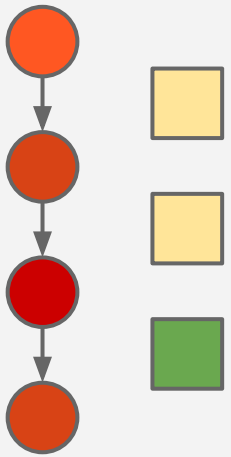

Result:

$t_{\blacksquare}(t_{\square}(t_{\square}(x)))$

Introducing symbolic parallelism

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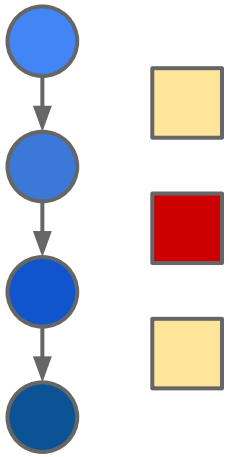

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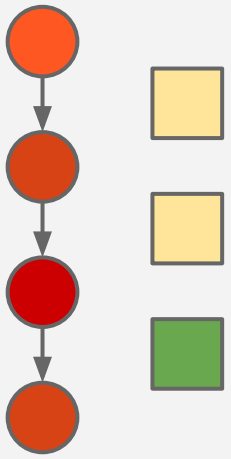

Result:

$t_{\blacksquare}(t_{\square}(t_{\square}(x)))$

Return the **function** on x

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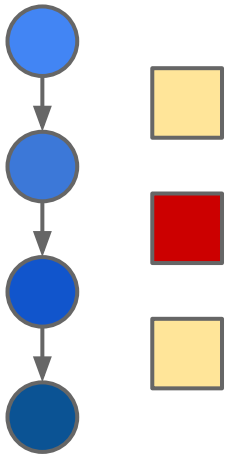


State **s**

Combine:

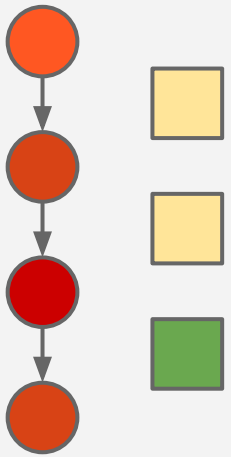
Final state:

$t_{\blacksquare}(t_{\square}(t_{\square}(s)))$

In parallel:

Records

(Symbolic)
Unknown state x



Result:

$t_{\blacksquare}(t_{\square}(t_{\square}(x)))$

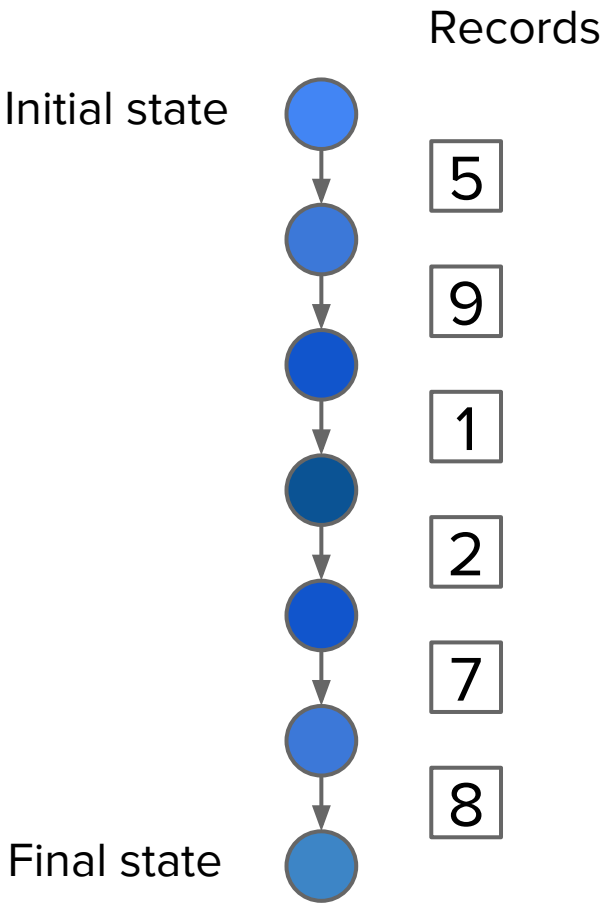
Return the **function** on x

Example aggregate: `max`

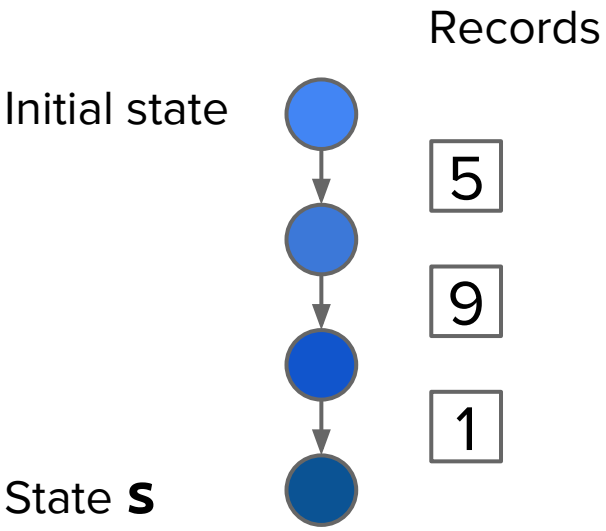
Implemented as:

```
if state < record then state = record
```

Example aggregate: `max`



Example aggregate: `max`



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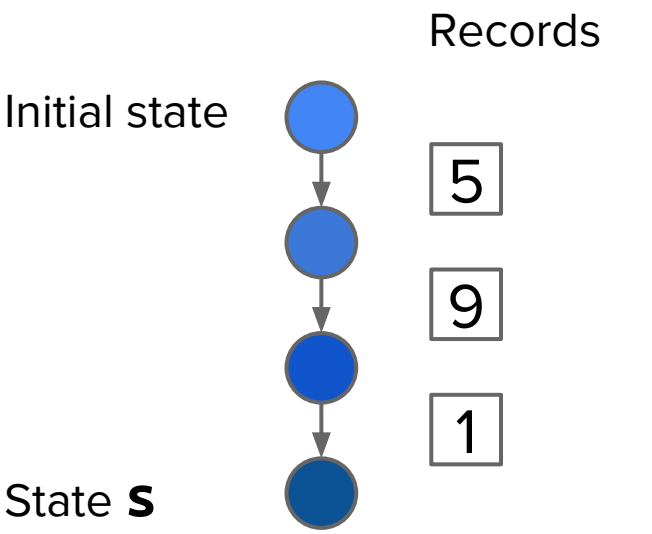
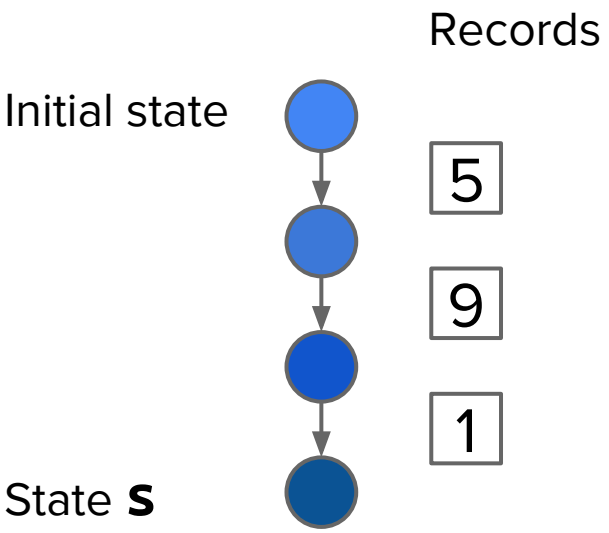


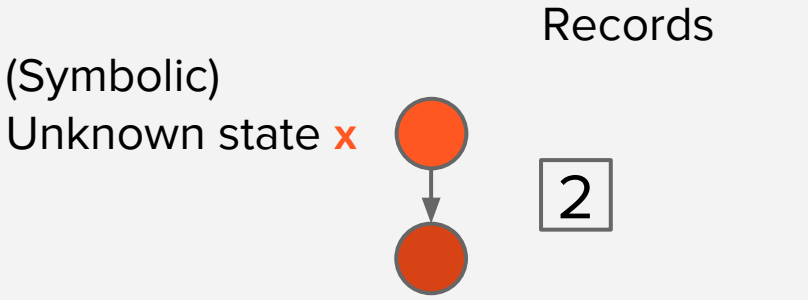
In parallel:

(Symbolic)
Unknown state **x**

Example aggregate: `max`



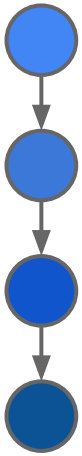
In parallel:



Example aggregate: `max`

Records

Initial state



5

9

1

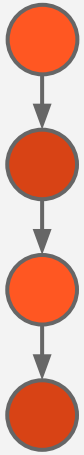
State **s**

In parallel:

Records

(Symbolic)
Unknown state x

```
if x<2
  then 2
else x
```



2

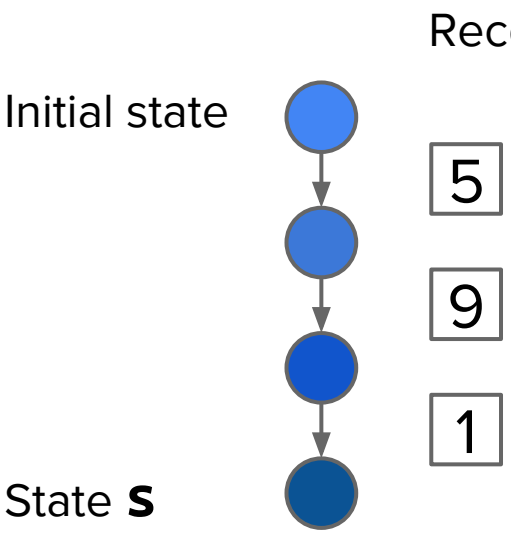
7

8

Result **f′**:

```
if x<2 then 8 else
if x<7 then 8 else
if x<8 then 8 else
else x
```

Example aggregate: `max`



Combined result

Final state:

