Secure Big Data Processing

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Outline

- Context
- Availability and integrity in big data analytics
- Privacy in big data analytics
- Conclusions and outlook

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- **Context**
- Availability and integrity in big data analytics
- Privacy in big data analytics
- Conclusions and outlook

Secure Big Data?

- Big data analytics is commonly performed in 3rd-party *cloud* datacenters (DCs)
- Geo-distribution exacerbates security issues
- Multi-tenancy issue even in single cloud DCs
  - Successful tampering with application *X* may yield access to app *Y*

Cloud Computing

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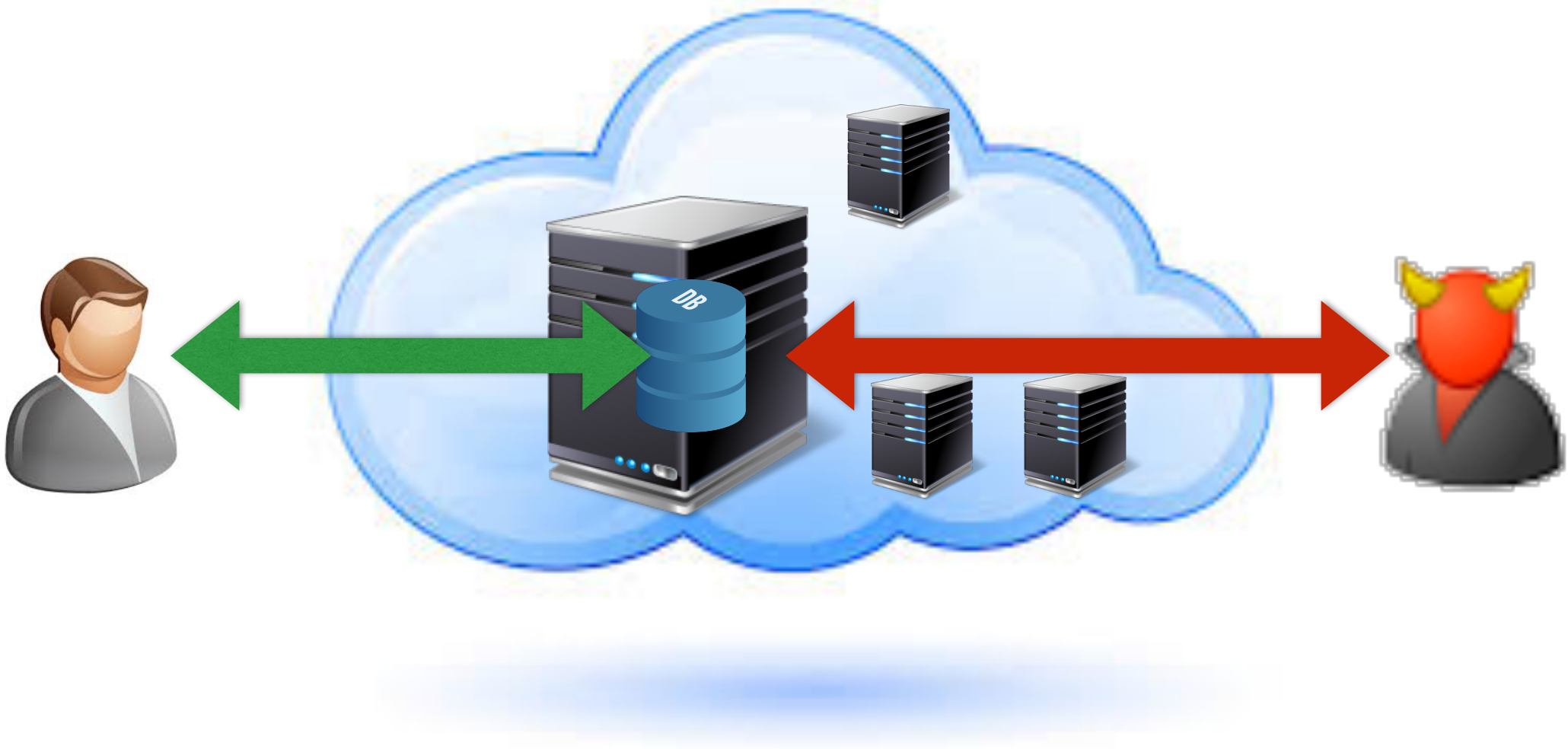

Assurance

- Multi-faceted problem including
  - Availability
  - Integrity
    - Code: mission-critical, e.g., government, business processes, CPS, disaster response
    - Data: similar
  - Privacy
    - Data: confidential, e.g., government, personal
    - Code: competitive, e.g., algorithmic trading and business processes
  - …

Existing Work

- **Communication-centric**: focus on exchanged messages
  - Firewalls, etc. - perimeter security
- **Data-centric**: mostly data at rest
  - Access control/"differential privacy" (e.g., Airavat [Roy et al.;NSDI'10]), encrypted storage (e.g., DepSky [Bessani et al.;Eurosys'11]), etc.
  - Homomorphic encryption (e.g., [Gentry;STOC'09])
    - Partial (e.g., CryptDB [Popa et al.;CACM'12], MrCrypt [Lesani et al.;OOPSLA'13])
- **Computation-centric**: generating "correct" results
  - Functional encryption, proof-based computation (e.g. Ginger [Setty et al.;S&P'12])

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Problem Statement

- How to prevent an attacker from tampering with computations?
- Cryptographic primitives such as zero-knowledge proofs costly (e.g. Ginger [Setty et al.;S&P'12])

Problem

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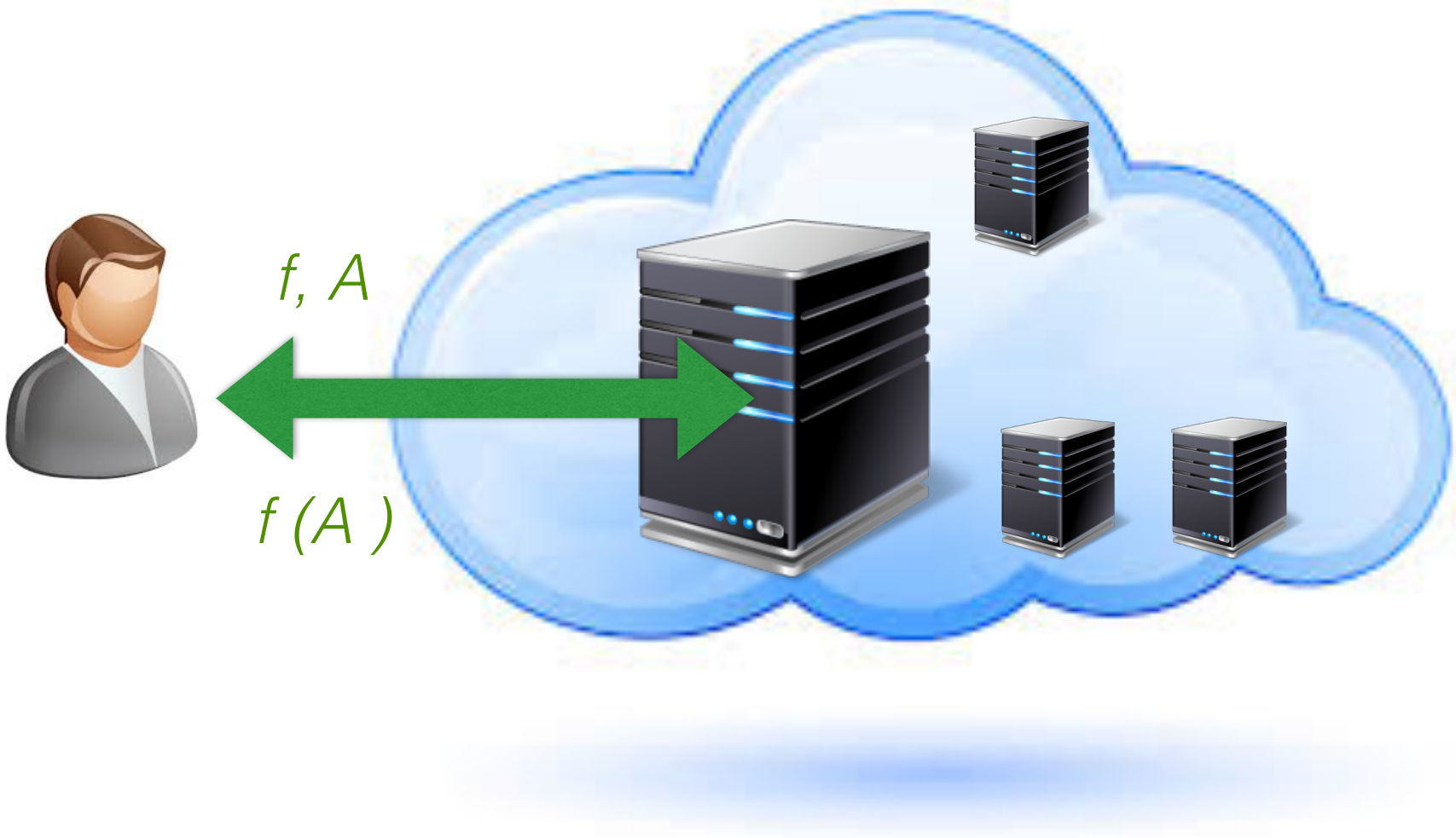

Problem

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Zero Knowledge Proofs

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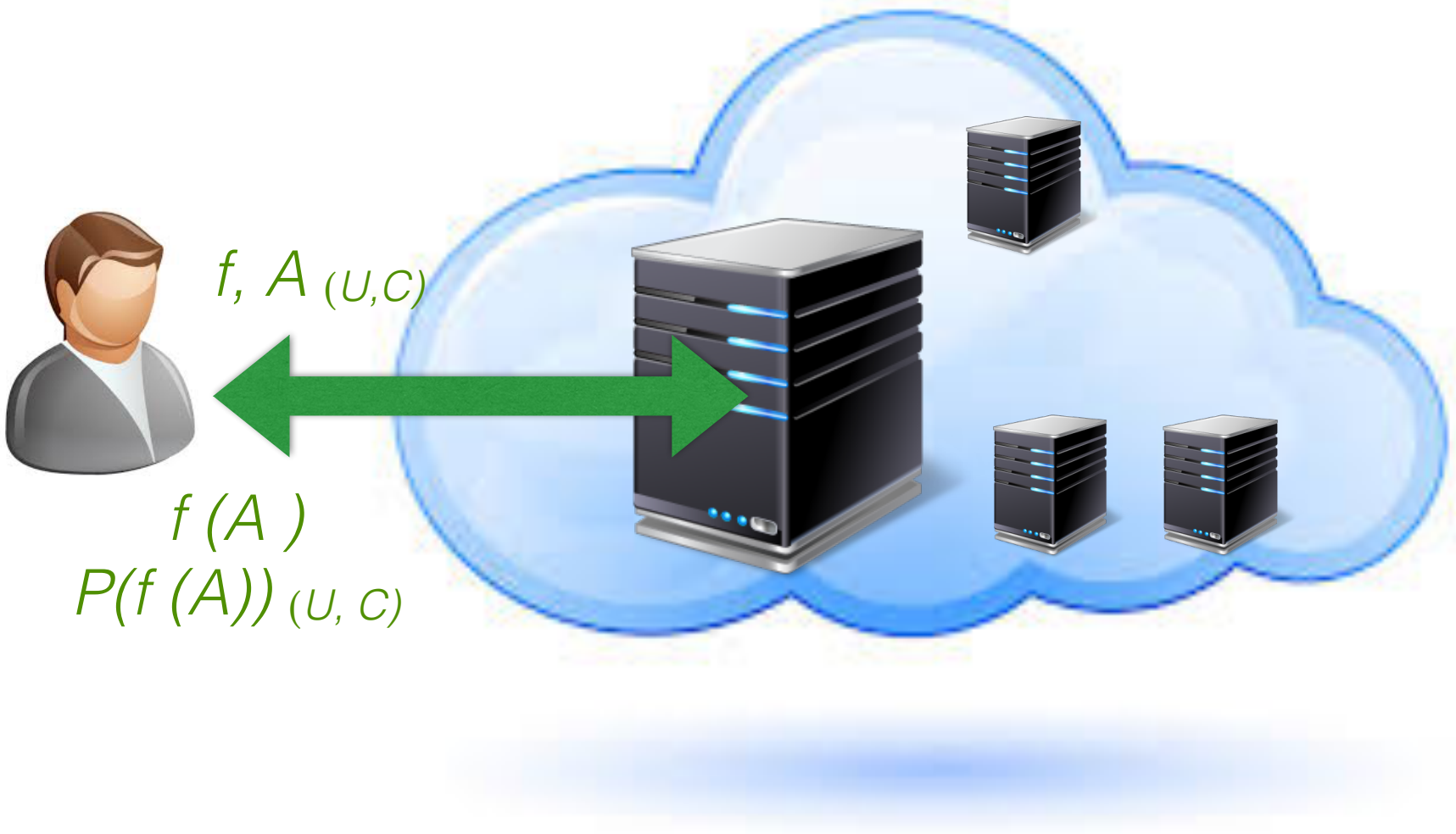

