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HELMHOLTZ CENTER FOR
INFORMATION SECURITY

SEAL: Capability-Based Access Control for Data-Analytic Scenarios

Hamed Rasifard, Rahul Gopinath, Michael Backes, Hamed Nemati |
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Trust Issues in Big-Data Sharing: Data Owners vs. Data Analysts

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- Big-data era

High Volume

High Velocity

High Variety

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- **Data owners** collaborate with **data analysts** to extract data-driven insights
- Data-sharing concerns
  - Data owners: data privacy and security
  - Data analysts: data quality and reliability

Data Sharing: Privacy Challenges

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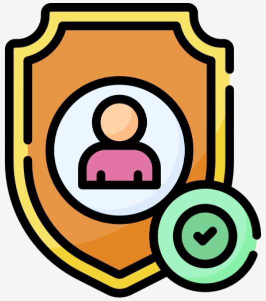
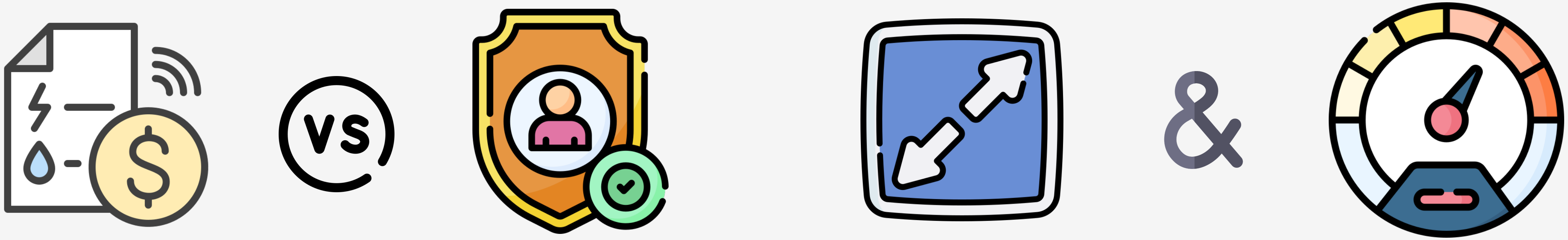
Data utility



Privacy

Data Sharing: Privacy Challenges



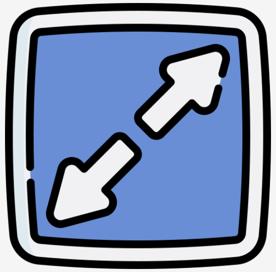
Data utility   Privacy   Scalability   Performance

Data Sharing: Privacy Challenges

Data utility

VS

Privacy



Scalability

&

Performance

Regulatory compliance

Data Sharing: Privacy Challenges

Data utility vs Privacy

Scalability & Performance

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Lack of data-owner control over data usage

Data Sharing: Privacy Challenges

Data utility

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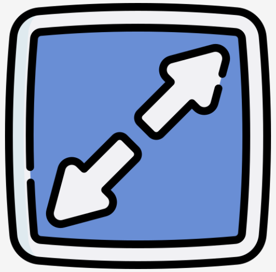

Scalability

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Emerging Threats and Attacks

Data Sharing: Access-Control Challenges

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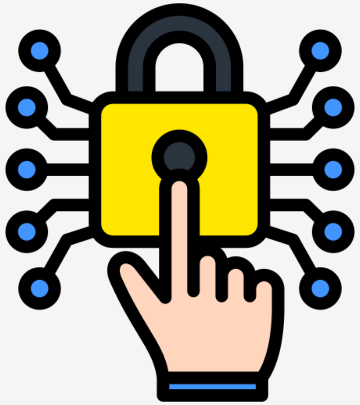

Fine-grained access control

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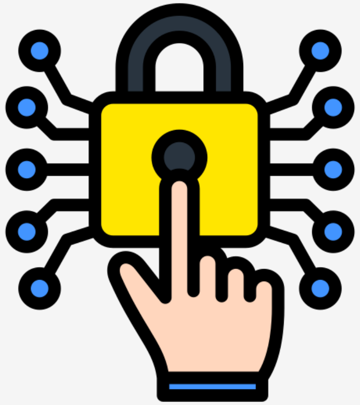

Fine-grained access control

Dynamic data access

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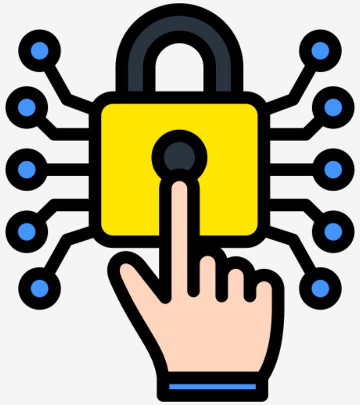

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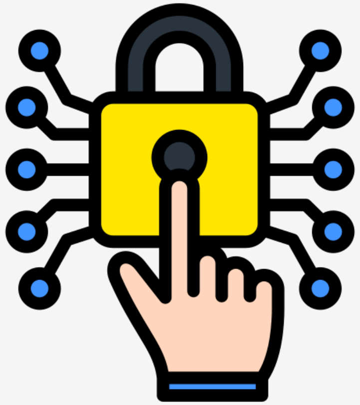

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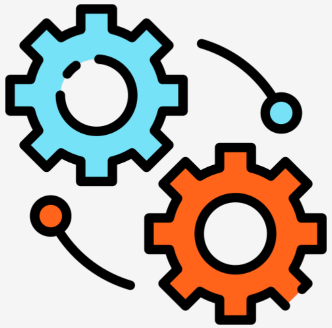

Integrating access-control systems with privacy-preserving techniques

Our Solution: Bringing Computation to Data

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📈 Data security

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  - Supporting fine-grained and dynamic access control
  - Supporting complex orders of computations
  - Maintaining data-owner control through all steps of computations

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SEAL: Capability-based Access-control Framework

Capability-based Access Control

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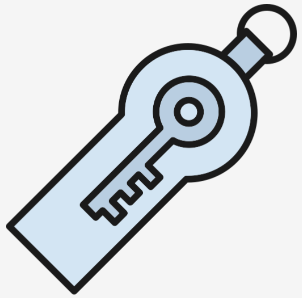
- Provides fined-grained access control
- Support the least-privilege principle
- A capability is an unforgeable token
- Access rights is granted based-on possessing of capabilities



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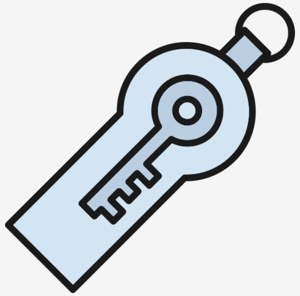

- **Capability-Object Model***
  - Combines **capabilities** and **objects** to enforce access control
  - Objects represent system resources or entities that are protected by the capability-object model

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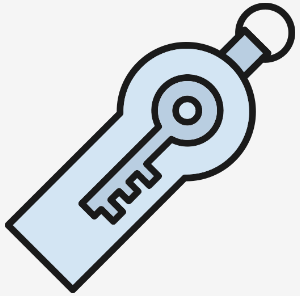

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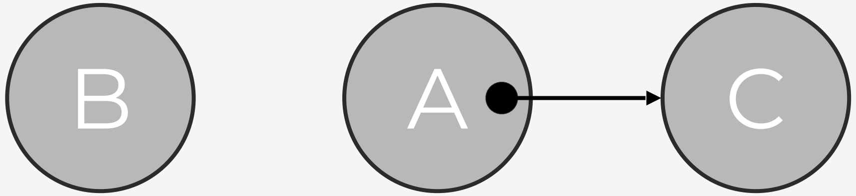

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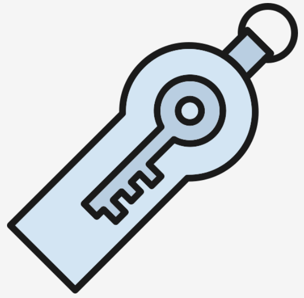

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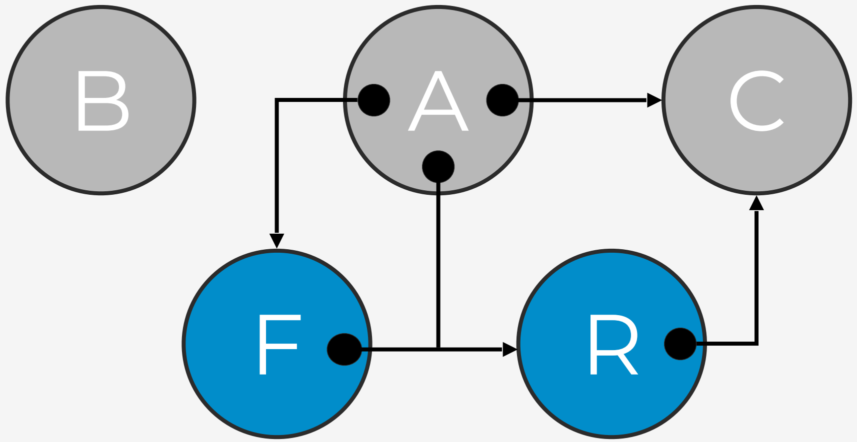

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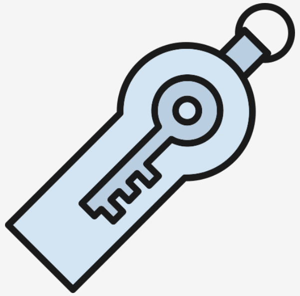

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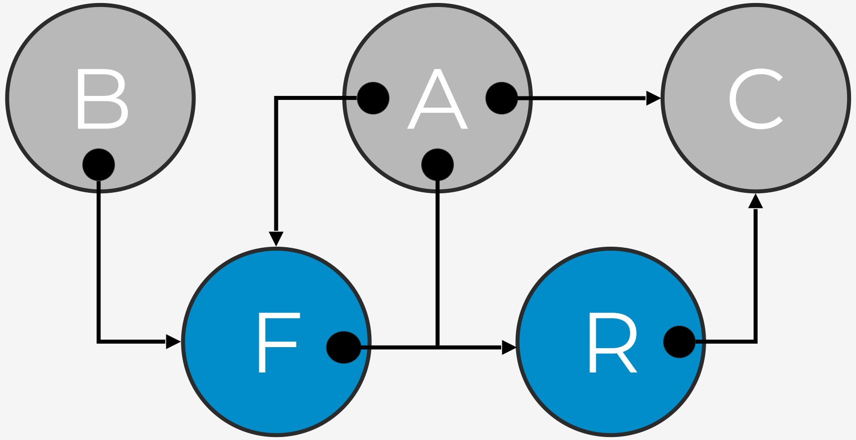

F: Forwarding Facet
R: Revoking Facet

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  - User capability ≡ Forwarding facet
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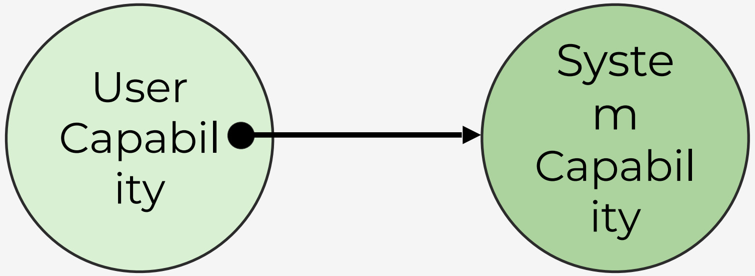

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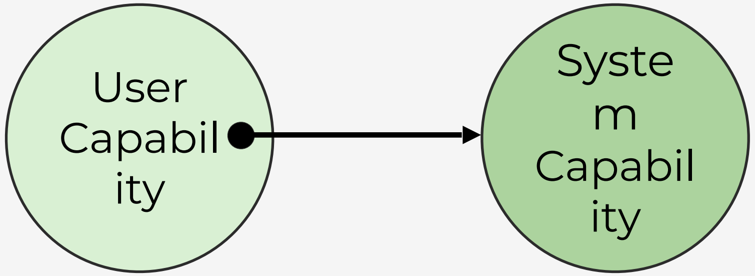
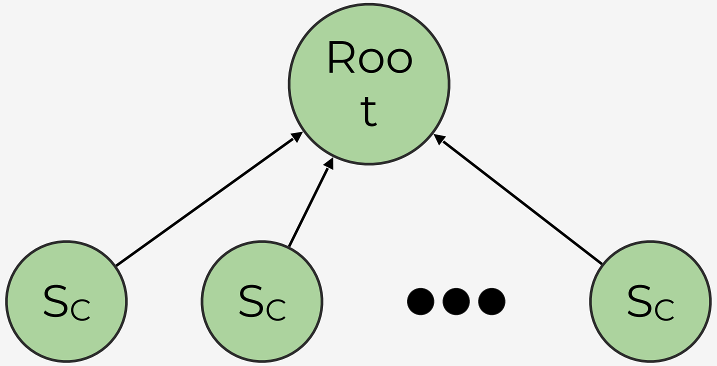