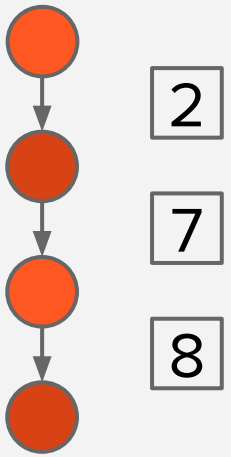
f′(s) = **f′**(9) = 9

In parallel:

Records

(Symbolic)
Unknown state x

```
if x<2
  then 2
else x
```



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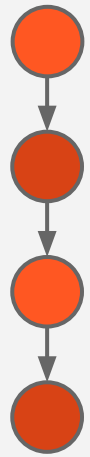


2

7

8

Result **f′**:

$x<8 \Rightarrow 8$

$x \geq 8 \Rightarrow x$

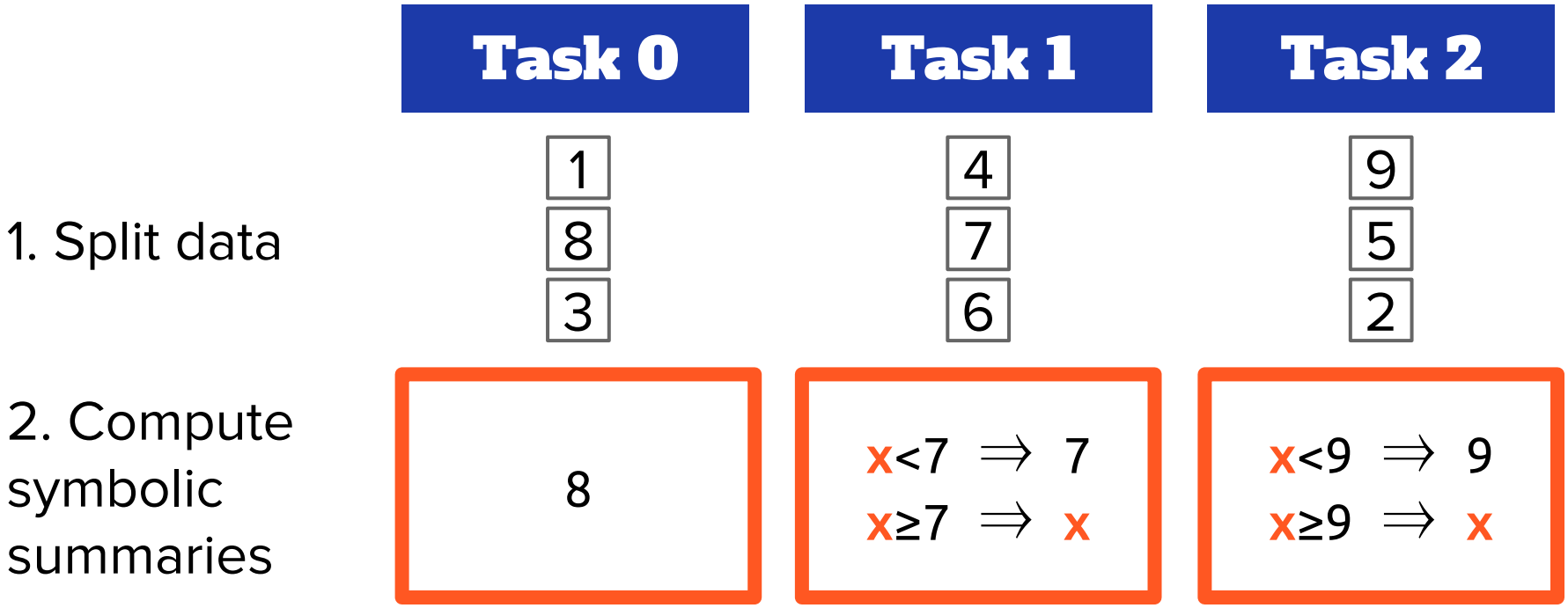
Wanted: a compact and efficient representation of a function

