Collaborative attacks extend

Zizheng Liu, Bharat Bhargava

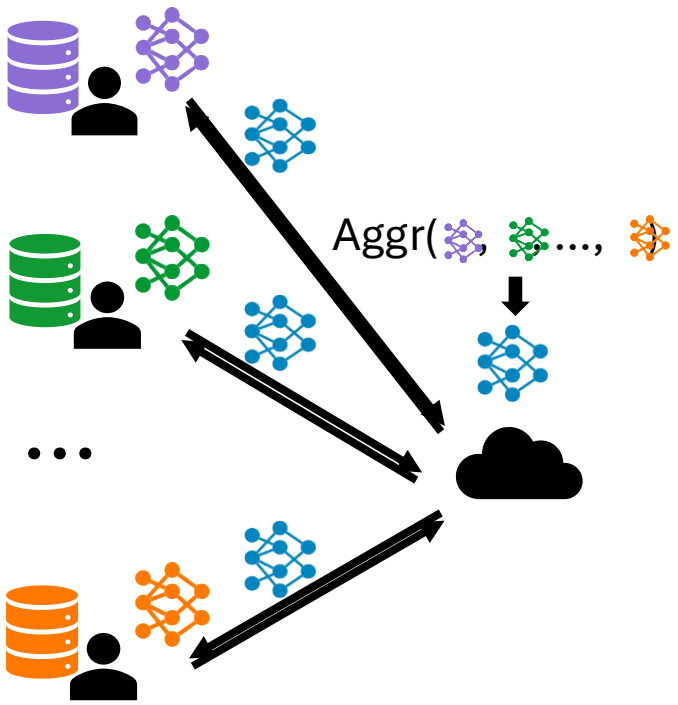
Robust Secure Aggregation for DFL

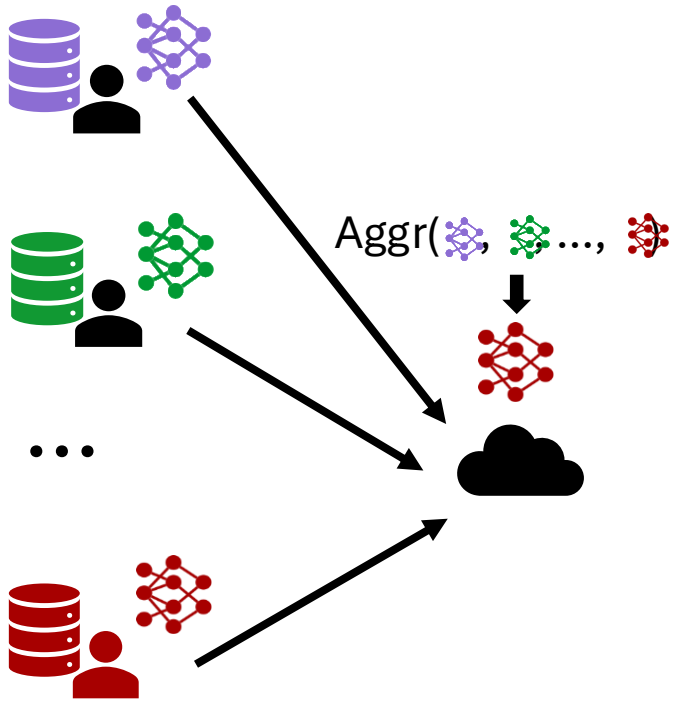
FL Security and Privacy

Federated Learning (FL)