- System-Capability Tree



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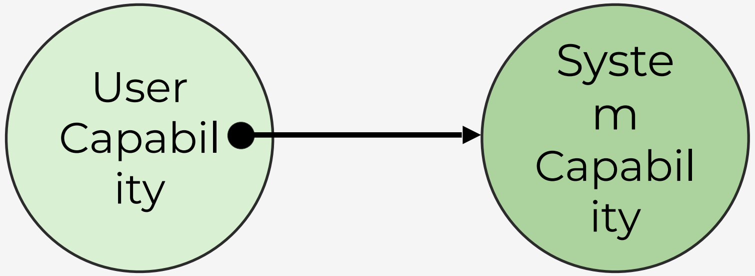
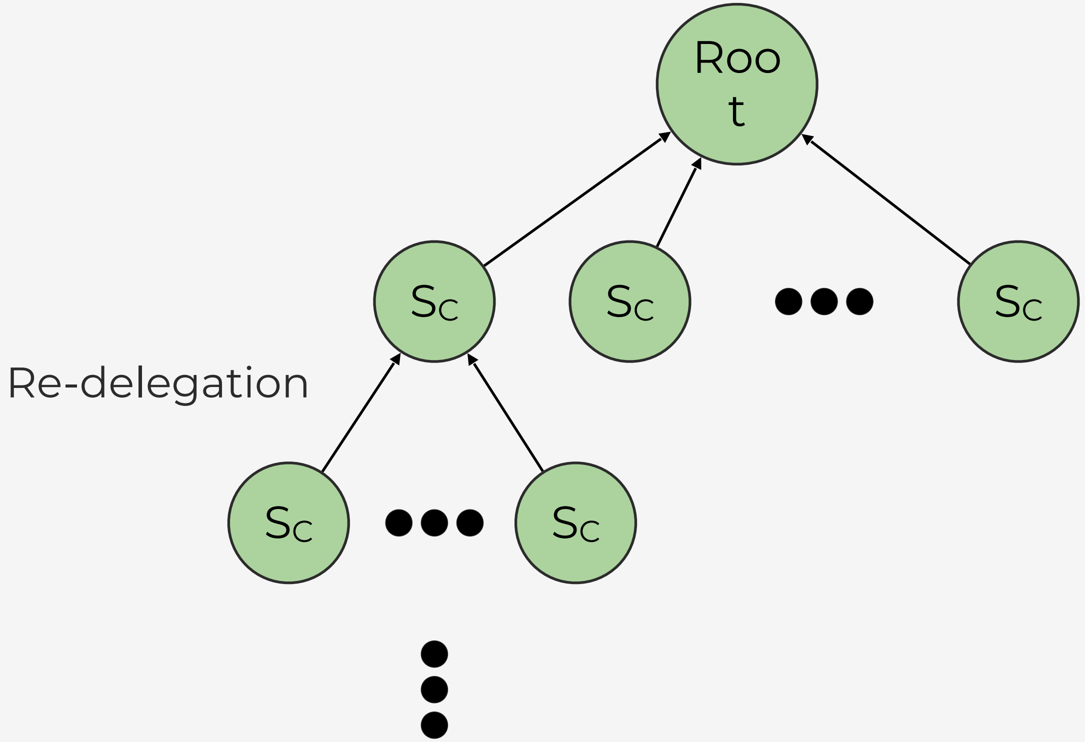


- System-Capability Tree
  - Tracking delegations



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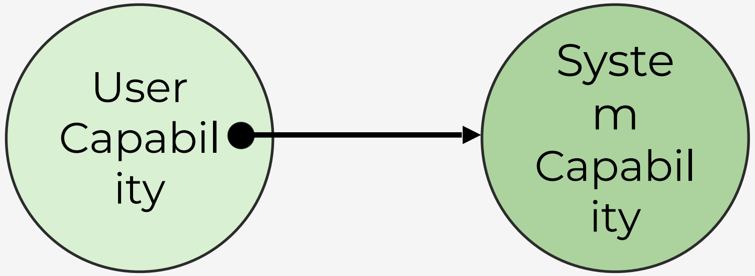

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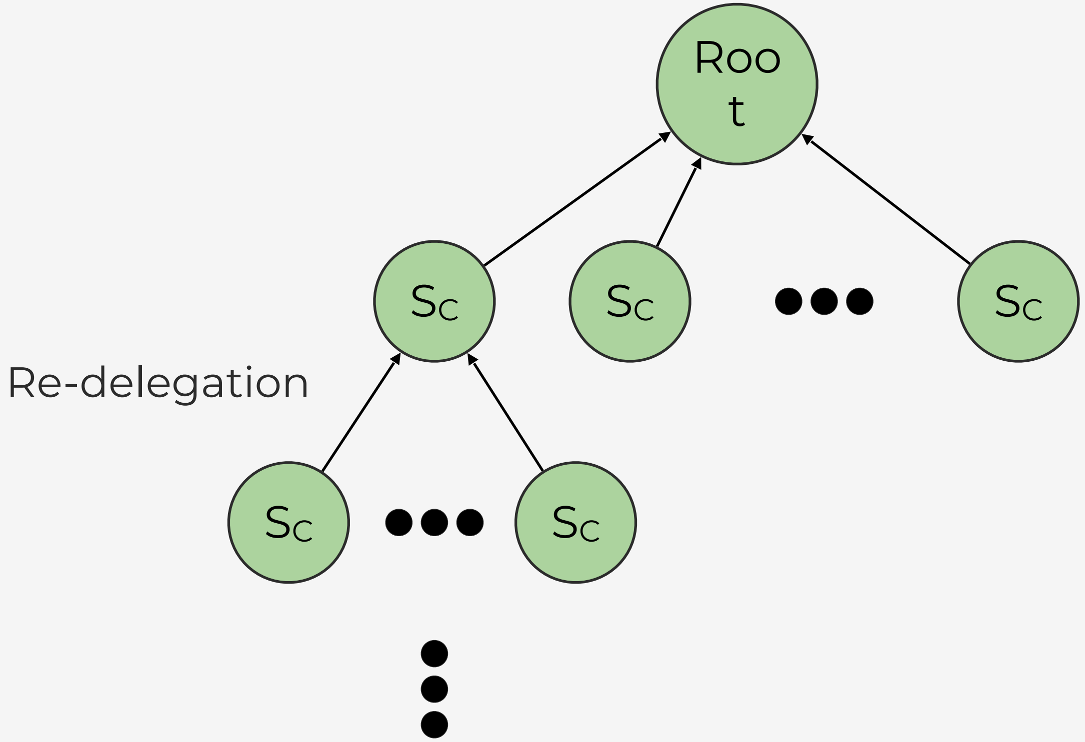

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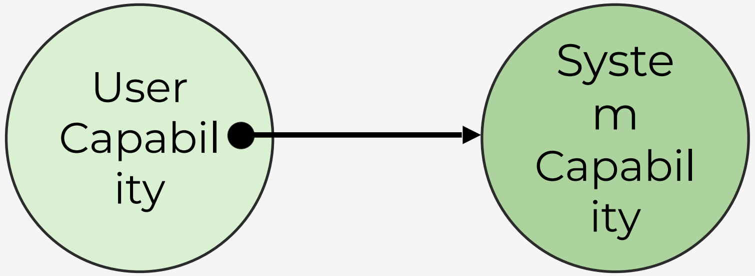

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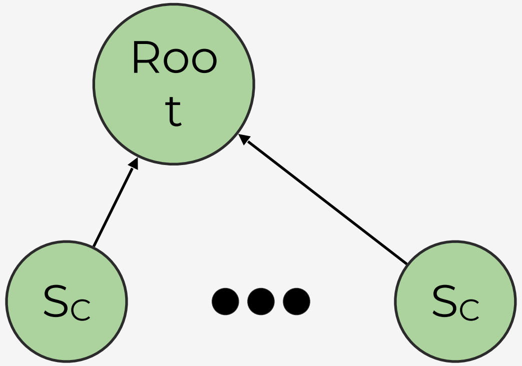

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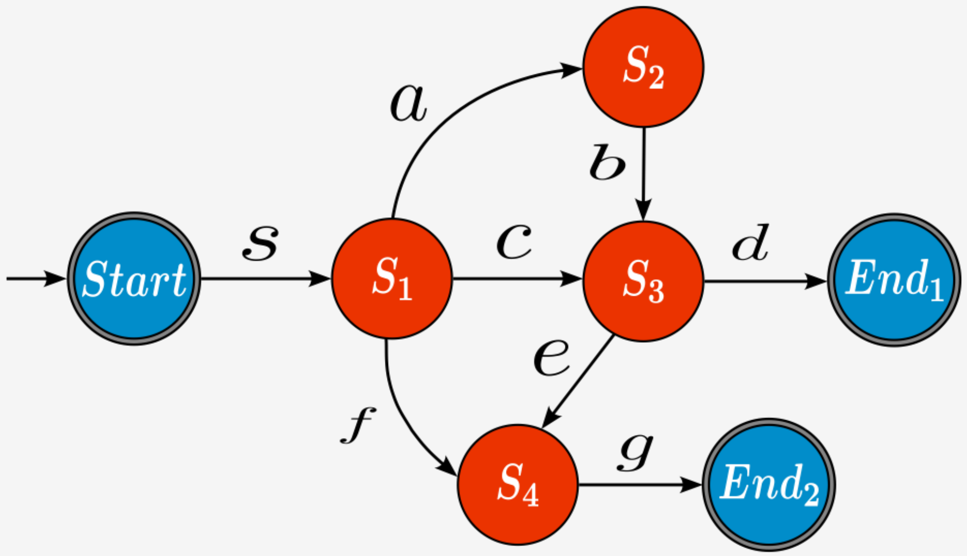

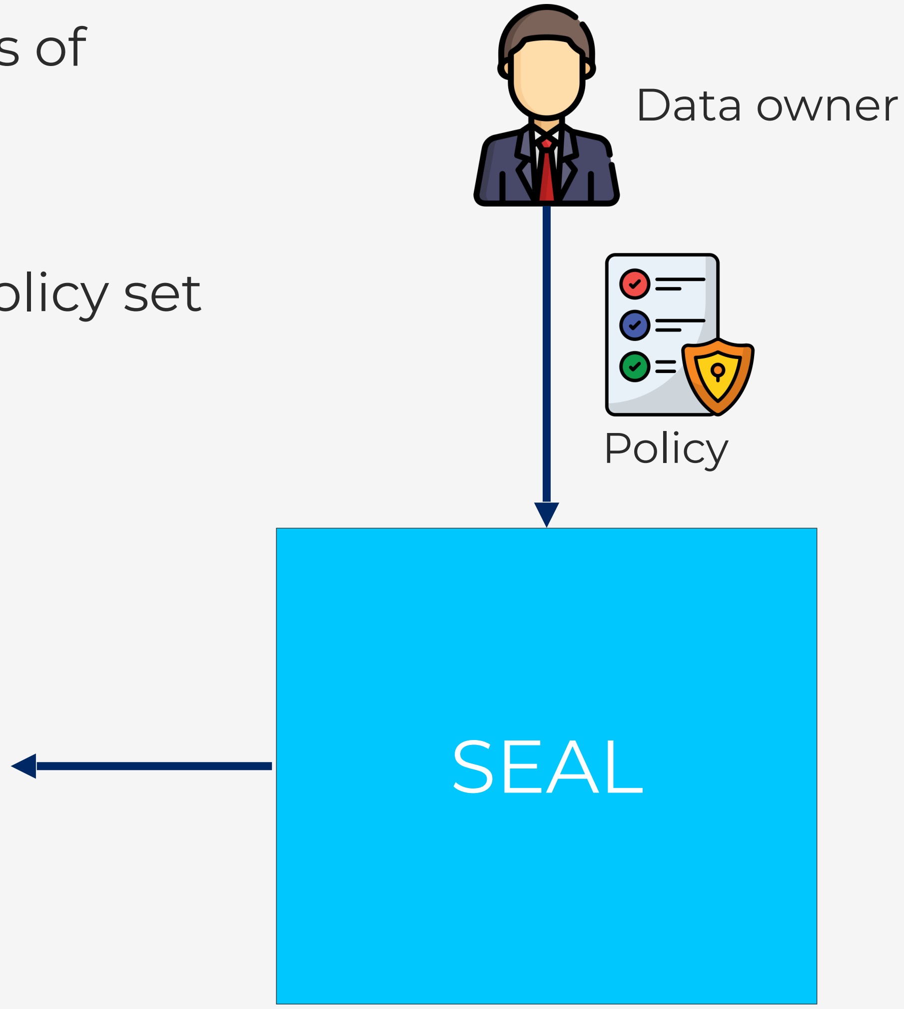

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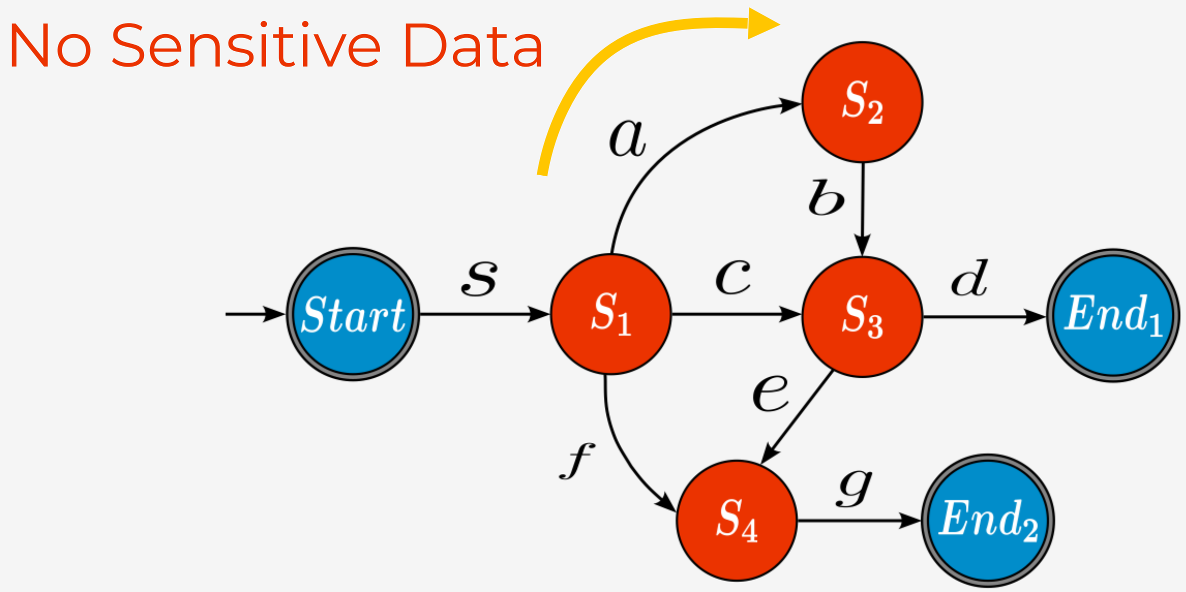