Full symbolic pipeline

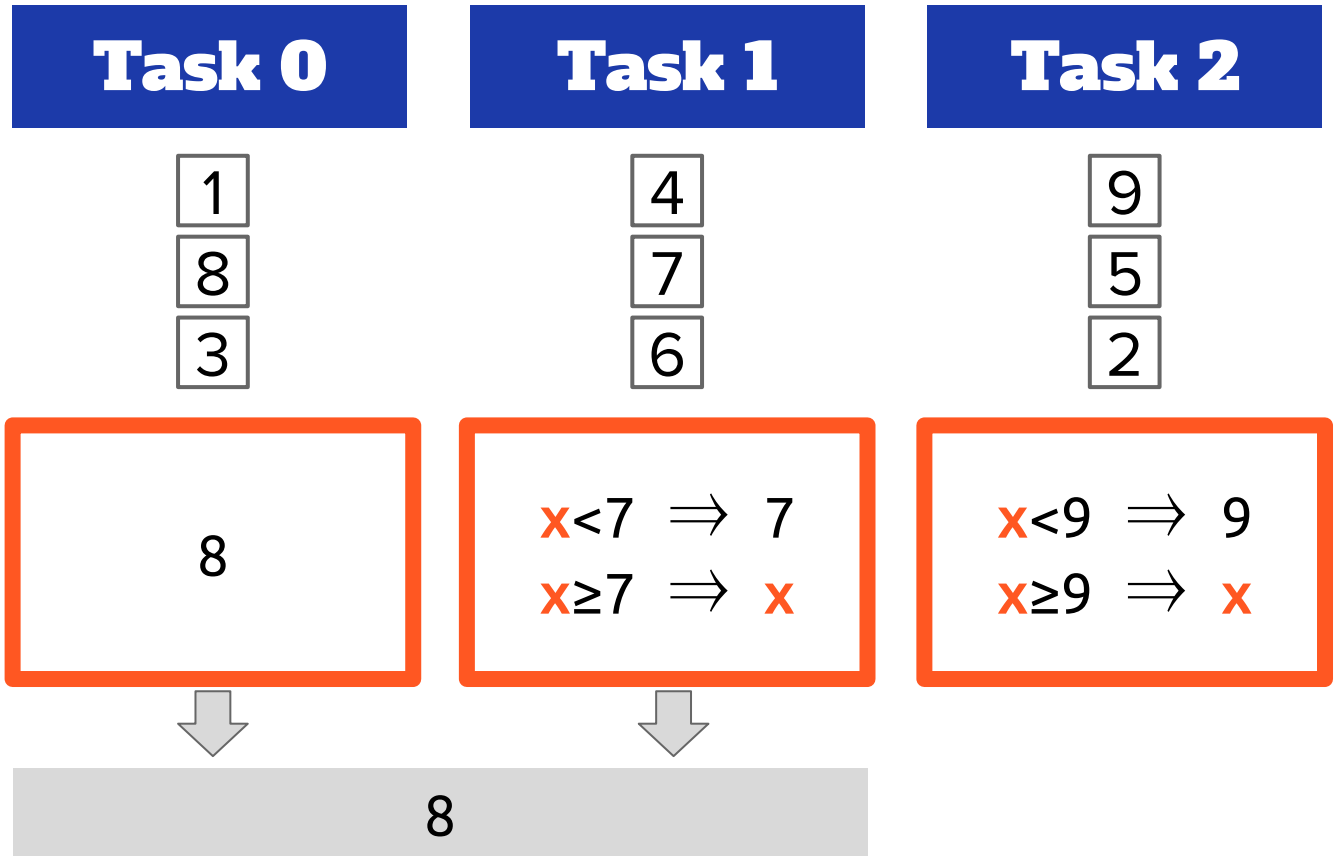
Full symbolic pipeline

	Task 0	Task 1	Task 2
1. Split data	1 8 3	4 7 6	9 5 2

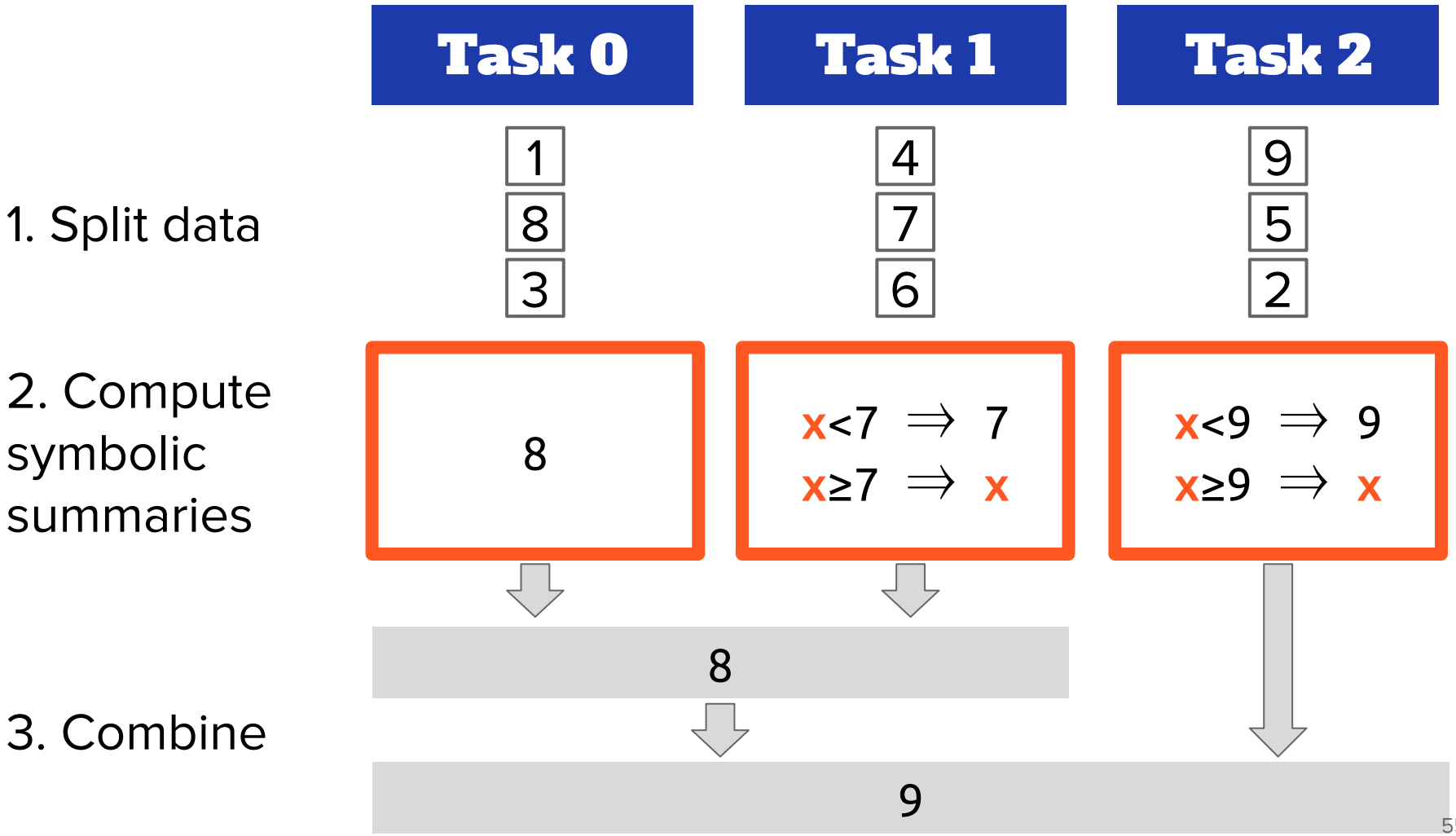
Full symbolic pipeline



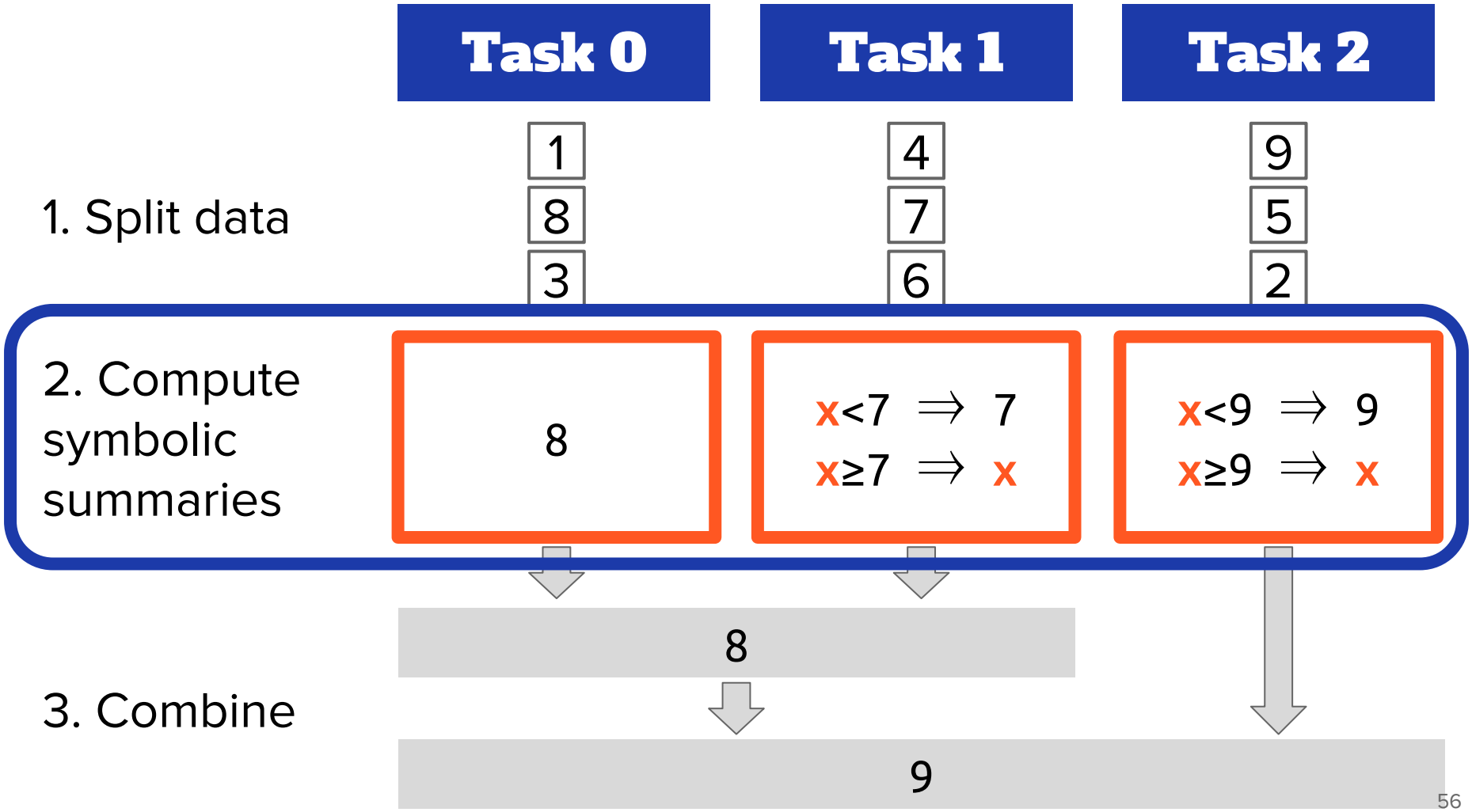
Full symbolic pipeline



Full symbolic pipeline



Full symbolic pipeline



Key insight: Symbolic data types

Representation of functions inspired by

symbolic execution and abstract interpretation

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symbolic execution and abstract interpretation

$$\texttt{PathConstraint}_1 \Rightarrow \texttt{f}_1(\texttt{x})$$

$$\texttt{PathConstraint}_2 \Rightarrow \texttt{f}_2(\texttt{x})$$

$$\texttt{PathConstraint}_3 \Rightarrow \texttt{f}_3(\texttt{x})$$

Key insight: Symbolic data types

Representation of functions inspired by

symbolic execution and abstract interpretation

Explore possible program paths and accumulate path constraints

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Specific shapes of formulas similar to abstract domains: data + decision procedures

Key insight: Symbolic data types

Representation of functions inspired by

symbolic execution and abstract interpretation

Explore possible program paths and accumulate path constraints

Specific shapes of formulas similar to abstract domains: data + decision procedures

Techniques typically used for correctness

Now we use it for performance

Outline

1. Symbolic parallelism

2. Data types

3. Evaluation

Symbolic integer type: `SymInt`

Shape: $x \in [l, u] \Rightarrow ax + b$

`l`,`u`,`a`,`b` - integer constants

Symbolic integer type: SymInt

Shape: $x \in [l, u] \Rightarrow ax + b$

l,u,a,b - integer constants

State s is a concrete value b:

$$x \in [-\infty, \infty] \Rightarrow 0x + b$$

Symbolic integer type: SymInt

Shape: $x \in [l, u] \Rightarrow ax + b$

l,u,a,b - integer constants

State s is a concrete value b:

$$x \in [-\infty, \infty] \Rightarrow 0x + b$$

State s stores a symbolic value x:

$$x \in [-\infty, \infty] \Rightarrow 1x + 0$$

Symbolic integer type: `SymInt`

Shape: $x \in [l, u] \Rightarrow ax + b$

Initial state **s**	Instruction	Resulting state **s**

Symbolic integer type: SymInt

Shape: $x \in [l, u] \Rightarrow ax + b$

Initial state **s**	Instruction	Resulting state **s**
$[l, u] \Rightarrow ax + b$	`s = 7;` →	$[l, u] \Rightarrow 0x + 7$

Symbolic integer type: SymInt

Shape: $x \in [l, u] \Rightarrow ax + b$

Initial state **s**	Instruction	Resulting state **s**
$[l, u] \Rightarrow ax + b$	`s = 7;` →	$[l, u] \Rightarrow 0x + 7$
$[l, u] \Rightarrow ax + b$	`s + 3` →	$[l, u] \Rightarrow ax + (b+3)$

Symbolic integer type: SymInt

Shape: $x \in [l, u] \Rightarrow ax + b$

Initial state **s**	Instruction	Resulting state **s**
$[l, u] \Rightarrow ax + b$	`s = 7;`	$[l, u] \Rightarrow 0x + 7$
$[l, u] \Rightarrow ax + b$	`s + 3`	$[l, u] \Rightarrow ax + (b+3)$
$[l, u] \Rightarrow ax + b$	`if (s ≤ 5)`	$[l, 5] \Rightarrow ax + b$

*for u > 5

Symbolic integer type: `SymInt`

Shape: $x \in [l, u] \Rightarrow ax + b$

Initial state **s**	Instruction	Resulting state **s**

Symbolic integer type: `SymInt`

Shape: $x \in [l, u] \Rightarrow ax + b$

Initial state **s**	Instruction	Resulting state **s**
$[l, u] \Rightarrow ax + b$	`s1 + s2` →	
$[l, u] \Rightarrow ax + b$	`if (s1 ≤ s2)` →	

Symbolic integer type: `SymInt`

Shape: $x \in [l, u] \Rightarrow ax + b$

Initial state **s**	Instruction	Resulting state **s**
$[l, u] \Rightarrow ax + b$	`s1 + s2` →	**Disallowed:** static type checking error
$[l, u] \Rightarrow ax + b$	`if (s1 ≤ s2)` →	Path constraints are an **interval, not relational**

Other data types - same idea

SymBool

SymEnum

SymVector

SymPredicate

Composing symbolic variables

Multiple symbolic variables

$PathConstraint_1 \Rightarrow f_1(x_1)$ $PathConstraint_2 \Rightarrow f_2(x_2)$

means

$PathConstraint_1 \wedge PathConstraint_2 \Rightarrow (f_1(x_1), f_2(x_2))$

Overall

Overall

Predefined data types

SymInt
SymBool
SymEnum
SymVector
SymPredicate

Overall

Predefined data types

SymInt
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Types can
be combined

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Extensible with new types

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Overall

Predefined data types

SymInt
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Extensible with new types

Types can be combined

Enable writing custom aggregates

SymInt num_reviews = 0;

SymBool search_done = false;

