# Structural Cloud Audits that Protect Private Information

Hongda Xiao, Bryan Ford, Joan Feigenbaum
Department of Computer Science
Yale University

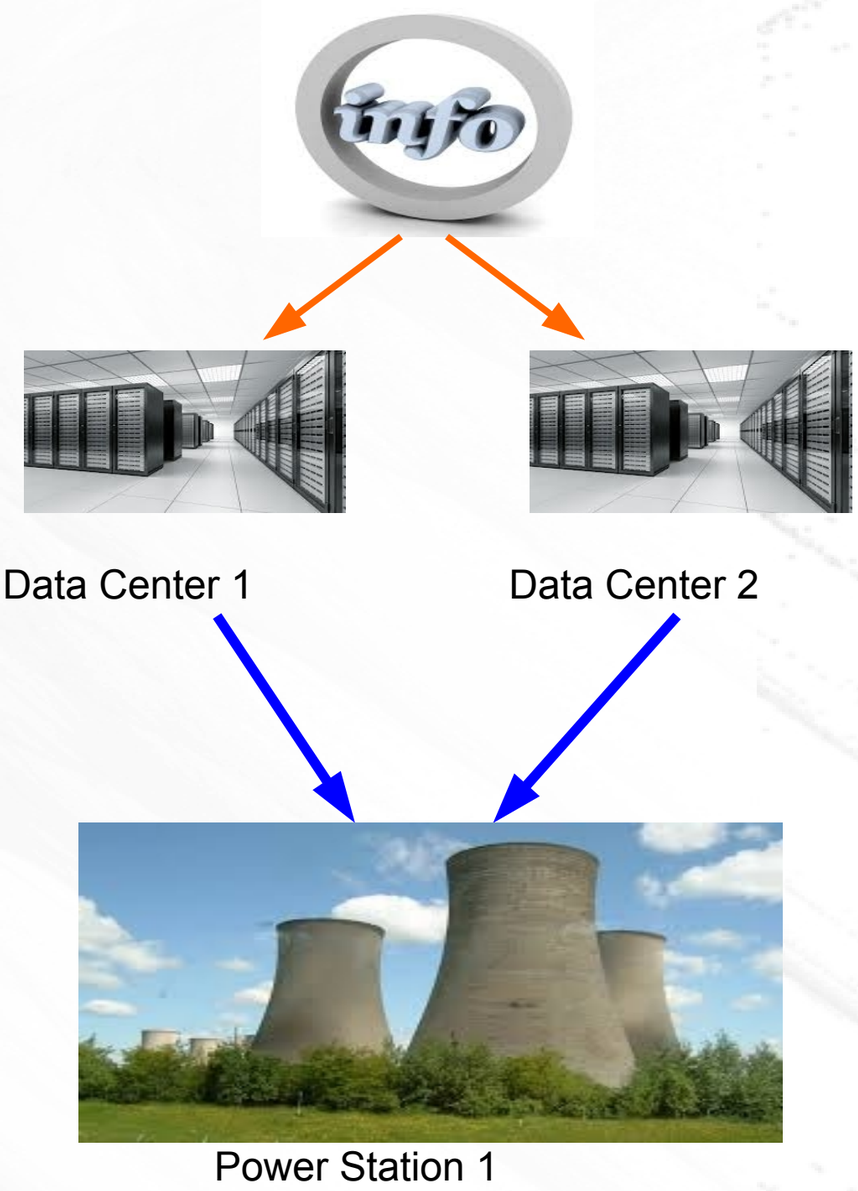
Cloud Computing Security Workshop – November 8, 2013

# Motivation

- Cloud computing and cloud storage now plays a central role in the daily lives of individuals and businesses.
  - Over a billion people use Gmail and Facebook to create, share, and store personal data
  - 20% of all organizations use the commercially available cloud-storage services provided both by established vendors and by cloud-storage start-ups
- Reliability of cloud-service providers grows in importance.

# Motivation

- Cloud-service providers use redundancy to achieve reliability




- But redundancy can fail due to Common Dependencies

[Ford, *Icebergs in the Clouds,* HotCloud '12]

# Motivation

- This is a real problem
  - e.g. a lightning storm in northern Virginia took out both the main power supply and the backup generator that powered all of Amazon EC2's data centers in the region

- We need a systematic way to discover and quantify vulnerabilities resulting from common dependencies

# Motivation

- Zhai et al. proposed Structural Reliability Auditing (SRA)
  - collect comprehensive information from infrastructure providers
  - construct a service-wide fault tree
  - identify critical components, estimiate likelihood of service outage

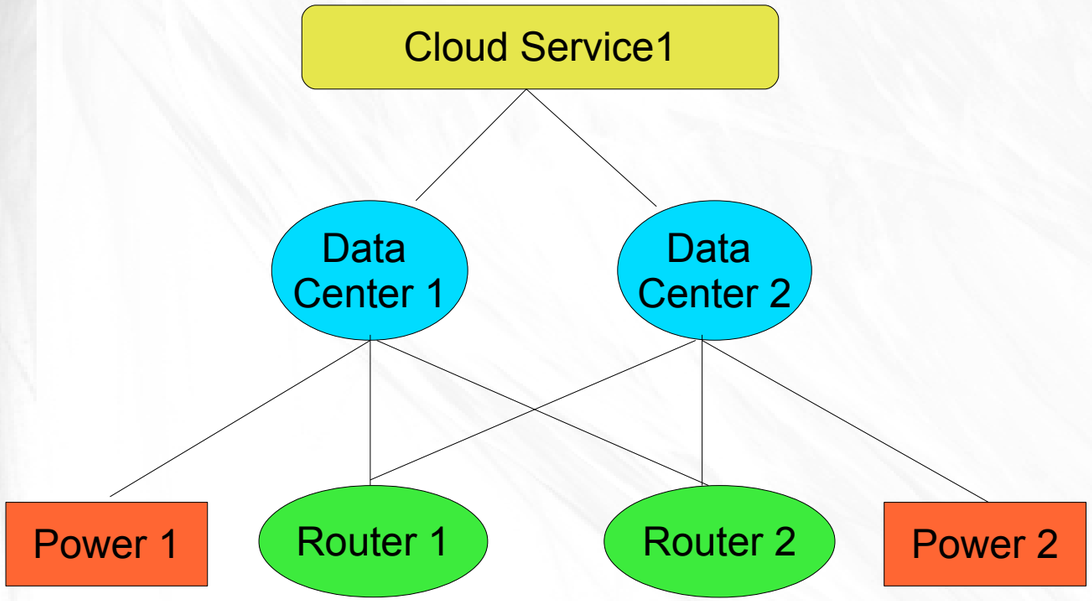
- A potential barrier to adoption of SRA is the sensitive nature of both its input and its output.
  - cloud service providers and infrastructure providers may not be willing to disclose the required information