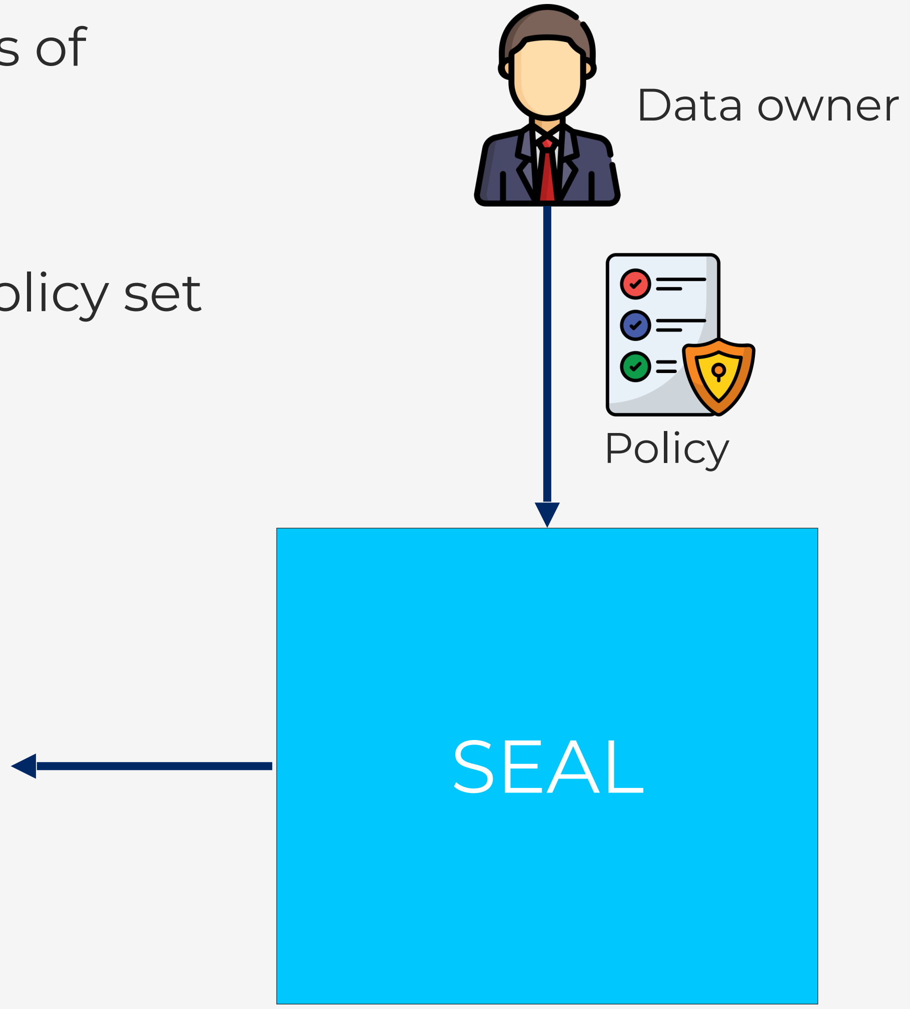

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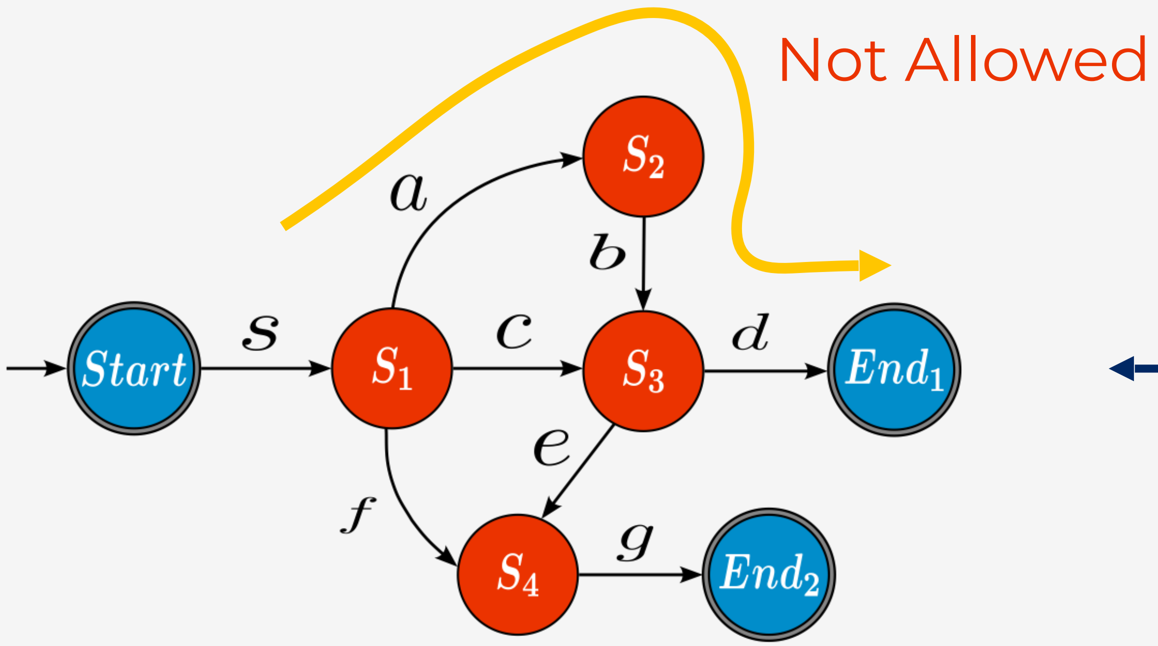

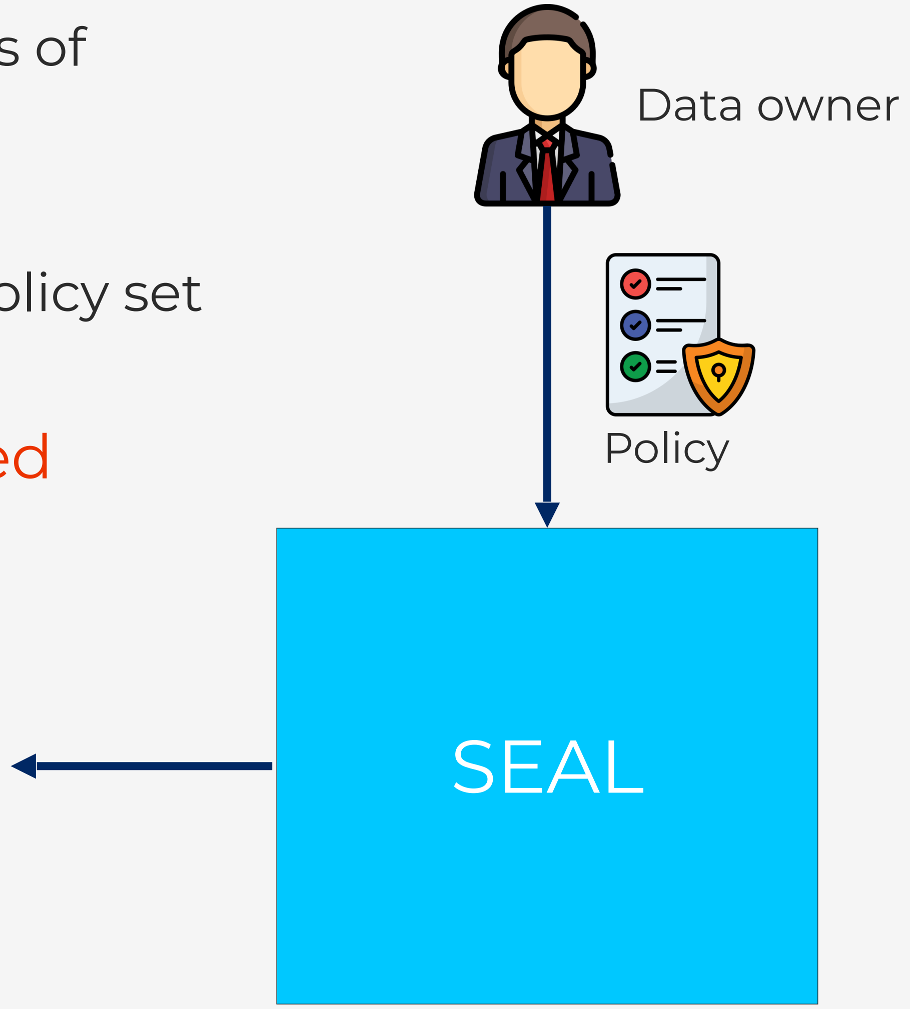

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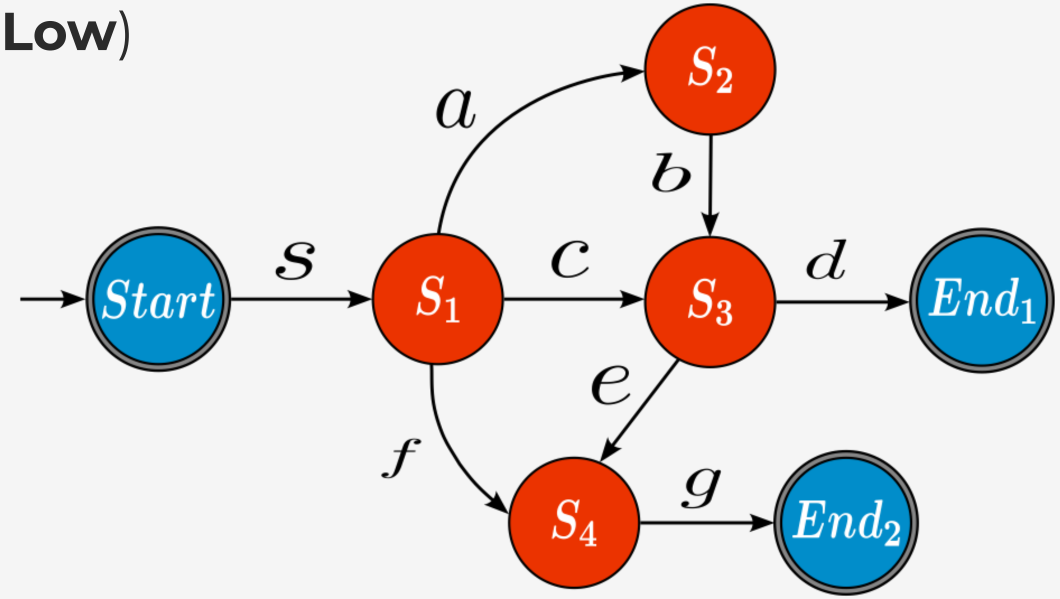

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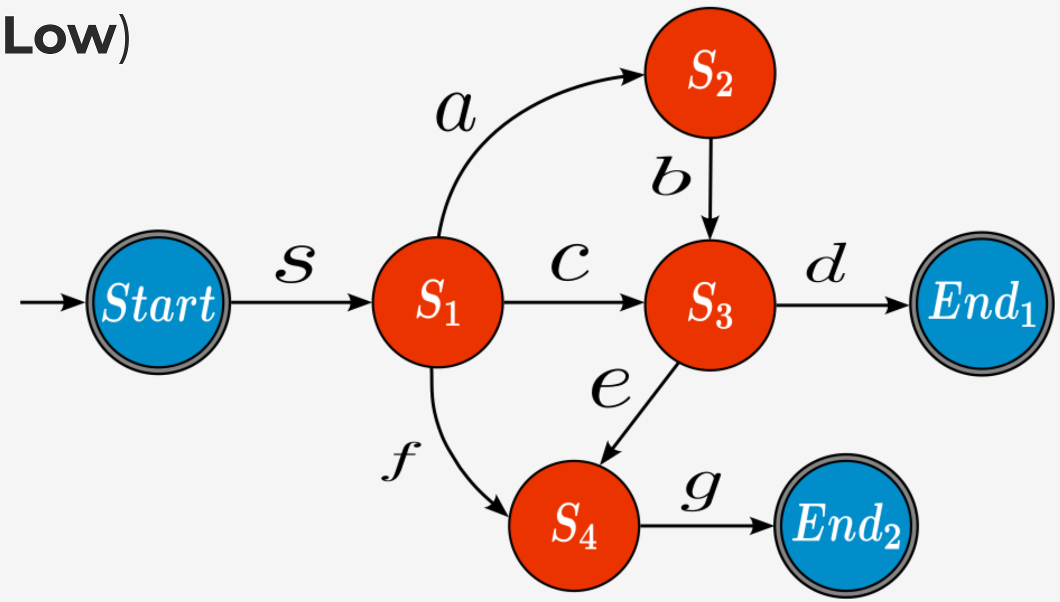