SymVector<**SymInt**> result;

```
foreach record in user records:
    switch record.type:
        case SEARCH:        num_reviews = 0;    search_done = true;
        case REVIEW:        num_reviews++;
        case PURCHASE:      if search_done:
                                search_done = false;
                                result.push_back(num_reviews);
```

Outline

1. Symbolic parallelism

2. Data types

3. Evaluation

Benchmarks

query logs from GitHub, RedShift, Bing, Twitter

example queries:

ID	Data	Description
1	GitHub	All operations on a repository directly preceding a delete operation
2	GitHub	Number of operations executed on a repository between pull open and close
3	RedShift	List of advertisers operating only in a single country
4	RedShift	Ads for an advertiser not showing for more than 1 hour

Implementation

User code

Symbolic data types Type checking (with C++) Execution engine

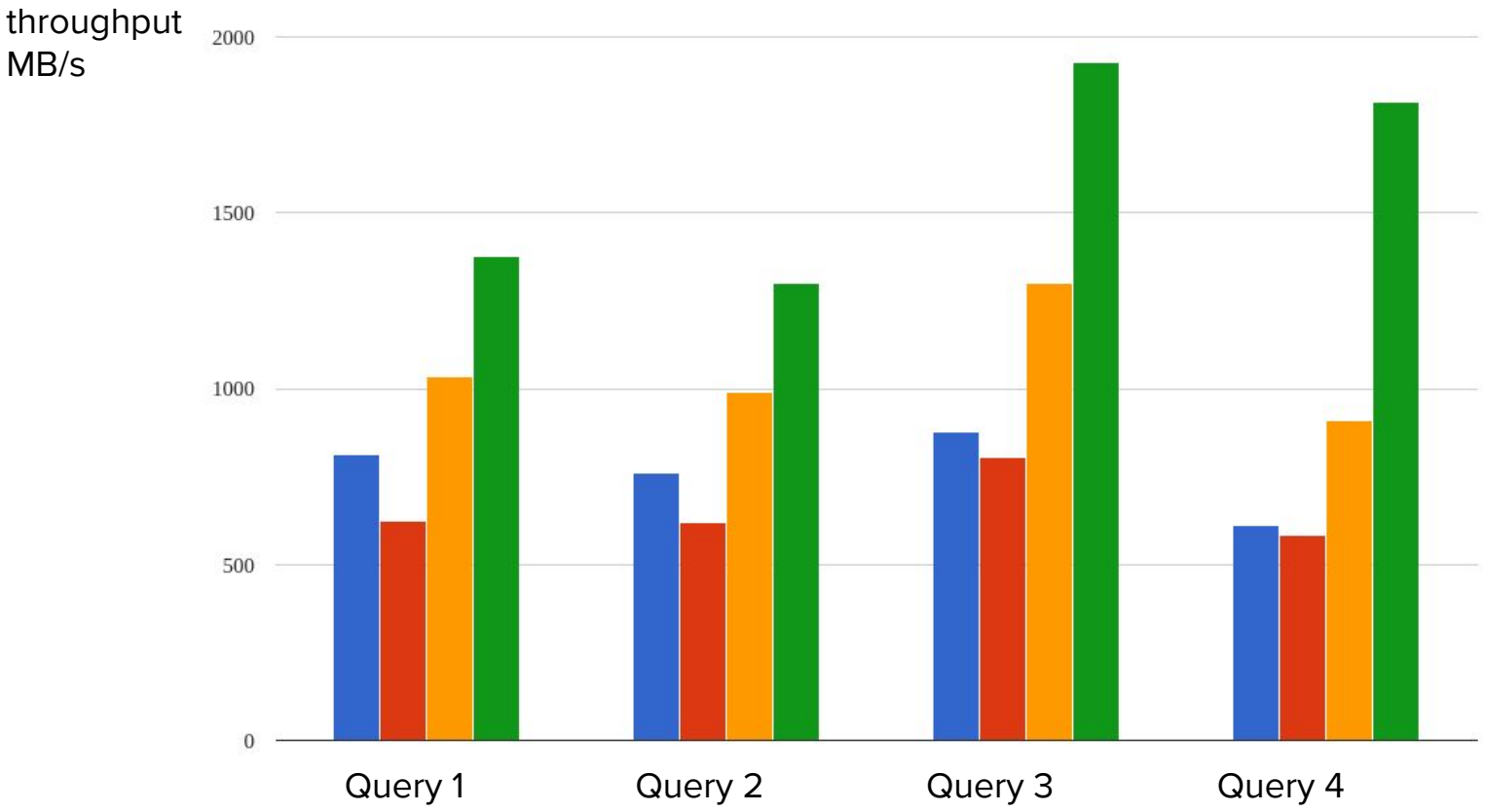
SYMPLE library

Single-machine Multi-core parallelism

hadoop

...

Single machine throughput



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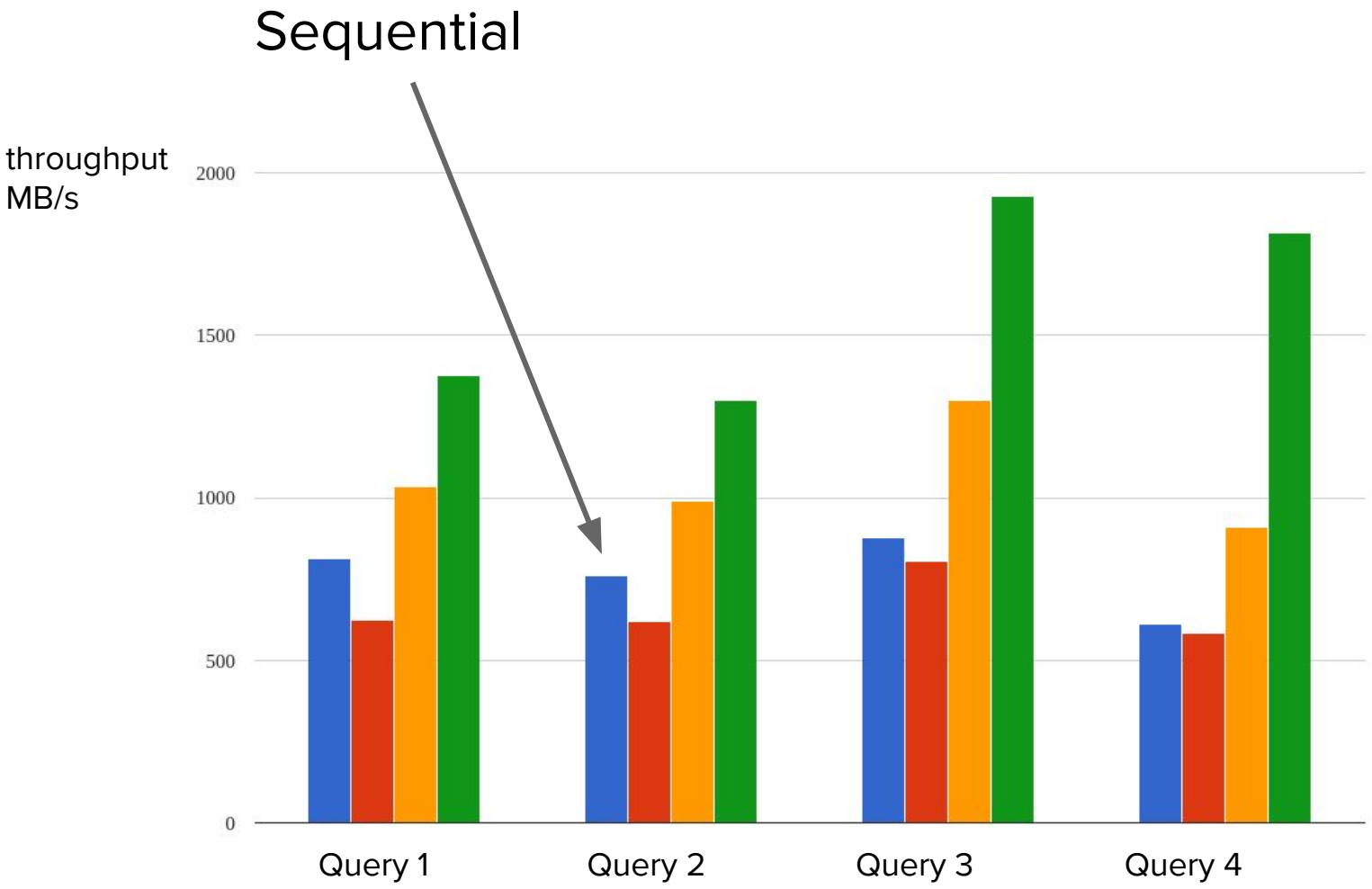