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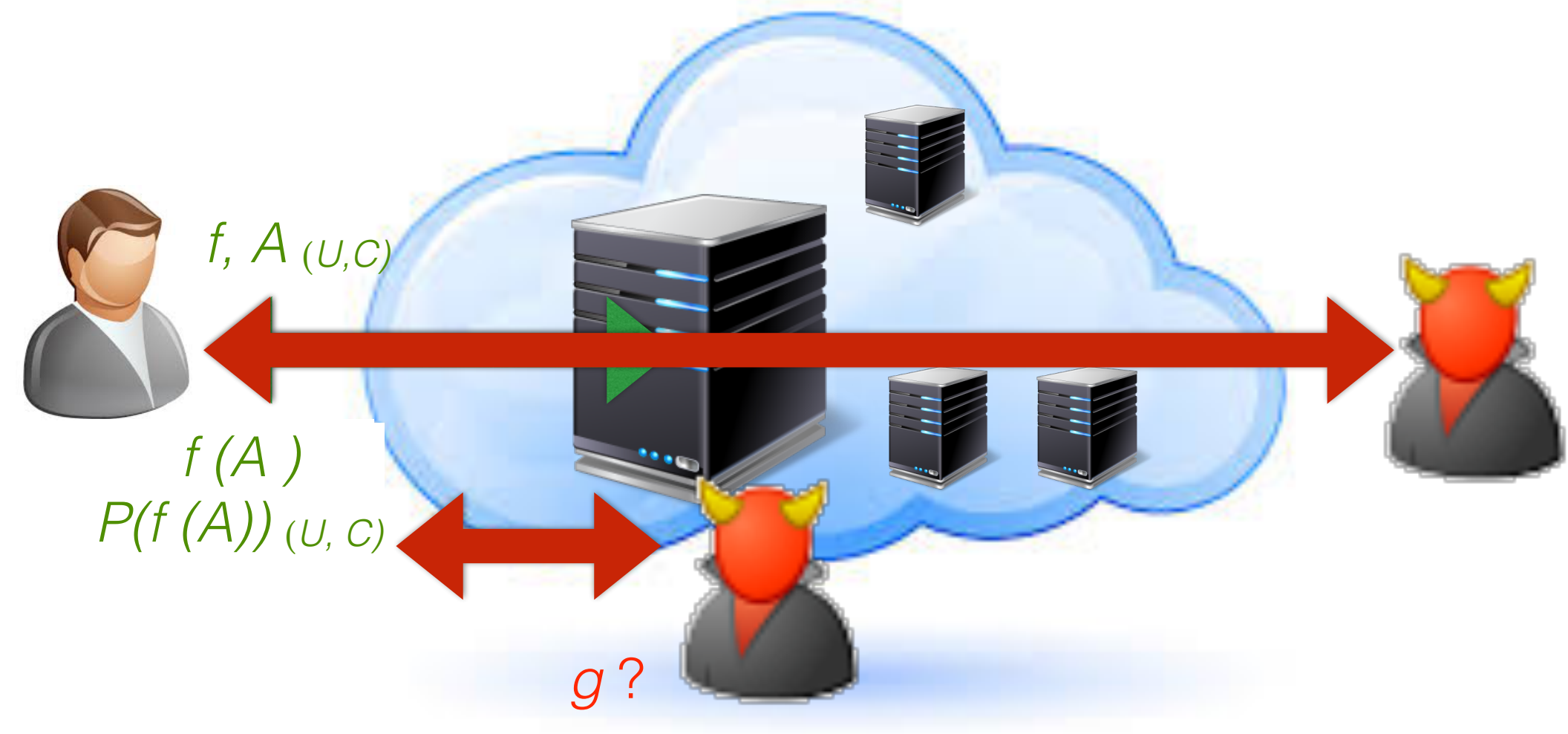

Byzantine Fault Tolerance

- Protect “computation” with BFT [Lamport, Shostak, Pease;TOPLAS’82] replication
  - Processes (state machines) with benign and malicious failures
  - $3f+1$ replicas for f failures in asynchronous distributed systems
    - Safety with $f+1$
    - Liveness with $2f+1$ in synchronous system
  - Comparison of outputs

BFT Replication

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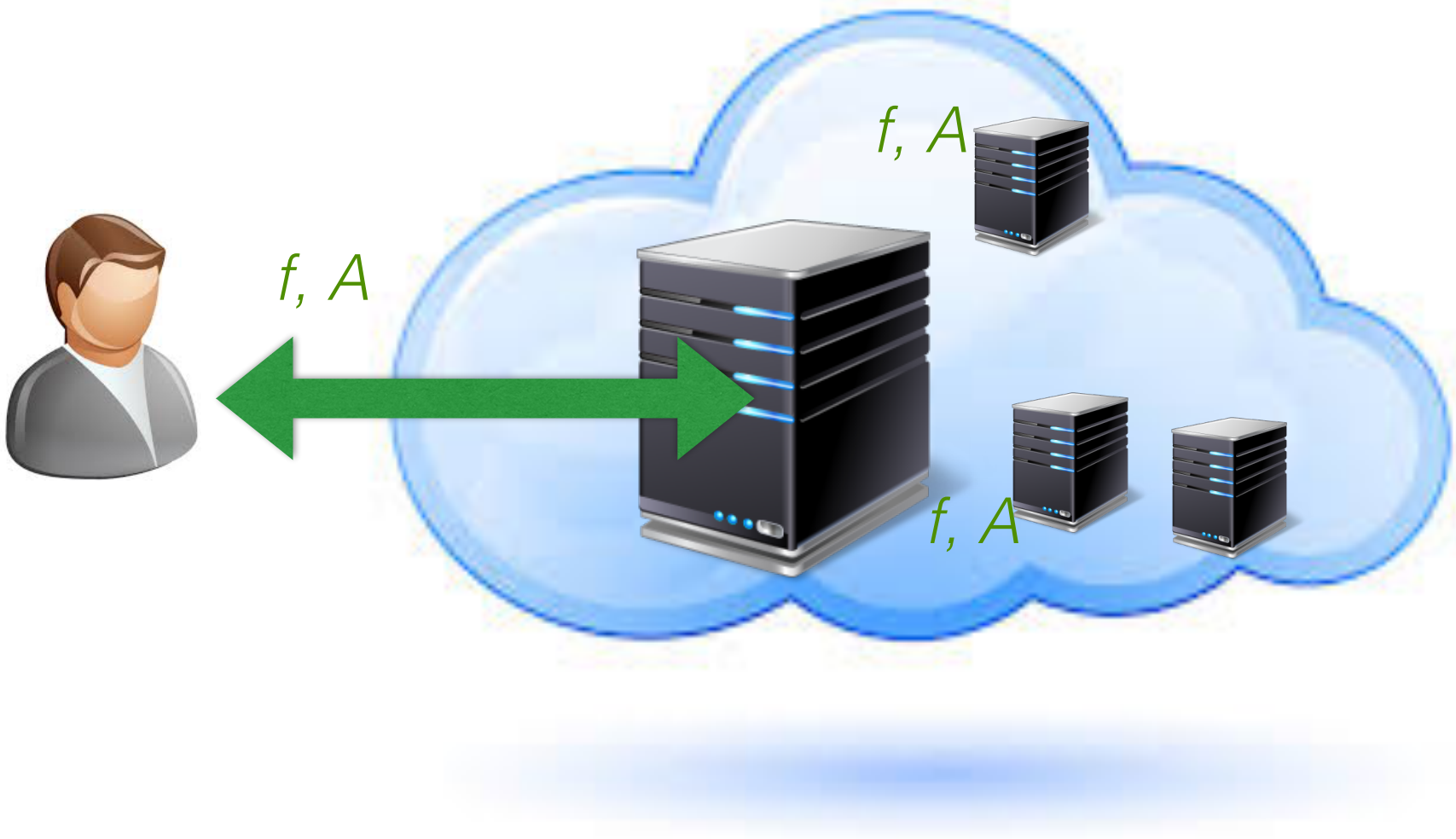
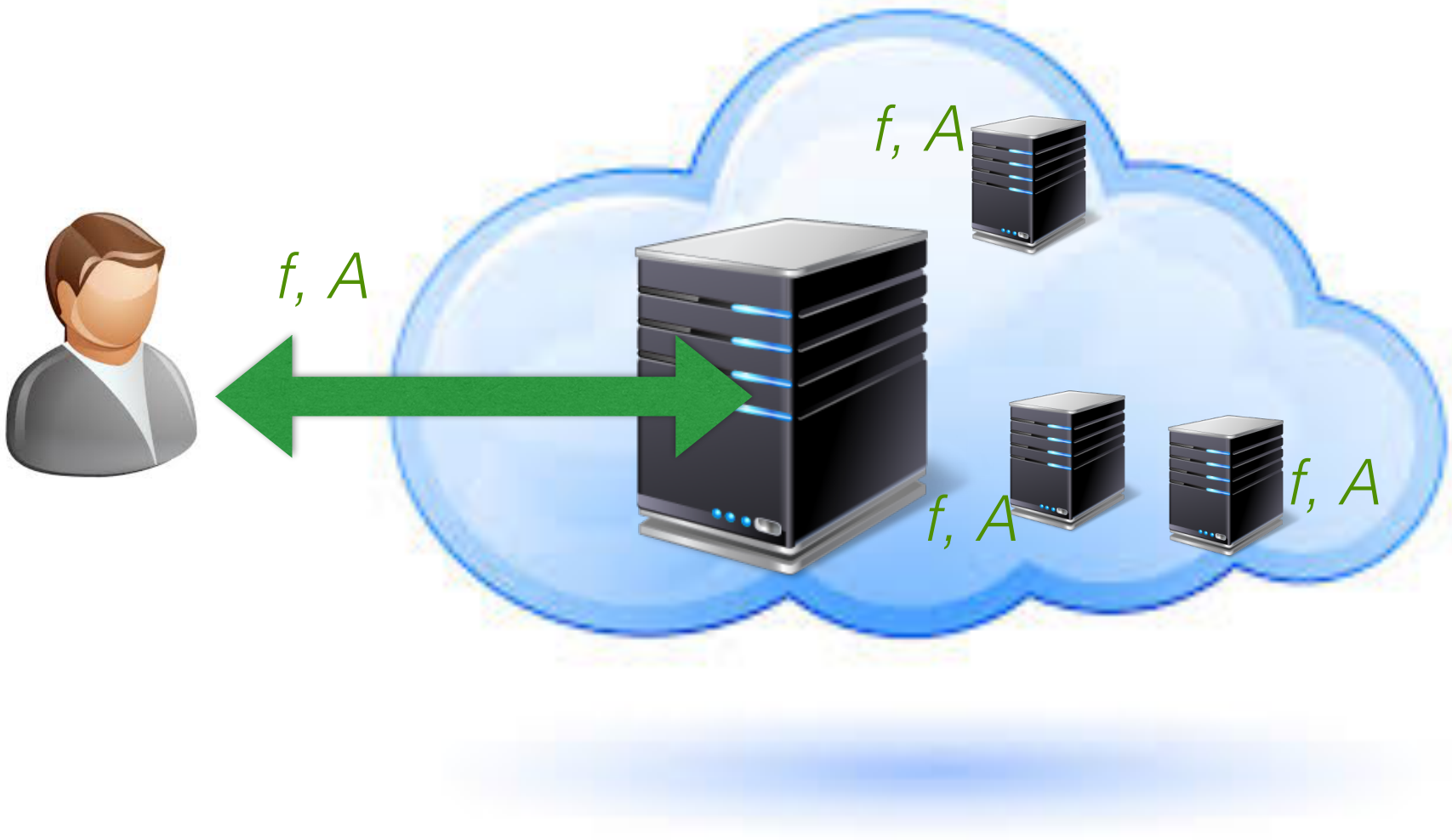
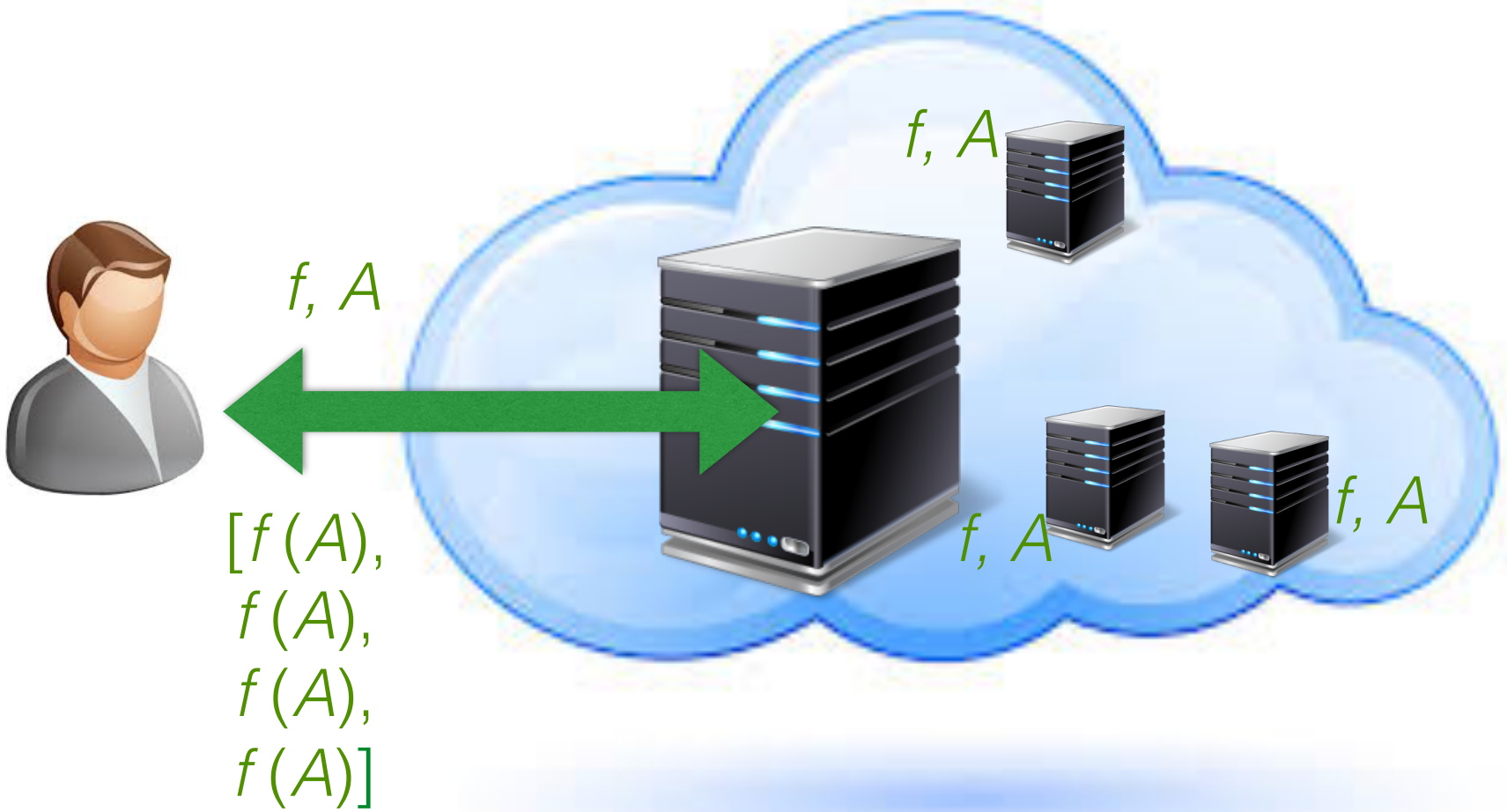