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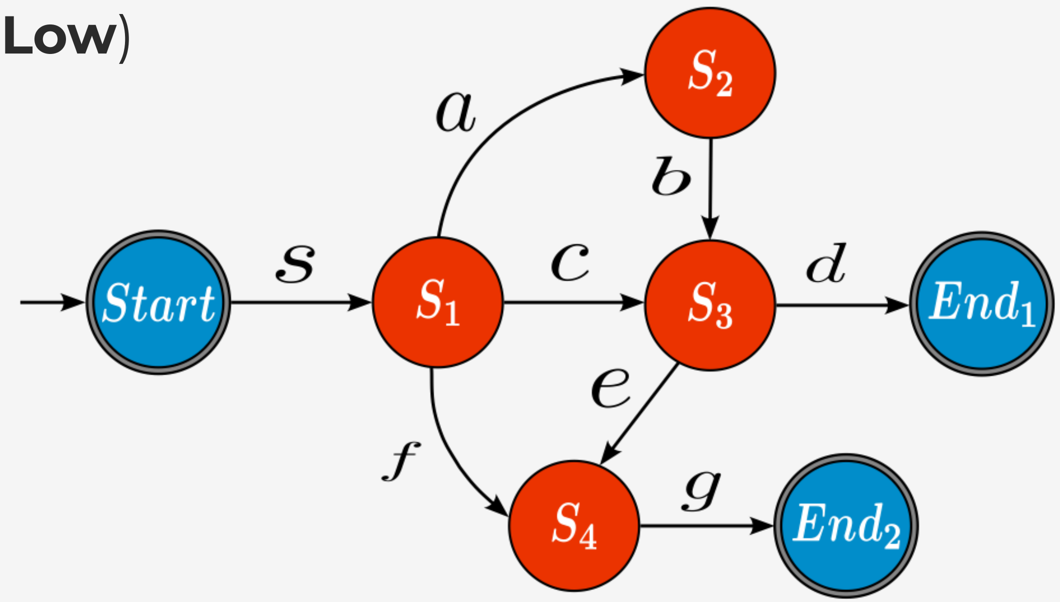

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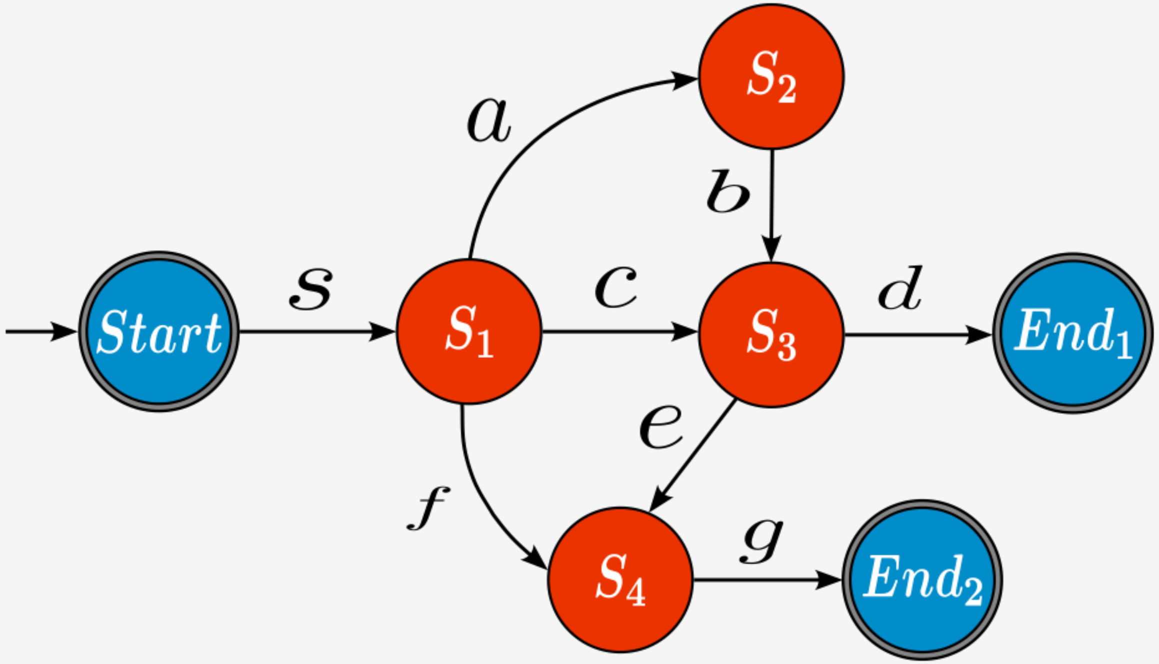

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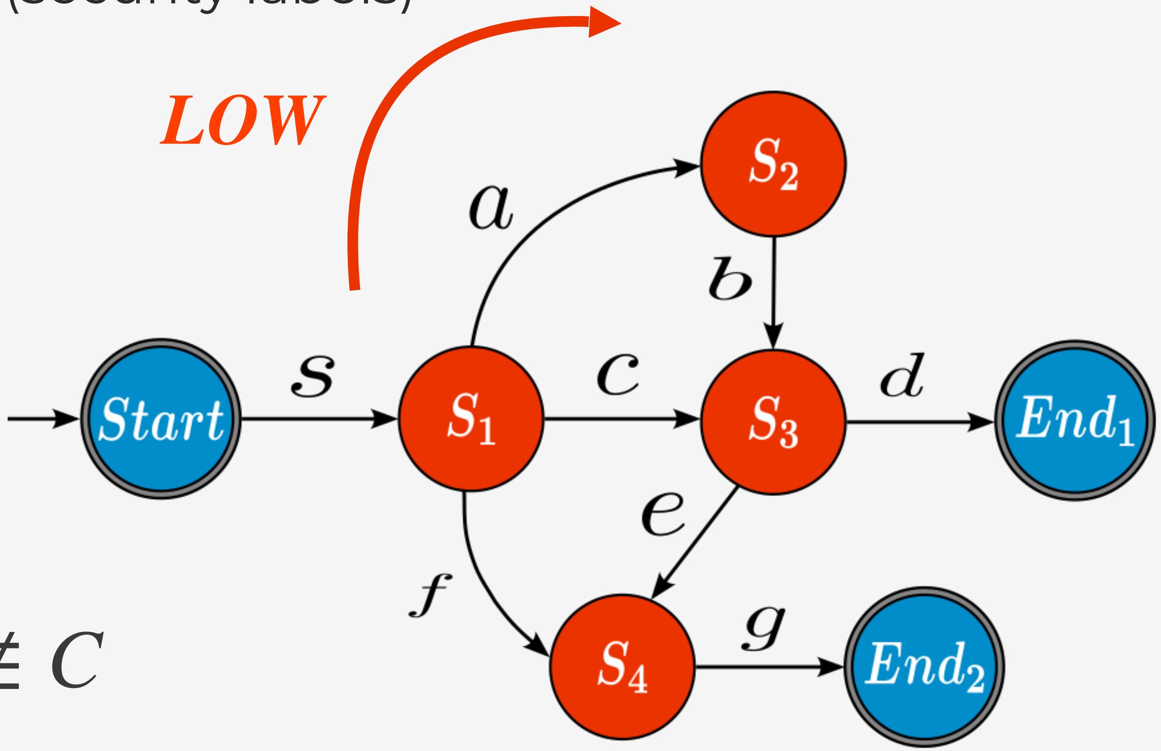
Analyst

$$C \ni P_2 \in C \wedge P_3 \notin C$$



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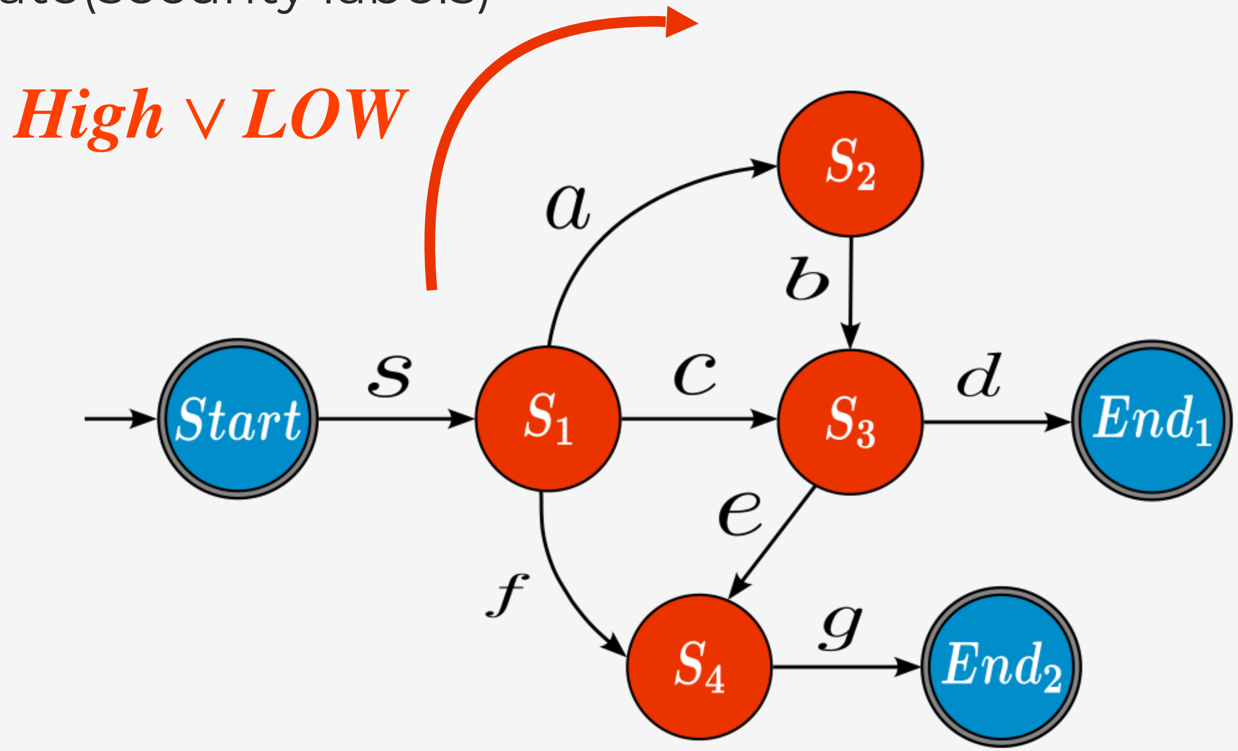
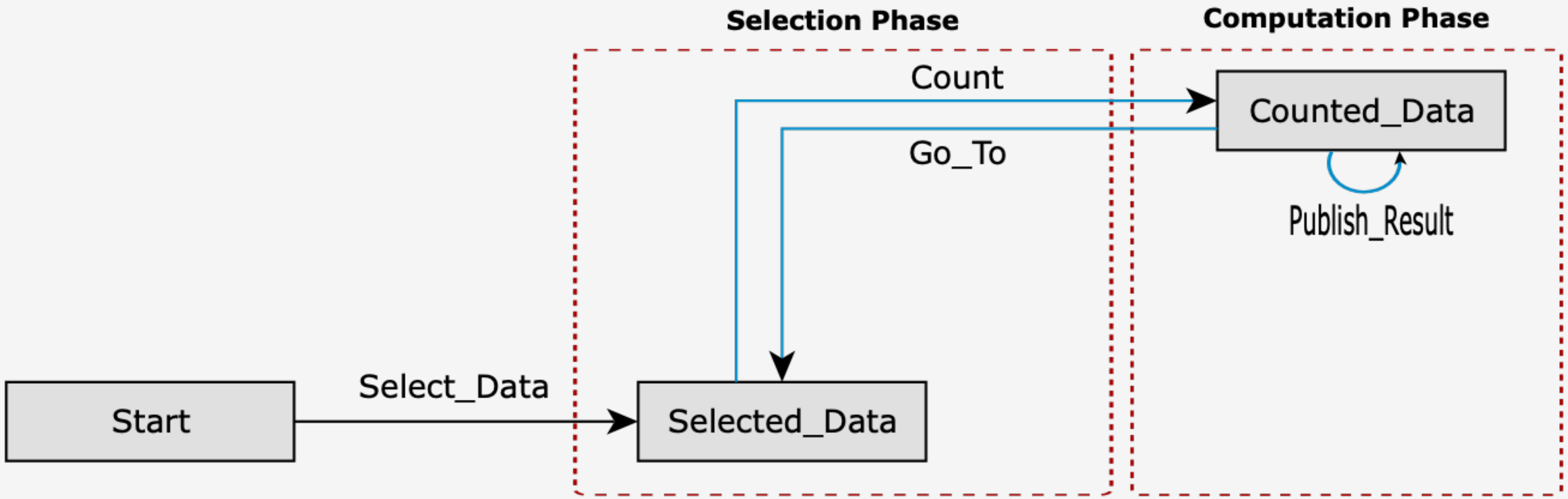
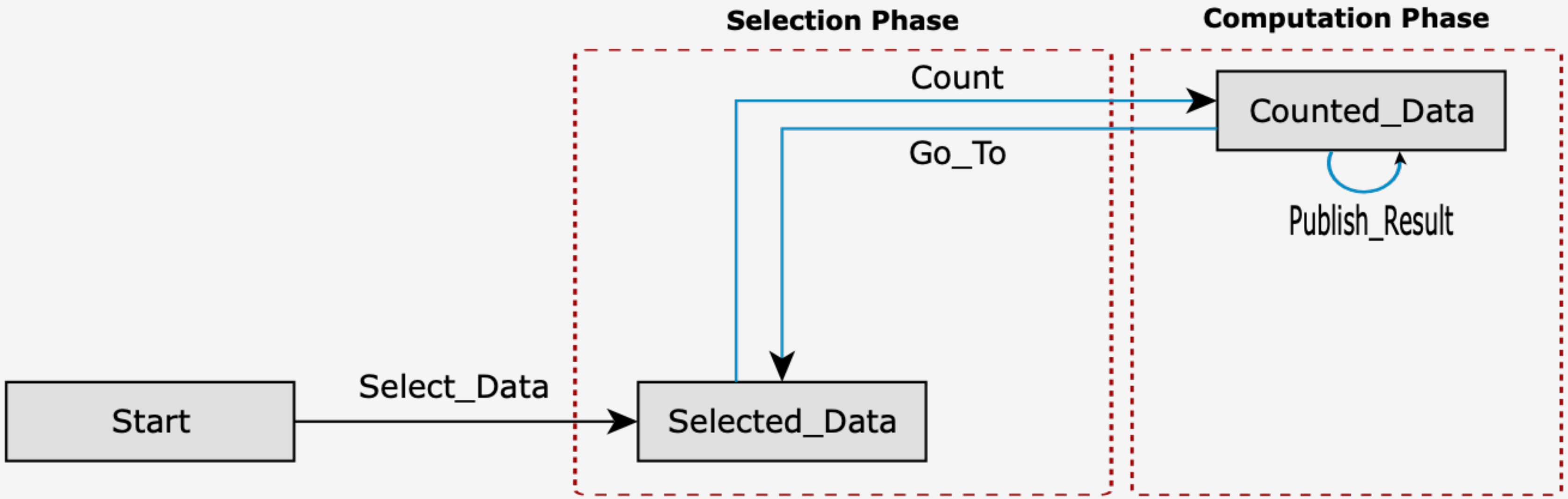