Security: Poisoning attack

Privacy leakage





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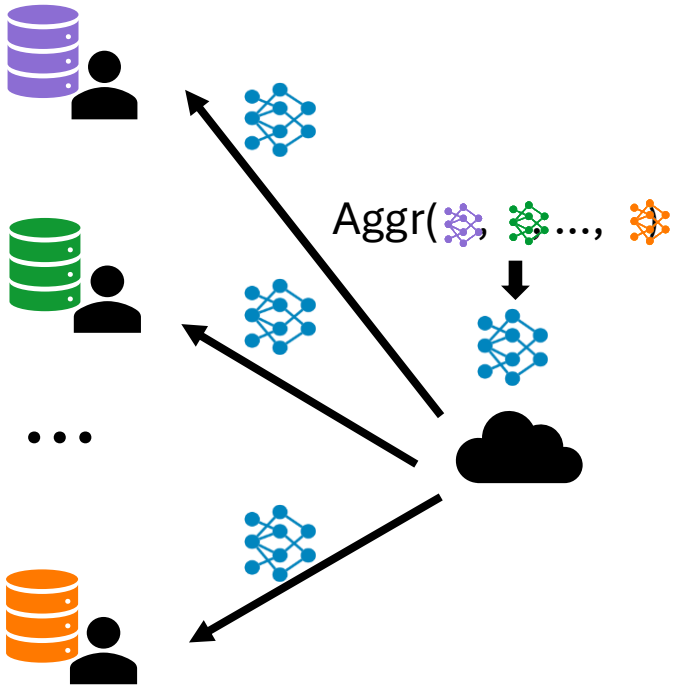
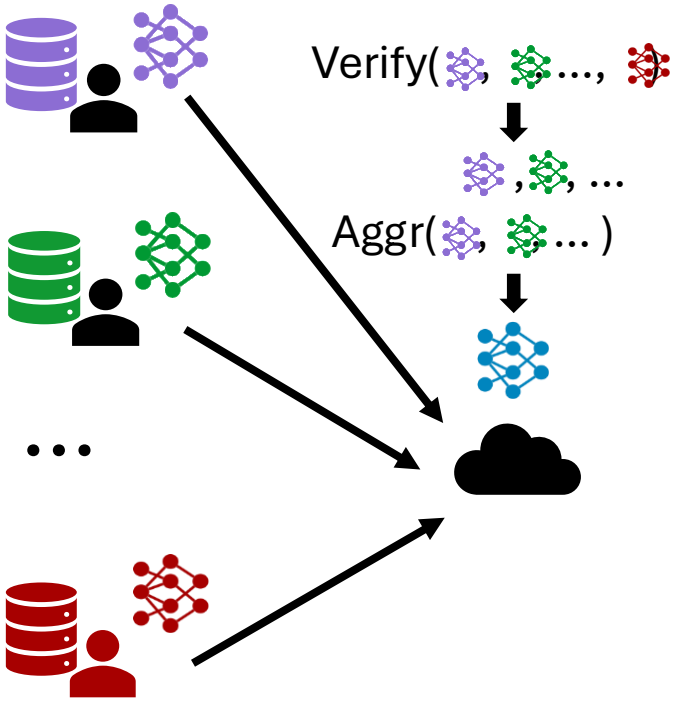
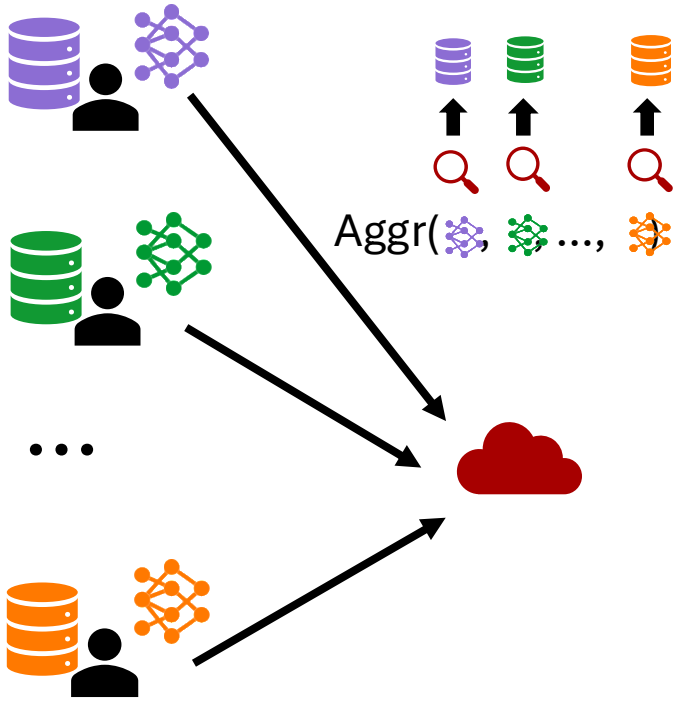


Security: Poisoning attack



Privacy leakage



Verify(W_1, W_2,...,W_n) = W_1, W_2,...