BFT Replication



BFT Replication



BFT Replication

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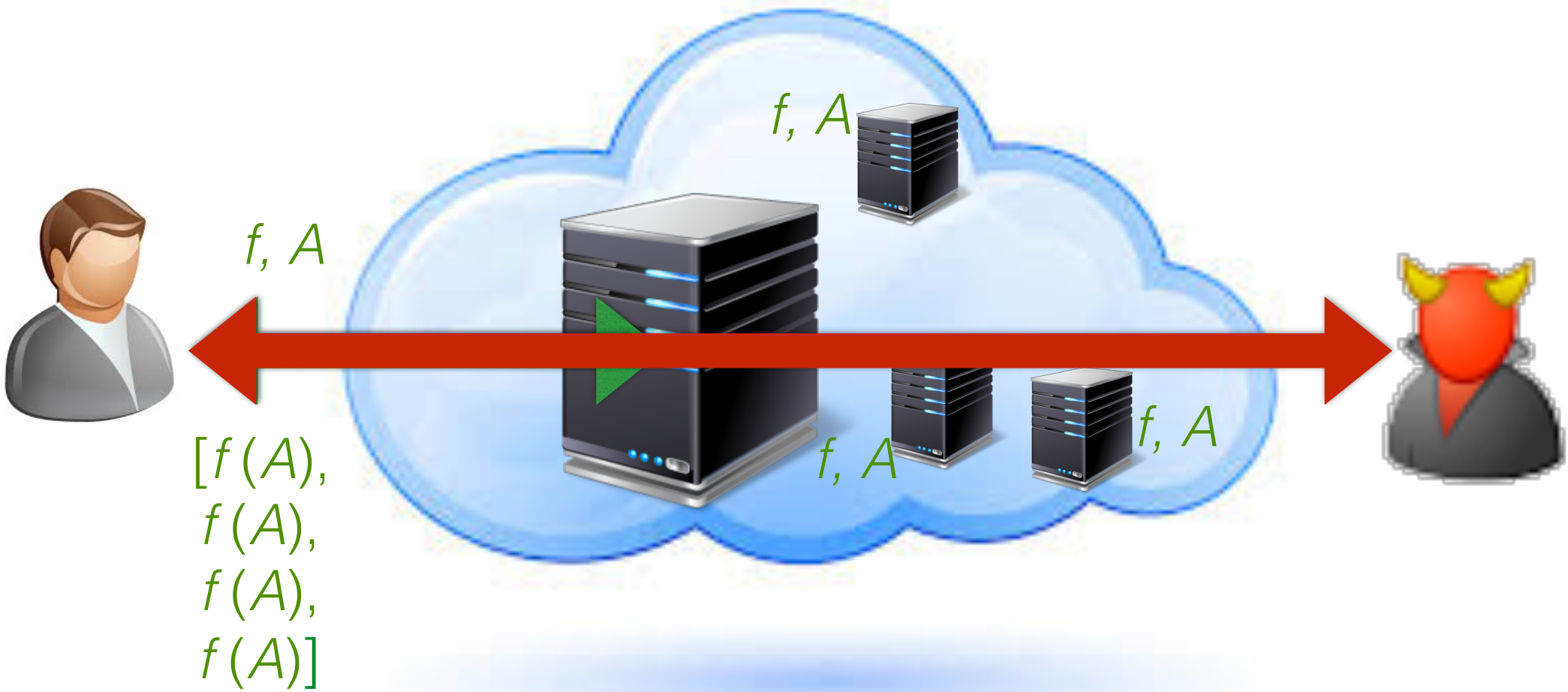
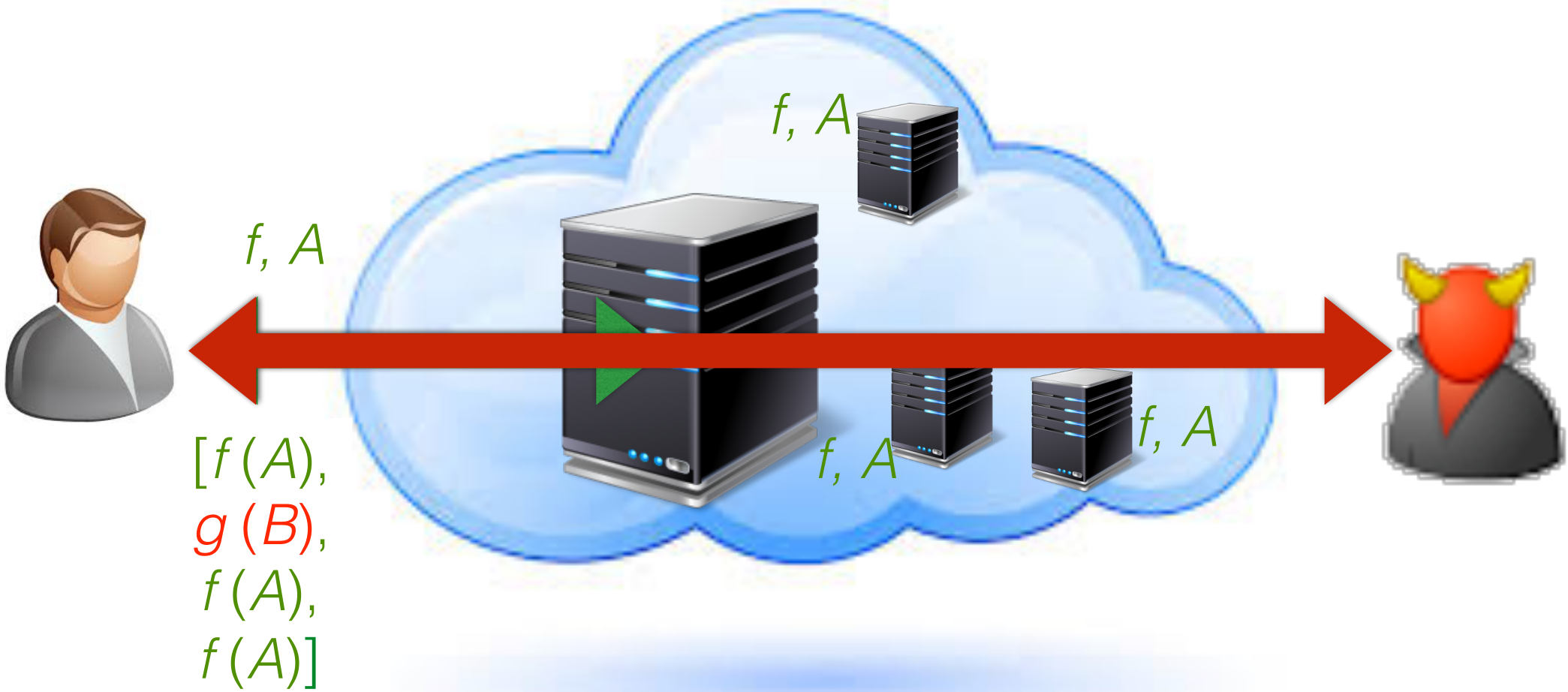


BFT Replication



BFT — Hammer or Nail?

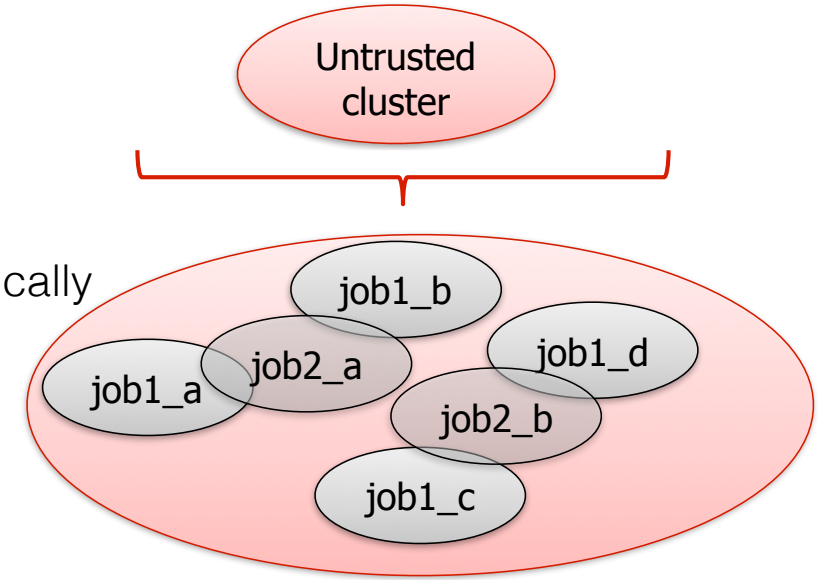
- Why BFT?
  - Masks faulty components (availability, integrity)
  - Identifies faulty components (attribution, isolation)
  - Solution higher up in protocol stack (interoperability, portability)
- Generic challenges of BFT
  - Homogeneity: cloud providers have different OSs, OS versions/images, ASLR standard
  - Non-determinism: largely avoided by deterministic parallelization
  - Agreement: only one “client”

Specific Challenges

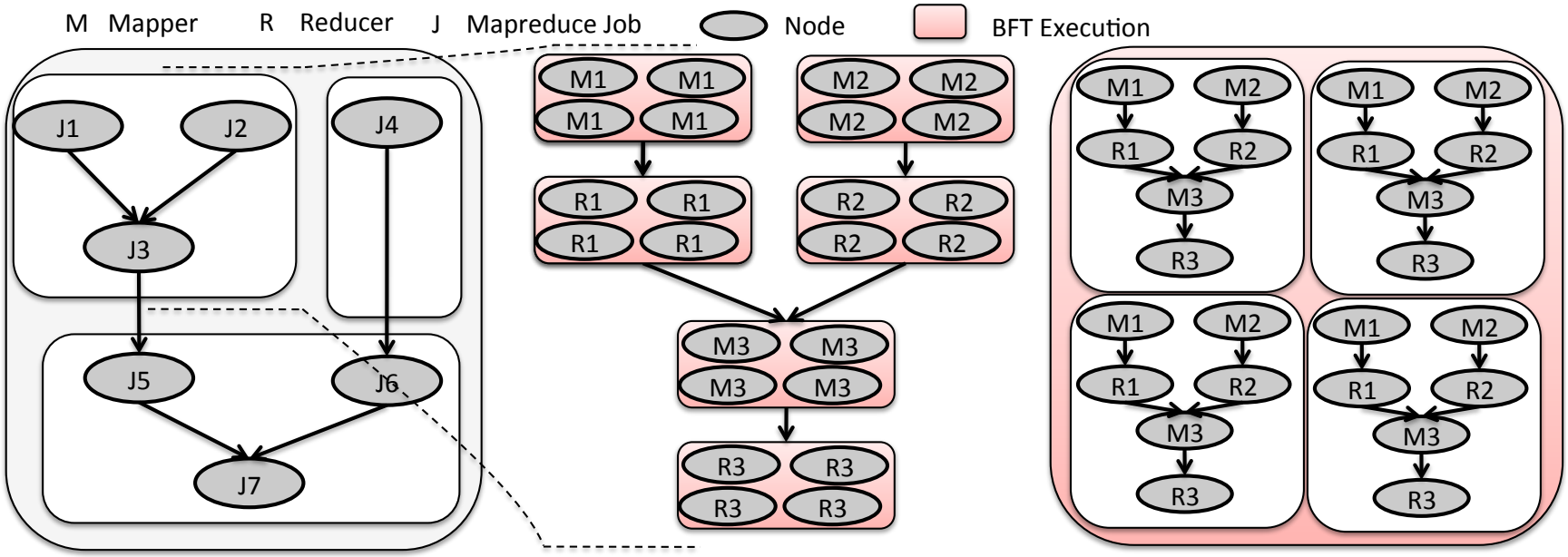
- No monolithic server — each job runs on multiple nodes
  - Cf. Zyzzyva [Kotla et al.;SOSP'07], Upright [Clement et al.;SOSP'09]
- Tasks may spawn multiple sub-tasks
- Size of data too high for naive agreement

ClusterBFT [Stephen&Eugster;Middleware'13]

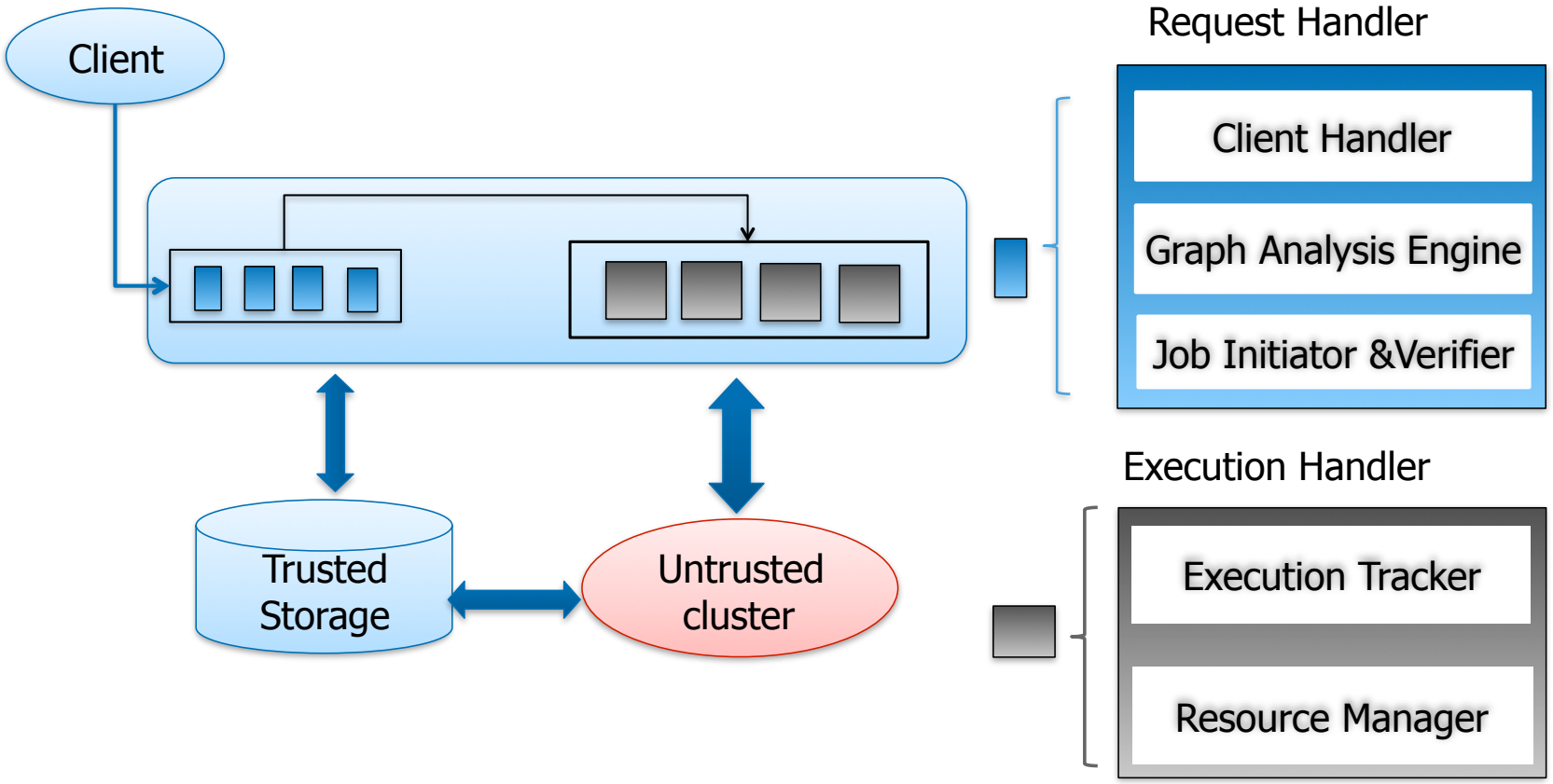
- Variable granularity replication
  - Replication level configurable
  - Trade overhead vs. guarantees
- Streaming and lazy validation
  - No need to wait for (2)*f*+1
  - Compare in background, continue optimistically
- Separation of duty with slim trust base
    - Untrusted nodes compute
    - Trusted nodes control
- Smart replica set overlapping
  - Restore accuracy