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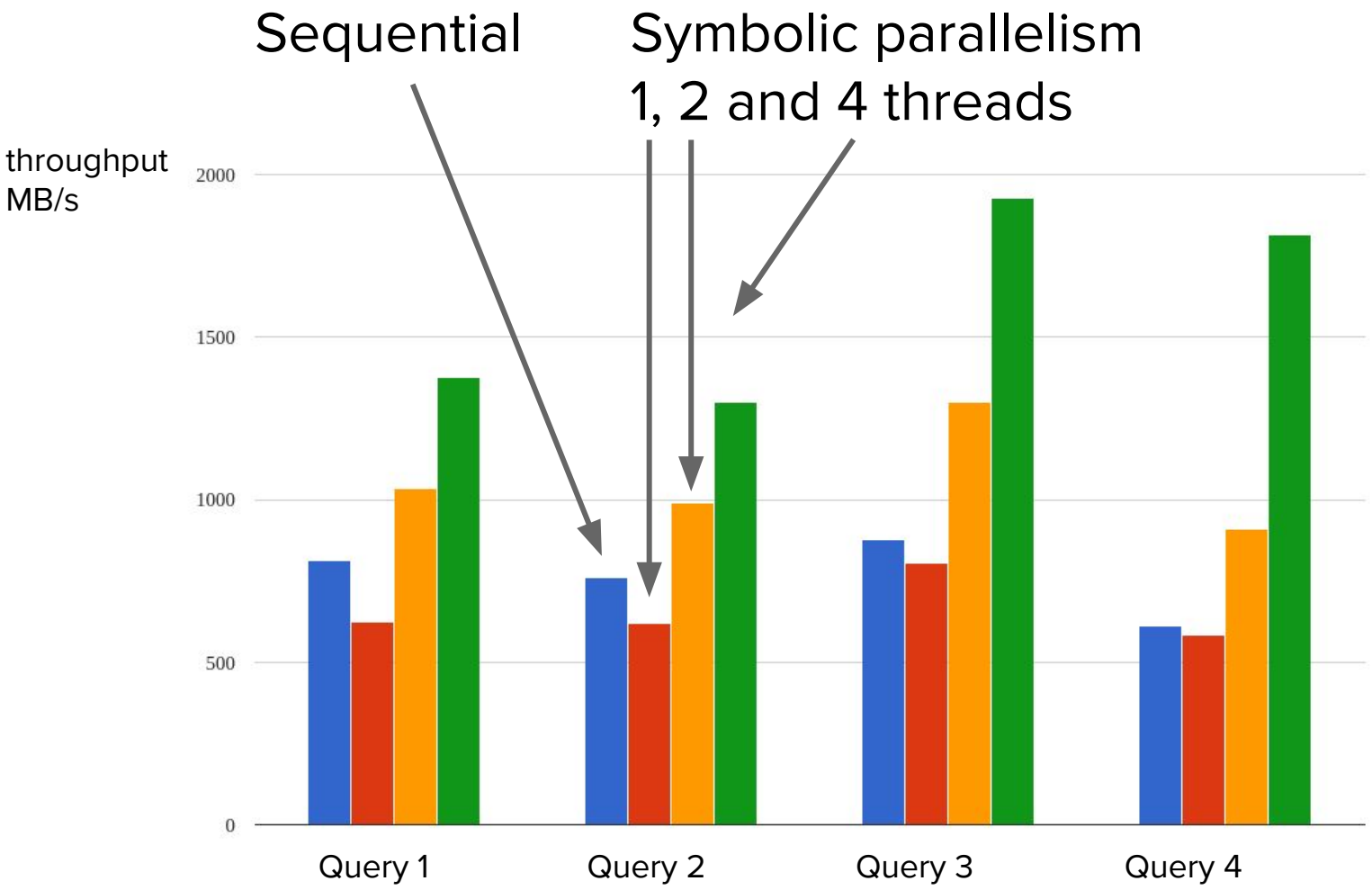

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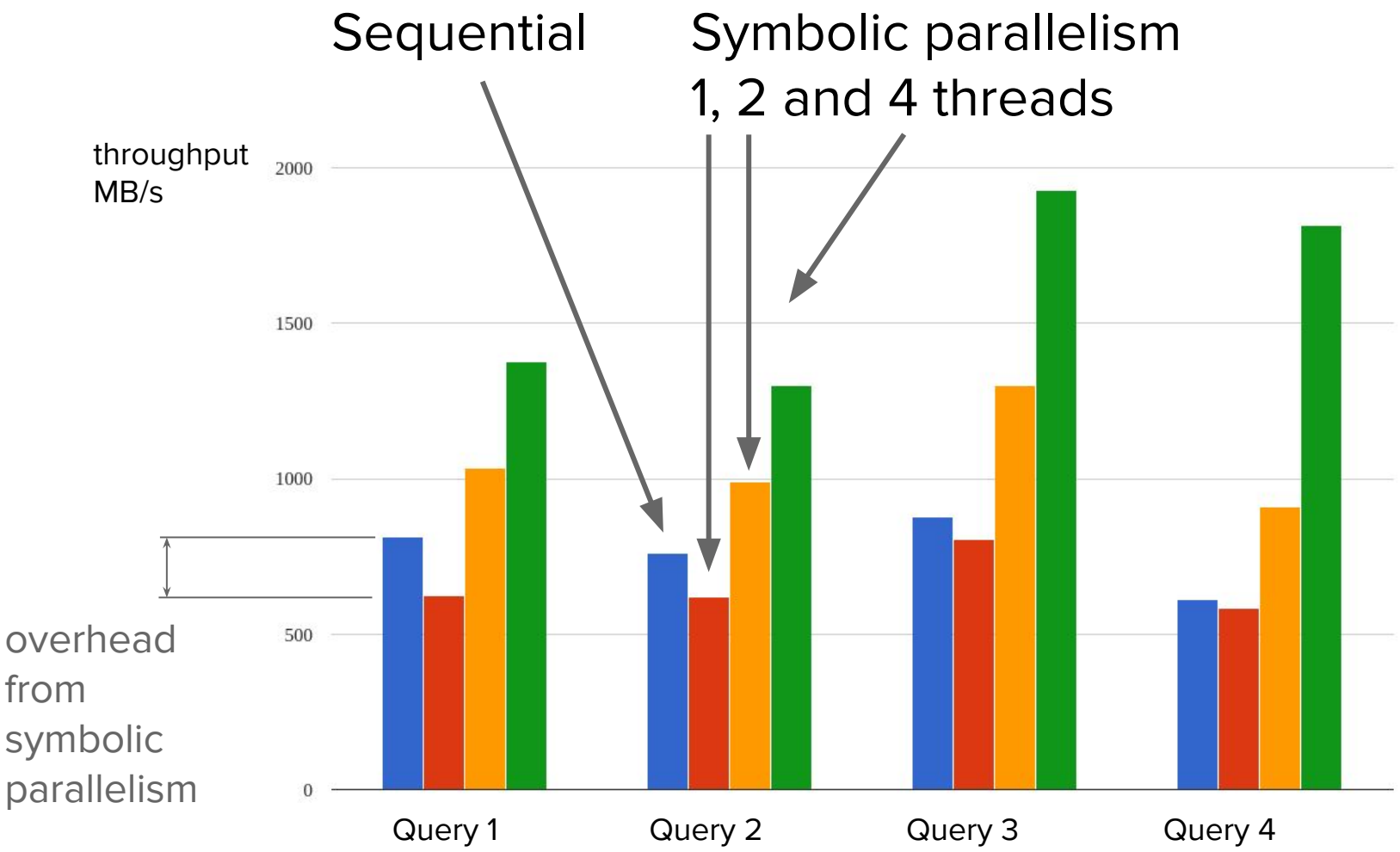
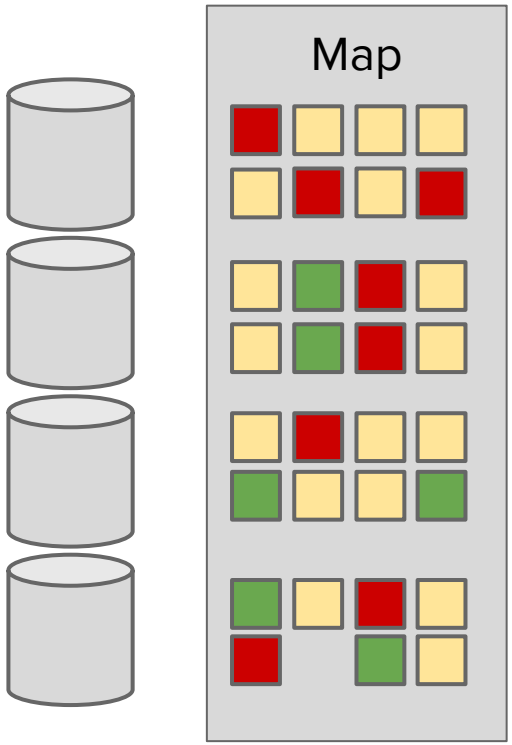


Handling large data (before)

Naive encoding in MapReduce

Distributed:
query logs



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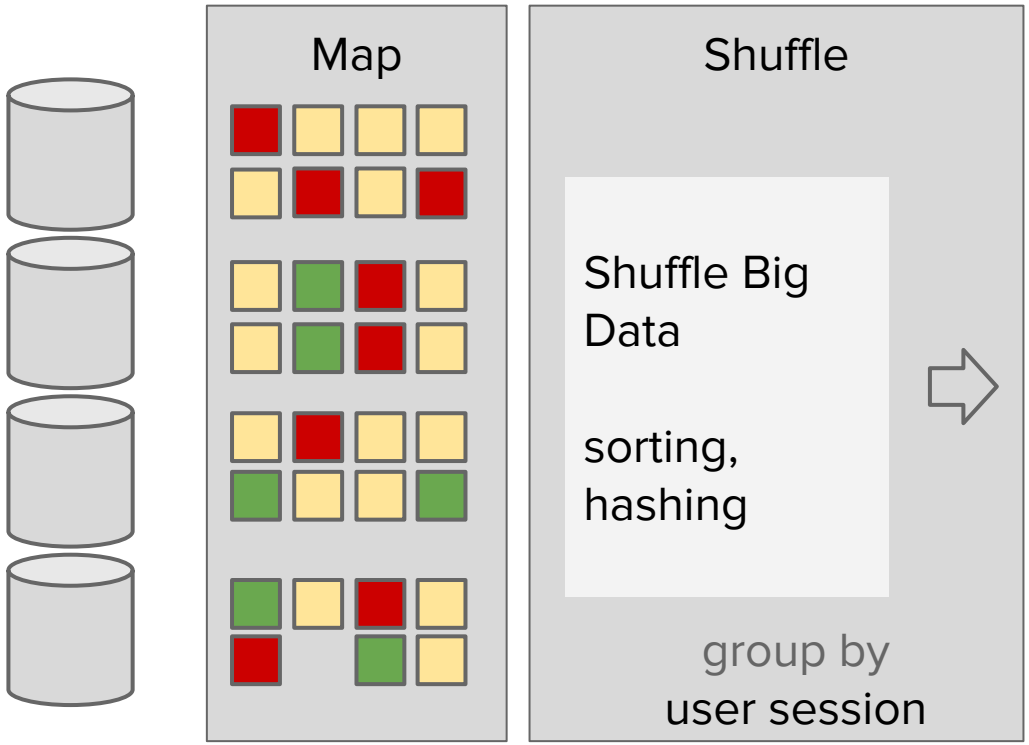