Case Study: Statistical Analysis



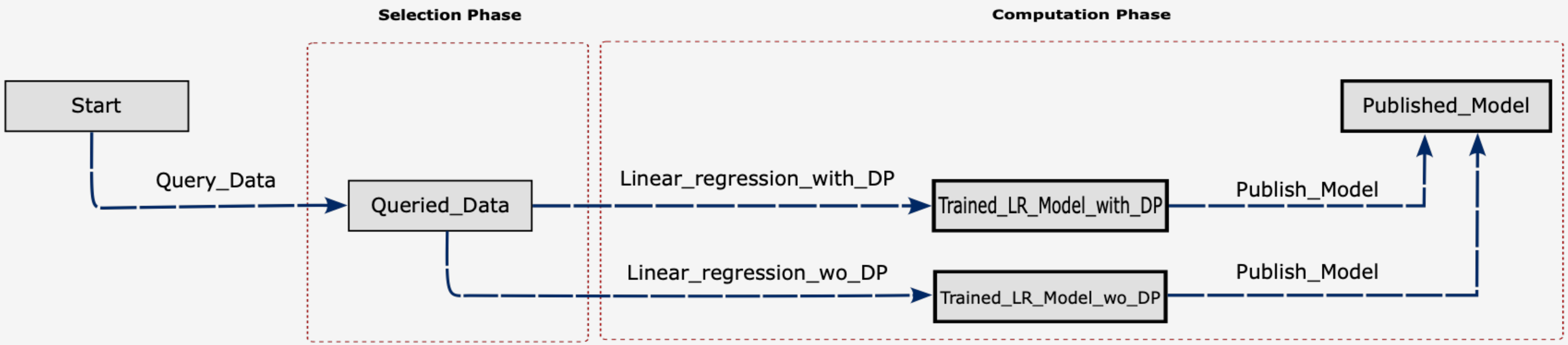
Case Study: Statistical Analysis

- Selecting a subset of data records and count them
- The *Publish_Result* action adds noise to the result



Case Study: Model Training with Taint Tracking

- SEAL can track the taint of every bit during a computation
- Data owners can leverage the provided taint-tracking mechanism



SEAL: Implementation

- A proof-of-concept implementation
- Secure program execution: **Capsicum** framework
- Taint-tracking:
  - **Data flow**: Python object proxies for direct taint propagation
  - **Control flow**: Statically instruments the source code to keep track of indirect taint propagation due to control flow
  - **Libraries**
    - Transfer libraries to LLVM-Intermediate representation (IR) using *Numba*
    - Static taint tracking using *PhASAR*

SEAL: Evaluation

- We evaluated scenarios on three real-world datasets *
  - ***Adult*** dataset (32, 561 entries)
  - ***Incident-Report*** dataset (141, 713 entries)
  - ***Household-Power-Consumption*** dataset (2, 075, 258 entries)

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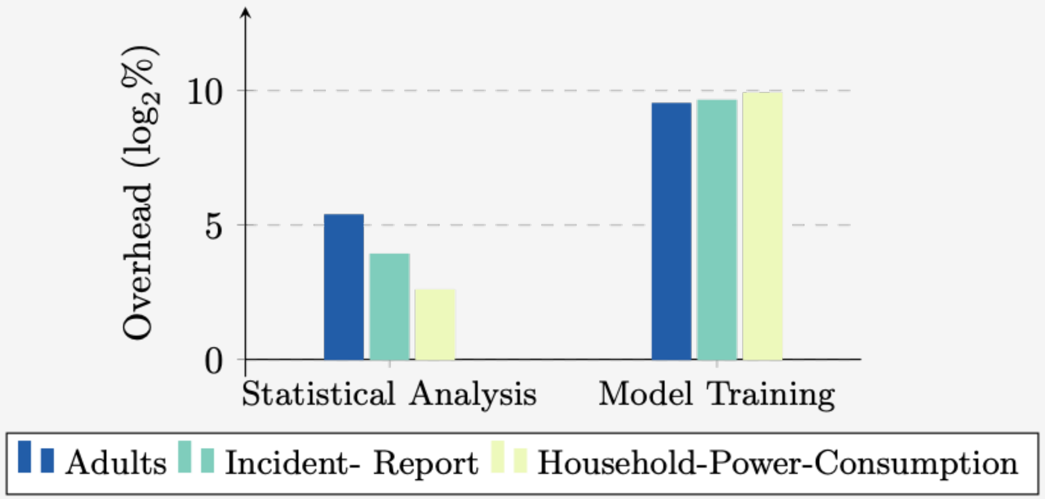
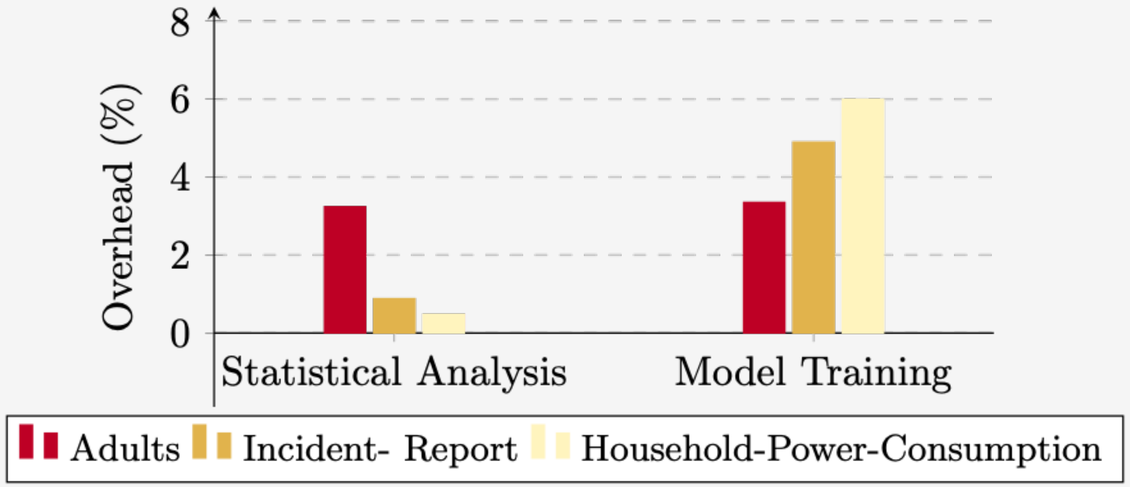


Framework Overhead



Capsicum Overhead

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- SEAL is a fine-grained access-control framework for data-analytics scenarios
  - Capability-object model
  - Stateful system model
  - Security label tracking
- SEAL can be employed in the real-world scenarios with a reasonable overhead

Rather short but strong title

Back-up Slides

SEAL: Threat Model

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  - **trusted**: the framework’s hosting machine **+** Capsicum

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  - ***weak*** adversaries: can train models and evaluate their data with trained models
  - ***medium*** adversaries: weak adversaries **+** can request models

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- System Security
  - **trusted**: the framework's hosting machine **+** Capsicum
  - **assumed**: analysts act as adversaries **+** secured connections **+** network-based attacks are prevented
- Data Privacy regarding machine learning (Following Nasr et al.*)
  - ***weak*** adversaries: can train models and evaluate their data with trained models
  - ***medium*** adversaries: weak adversaries **+** can request models
  - ***strong*** adversaries: medium adversaries **+** can apply their datasets during training models

* Nasr et al., "Adversary Instantiation: Lower Bounds for Differentially Private Machine Learning". In 2021 IEEE Symposium on Security and Privacy (SP)

Seal: Approach

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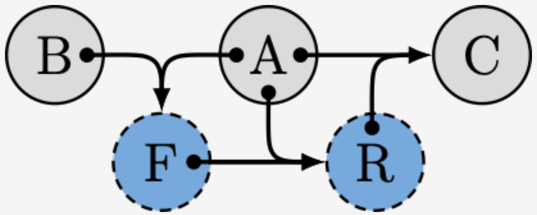
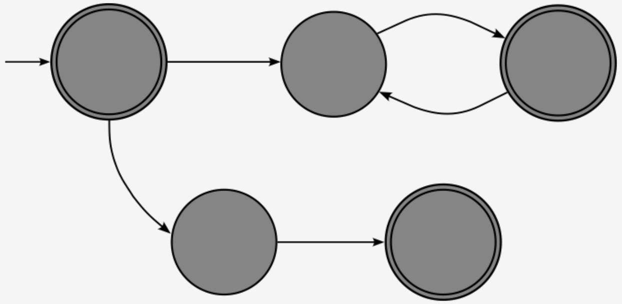
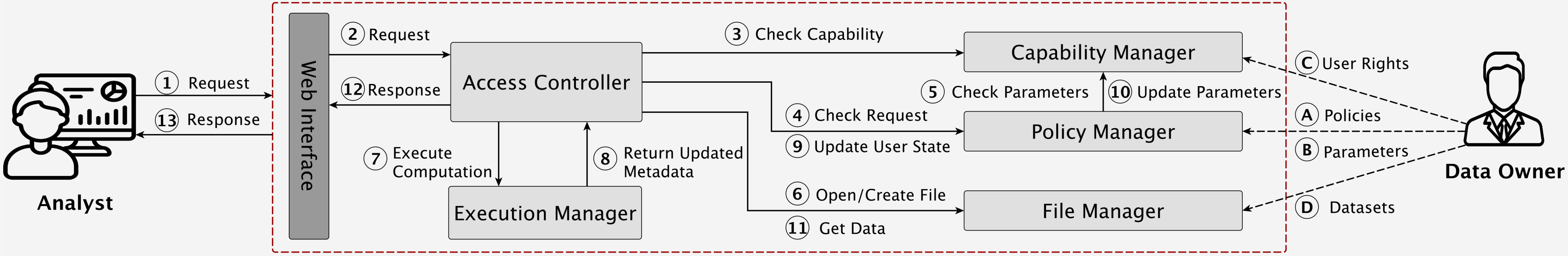




- Based on capability-object model
  - tracking capabilities
  - revoking capability hierarchies
- Stateful system model
  - defining possible orders of computations
- Security labels tracking
  - data level
  - computation level

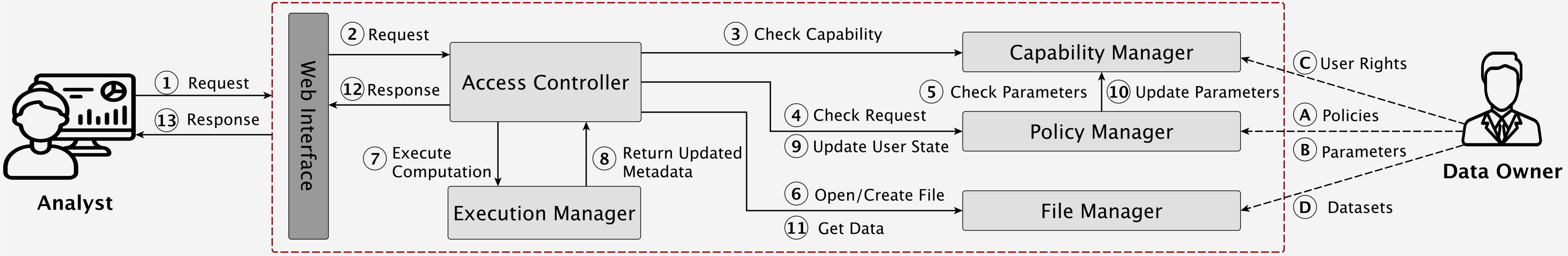
SEAL



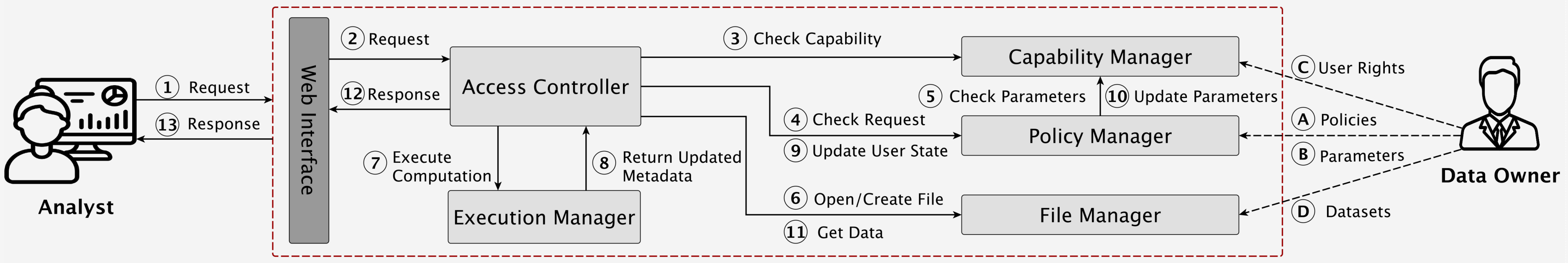
Analyst
1 Request
13 Response
Web Interface
2 Request
12 Response
Access Controller
7 Execute Computation
8 Return Updated Metadata
Execution Manager
3 Check Capability
Capability Manager
5 Check Parameters
10 Update Parameters
4 Check Request
9 Update User State
Policy Manager
6 Open/Create File
11 Get Data
File Manager
C User Rights
A Policies
B Parameters
D Datasets
Data Owner