# Objective

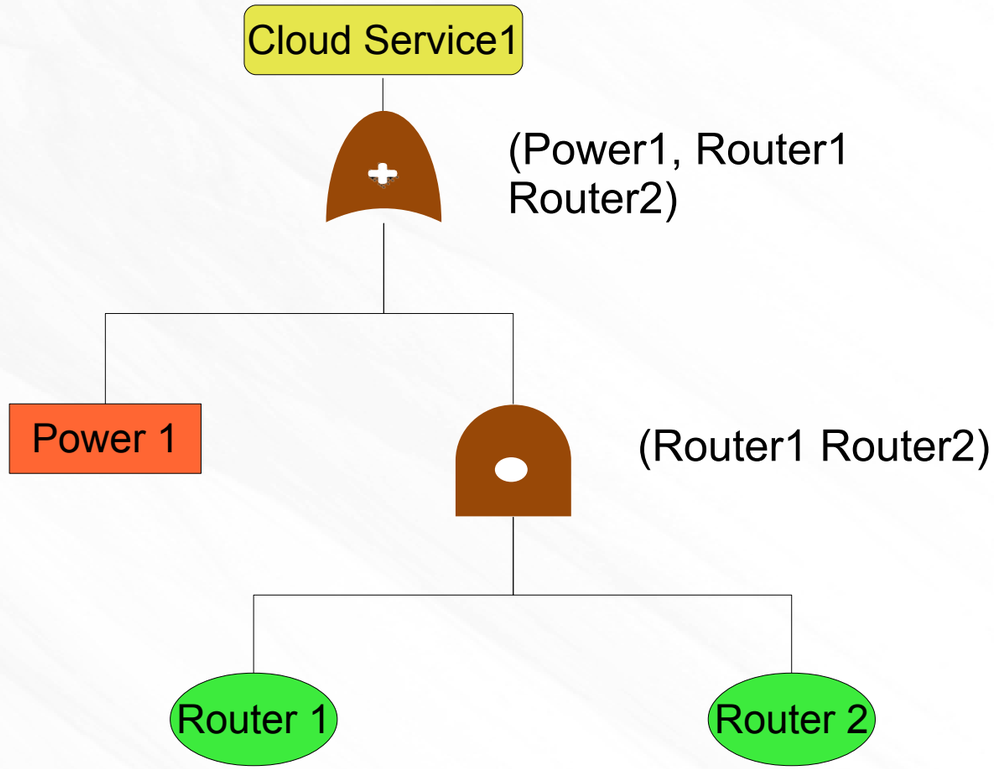
- Privacy-Preserving SRA (P-SRA): investigate the use of secure multi-party computation (SMPC) to perform SRA in a privacy preserving manner
    - Perform SMPC on complex, linked data structures of cloud topology, which has not often been explored yet

# Basic Idea

Step 1: Build a *structural model* of cloud infrastructure of interest




Step 2: Perform *fault tree analysis* to detect hidden failure risks




[Zhai et al., *Auditing the Structural Reliability of the Clouds,* Yale TR-1479]

# Challenges

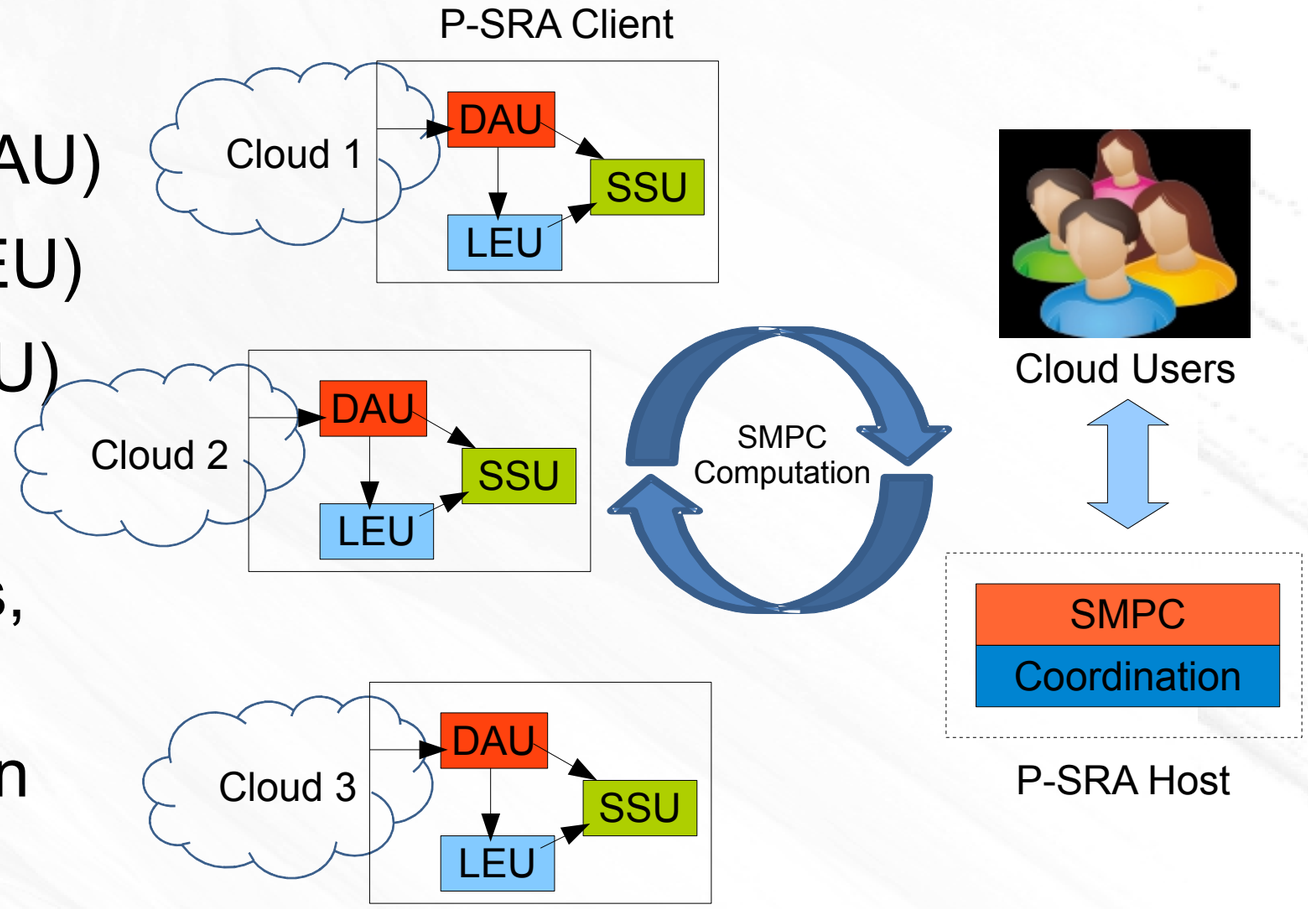
- Private Data Acquisition
  - How to collect complex, linked data of cloud topology without compromising the privacy of the cloud and infrastructure providers?
- Privacy-Preserving Analysis
  - How to identify common dependencies and correlated failure risk without requiring providers to disclose confidential information?
- Efficiency
  - SMPC is NOT very efficient especially when the size of inputs are large