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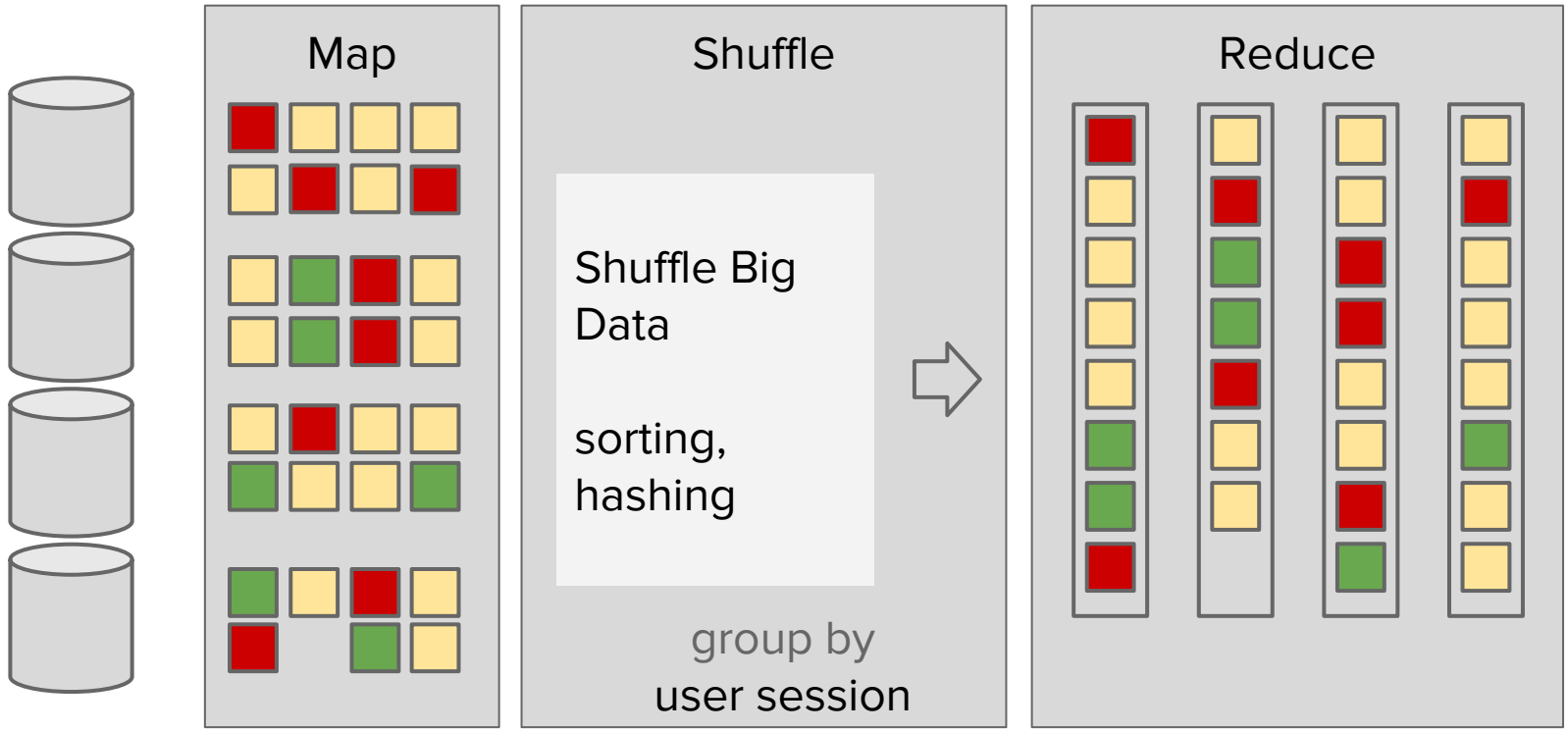

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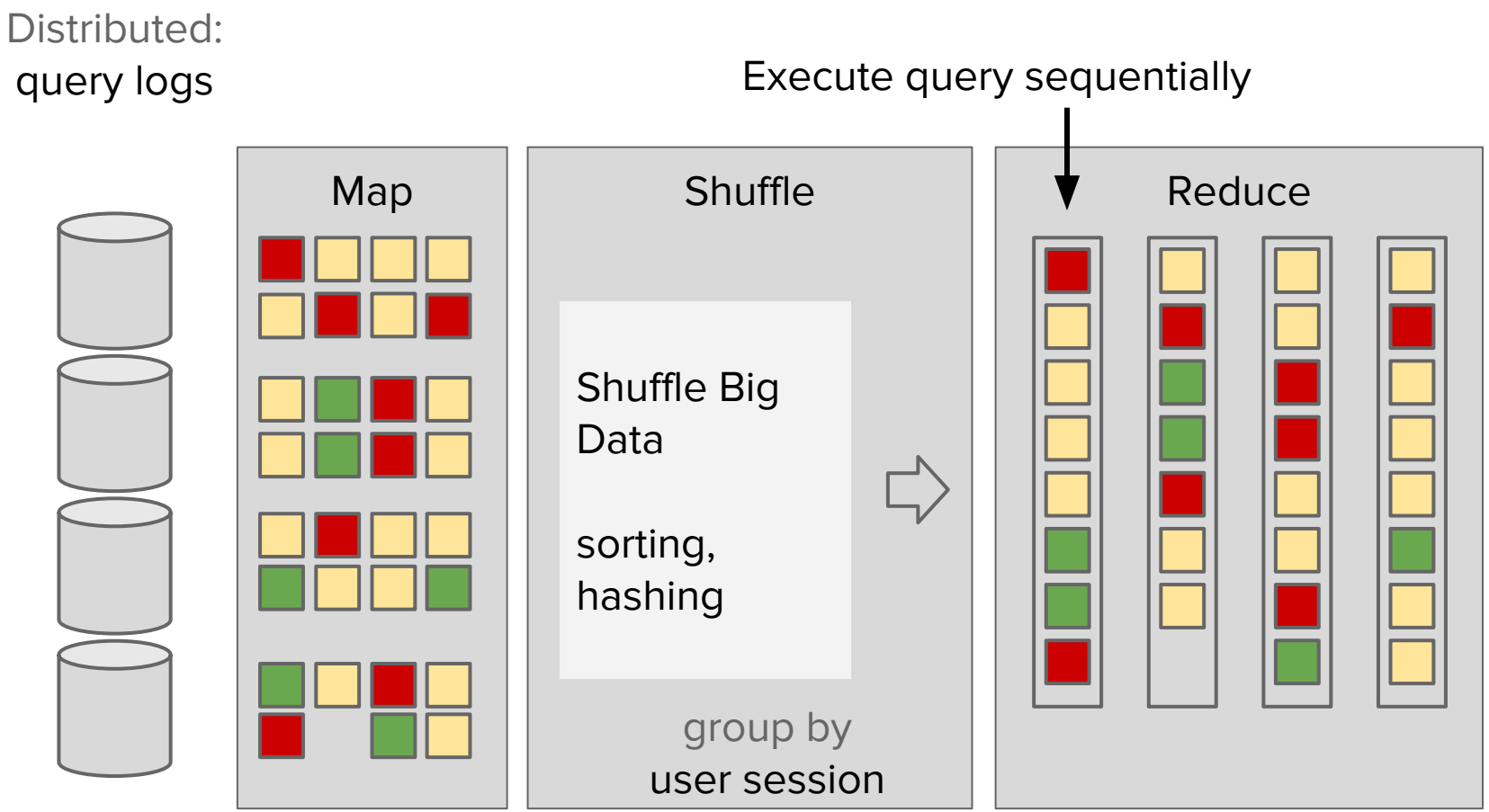
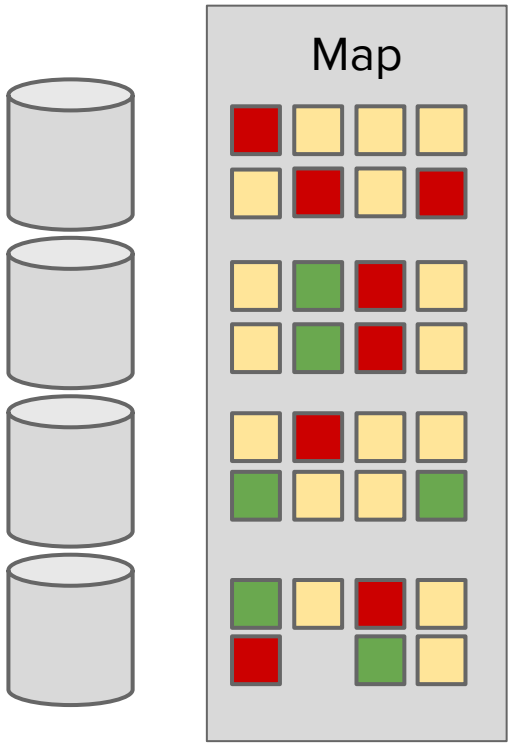


Handling large data (now)

Our tool: **SYMPLE**

Distributed:
query logs



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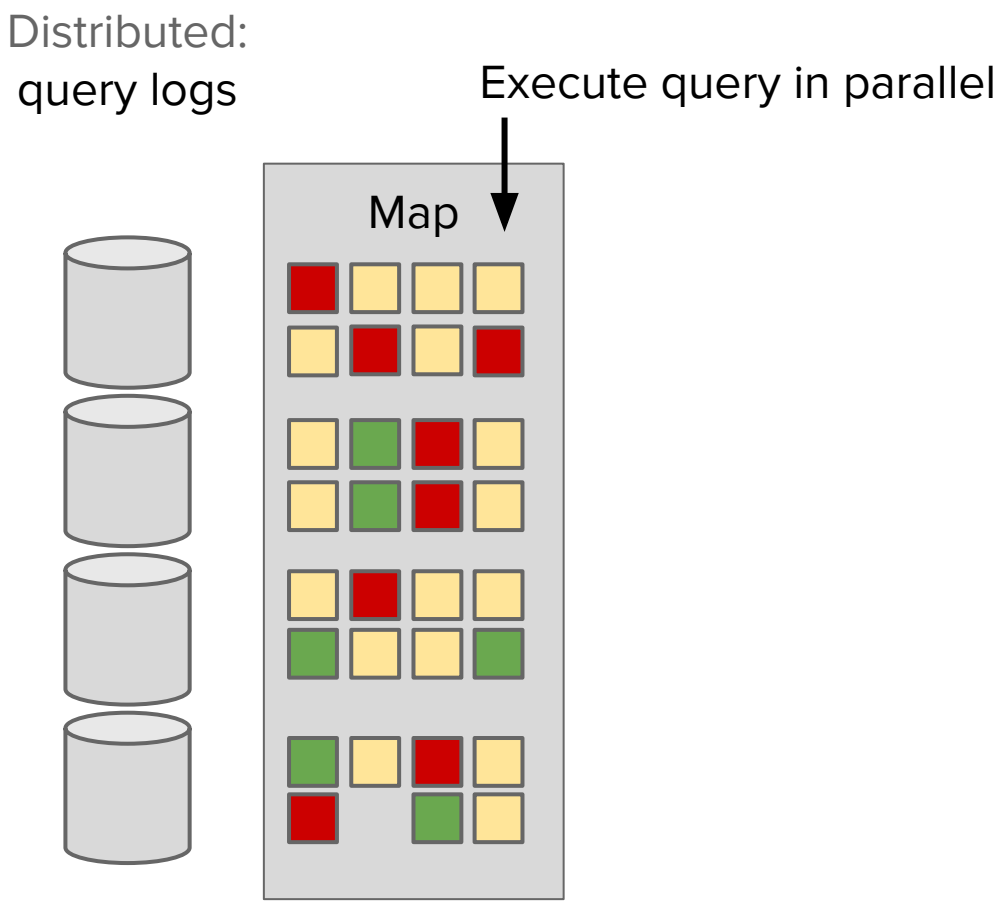