SEAL

- Operates in two phases
  - initialisation phase (steps A - D)
  - execution phase (steps 1 - 13)

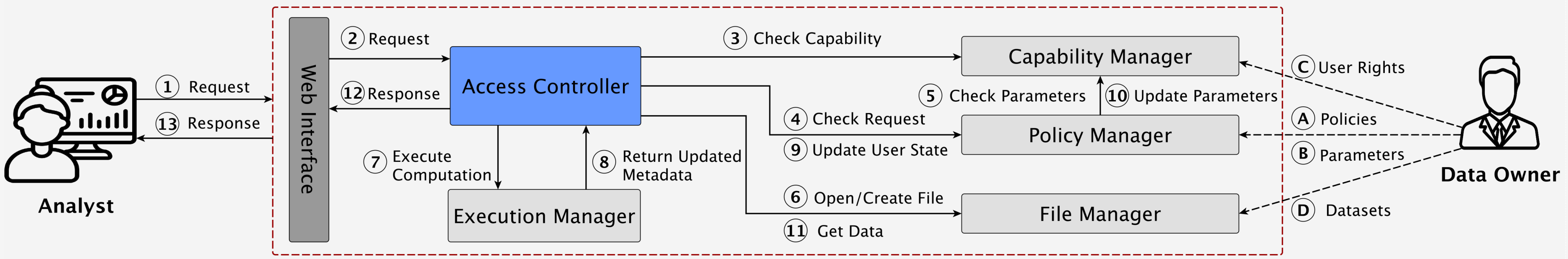


SEAL: Components



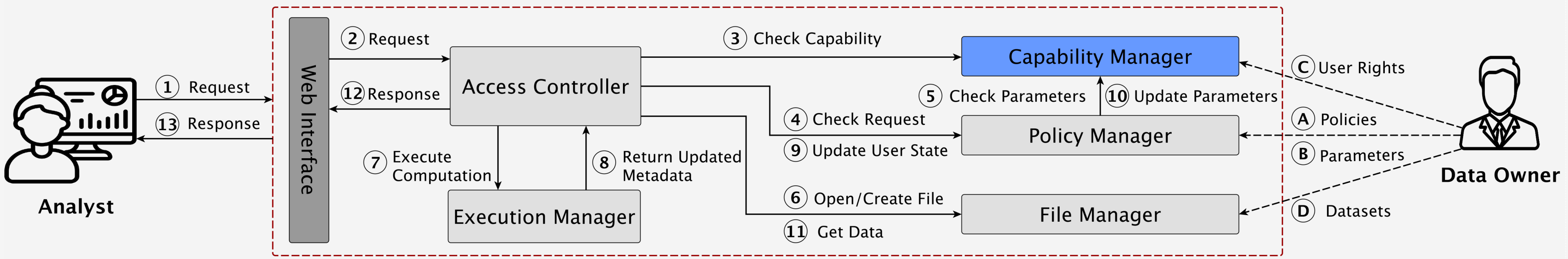
SEAL: Components

- *Access Controller*
  - orchestrates operations
- *Capability Manager*



SEAL: Components

- *Access Controller*
  - orchestrates operations
- *Capability Manager*
  - handles delegating/revoking capabilities
  - verifies capabilities



SEAL: Components

- *Access Controller*
  - orchestrates operations
- *Capability Manager*
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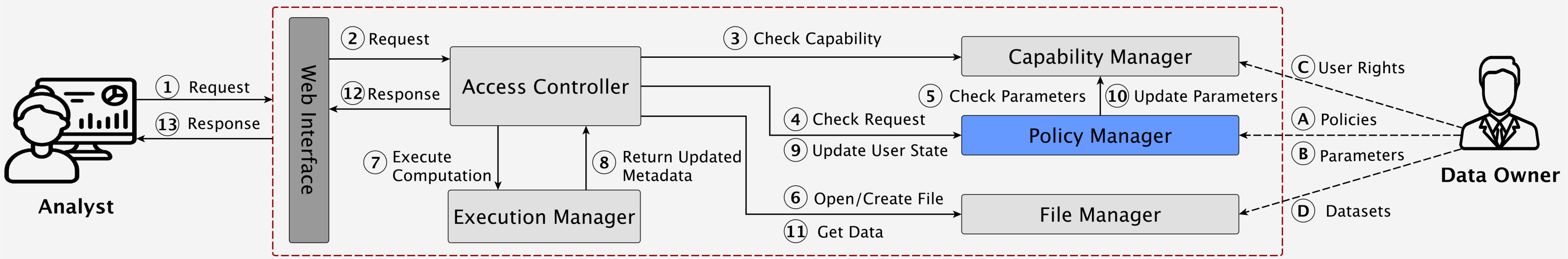
- *Policy Manager*
  - checks requests and keeps their trace
- *File Manager*



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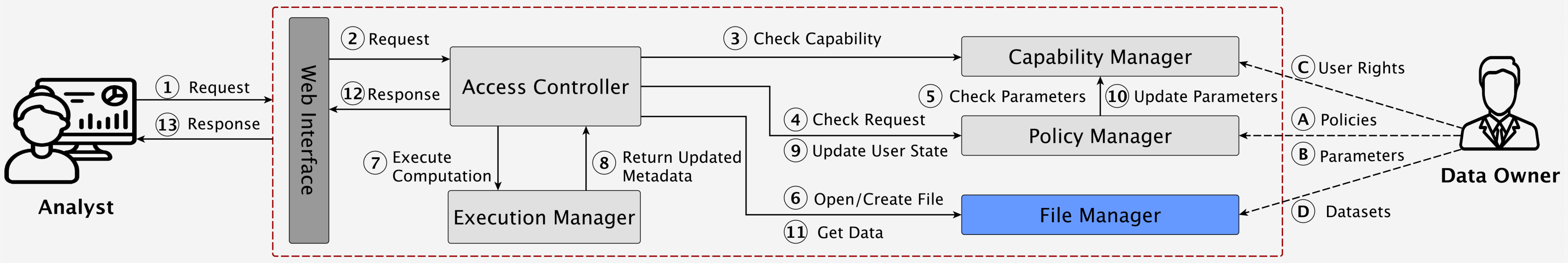
  - creates file handlers (using Capsicum)
- *Execution Manager*



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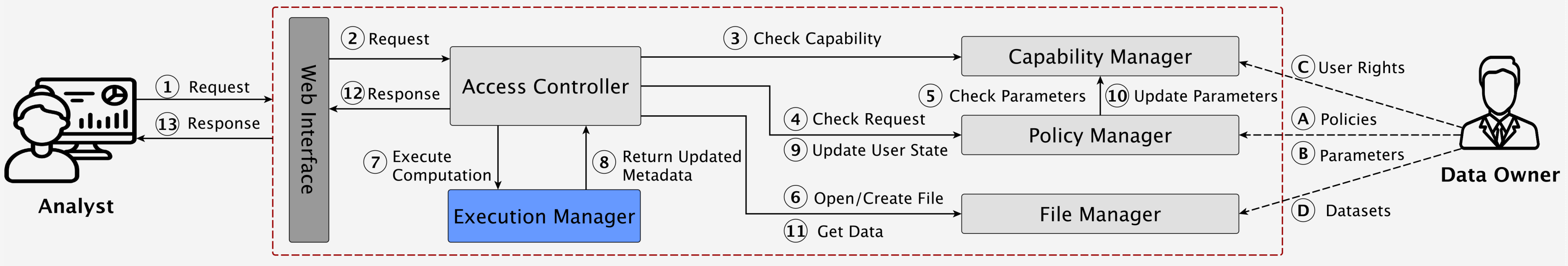
  - checks requests and keeps their trace
- *File Manager*
  - creates file handlers (using Capsicum)
- *Execution Manager*
  - execute computations (inside Capsicum sandboxes)



SEAL: Security Policies

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- A system's state transforms based on policies
- Extended Rei policy language

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  - ***StateObject***: defines a system's state
  - ***ACTION***: defines a possible computation

StateObject(Src_State)

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- Extended Rei policy language
  - Rei consists of constructs: *rights*, *prohibitions*, *obligations*
- Added Two policy constructs
  - ***StateObject***: defines a system's state
  - ***ACTION***: defines a possible computation
- Rights define state transitions

```
StateObject(Src_State)
```

```
ACTION(action-name, computation-name,
  Paramset(paramset-name,
    params(param(param-name, param-type), ...)),
  Require(action-requirements)
```

SEAL: Security Policies

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```
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```
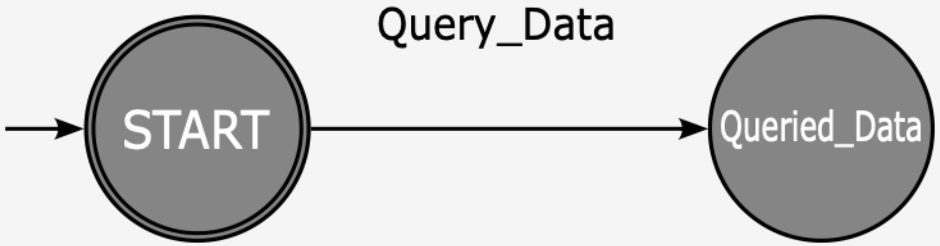

```
ACTION(action-name, computation-name,
  Paramset(paramset-name,
    params(param(param-name, param-type), ...)),
  Require(action-requirements)
```

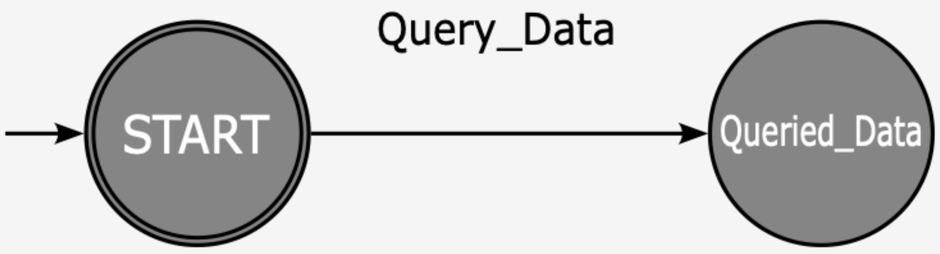
- Added Two policy constructs
  - ***StateObject***: defines a system's state
  - ***ACTION***: defines a possible computation
- Rights define state transitions
- A capability includes rights

```
RIGHT(right-name, action-name,
  StateObject(Src_State),
  StateObject(Dst_State),
  Obligation(right-conditions))
```

Security Policies - An Example

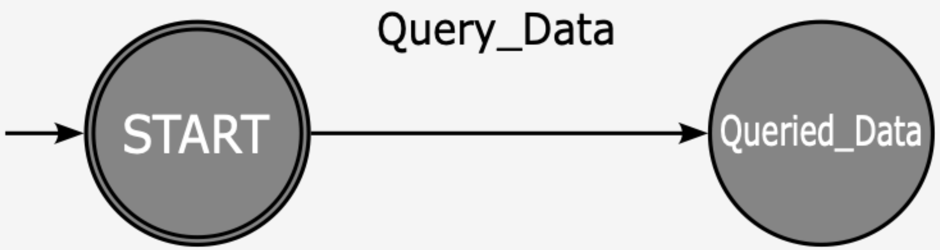


Security Policies - An Example




```
ACTION(Query_Data, query_data_function,
  Paramset(query_data_parameters,
  params(param(any-of-these, Listkv_String),
              param(all-of-these, Listkv_String))),
  Require(taint-tracking))
```

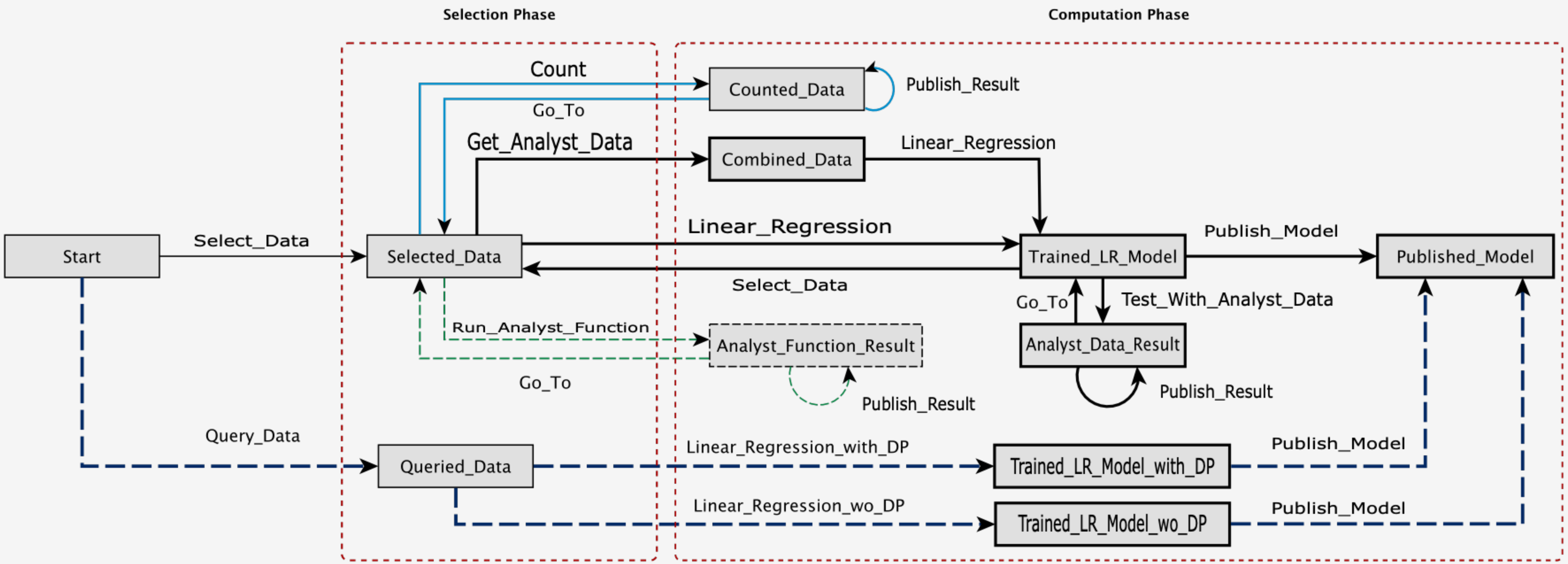
Security Policies - An Example




```
ACTION(Query_Data, query_data_function,
  Paramset(query_data_parameters,
  params(param(any-of-these, Listkv_String),
              param(all-of-these, Listkv_String))),
  Require(taint-tracking))
```