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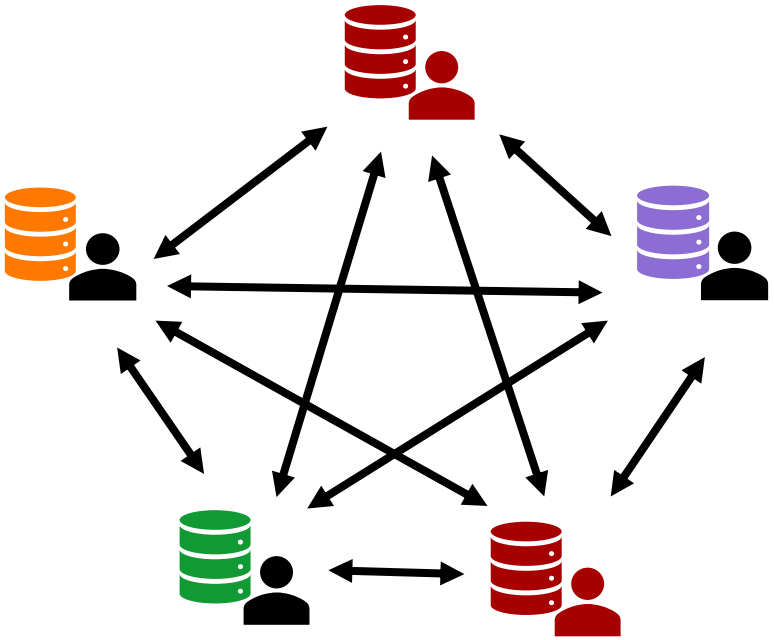
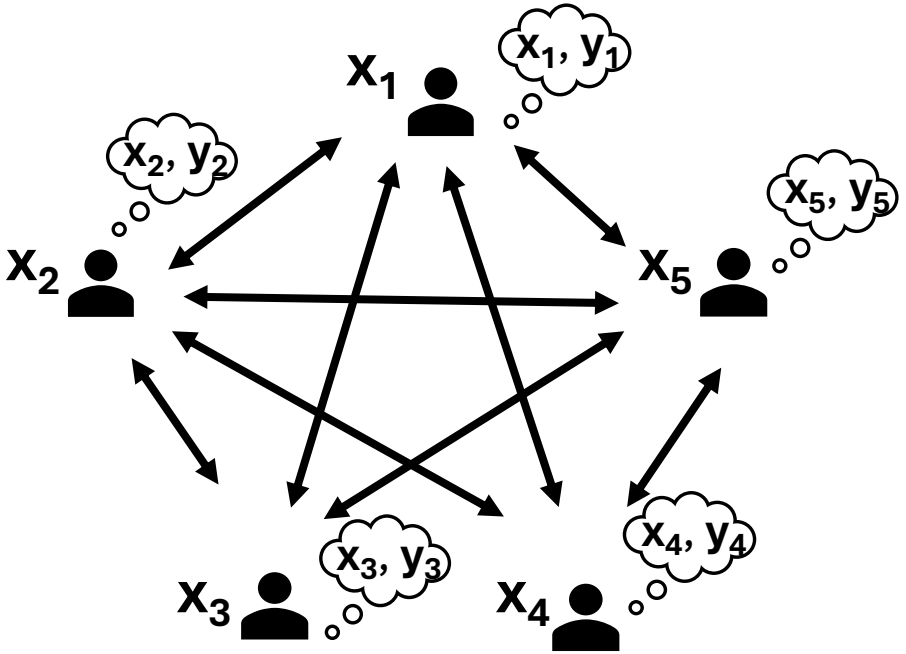
Decentralized FL and Secure Multi-party Computation

Decentralized Federated Learning MPC: Secure Multi-Party Computation





Verify(W_1, W_2,...,W_n) = W_1, W_2,...

Aggr(W_1, W_2,...,W_n) = G

$f(\mathbf{x_1}, \mathbf{x_2}, \mathbf{x_3}, \mathbf{x_4}, \mathbf{x_5}) = \mathbf{y_1}, \mathbf{y_2}, \mathbf{y_3}, \mathbf{y_4}, \mathbf{y_5}$

Secure Aggregation: $f()$:= Aggr(); $\mathbf{x_i}$:= W_i; $\mathbf{y_1}$ = ... = $\mathbf{y_n}$:= G

Robust Secure Aggregation: $f()$:= Aggr(Verify()); $\mathbf{x_i}$:= W_i; $\mathbf{y_1}$ = ... = $\mathbf{y_n}$:= G