# Our Solutions

- Private Data Acquisition
  - Leverage secret sharing techniques in SMPC
  - Specify valid output protecting privacy
- Privacy-Preserving Analysis
  - Specialized graph representation techniques to build fault tree in a privacy preserving manner
- Efficiency
  - Novel data partitioning techniques to effectively reduce the input size of SMPC and leave most of the computations locally

# System Design Overview

- P-SRA Client
  - Data Acquisition Unit (DAU)
  - Local Execution Unit (LEU)
  - Secret Sharing Unit (SSU)
- P-SRA Host
  - Represents Cloud Users, Reliability Auditors
  - Does SMPC coordination



# Cloud Provider

- Install and control a P-SRA Client
- Input their private infrastructure information, which is considered private
- Semi-honest Threat Model
    - The Cloud Providers are honest but curious

# P-SRA Client

- Fully controlled by Cloud Providers
- Data Acquisition Unit
    - Collects component and dependency information
- Local Execution Unit
    - Perform local stractural reliability analysis
- Secret Sharing Unit
    - Perform SMPC with P-SRA Host

# P-SRA Host

- SMPC module
  - Perform SMPC with each P-SRA client installed by cloud providers
- Coordination module
  - Coordinate the communication between P-SRA Clients and P-SRA Host
- Semi-honest Model
  - The P-SRA Host is honest but curious

# Outline of How the System Works

- Step 1: Privacy-preserving dependency acquisition
- Step 2: Subgraph abstraction to reduce problem size
- Step 3: SMPC protocol execution and local computation
- Step 4: Privacy-preserving output delivery

# Privacy-preserving dependency acquisition

- The DAU of each cloud-service provider collects information about the components and dependencies of this provider
  - network dependencies
  - hardware dependencies
  - software dependencies
  - failure probability estimates for components
- Store the information in a local database for use by P-SRA's other modules.

# Subgraph Abstraction

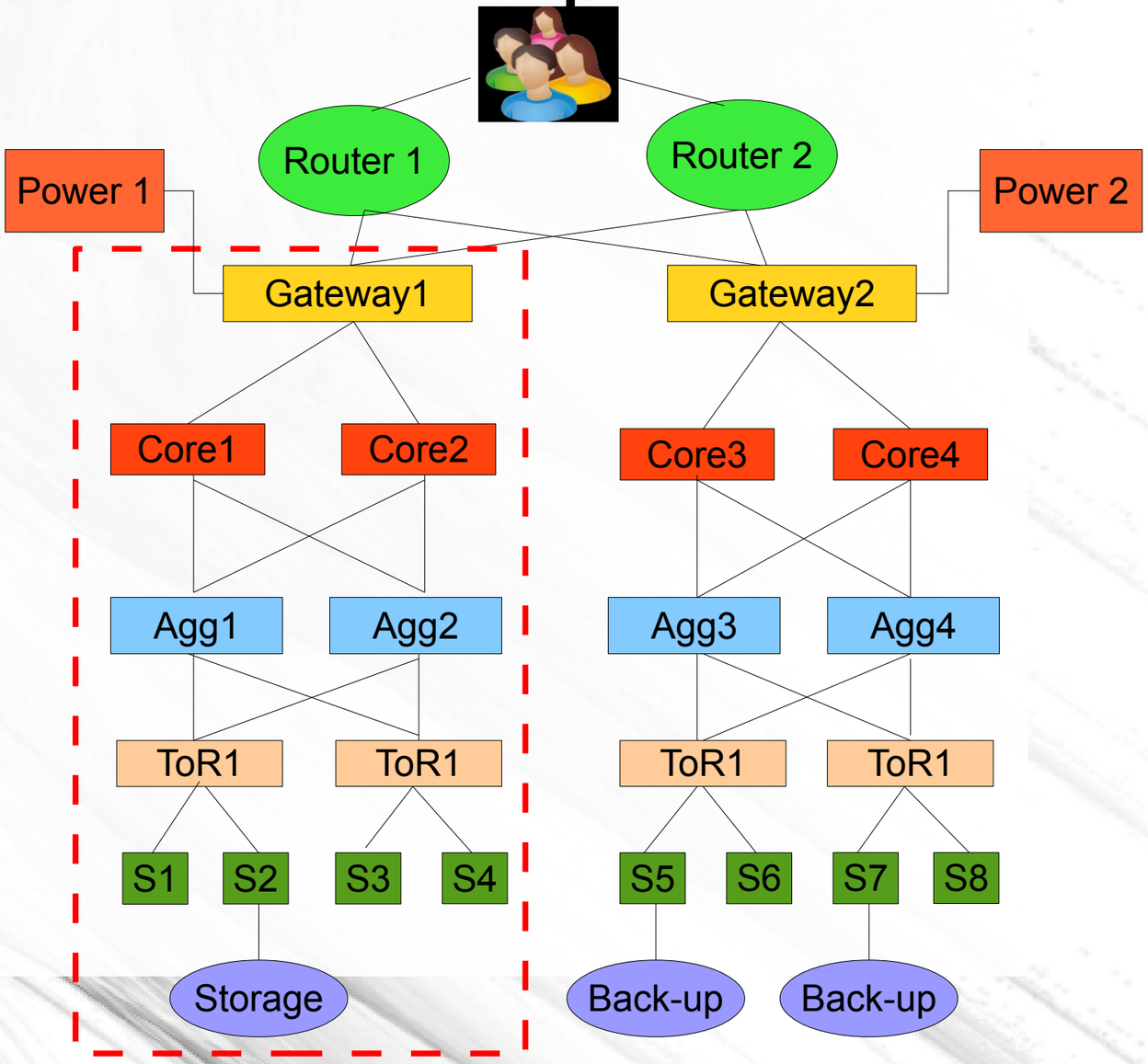
- The Client's SSU abstracts the dependency information of private components as a set of macro-components, which are the actual inputs of the SMPC
- Key step to reduce the input size of SMPC
- The choice of abstraction policy is flexible as long as satisfying the proper criterions
- Can be generalized to other SMPC problem on complex and linked data structure