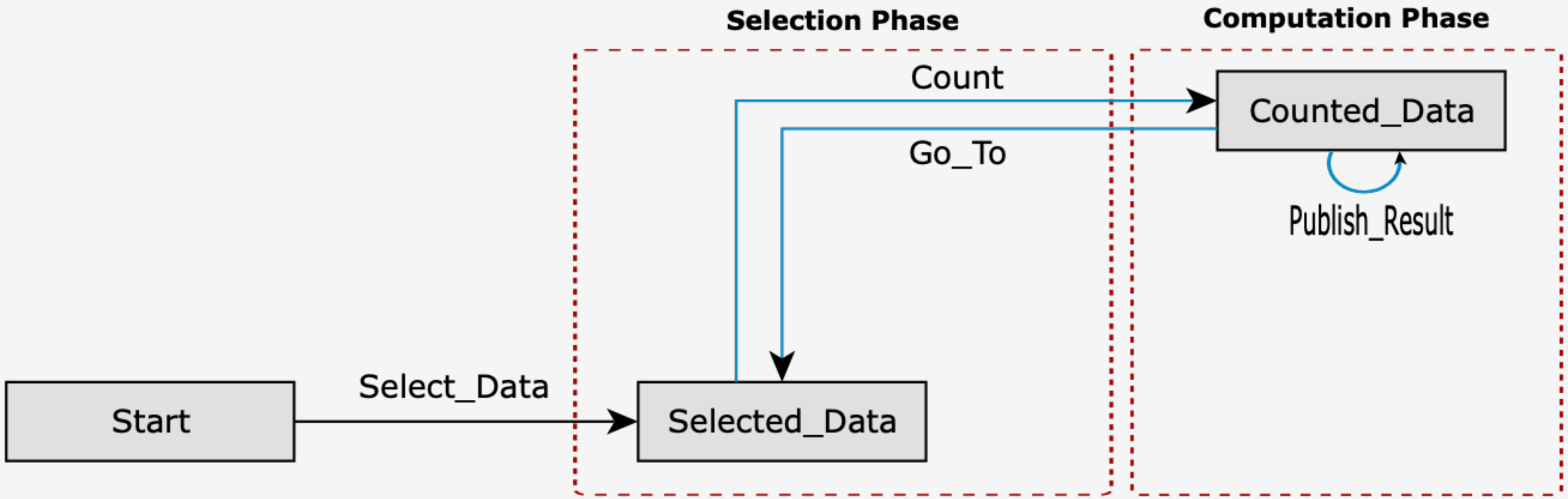
```
RIGHT(data_query, Query_Data,
  StateObject(START),
  StateObject(Queried_Data),
  Obligation())
```

Case Study



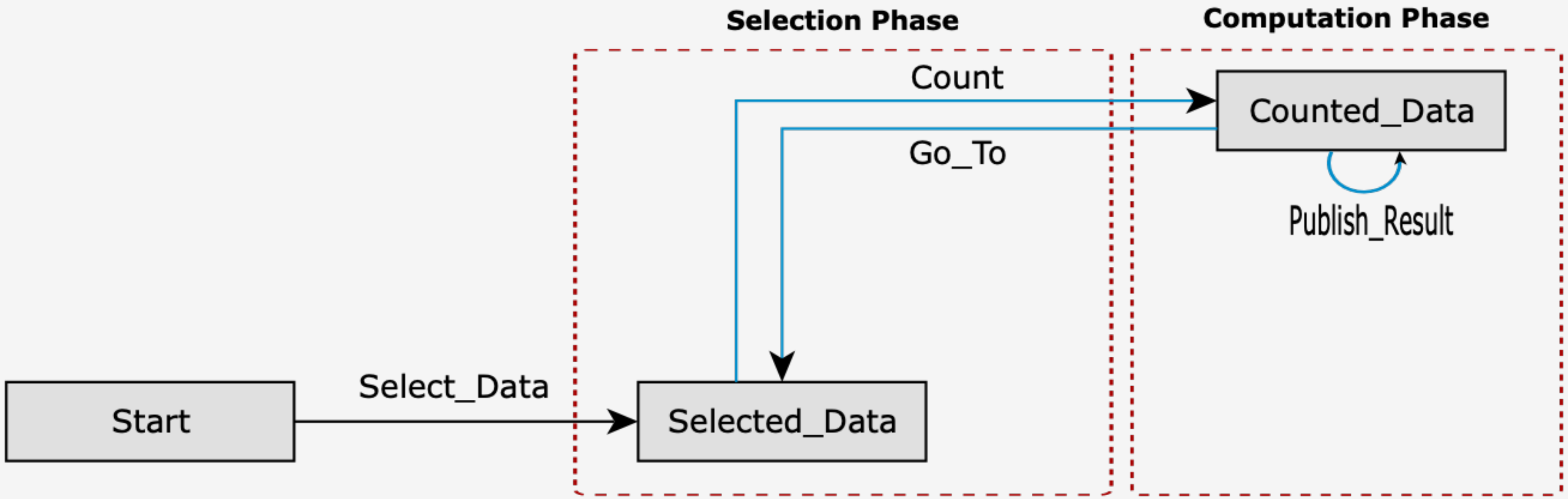
Selection Phase
Computation Phase
Count
Counted_Data
Publish_Result
Go_To
Get_Analyst_Data
Combined_Data
Linear_Regression
Linear_Regression
Publish_Model
Start
Select_Data
Selected_Data
Trained_LR_Model
Published_Model
Select_Data
Go_To
Test_With_Analyst_Data
Run_Analyst_Function
Analyst_Function_Result
Analyst_Data_Result
Go_To
Publish_Result
Publish_Result
Query_Data
Linear_Regression_with_DP
Publish_Model
Queried_Data
Trained_LR_Model_with_DP
Linear_Regression_wo_DP
Publish_Model
Trained_LR_Model_wo_DP

Case Study: First Scenario



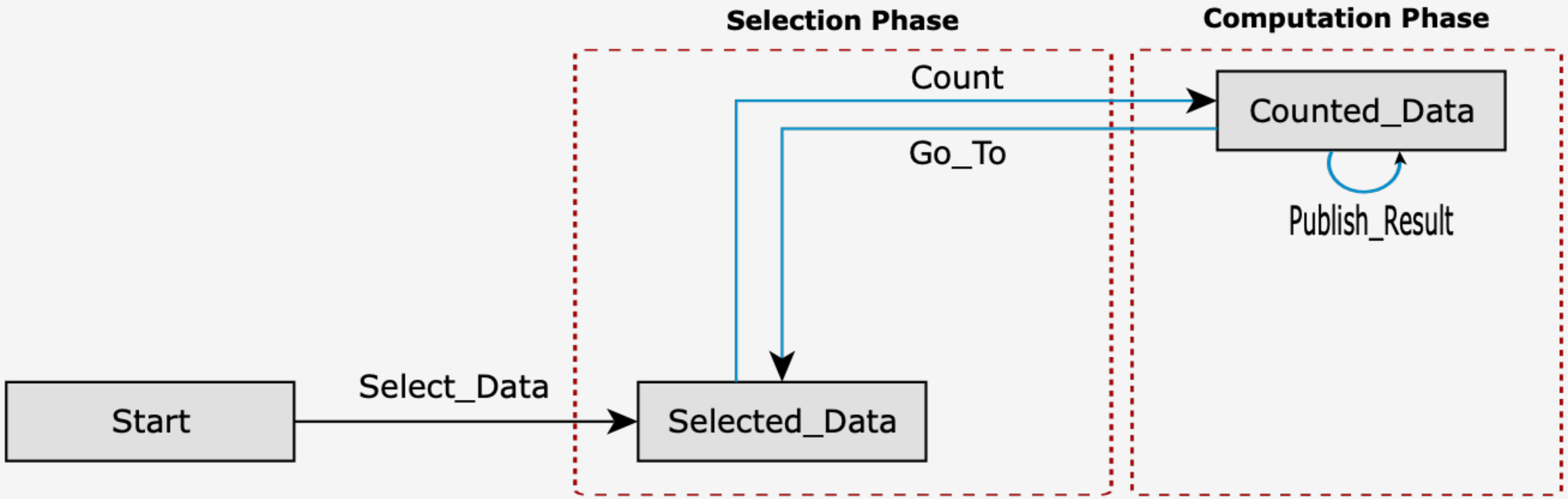
Case Study: First Scenario

- Statistical Analysis
- Selecting a subset of data records and count them

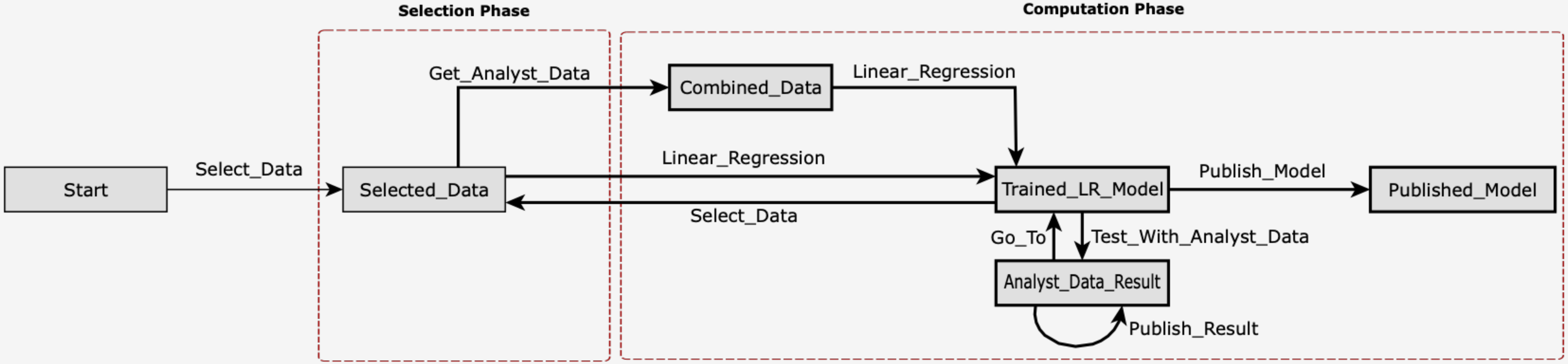


Case Study: First Scenario

- Statistical Analysis
- Selecting a subset of data records and count them
- The *Publish_Result* action adds noise to the result

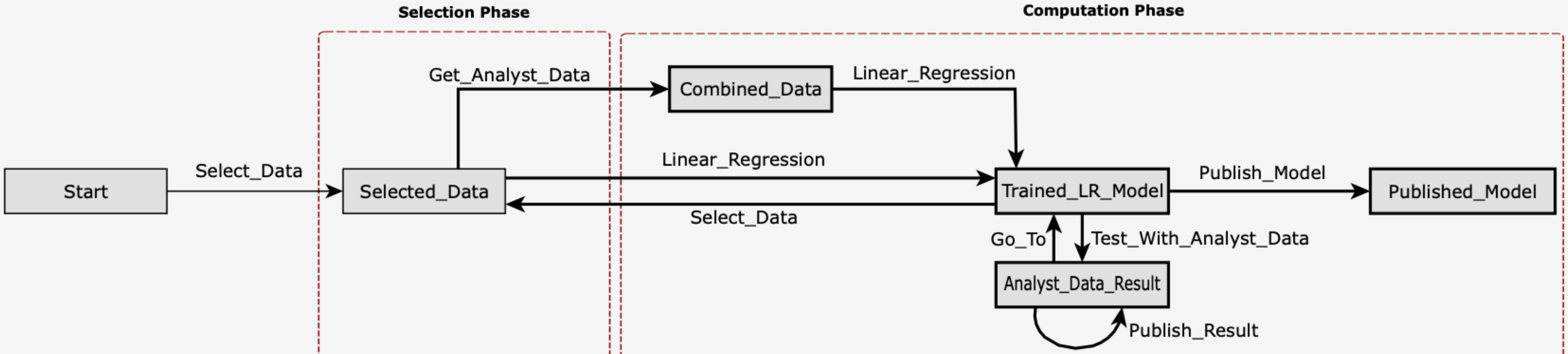


Case Study: Second Scenario



Case Study: Second Scenario

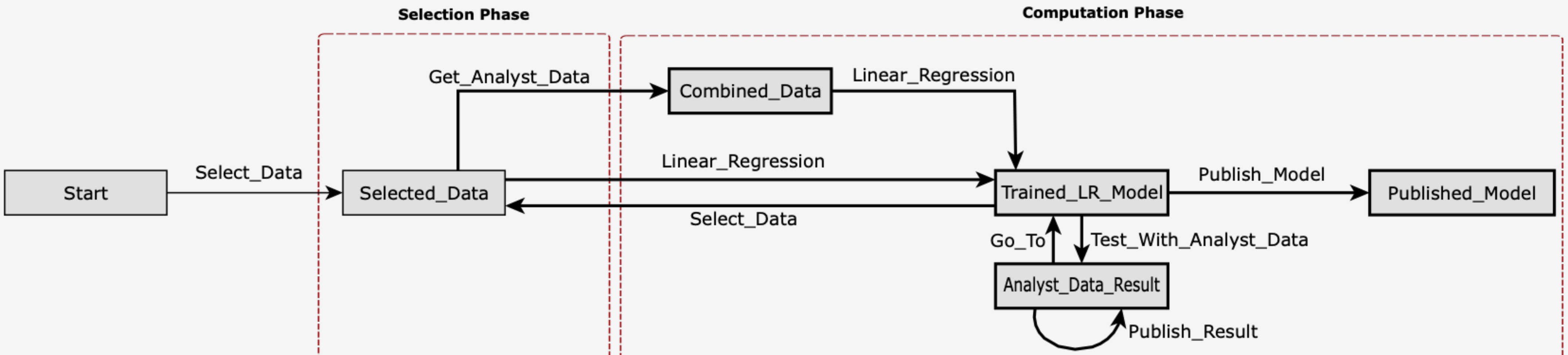
- Differentially Private Machine Learning
- Reduce an analyst' budget based on the types of adversaries