Intuition


M Mapper
R Reducer
J Mapreduce Job
Node
BFT Execution
J1
J2
J3
J4
J5
J6
J7
M1
M2
R1
R2
M3
R3

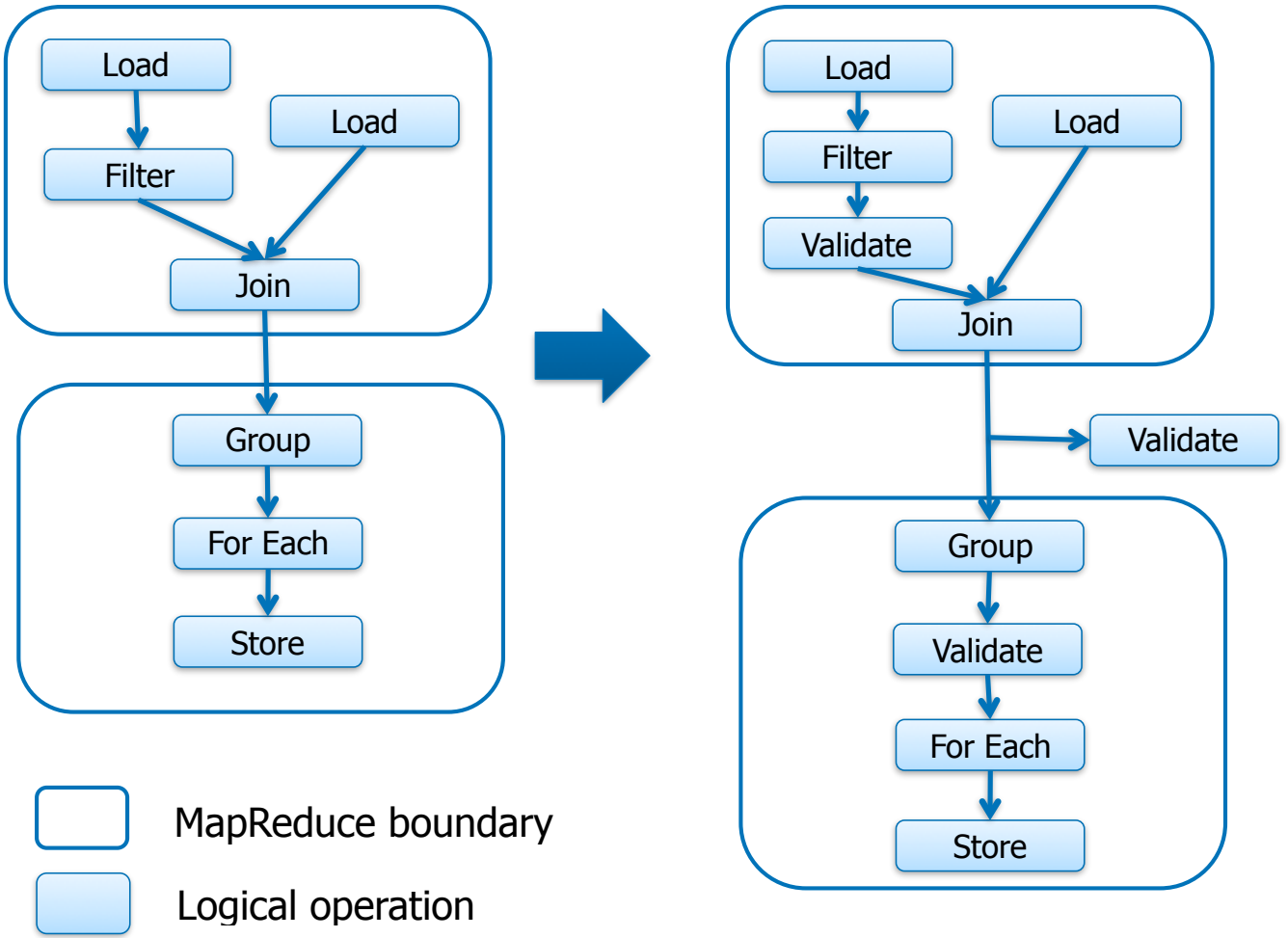
Architecture



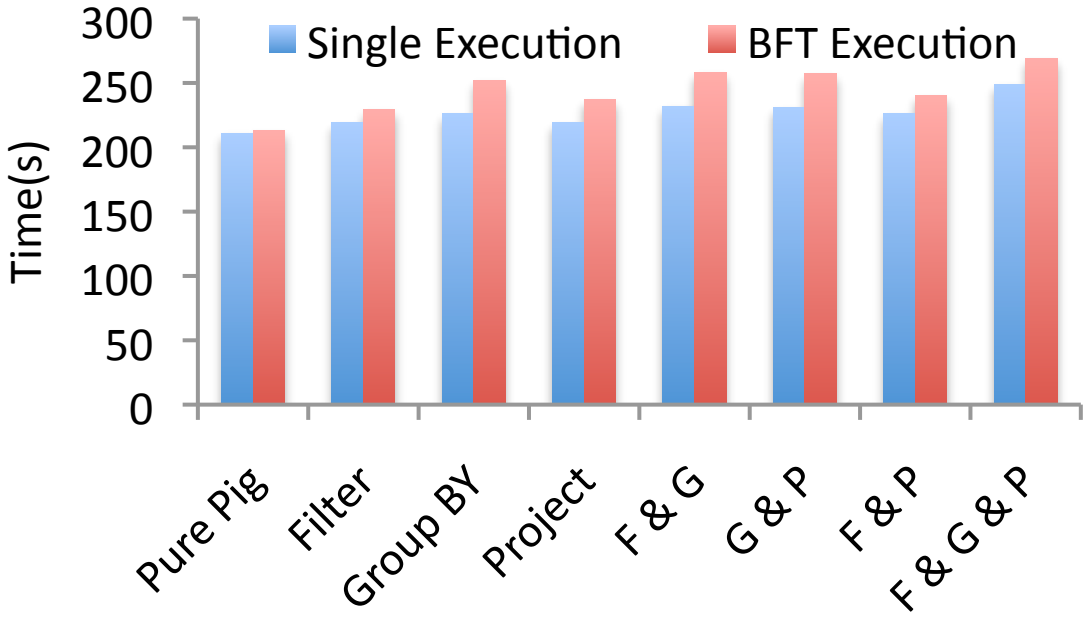
Components

- *Request Handler*
  - Creates logical graph
  - Automatically instruments and embeds validation
  - Sets up inter and/or intra MR validation points
  - Submits job to MR engine (modified Hadoop)
- *Execution Handler*
  - Keeps track of execution progress
  - Ensures cluster overlap
  - Ensures task replicas do not overlap

Illustration



Evaluation



- 11 node cluster (10 data nodes + 1 name node / job tracker)
- Twitter dataset
- Pig script counting number of followers for each user

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Problem Statement

- How to ensure that data does not leak in the face of tampering?
  - Intruders, internal threats
- Holy grail — fully homomorphic encryption (FHE)
  - Prohibitive costs in general case
  - Fine-print in expressiveness

Fully Homomorphic Encryption

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Fully Homomorphic Encryption

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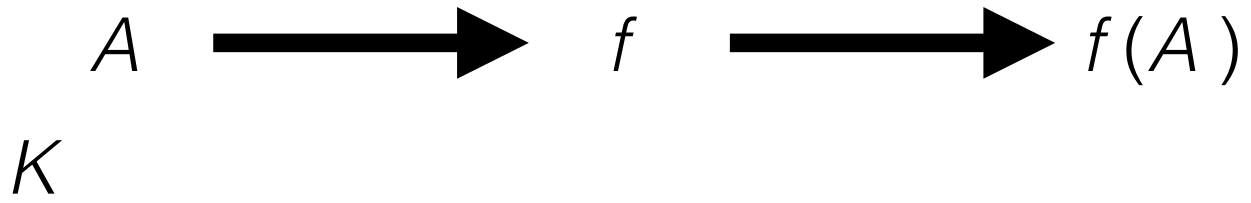
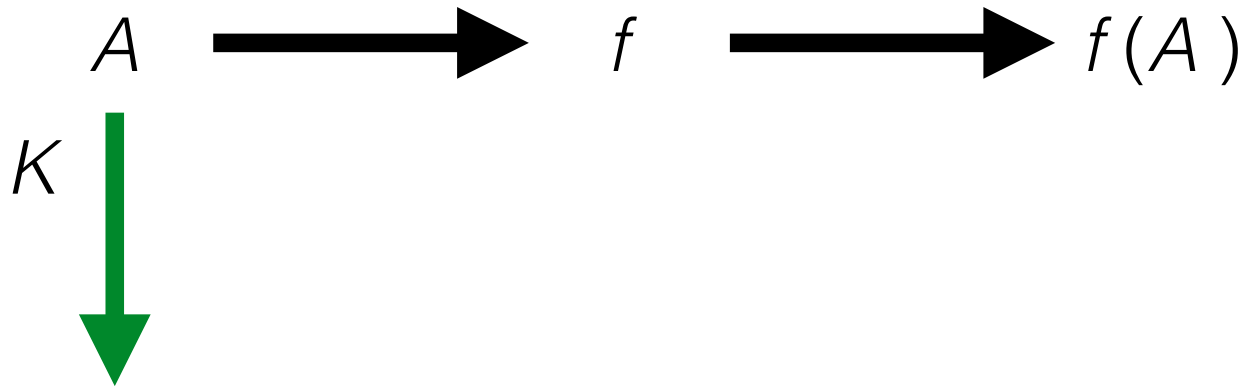


Fully Homomorphic Encryption



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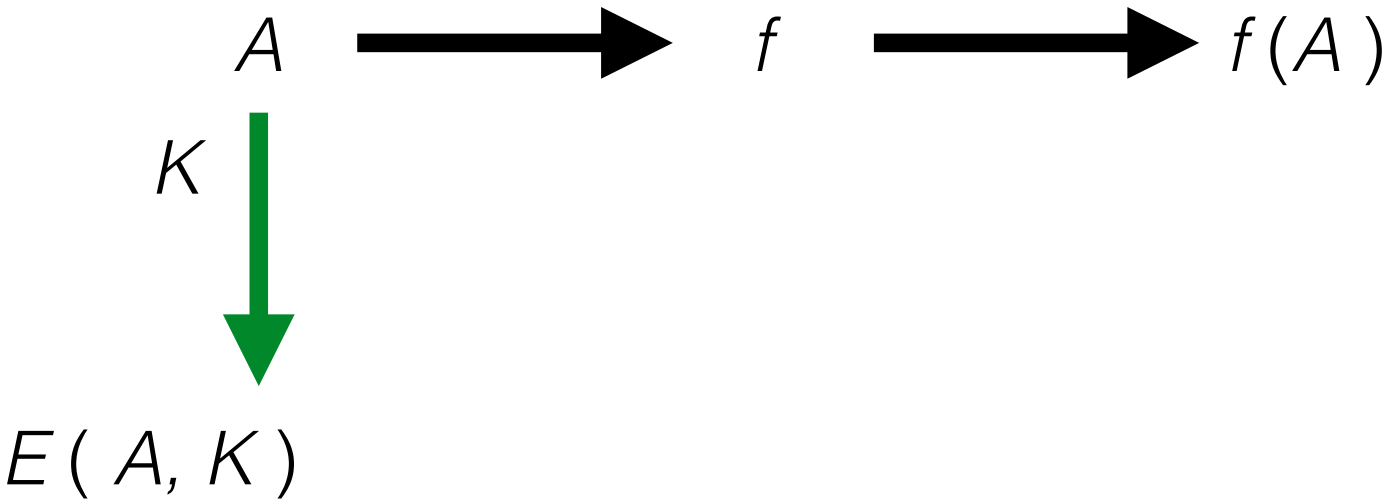