# Subgraph Abstraction Policy

- A subgraph H of the full dependency graph G of a cloud-service provider S should have two properties in order to be eligible for abstraction as a macro-component
  - all components in H must be used only by S
  - for any two components v and w in H, the dependency information of v with respect to components outside of H is identical to that of w
- SSU collapses H to a single node to transfer G to a smaller graph G'

# Subgraph Abstraction: Example

- Dependency Graph of a Simple Data Center
  - A Storage Service
  - Two Data Centers, one for service and the other for back-up
- Red Frame is the data center 1, which satisfies the two properties



# Subgraph Abstraction: Example

Red frame on the left is data center 1, which is abstracted as Data Center 1 on the right

Router 1
Router 2
Power 1
Power 2
Gateway1
Gateway2
Core1
Core2
Core3
Core4
Agg1
Agg2
Agg3
Agg4
ToR1
ToR1
ToR1
ToR1
S1
S2
S3
S4
S5
S6
S7
S8
Storage
Back-up
Back-up

Cloud Service1
Data Center 1
Data Center 2
Power 1
Router 1
Router 2
Power 2

# SMPC and Local Computation

- SMPC
  - Perform SMPC to identify common dependency and reliability analysis across cloud providers
  - SSUs of P-SRA Clients work with SMPC of P-SRA Host
- Local Computation
  - SSU passes the dependency informaiton within macro-components to LEU
  - LEU performs structural reliability analysis locally

# SMPC Protocol

- Fault-tree construction
- Generate input for the SMPC
- Identify common dependencies
- Calculate failure sets

# Fault Tree Analysis

- FTA is a deductive reasoning technique
    - Occurence of top event is a boolean combination of occurence of lower level events
- Fault Tree is a Directed Acyclic Graph (DAG)
    - Node: gate or event
    - Link: dependency information
- Failure Set is a set of components whose simultaneous failure results in cloud service outage