Case Study: Second Scenario

- Differentially Private Machine Learning
- Reduce an analyst' budget based on the types of adversaries

  weak adversaries

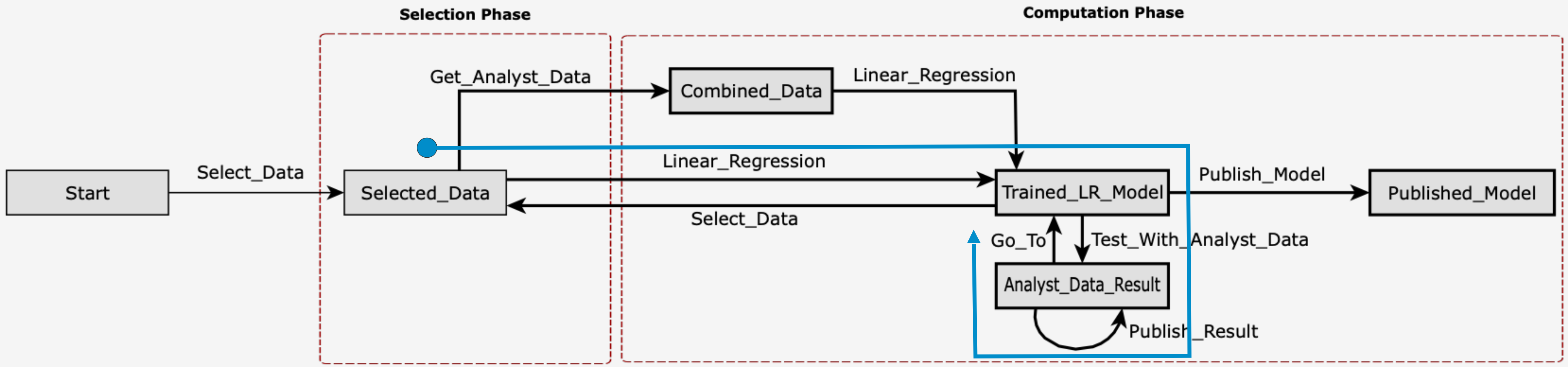


Case Study: Second Scenario

- Differentially Private Machine Learning
- Reduce an analyst’ budget based on the types of adversaries

  weak adversaries

  medium adversaries



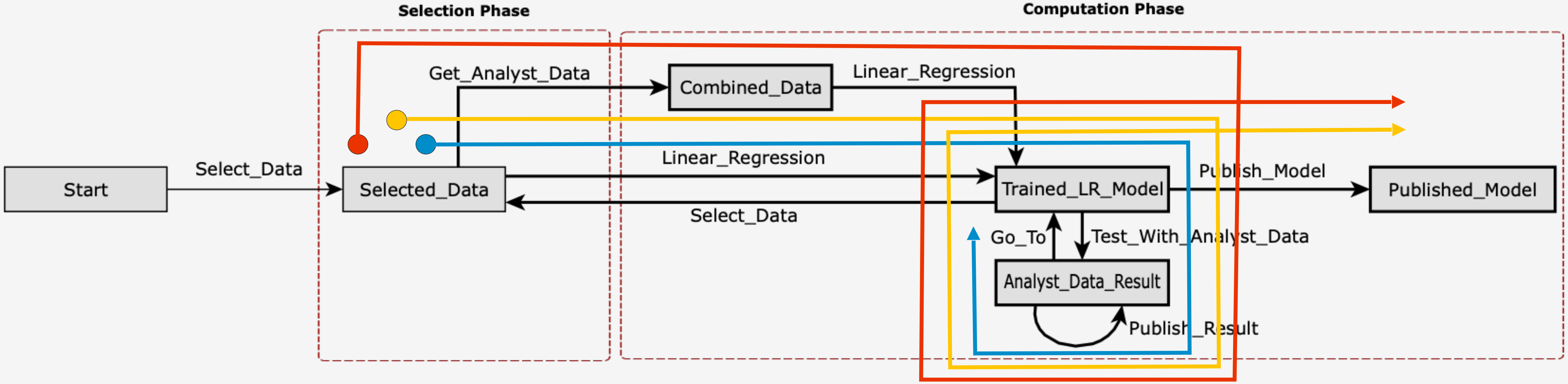
Case Study: Second Scenario

- Differentially Private Machine Learning
- Reduce an analyst' budget based on the types of adversaries

  weak adversaries

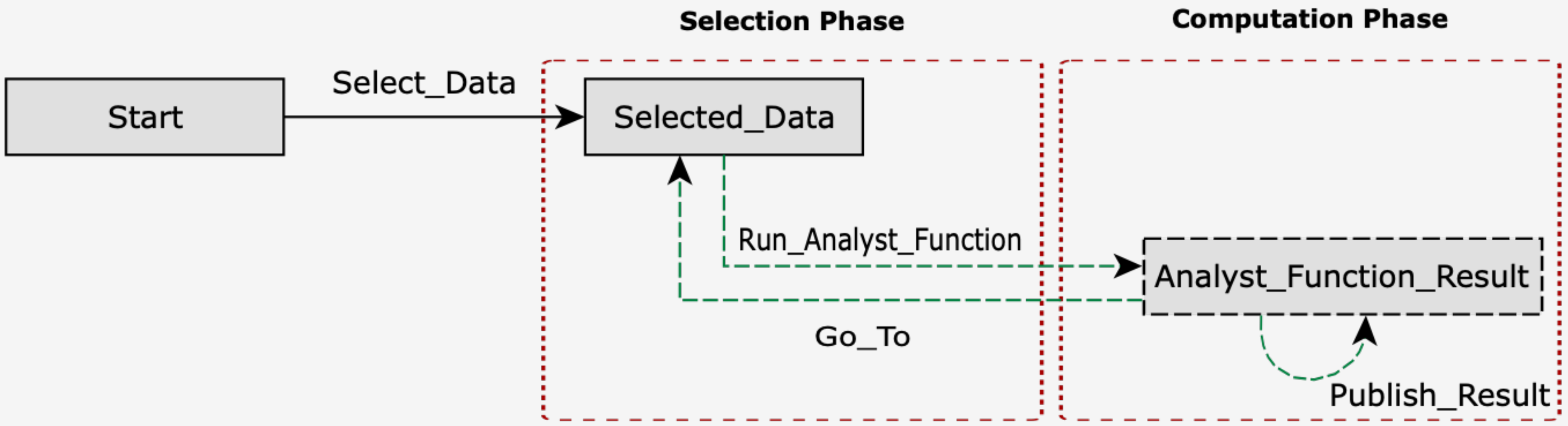
  medium adversaries

  strong adversaries



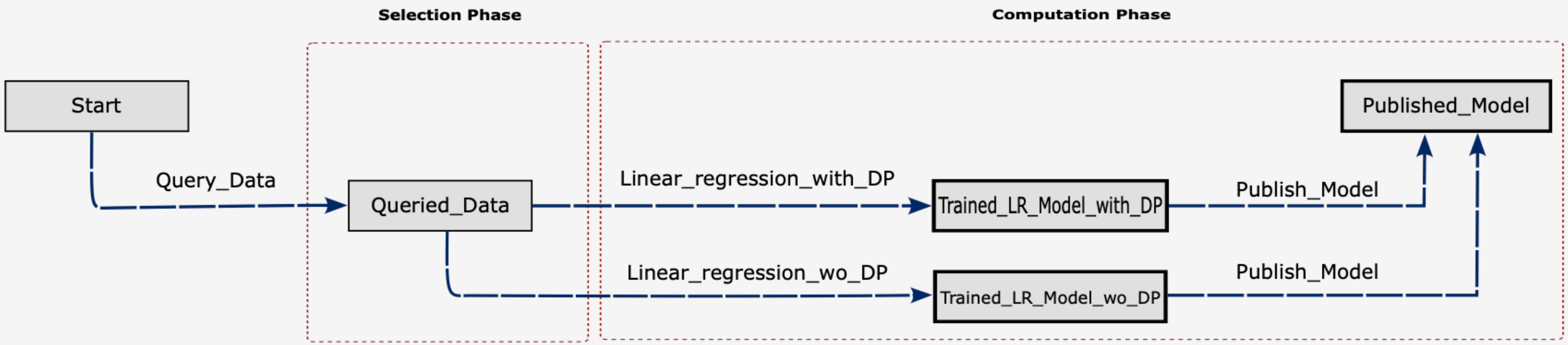
Case Study: Third Scenario

- Processing data with analysts' programs
- The *Publish_Result* action adds noise to the result



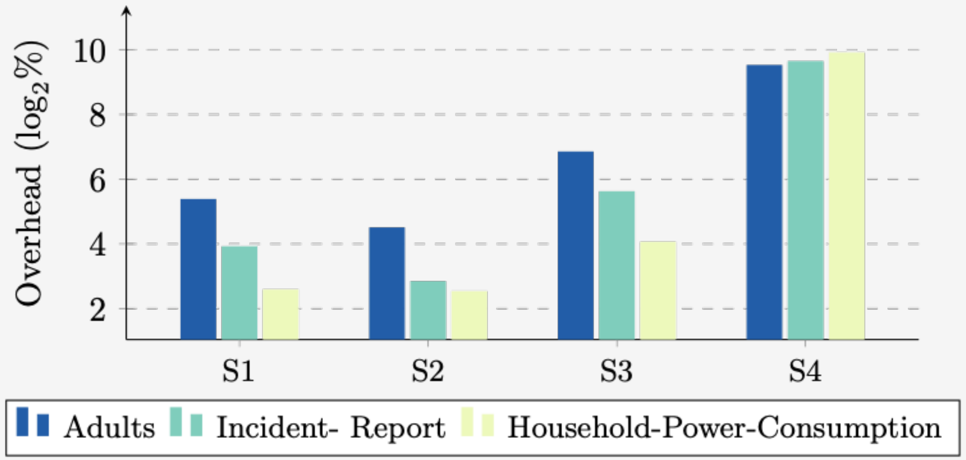
Fourth Scenario: Model Training with Taint Tracking

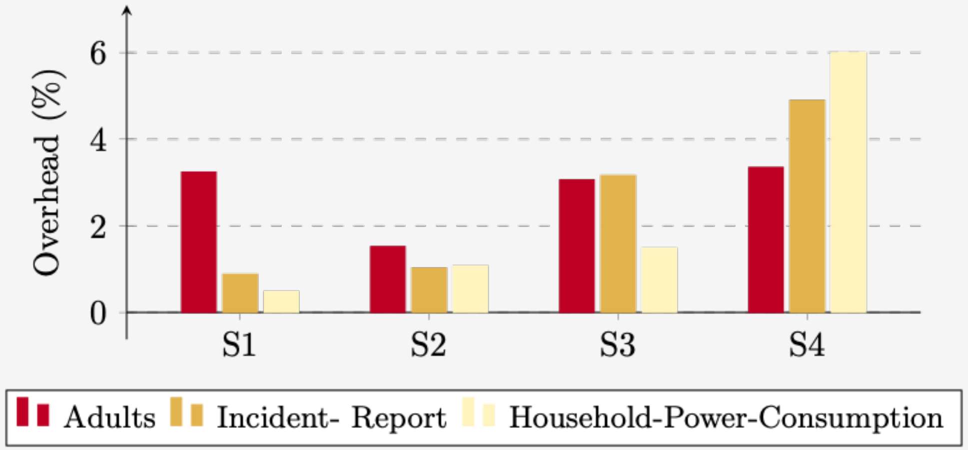
- SEAL can track the taint of every bit during a computation
- Data owners can leverage the provided taint-tracking mechanism
- SEAL Can evaluate Rights based on the data taints



SEAL: Evaluation

- We evaluated on three real-world datasets *
  - ***Adult*** dataset (32, 561 entries)
  - ***Incident-Report*** dataset (141, 713 entries)
  - ***Household-Power-Consumption*** dataset (2, 075, 258 entries)





* from UCI Machine-Learning Repository