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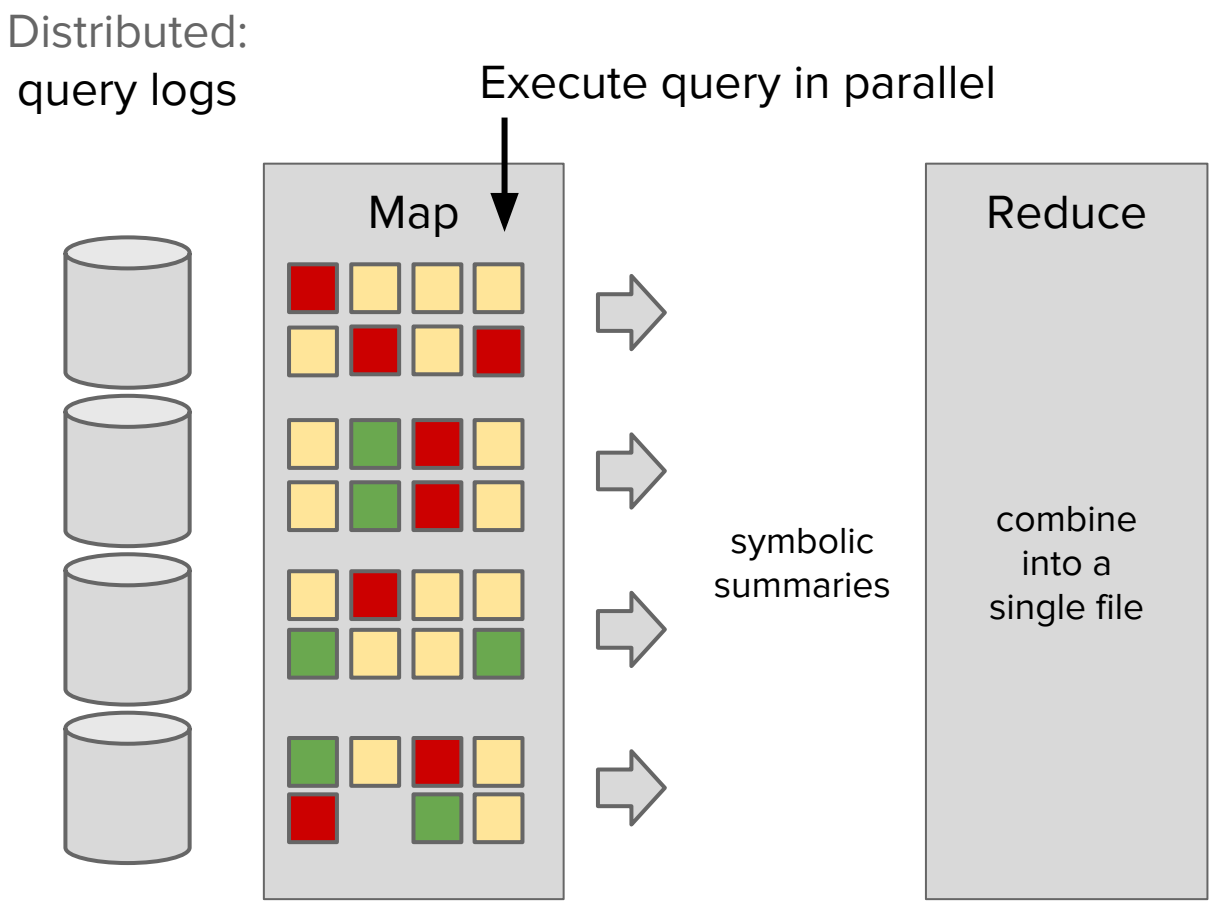
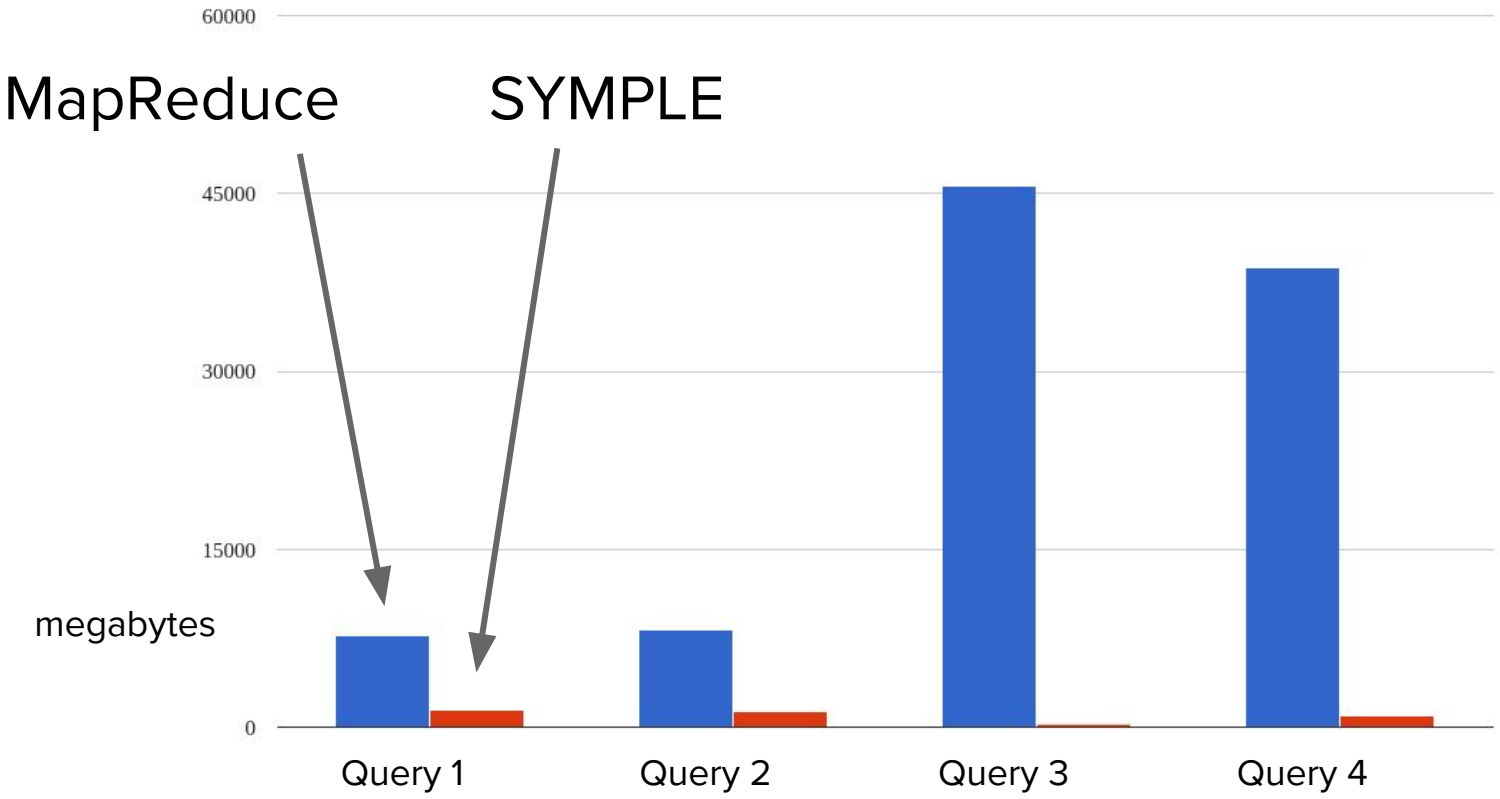