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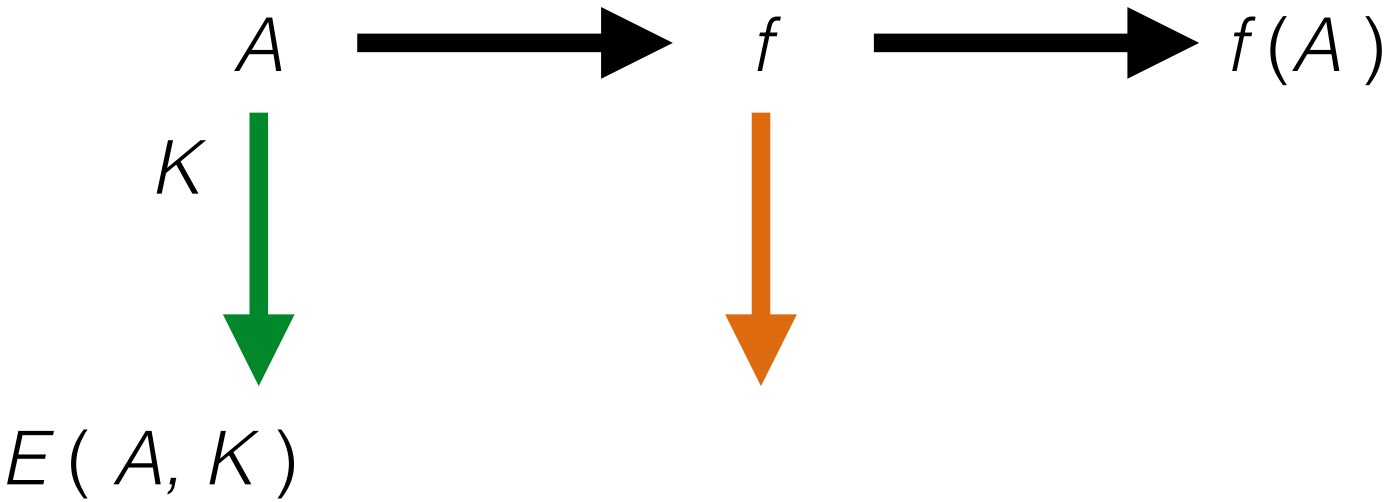

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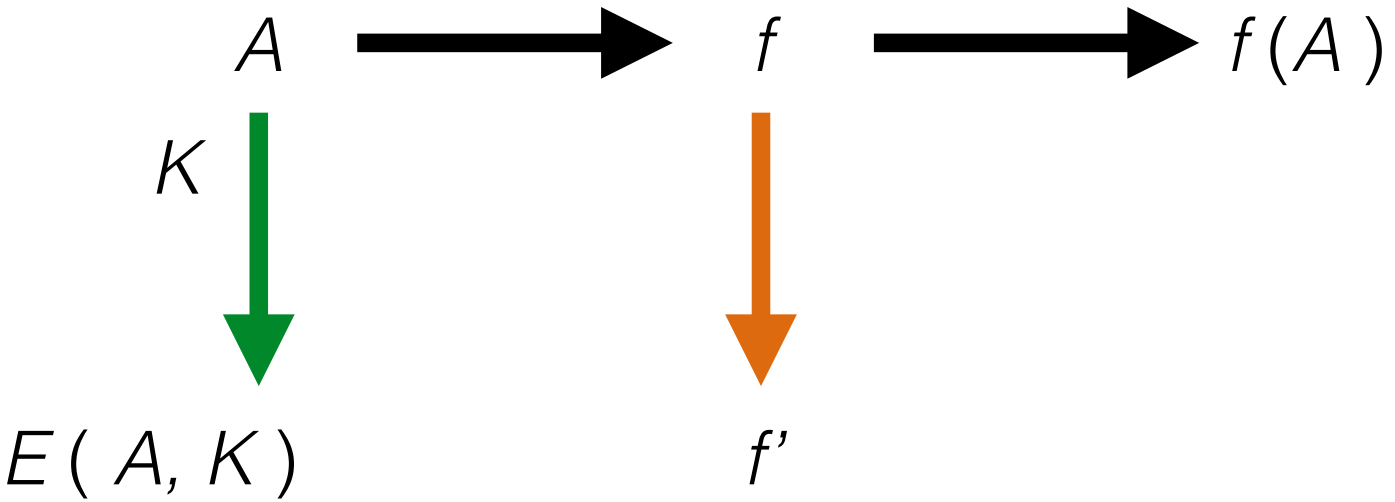

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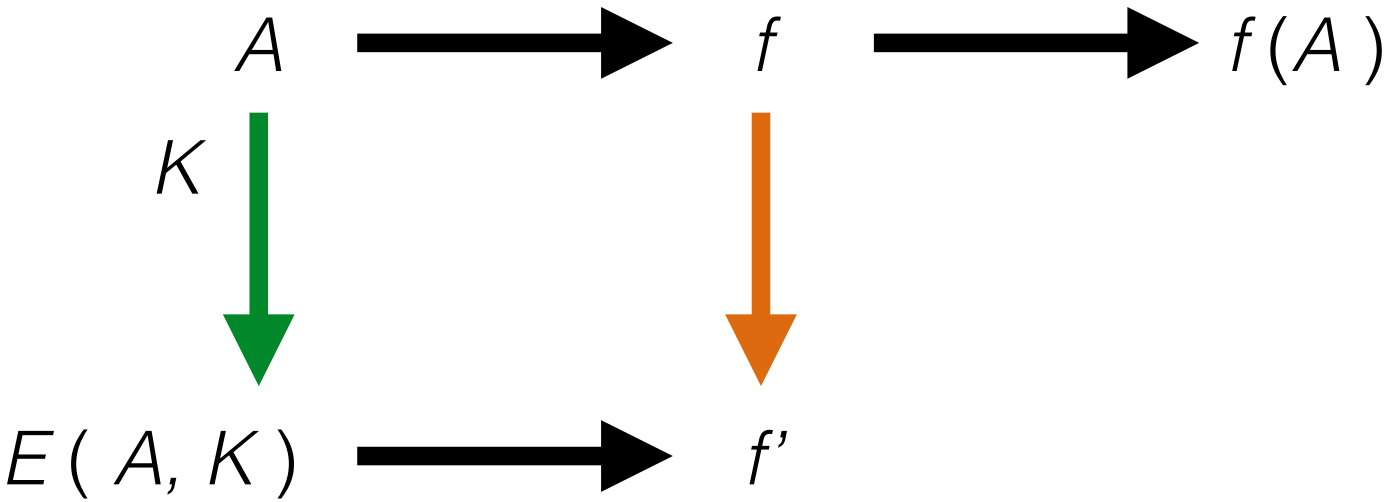

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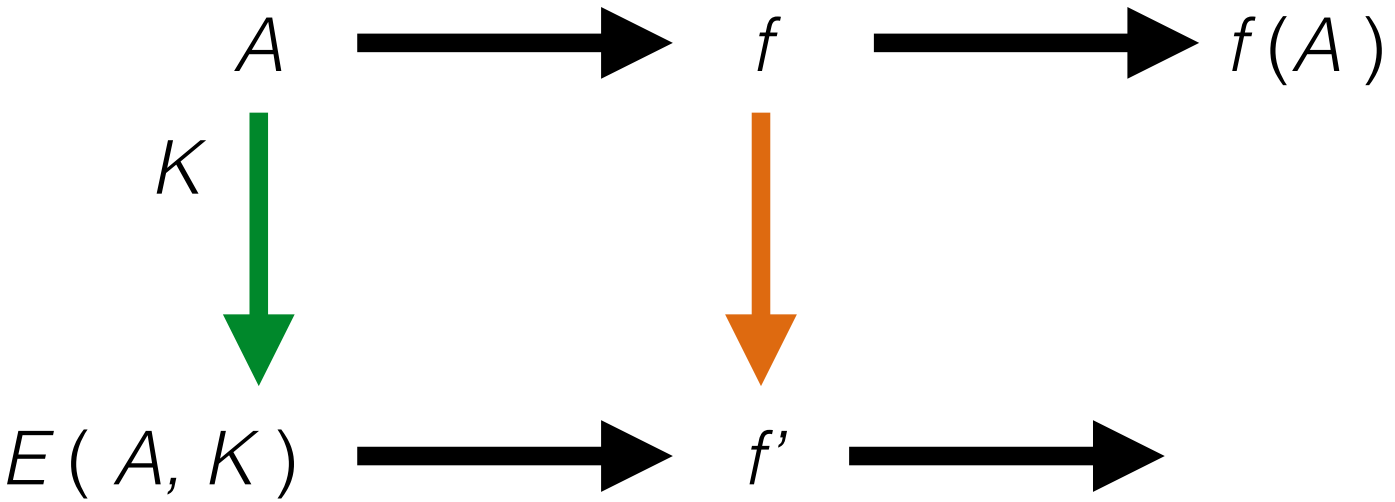

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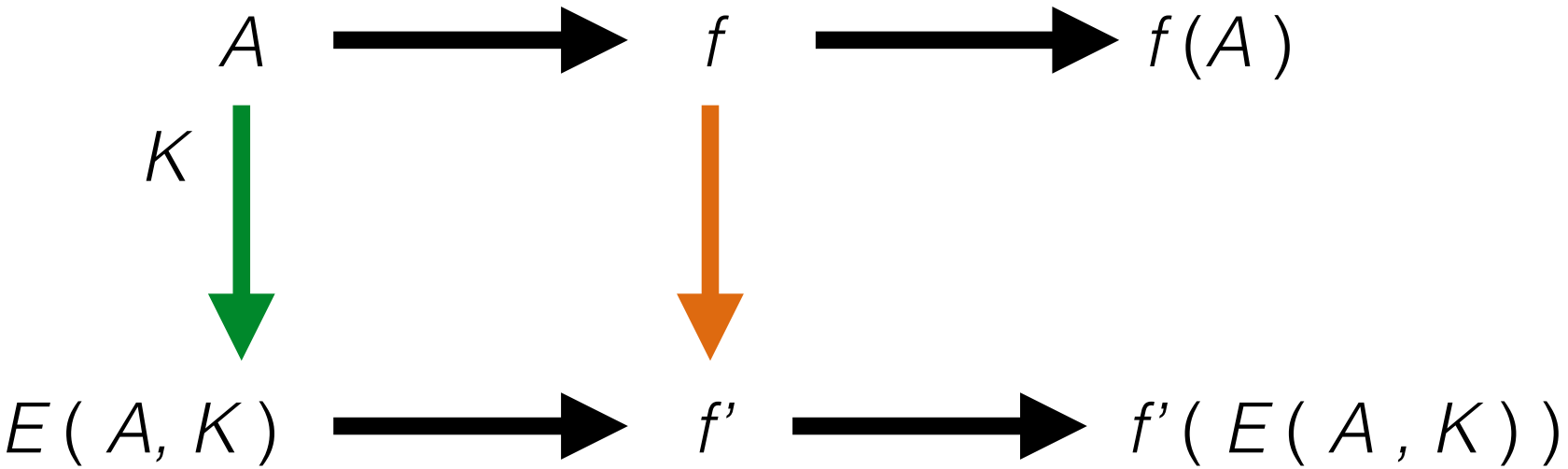

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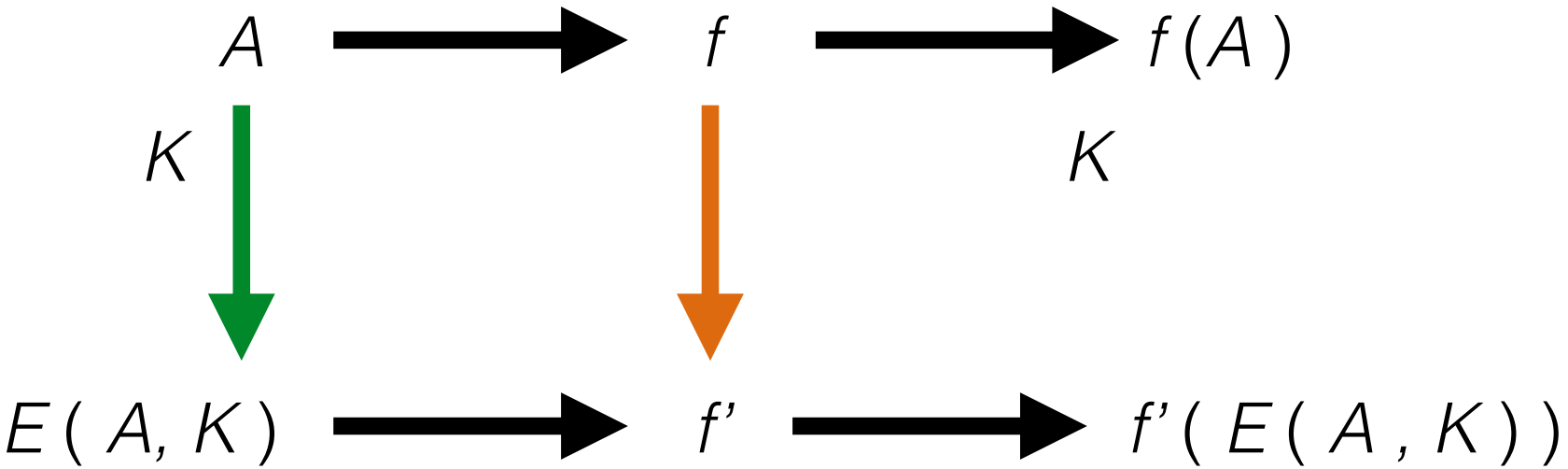

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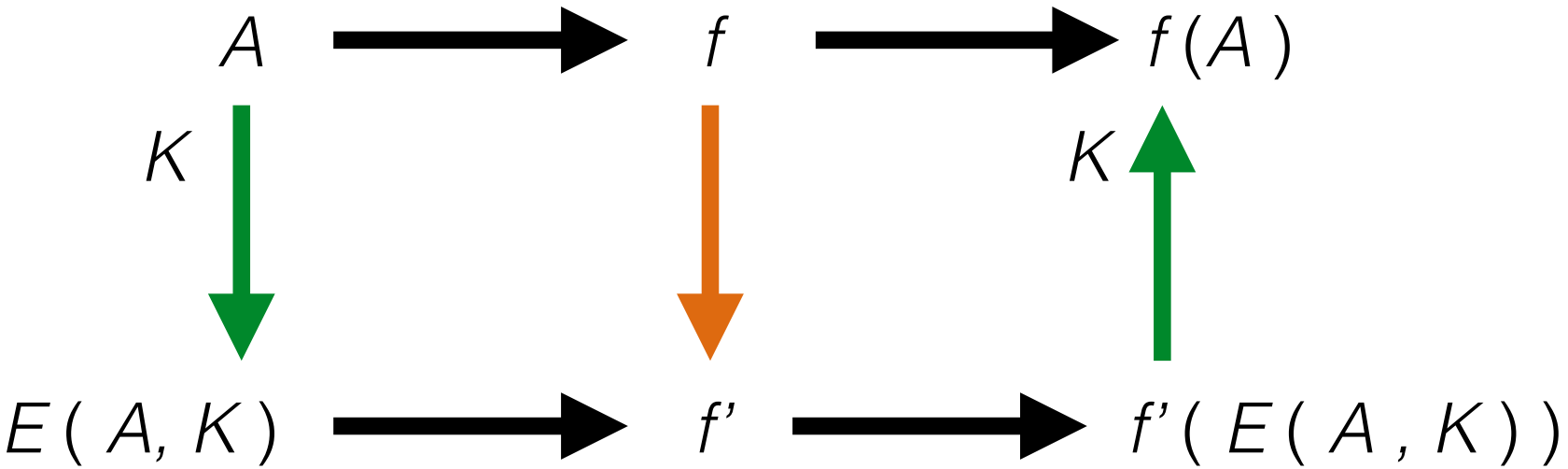