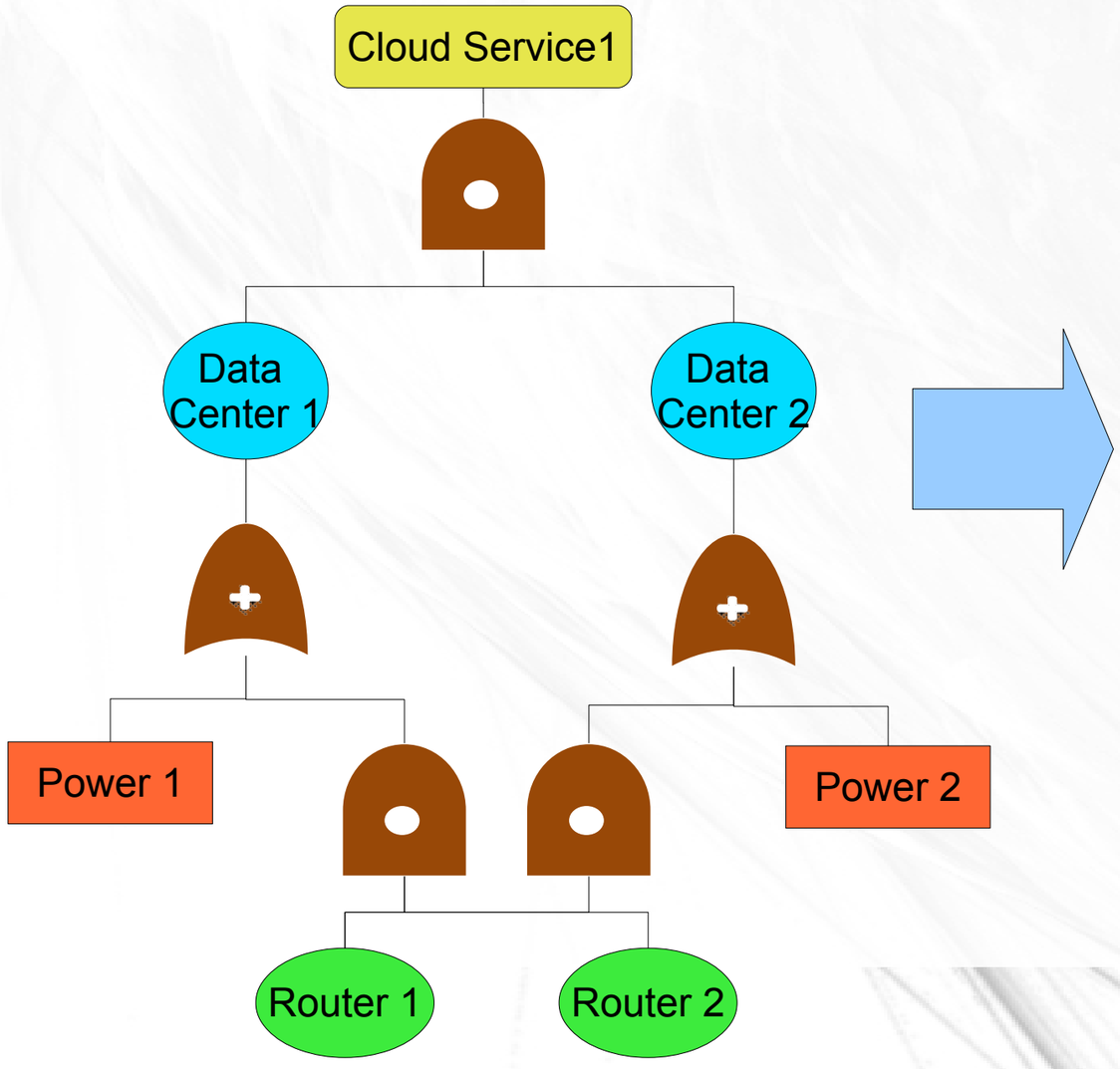
# SMPC Fault Tree Construction

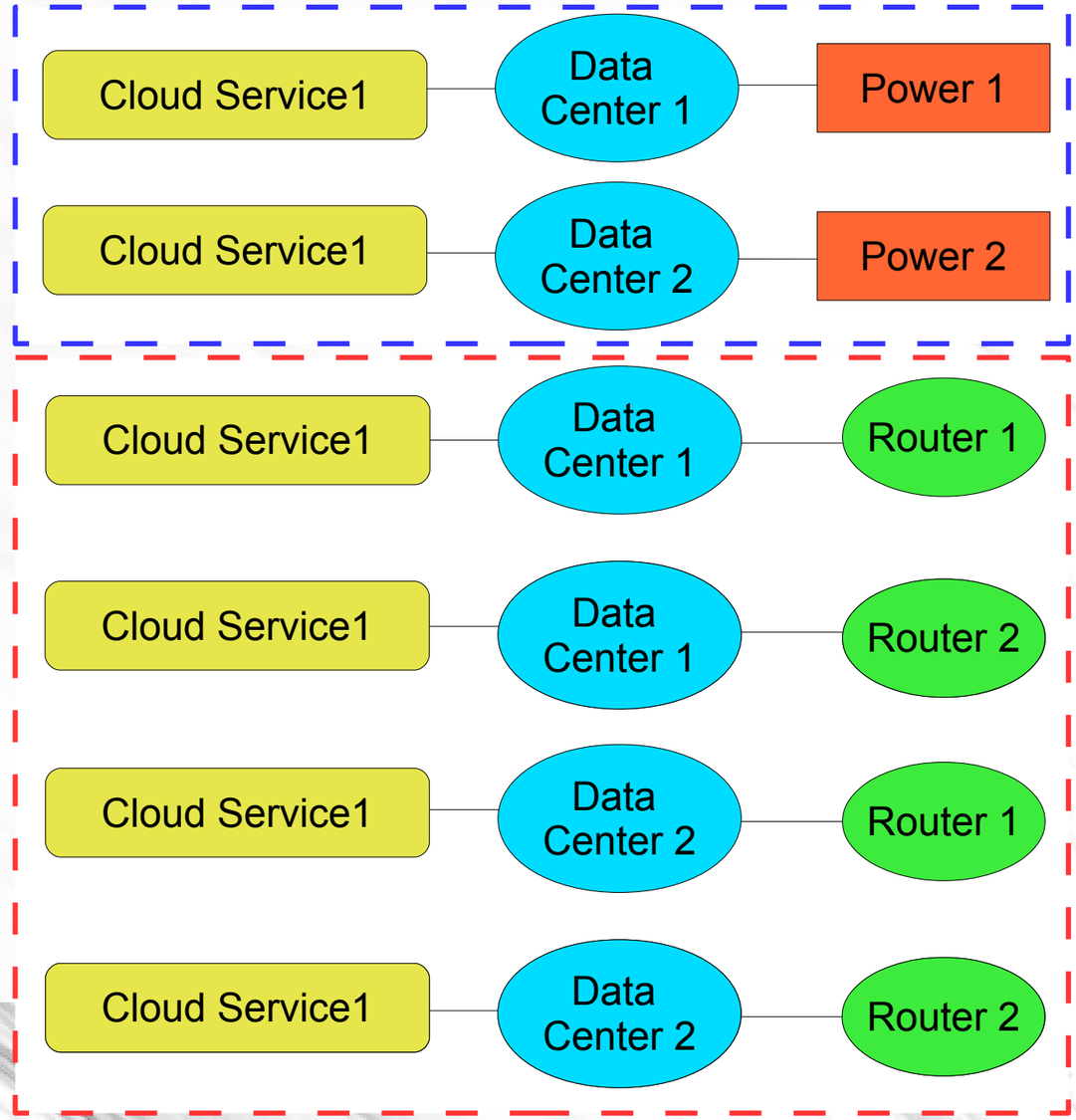
- Challenge
  - SMPC cannot readily handle conditionals, which are necessary in traditional ways of processing Fault Trees
- Solution
  - Rewrite the fault tree as topology paths form with types
  - Eliminates use of conditionals

# Topology Paths with Types

- Extract all paths through dependency DAG
  - root node → intermediate nodes → leaf node
  - Unpacks the DAG for "circuit" processing
  - Can be exponentially larger than DAG in worst case :(
- Types of topology paths
  - The SSU builds a disjunction of conjunctions of disjunctions data structure by assigning each path a type

# Topology Paths with Types: Example



# Local Execution Protocol

- Generate fault tree for components within macro-components
- Compute the failure sets of each macro-component

# Generate input for the SMPC

- SSUs pad the fault tree in order to avoid leaking structural informatoin such as the size of the cloud infrastructure
  - Add dummy nodes with zero ID into each topology path
  - Add zero paths into the fault tree with randomly assigned types
  - Zero ID nodes do not affect the result

# Identify common dependencies

- SSUs and P-SRA Host cooperate to identify common dependency
    - doing multiple (privacy-preserving) set intersections, followed by one (privacy-preserving) union
- Strict security requires doing it without conditional statements
    - Transfer conditional statements into arithmetic computation