Data movement

Data shuffled from mappers to reducers



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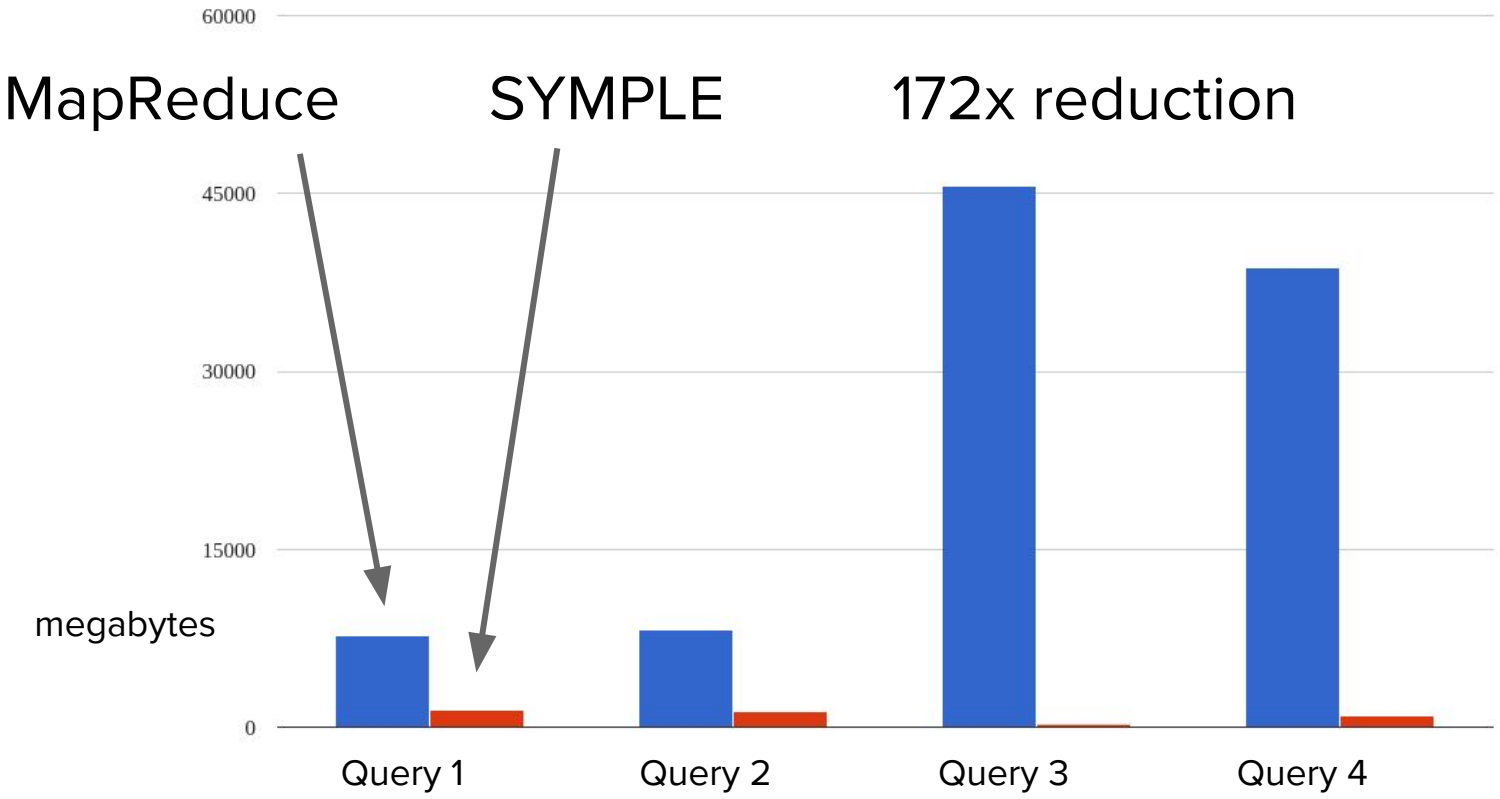
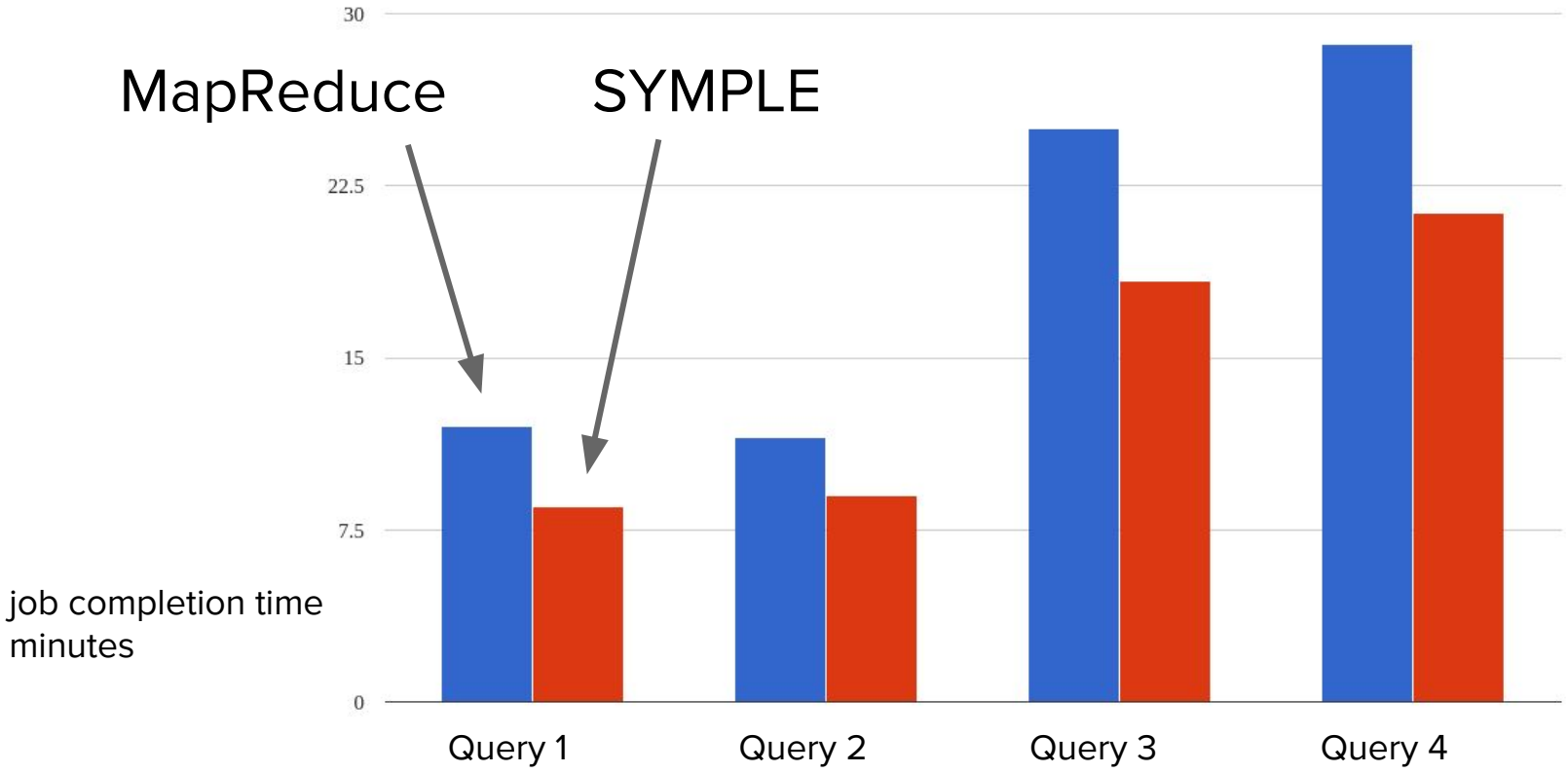


End-to-end latency

On Amazon Web Services, Hadoop and S3



End-to-end latency

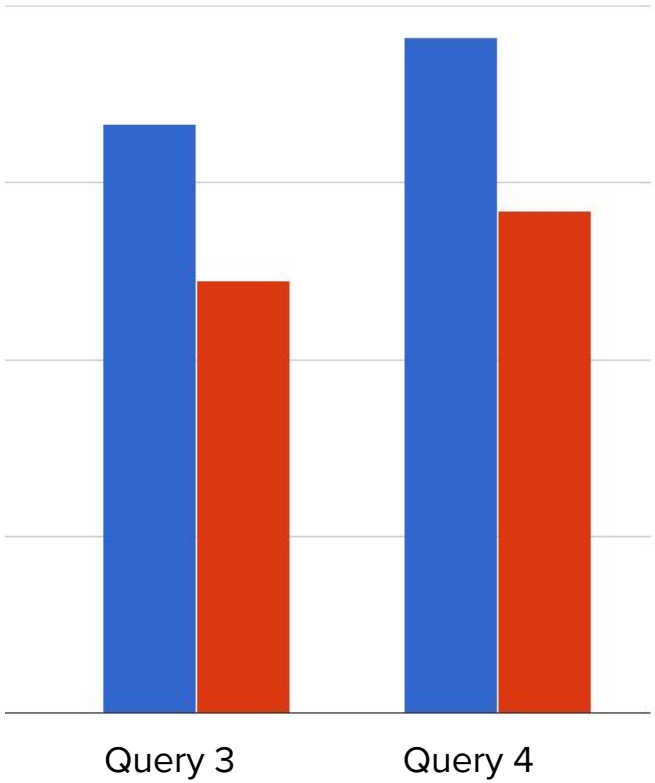
On Amazon Web Services, Hadoop and S3

Fixing shuffle inefficiency exposes us to next bottleneck:

reading input and throwing most of it away

easy solution:

compress input or use data with smaller records



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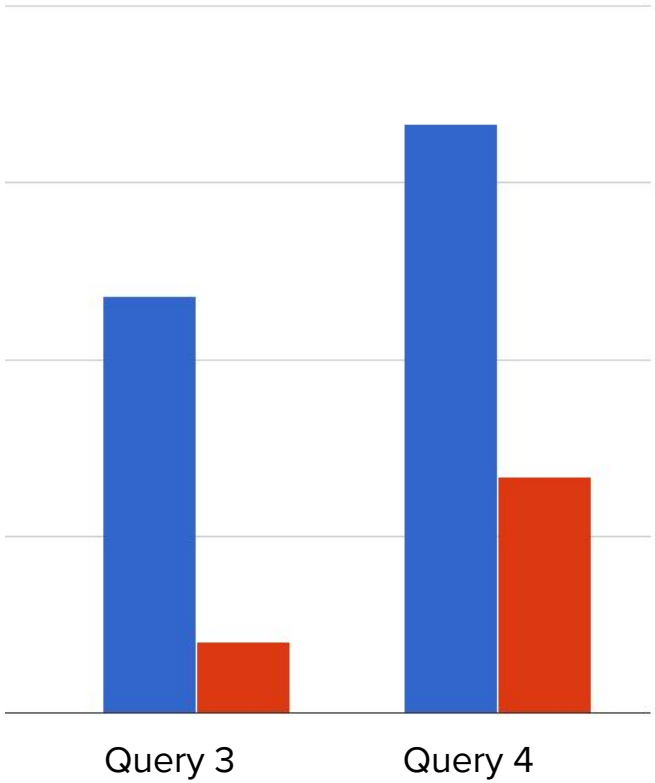

Summary

Symbolic parallelism

Data types

Type checking

Efficient implementation

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