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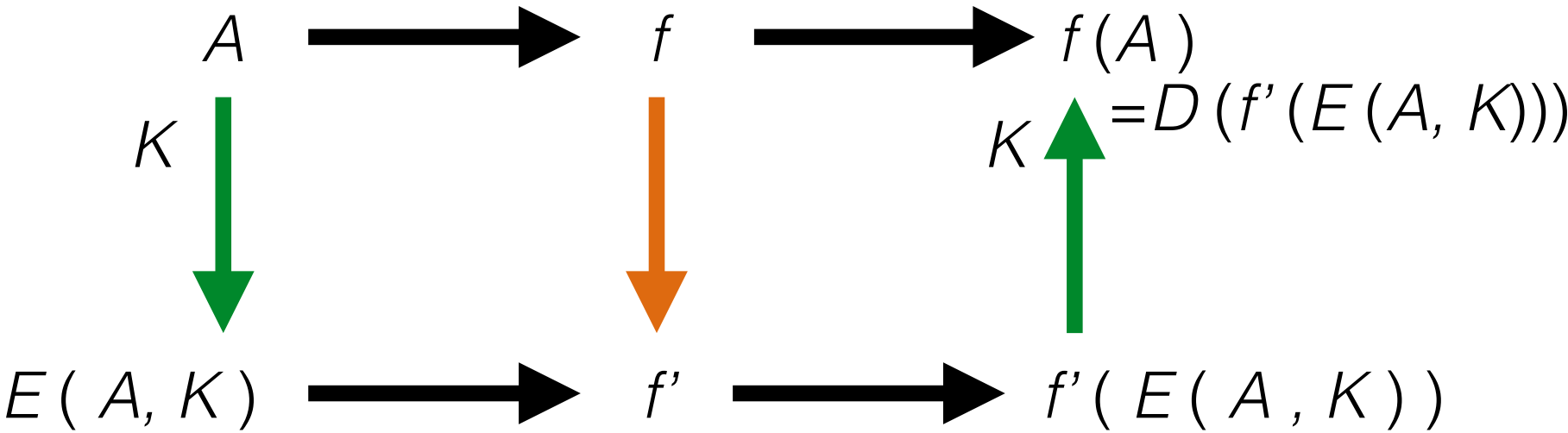

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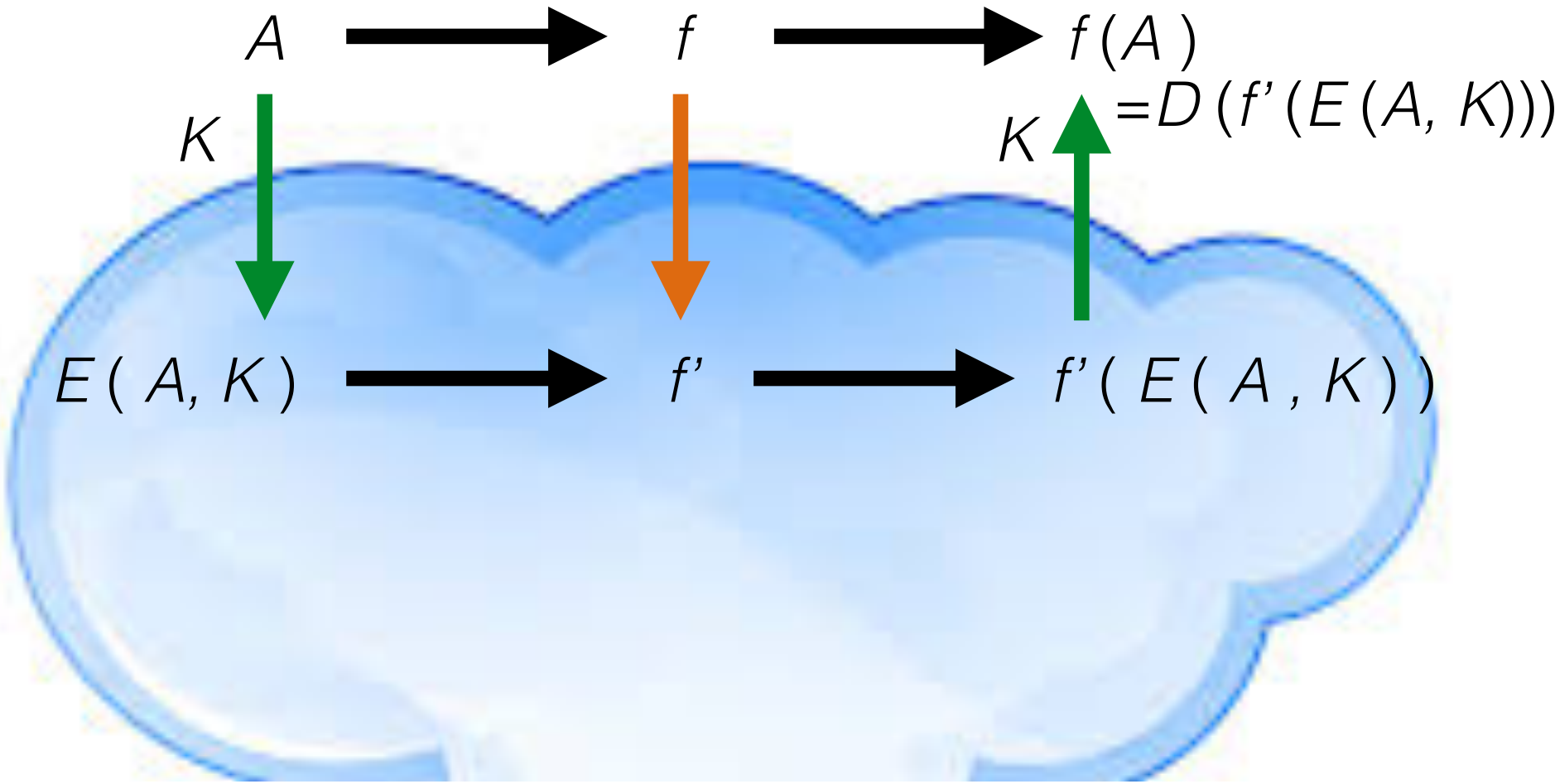


Partially Homomorphic Encryption (PHE)

- Some crypto systems can perform certain operations "under encryption",e.g.,
  - Paillier [Paillier;EuroCrypt'99] ▶ AHE: $\exists \oplus$ s.t. $D(E(x_1) \oplus E(x_2)) = x_1 + x_2$
  - Unpadded RSA [Rivest et al.;CACM'78], ElGamal [ElGamal;ToIT'86]

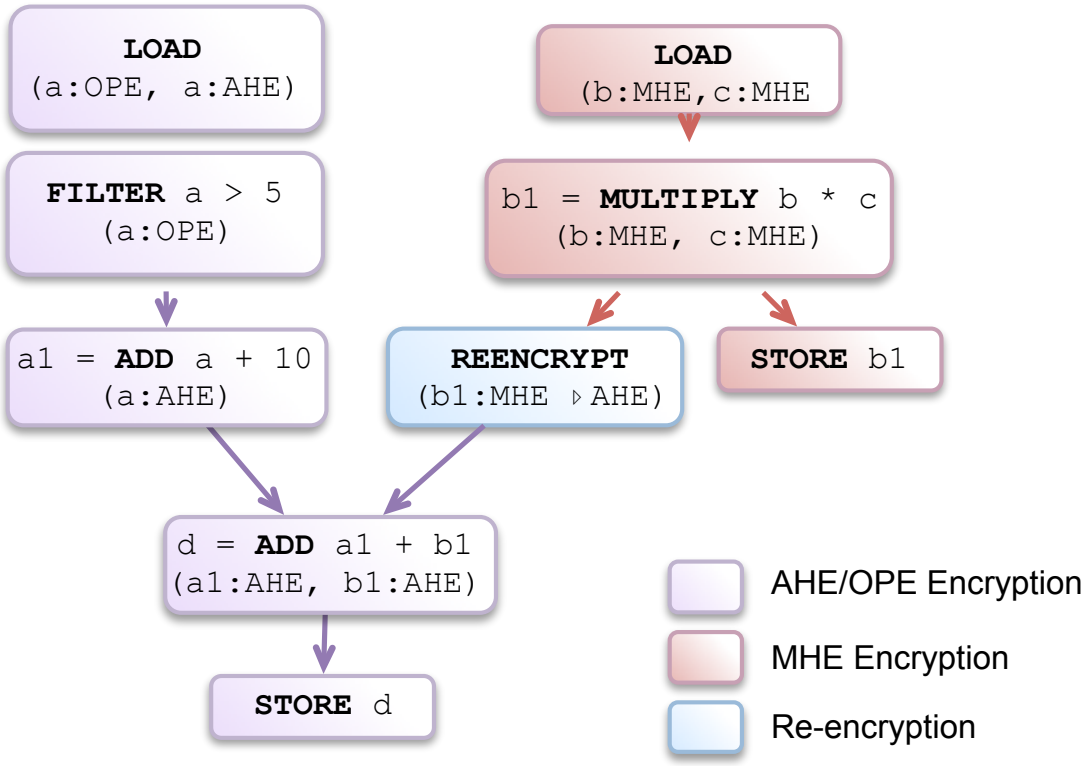
    ▶ MHE: $\exists \circledast$ s.t. $D(E(x_1) \circledast E(x_2)) = x_1 * x_2$
  - DET (=), OPE (<), SRCH

Privacy in Big Data Analytics

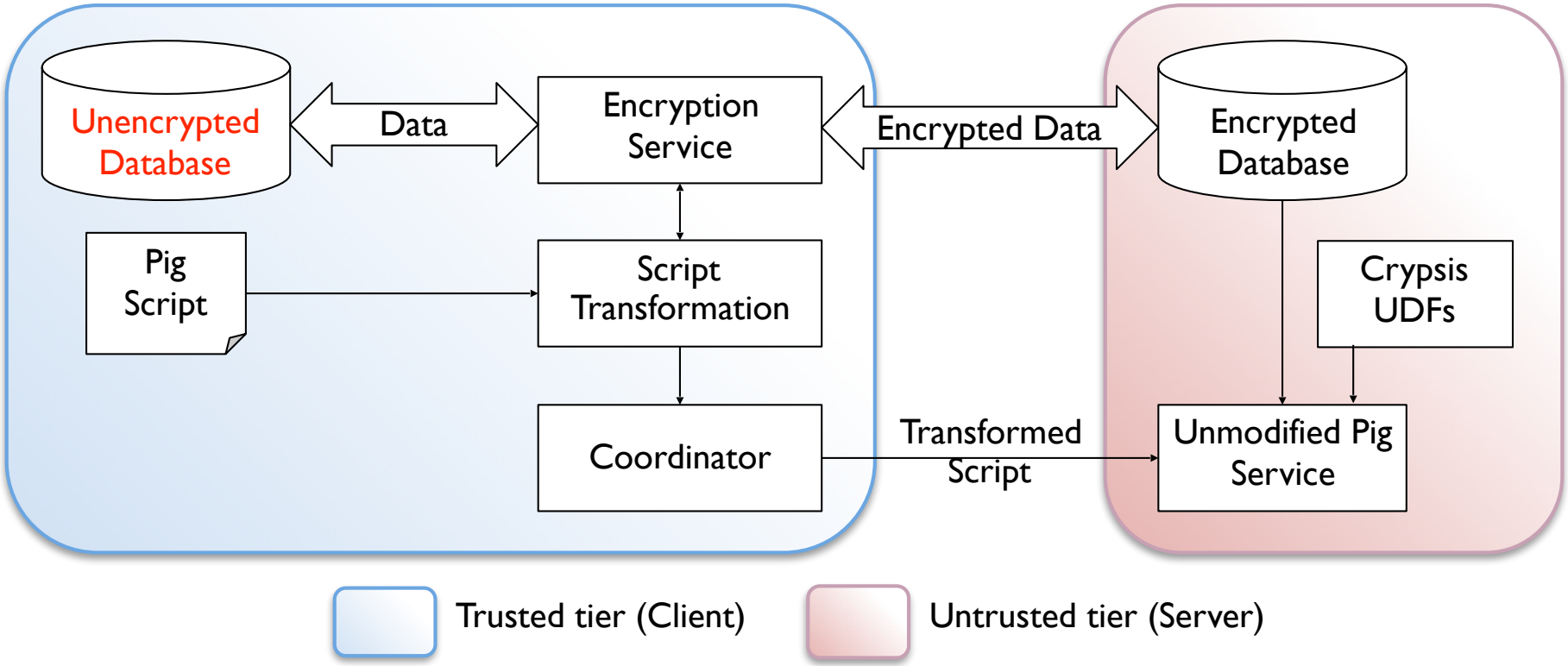
[Stephen et al.;HotCloud'14],[Stephen et al.;ASE'14]

- Intuition
  - Can use multiple cryptosystems side-by-side
  - Leverage parallelization (vs CryptDB [Popa et al.;CACM'12], Monomi [Pu et al.;PVLDB'13], Talos [Shafagh et al.;SenSys'15])
  - Client-side completion or re-encryption (vs MrCrypt [Lesani et al.;OOPSLA'13])