# Identify common dependencies

**Algorithm 1:** Common-Dependency Finder

**Input**: Fault tree $T_i$, $i = 1$ *to* $N$, where N is the number of participating cloud-service providers

**Output**: Common Dependency

```
1 foreach T_I and T_J, I ≠ J do
2     private mask.clear();
3     foreach node_i ∈ T_I and node_j ∈ T_J do
4         private mask[i][j] = (node_i.ID == node_j.ID);
5     private CommonDep.clear();
6     foreach node_i ∈ T_i and node_j ∈ T_j do
7         private CommonDep[i] =
          mask[i][j] × node_j.ID + CommonDep[i];
8     private CommonDependent.append(CommonDep);
9 return private CommonDependent;
```

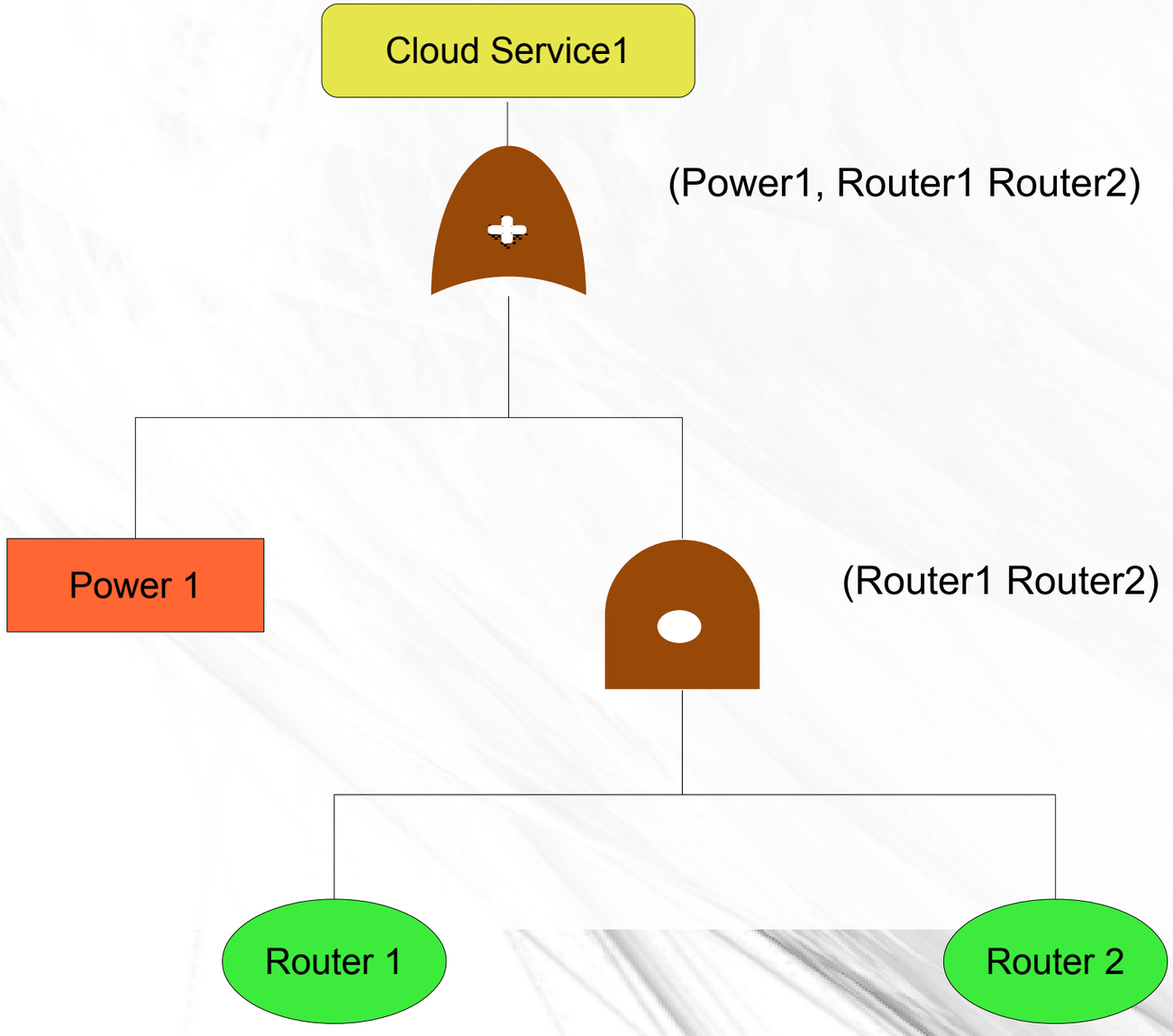
# Privacy Preserving Fault Tree Analysis: Calculate failure sets

- Minimal FSes algorithm
  - Find minimal FSes
  - Exponential complexity
- Heuristic failure-sampling algorithm
  - Faster
  - Not necessarily the minimal FSes

# Minimal FSes Algorithm

- The algorithm traverses the Fault Tree
- Basic events generate FSes containing only themselves, while non-basic events produce FSes based on the FSes of their child events and their gate types.
- For an OR gate, any FS of one of the input nodes is an FS of the OR.
- For an AND gate, take cartesian product of the sets of FSes of the input nodes then combine each element of the cartesian product into a single FS by taking a union.