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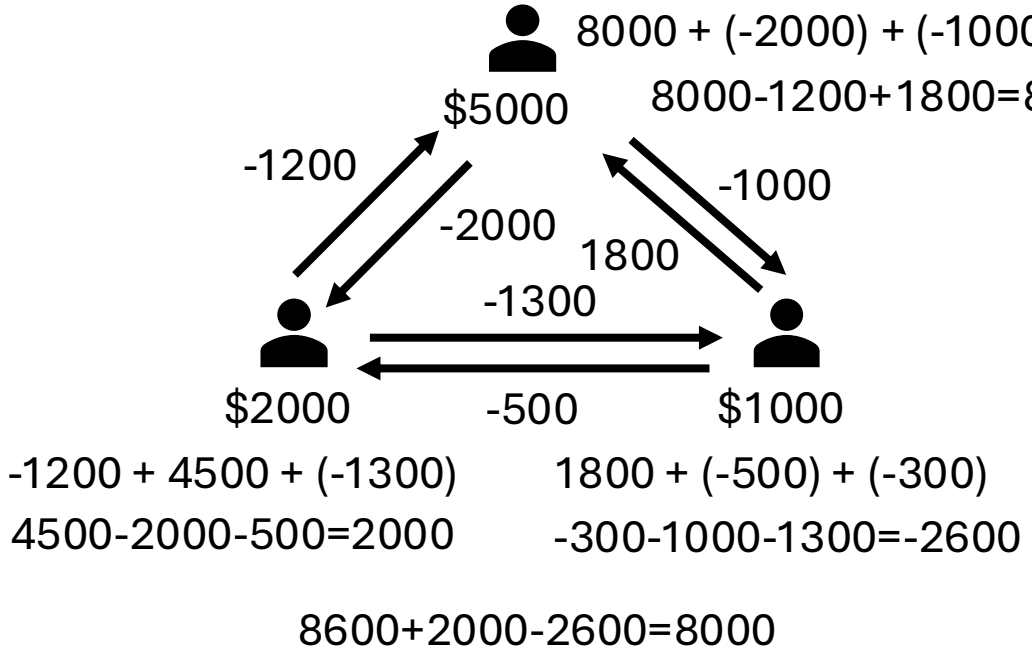
An example of MPC

MPC Example: compute average salary



Additive secret sharing: needs all secret shares to reconstruct the secret

- **If all participants are honest**, then by replacing salaries with model parameters and setting the aggregation function Aggr() to Avg(), the problem is resolved.
- If some participants submit malicious inputs, a Verify() function must be introduced.
  - Verify() involves more than simple addition; it requires additional computational operations.
- Beyond injecting malicious inputs, an adversary may also cheat during the secure computation process.
  - For example, the adversary may perform incorrect local computations to prevent the protocol from producing an output.
  - Alternatively, the adversary may simply refuse to participate in the computation.

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Threat Model

From Machine Learning Perspective

Security: Use **Verify()** to filter out malicious models.
Privacy: Use secure multiparty computation to aggregate models (execute **Aggr()**).

Security and Privacy:

- Use secure multiparty computation to execute **Verify()**, then perform **Aggr()** on the accepted models.

From MPC Perspective

Execute more operations

- Verify(W_t, W_r) = $\mathbb{I}\|W_t - W_r\|_2 \leq \rho$
  - $\|.\|_2$ needs multiplication and square root computation

Threat Models

- Semi-honest: all parties behave honestly to follow the protocol
- Malicious: parties deviate
  - Secure with abort: halt the protocol when cheating detected
  - Guaranteed output delivery: find the deviating party, exclude it and continue

Robust and Secure Aggregation for DFL

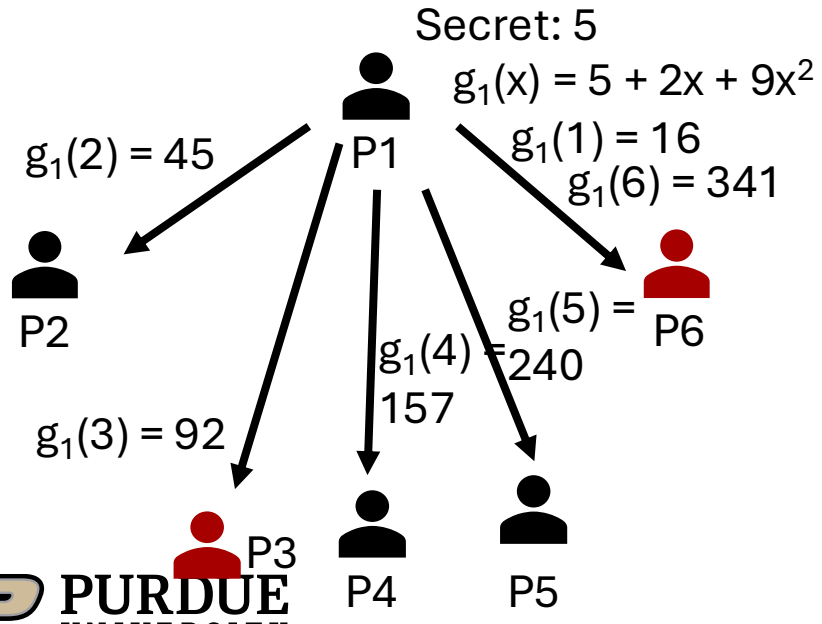
Shamir's Secret Sharing and DN multiplication Protocol