Crypsis Intuition

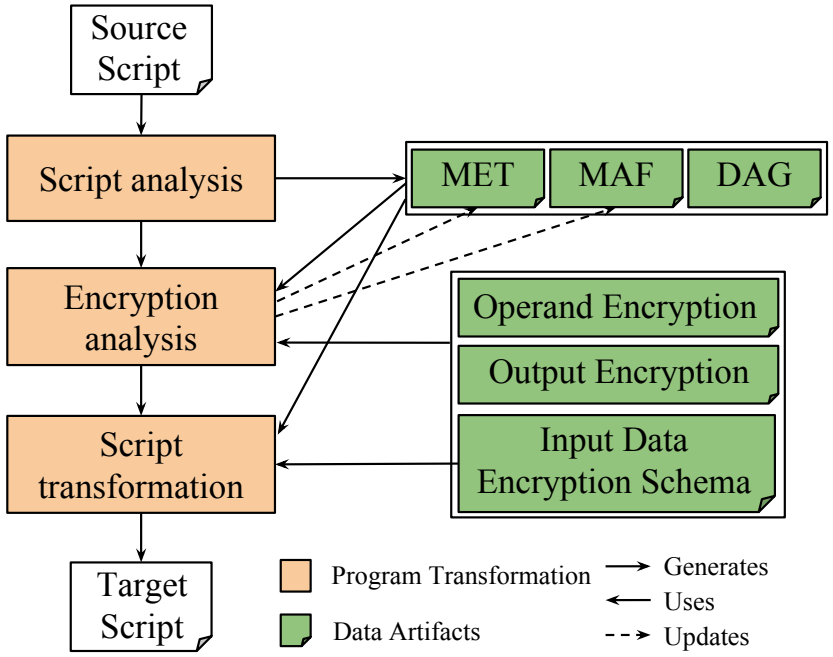


Architecture Overview



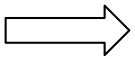
Script Transformation

- Generate d*ata-flow graph* (DFG)
  - Nodes are relations (**`LOAD`**, **`FOREACH`**, …)
  - Edges are data-flow between operators
- Generate *map of expression trees* (MET)
  - Contains all expressions
  - Keys are used to assign expressions to DFG
- Generate *set of annotated fields* (SAF)
  - One entry for each ⟨*relation*, *field* ⟩ of script
  - ⟨*relation*, *field* ⟩, parent, available encryptions, required encryptions
  - Get available encryptions from lineage of field, required encryptions using MET



Example Transformation

```
A = LOAD 'input1' AS
      (a0, a1);
B = LOAD 'input2' AS (x0);
C = FILTER A BY a0 > 10;
D = GROUP C BY a1;
E = FOREACH D GENERATE group AS
       b0, SUM(C.a0) AS b1;
F = JOIN E BY b0, B BY x0;
STORE F INTO 'out';
```

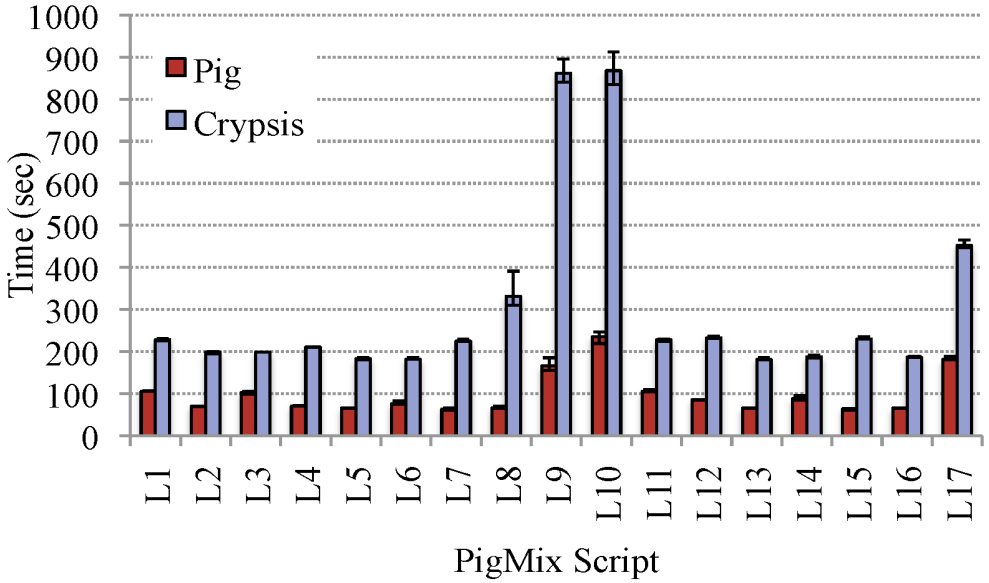


```
A = LOAD 'enc_input1' AS
       (a0_ope, a0_ah, a1_det);
B = LOAD 'enc_input2' AS (x0_det);
C = FILTER A BY a0_ope > OPE(10);
D = GROUP C BY a1_det;
E = FOREACH D GENERATE group AS
       b0, ENCSUM(C.a0_ah) AS b1;
F = JOIN E BY b0, B BY x0_det;
STORE F INTO 'out';
```

Simple Re-Encryption

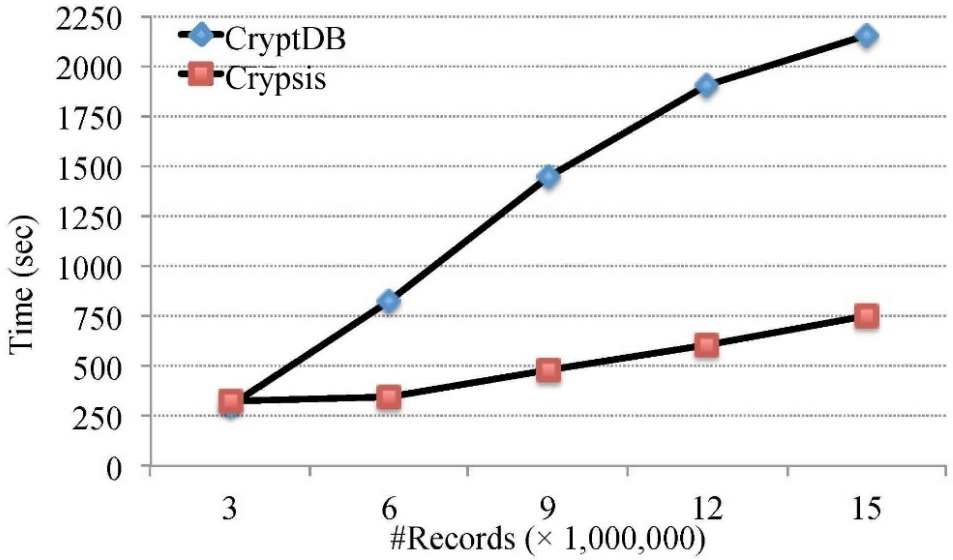
- Re-encryption required when
  - Required encryption unavailable
  - Incompatible operations, e.g., addition followed by multiplication
- Re-encryption conceptual
  - Can continue on client side
- 17 PigMix II benchmarks
  - Only script 8 requires re-encyption (averaging)
  - 1 script gets by with same attribute in several cryptosystems

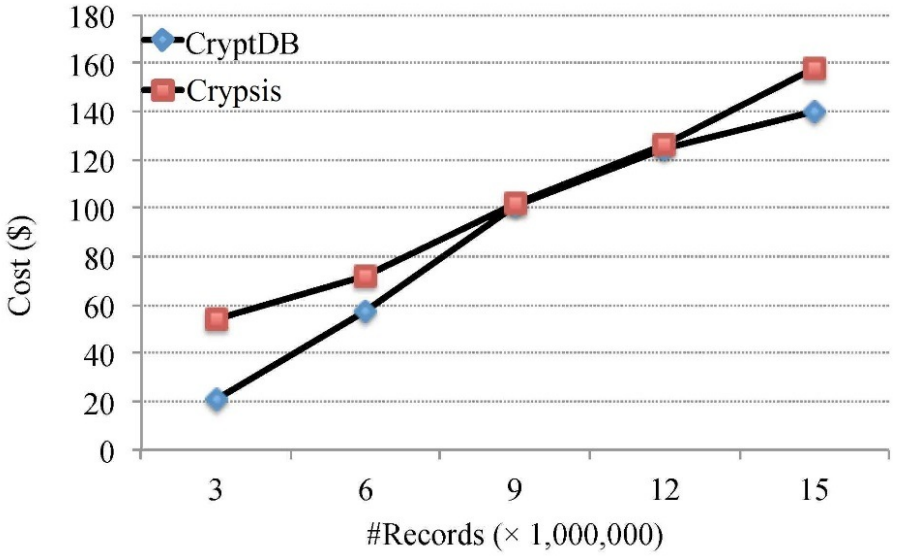
Evaluation (PigMix II)



- 11 EC2 large instances (2 CPUs, 3.75BB RAM)
- 5 GB data
- Average of 3x overhead (FHE can lead to 1000…s)

Crypsis Comparison





- 3 EC2 medium instances
- ~3x faster for 15Mio records
- Similar overall cost

as fast as cryptdb when only on 1 node, because CPU dominated

Limitations

- Drawback of PHE based solutions
  - Multiple users must share same key
  - Dealing with multiple domains adds complexity, e.g., garbled circuits, re-encryption
- Transparent solutions rarely yield optimal performance
  - Encrypting everything is costly
- Data specification
  - Only owners of data can know which parts of their datasets can be shared, and to what extent
- Queries
  - Can be expressed only if structure of data and accessibility constraints are known

PECCARY (**P**rivacy-preserving **E**fficient **C**loud-based **C**omputation **a**pplying **R**e-Encr**y**ption)

- Specification language
  - Structure of data
  - Constraints on visibility of attributes
  - Relationships between attributes
  - Precise model of data types (e.g., 100 > `value` > 0)
  - E.g., data owners specify which (aggregation) operations are supported on which attributes

- Query language/compilation
  - Allow access requirements to be derived
  - Allow feasibility to be matched with specification
  - Optimization, especially reduction of re-encryption

Secure Data Types (SDTs)

- Sensitivity levels
  - **`HIGH, LOW, NONE`**
  - Accounts for different security guarantees offered by crypto systems, avoids unnecessary overhead
- Ranges and precision for data
  - Positive/negative numbers
  - Fixed ranges e.g. 0-100
  - Decimal points for floats to preserve
- Enumerations
  - Fixed set of values, e.g. **`enum{`**`EUROPE, ASIA, AMERICA, AFRICA`**`}`**
- Composite data types
  - Values containing multiple parts, e.g. country code&local in phone #, year&month&day in date

```
composite[(4:int[+])-(2:int[range(1-12)])]
```

SDT Example

```
DEFINE Lineitem AS {
  orderkey:          long[+],
  linenumber:        long[+, unique],
  tax:               double[2]<NONE>,
  price:             double[2]<HIGH>,
  shipdate:          composite[(4:int[+])-(2:int[range(1-12)])-
                     (2:int[range(1-31)])],
  shipinstruct:      enum{IN_PERSON, COLLECT_COD, RETURN, NONE},
  comment:           chararray
  …
}
```

Compilation Techniqes

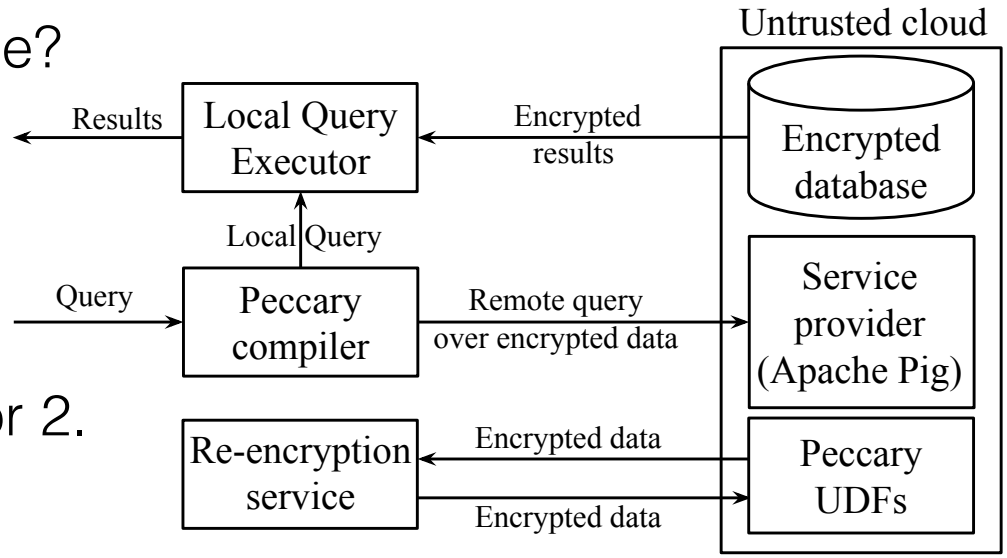
- Expression rewriting, e.g.,
  - `SUBSTRING(shipdate, 0, 4) == `1994' -> shipdate.year == `1994'`
  - `x, y >= 0; x + y > 0 -> x > 0 || y > 0`
  - `((a * b) + c) * d -> (a * b * d) + (c * d)`
- Selective encryption, e.g.,
  - **NONE** attributes
  - `(a+b)*c` with non-sensitive c -> Paillier secondary homomorphic property

Compilation Techniques

- Subexpression elimination, e.g. (TPC-H Q01)
  - `price*(1-discount)` vs `price*(1-discount)*(1+tax)`
  - `SUM, AVG, COUNT` vs `SUM, COUNT; AVG = SUM/COUNT`
- Efficient encryption, e.g.,
  - Enum types with only DET and ORD -> (random) int values
  - OPE -> DET
  - unpadded RSA for AHE and '=='
  - Boneh-Dan-Goh [Boneh et al.;TCC'05] for (multiple) AHE followed by (one) MHE
  - Packing multiple values

Re-Encryption

- Why throw in the towel when you can…
  - … complete computation on the client side?
  - … re-encrypt on the client side?
- Or better yet generalize?
  - Whenever hitting a PHE limit
  - Apply heuristic to choose 1. or 2.
- Plus
  - Caching of DET values
  - Speculative re-encryption for DET