# Minimal FSes Algorithm: Example



# Minimal FSes Algorithm

**Algorithm 2:** Minimal-FS algorithm

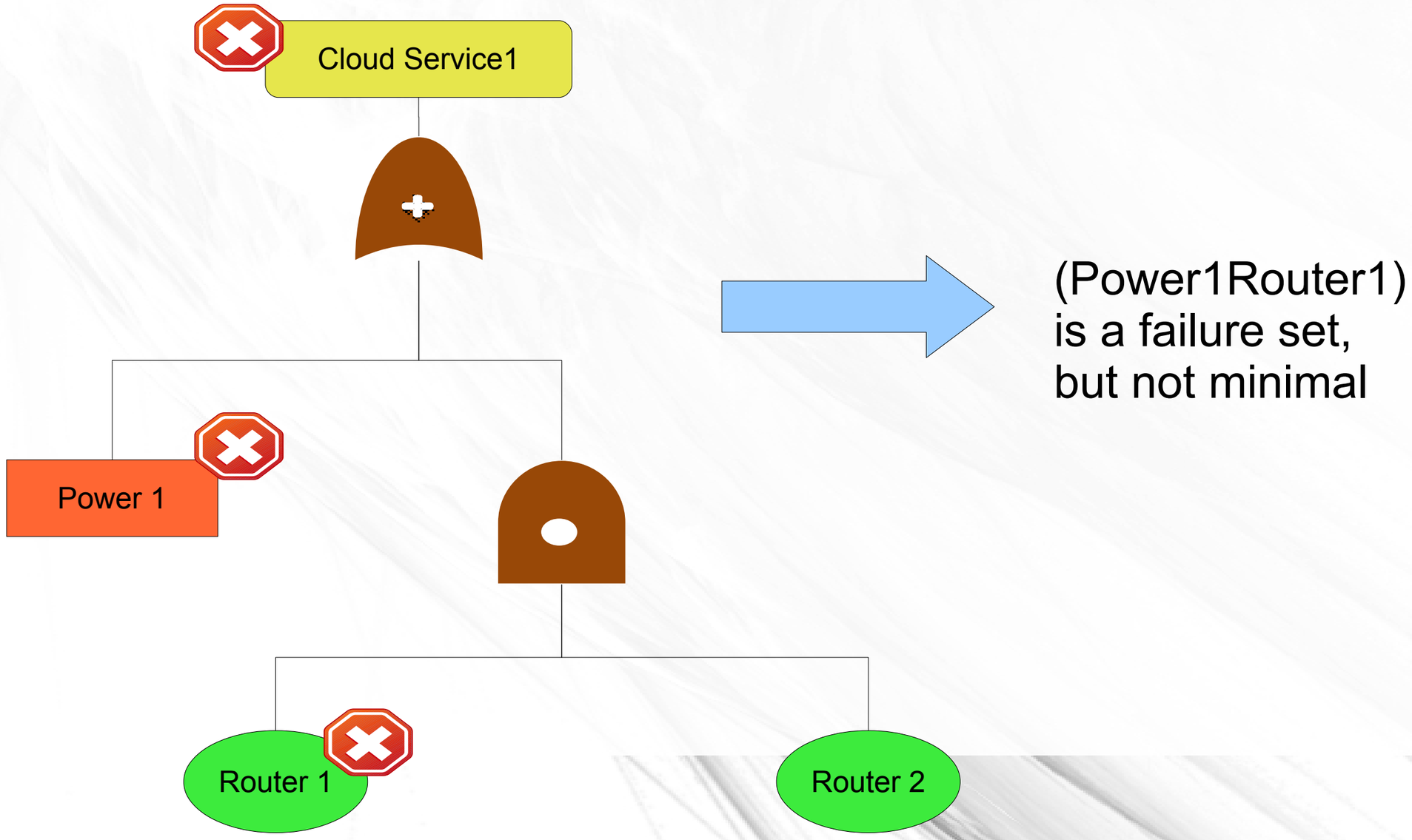
**Input**: Global Fault tree $T$
**Output**: MinimalFS

```
1  foreach private path_i ∈ T do
2      foreach private node_j ∈ private path_i do
3          private path_i.FS.apped(node_j);
           /* each path corresponds to an OR gate with
              input as the nodes along the path          */
4  foreach AndGate_i ∈ T do
5      AndGate_i.FS.clear();
6      foreach path_j ∈ AndGate_i do
7          AndGate_i.FS ← AndGate_i.FS × path_j.FS;
           /* process the AndGate for each type of
              topology paths                             */
           /* FS of AndGate_i is the Cartesian Product of
              AndGate_i.FS and path_j.FS.                */
8  private minimalFS.clear();
9  foreach AndGate_i ∈ T do
10     minimalFS.append(AndGate_i.FS);
       /* process the OR gate connecting to the And
          Gates                                          */
   /* reduce redundant items in minimumFS and assign the
      result to minimalFS, and then simplify minimalFS.
      */
11 minimalFS ← reduce_redundancy(minimalFS);
12 minimalFS ← simplify(minimalFS);
13 return minimalFS;
```

# Failure Sampling Algorithm

- Randomly assigns fail or no fail to the basic events of the Fault Tree
- Compute whether the top event fails
- If the top event fails, the failed basic events consist of a FS