Additive secret sharing: needs all secret shares to reconstruct the secret

Shamir's n-t secret sharing

Any t+1 parties can reconstruct the secret

n = 6 parties, t = 2 are corrupted, honest majority, $2t + 1 \leq n$



Shamie SS Properties

- Denote $[x]_t$ as a degree-t sharing of x. [(1,16), …, (6,341)] is a degree-2 sharing of 5.
  - $[x]_t + [y]_t = [x+y]_t$
  - $k * [x]_t = [kx]_t$
  - $[x]_t * [y]_t = [x*y]_{2t}$ – needs 2t+1 shares to reconstruct the secret

DN Multiplication Protocol

1. The parties prepare ([r]*t, [r]*2t), where r is a secret random value.
2. Each party locally computes [x]*t* * *[y]t = [xy]2t and sets [e]*2t := [xy]*2t* + *[r]*2t.
3. The parties select a coordinator Pking and send [e]2t to him.
4. Pking reconstructs e, generates [e]t, and distributes it to the parties.
5. Each party then locally computes [z]t = [xy]t = [e]t - [r]t.

During this process, any party, including Pking, may cheat.
This protocol provides only semi-honest security.

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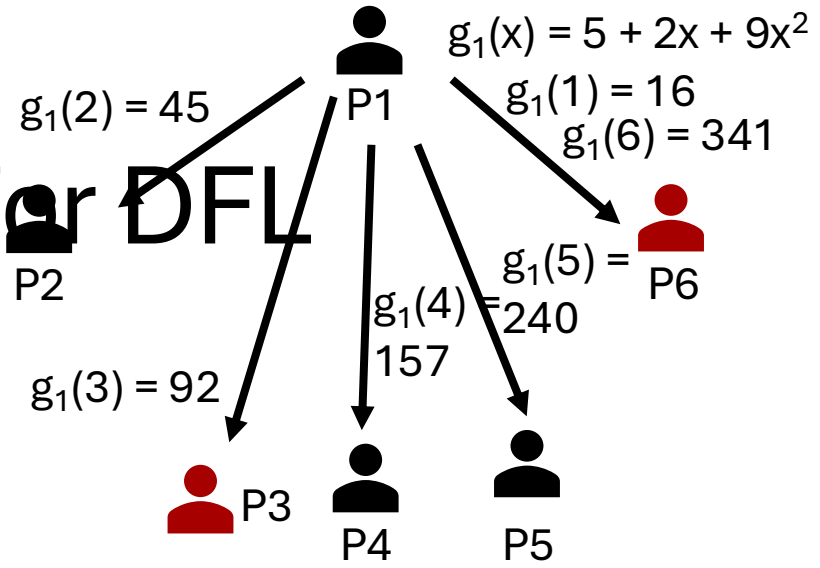
Secure with Abort



Secure with Abort

The tuple ([x]_t, [y]*t, [r]t, [r]{2t}, [e]*{2t}, [e]_t, [z]_t) is called the **transcript** of the DN protocol. All parties must verify that every value in the transcript is consistent, i.e., that all corresponding shares are well-formed.

- Recall the example of Shamir secret sharing: the parties must ensure that all (id, share) pairs lie on the same polynomial, e.g., $5 + 2x + 9x^2$.
- However, directly revealing shares would compromise privacy.

Suppose $\{([x^{(i)}]_t, [y^{(i)}]_t, [r^{(i)}]_t, [r^{(i)}]_{2t}, [e^{(i)}]_{2t}, [e^{(i)}]_t, [z^{(i)}]_t)\}_{i=1}^{m}$ are the m transcripts that need to be verified.