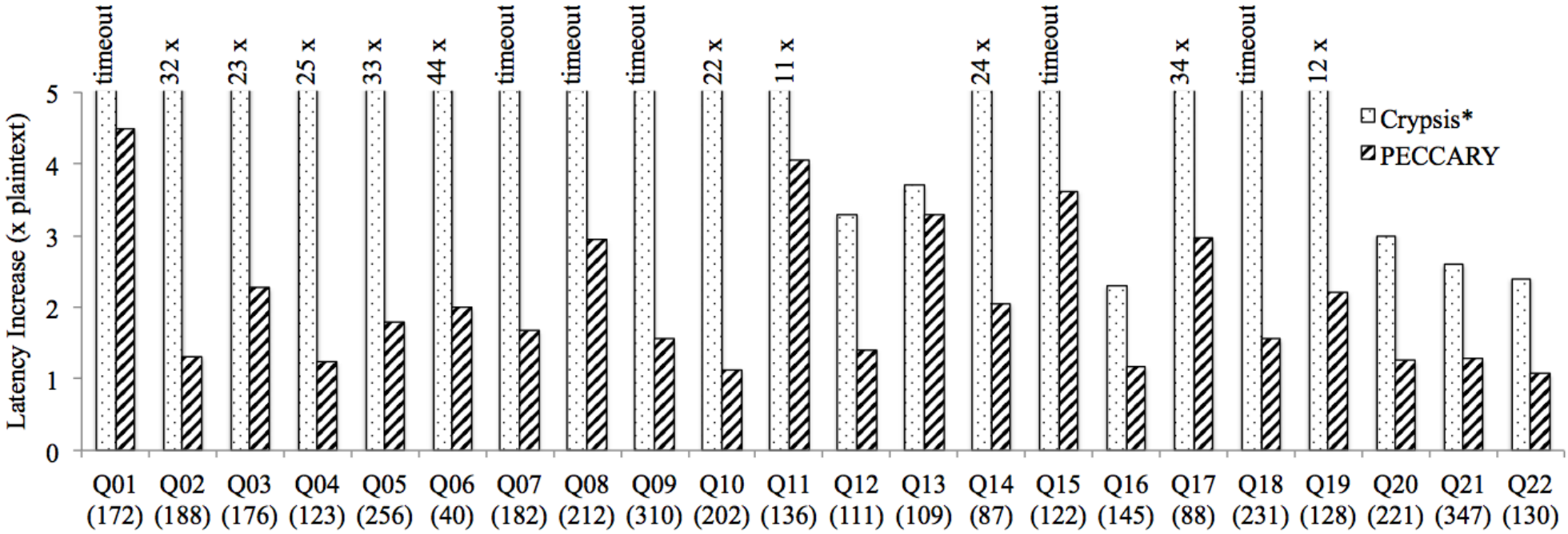


Benefits

	Expression rewriting	Selective encryption	Subexpr. elimination	Efficient encryption	Caching and speculative encryption
Secure data types		✓		✓	
Data range and precision	✓				✓
Enumerated type				✓	
Composite type	✓				

Performance

- TPC-H
  - 10GB plaintext
  - Amazon EC2 (10 xlarge nodes)
  - Only system to execute Q1 and Q15 entirely in the cloud



* Augmented to support (sub)string queries, floating points

Effectiveness

NORTHROP GRUMMAN

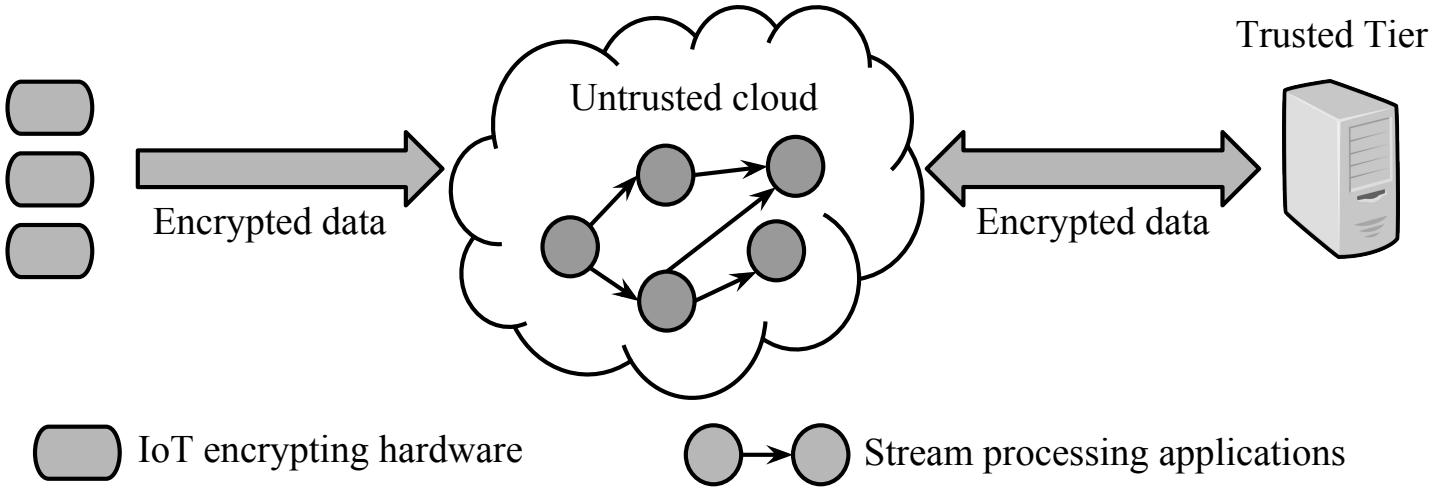
	# of scripts	
	PigMix2	TPC-H
Expression Rewriting	-	1
Selective Encryption	7	14
Efficient Encryption Strategy	2	20
Caching and Speculative Re-encryption	-	6
Subexpression Elimination	-	1

	Crypsis*	PECCARY
# of queries with re-encryption	18	6
Total # of re-encryptions	51	7

* Augmented to support (sub)string queries, floating points

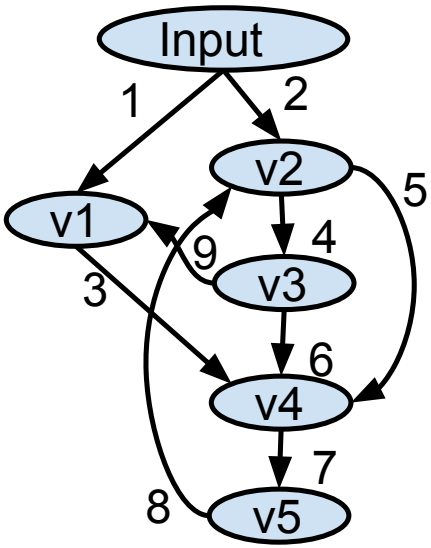
Online Processing

- Same principles (transformation) can be applied online
  - Implemented in Apache Storm (STYX — **s**tream processing with **t**rustworth**y** cloud-based e**x**ecution)
- Need to merge with corresponding optimizations

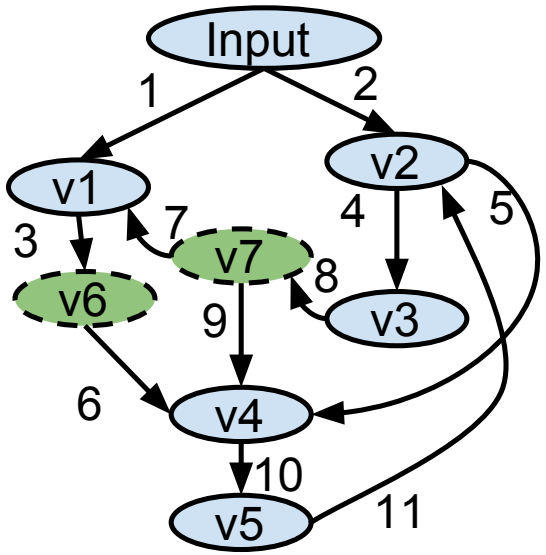


Linear Road Benchmark

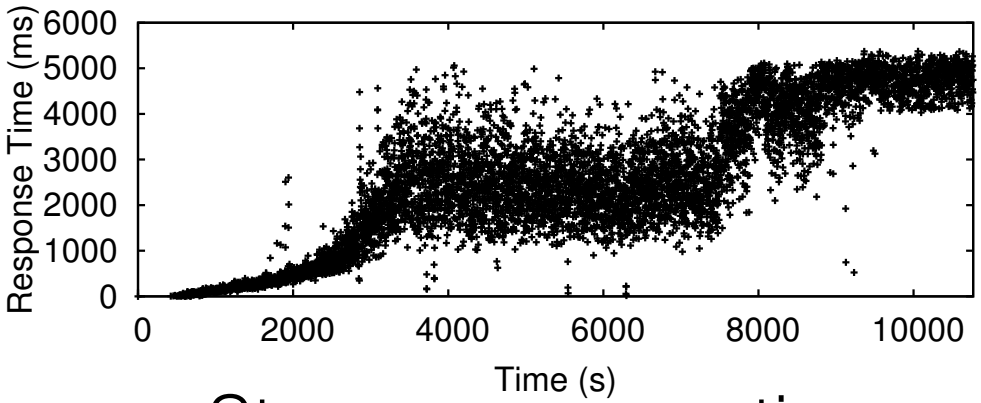
Storm



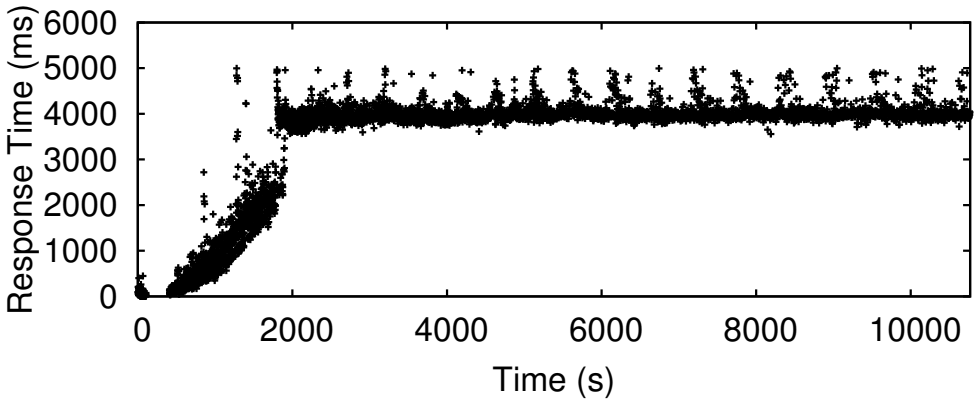
STYX



v6, v7 for re-encr.



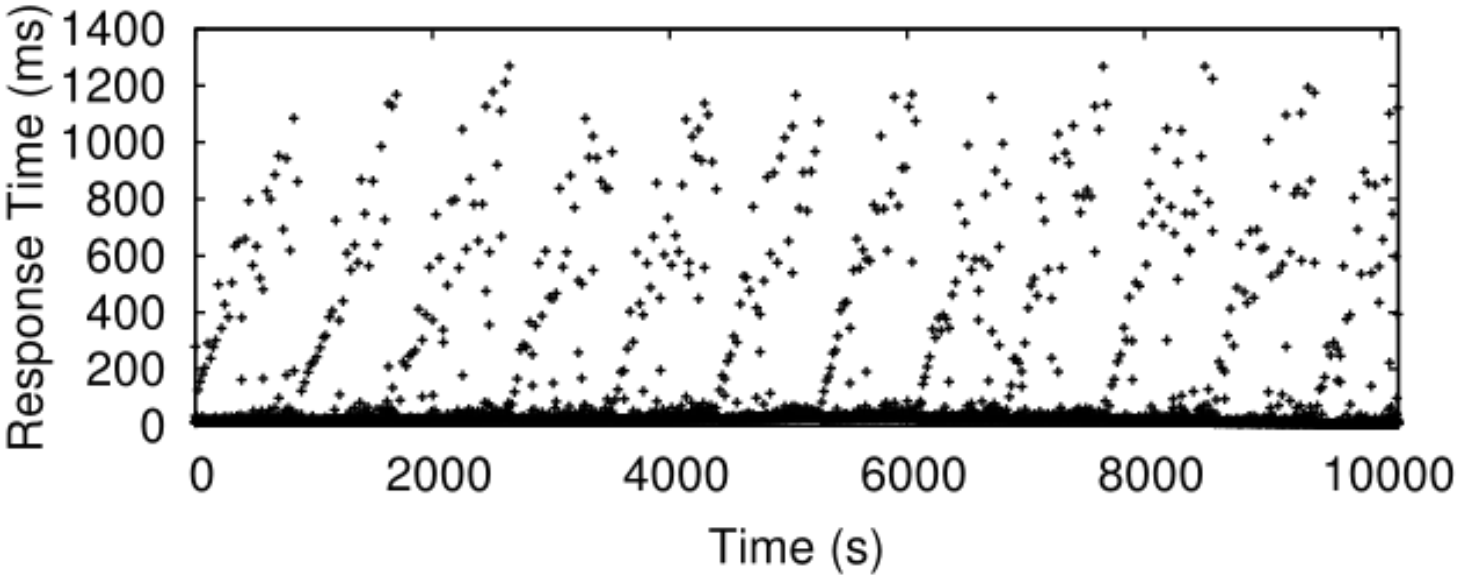
Storm response times



STYX response times

Re-Keying

- Key change
  - New York taxi route data (10G)
  - Application finds the top 10 most frequent routes during the last 30 minutes of taxi servicing
  - Amazon EC2 (9 large nodes)



Outline

- Context
- Availability and integrity in big data analytics
- Privacy in big data analytics
- **Conclusions and outlook**

Conclusions and Outlook

- Cloud security is gigantic topic
  - Big data security subset still huge
  - Many building blocks, e.g., also functional encryption, oblivious RAM, garbled circuits
- Much work left for described approaches, e.g.,
  - BFT
    - Peer-based trust management and attribution
  - PHE
    - Heuristics for re-encryption vs. client side completion

Conclusions and Outlook

- Much potential in hybrid techniques
  - E.g. garbled circuits + PHE, HW extensions (Intel SGX) + …?
  - Also PL + SE + DS + Crypto + NW + OS + HW + …

Conclusions and Outlook

- Much potential in [illegible]ques
  - E.g. garbled circuits + PHE, HW extensions (Intel SGX) + …?
  - Also PL + SE + DS + Crypto + NW + OS + HW + …