# Failure Sampling Algorithm: Example



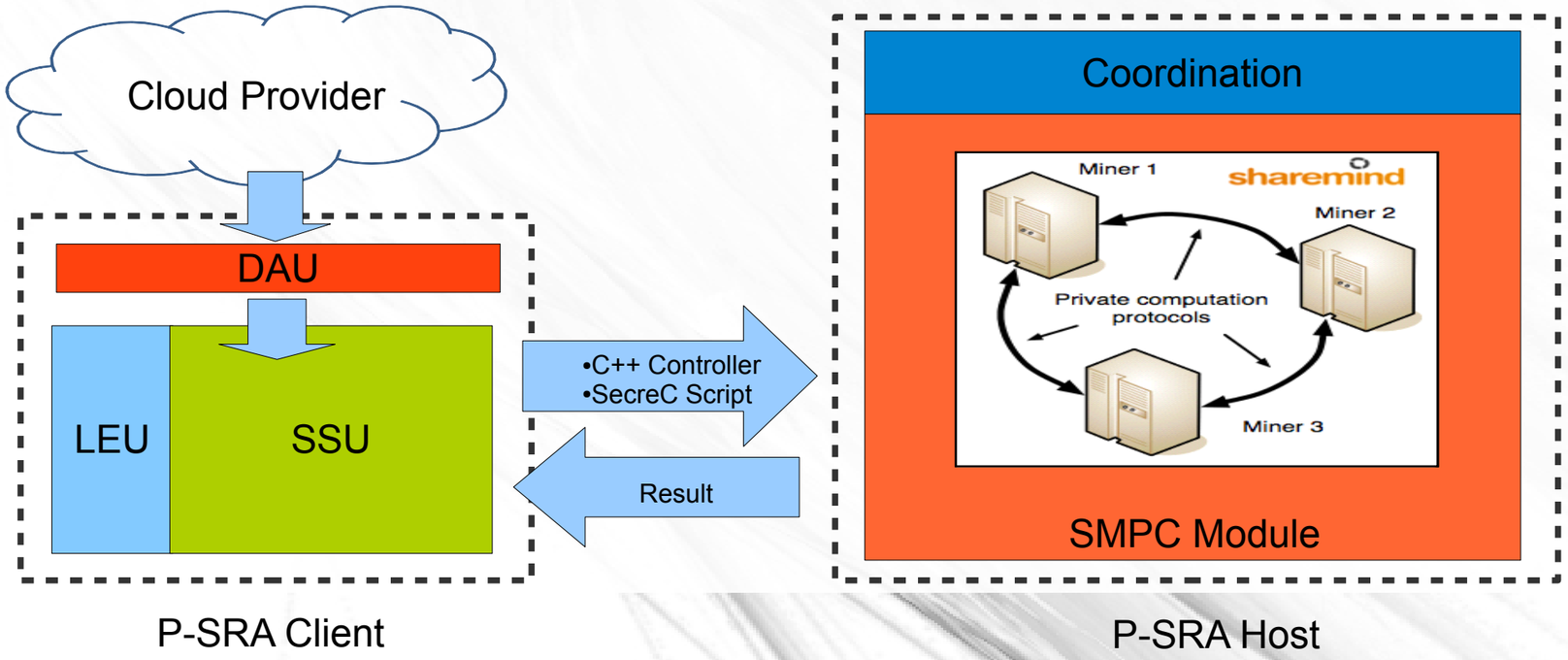

(Power1Router1)
is a failure set,
but not minimal

# Privacy-preserving Output Delivery

- Output for Cloud-Service Providers
  - Common dependency
  - Partial failure sets
- Output for Cloud-Service Users
  - Common-dependency ratio
  - Overall failure probabilities of cloud services
  - Top-ranked failure sets

# Implementation

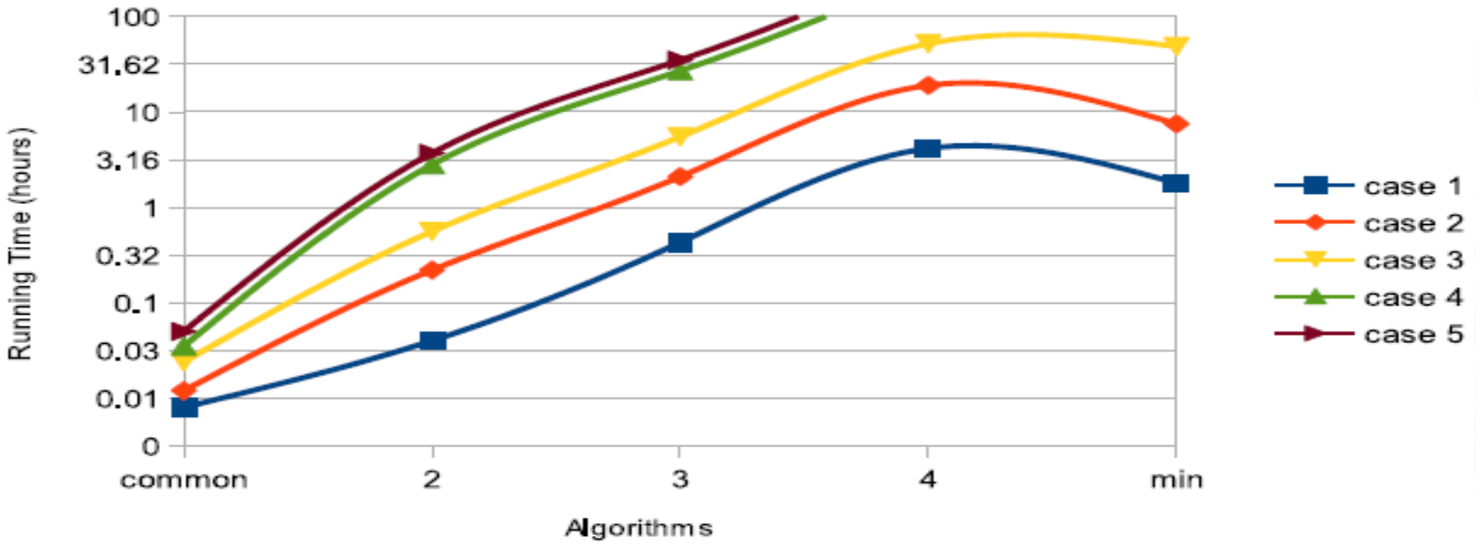
- Sharemind SecreC
  - C-like SMPC programming language
  - Specialized assembly to execute the code



# Simulation: SMPC

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| # of cloud providers | 2 | 2 | 3 | 3 | 2 |
| # of data center | 1 | 3 | 8 | 10 | 3 |
| # of internet router | 3 | 5 | 10 | 15 | 5 |
| # of power stations | 1 | 2 | 3 | 5 | 2 |
| ratio of common dep. | 0.8 | 0.2 | 0.2 | 0.2 | 0.2 |
| ratio of padding | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 |

Table 1: Configuration of Test Data Sets



# Simulation: Local Execution

Table 2: Performance of the LEU of a P-SRA client

| Configuration | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| # of switch ports | 4 | 8 | 16 | 24 | 48 |
| # of core routers | 4 | 16 | 64 | 144 | 576 |
| # of agg switches | 8 | 32 | 128 | 288 | 1152 |
| # of ToR switches | 8 | 32 | 128 | 288 | 1152 |
| # of servers | 16 | 128 | 1024 | 3456 | 13824 |
| Total # of components | 40 | 216 | 1360 | 4200 | 16752 |
| Running time (minutes) | | | | | |
| FS round $10^3$ | $< 0.7$ | $< 0.7$ | $< 0.7$ | $< 0.7$ | $< 0.7$ |
| FS round $10^4$ | 0.7 | 0.7 | 1.7 | 2.3 | 6.9 |
| FS round $10^5$ | 0.8 | 0.9 | 5.3 | 28.1 | 6.9 |
| FS round $10^6$ | 1.7 | 4.5 | 65.0 | 243.5 | 462.9 |
| FS round $10^7$ | 28.3 | 56.6 | 512.1 | NA | NA |
| Minimal FS | 0.8 | 14.8 | 309.7 | NA | NA |

# Conclusion

- We designed P-SRA, a private, structural-reliability auditor for cloud services based on SMPC, and prototyped it using the Sharemind SecreC platform
- We explored the use of data partitioning and subgraph abstraction SMPC on large graphs, with promising results.
- Our preliminary experiments indicate that P-SRA could be a practical, off-line service, at least for small-scale cloud services or for ones that permit significant subgraph abstraction.

# Thank you
# Any Questions?