1. The parties first run the DN protocol on random inputs $([x^{(0)}]_t, [y^{(0)}]_t)$ to obtain an additional transcript $([x^{(0)}]_t, [y^{(0)}]_t, [r^{(0)}]_t, [r^{(0)}]_{2t}, [e^{(0)}]_{2t}, [e^{(0)}]_t, [z^{(0)}]_t)$
2. Next, the parties generate a public random value λ. Each party locally computes
$$([\alpha]_t,[\beta]_t,[\delta]_t,[\delta]_{2t},[\eta]_{2t},[\eta]_t,[\gamma]_t) = \sum_{i=0}^{m} \lambda^i \, ([x^{(i)}]_t, [y^{(i)}]_t, [r^{(i)}]_t, [r^{(i)}]_{2t}, [e^{(i)}]_{2t}, [e^{(i)}]_t, [z^{(i)}]_t)$$
3. Each party then reveals its shares of $([\alpha]_t,[\beta]_t,[\delta]_t,[\delta]_{2t},[\eta]_{2t},[\eta]_t,[\gamma]_t)$, and the parties check whether all revealed shares lie on the same degree-t or degree-2t polynomial, respectively.

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Guaranteed Output Delivery

Guaranteed Output Delivery

1. For each share that a sender Pd distributes to a receiver Pi, denote it by $\sigma i(d)$. All other parties Pv act as **verifiers** for this share.
2. Each verifier Pv prepares an authentication key $\mu_{v \to i}$, for the receiver Pi. The verifier and the sender Pd then run a protocol to compute an authentication tag $\tau_{d,i,v} = \mu_{v \to i} * \sigma_i(d)$, and the result is delivered **only to Pi** (neither Pd nor Pv receives the output. That is, $x_d = \sigma_i(d)$, $x_v = \mu_{v \to i}$, $y_i = \tau_{d,i,v}$, and all other inputs and outputs are empty.
3. Whenever $\sigma_i(d)$ is disputed — for example, when all other shares lie on a certain polynomial but this one does not — Pi reveals the corresponding authentication tags to all verifiers. The verifiers then perform a **majority vote** to determine whether the sender Pd or the receiver Pi is cheating.
4. The cheating party is eliminated, and the computation is restarted.

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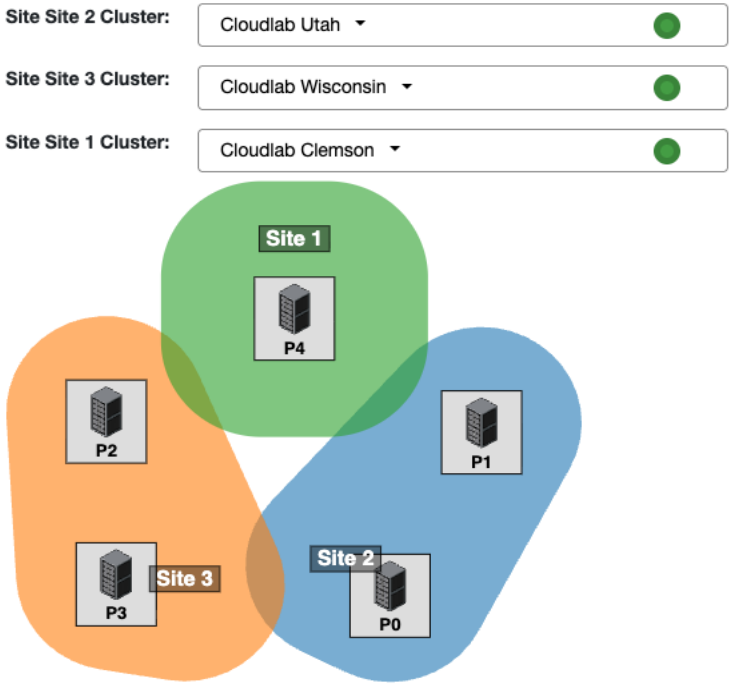
Remainder questions and Experimental Results

- During the computation of authentication keys and authentication tags, parties may still behave maliciously.
- When a party is eliminated due to detected misbehavior, the number of remaining parties may fall below 2t+1, in which case degree-2t secret sharings can no longer be reconstructed.
- In addition to addition and multiplication, protocols are required for other types of operations as well.
- Machine learning computations typically use floating-point numbers, whereas secret sharing schemes operate over fixed-point representations.
- All of the above issues are addressed by specialized secure multiparty computation protocols. This project involves approximately 40 such protocols.

Implementation: Based on the semi-honest DN multiplication protocol in MP-SPDZ, we incorporated additional operation logic and ensured that all operations provide guaranteed output delivery under malicious behavior. The implementation consists of 3,000+ lines of C++ code.

The protocol was successfully executed in a distributed network with nodes located in Utah, Wisconsin, and South Carolina.



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