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Data Privacy

CMSC 491/691

L09 – Edge Computing: Federated Learning

Icons from https://thenounproject.com/

Previously on…

- Secure Multi-Party Computation (MPC) replaces replace trusted party with technology to promote collaboration
- Based on adversarial model (e.g., honest-but-curious)
- Components: Shamir Secret Sharing (SSS), Oblivious Transfer (OT), ...
- High computational and communication costs!

Community

How Big Tech uses data privacy concerns for market dominance

Google gives Europe a 'reject all' button for tracking cookies after fines from watchdogs

In the news!

Cloud Computing

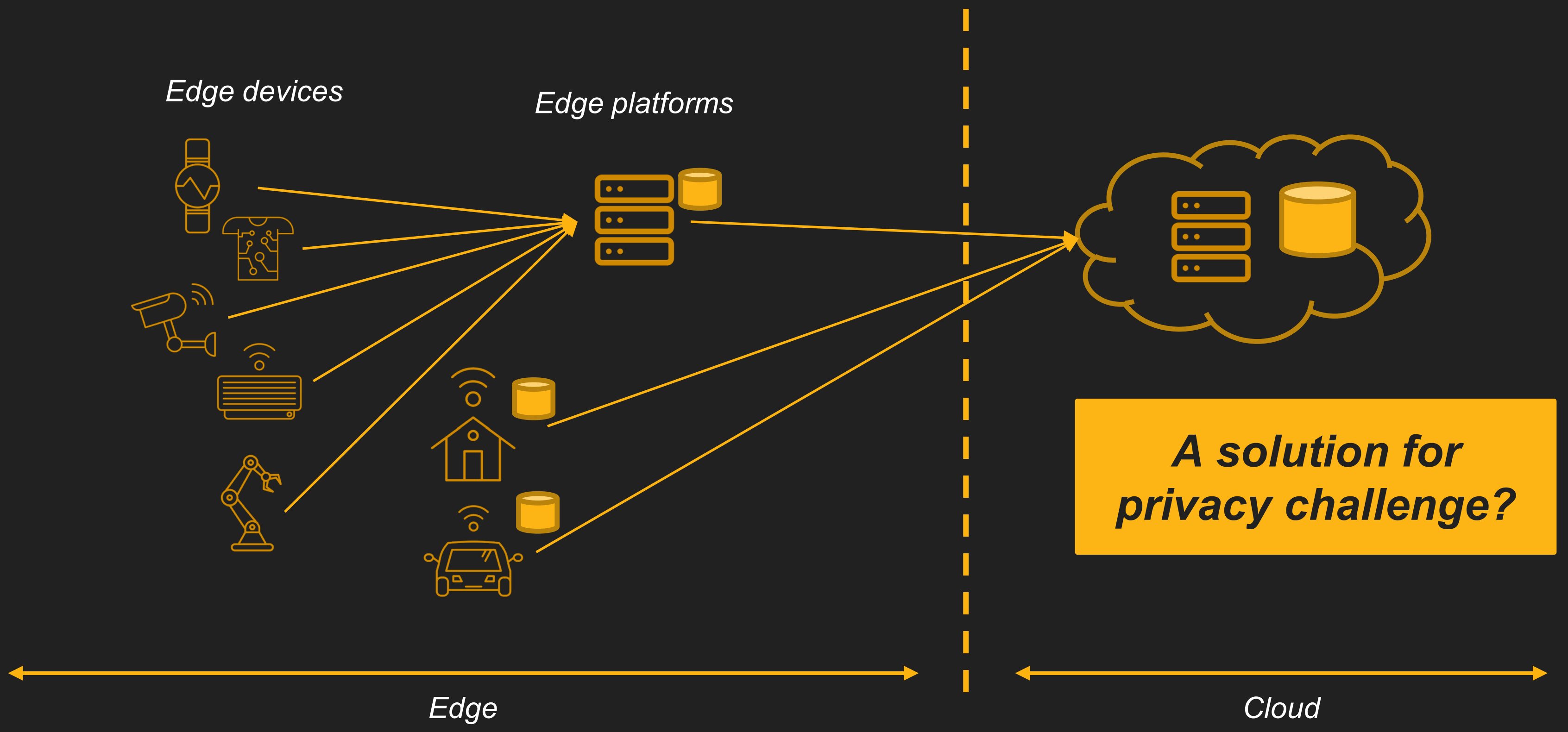
Huge, highly scalable computing and storage power

Cloud Computing Challenges

- **Latency**
  - Round-trip time to the cloud
- **Bandwidth**
  - Transference of large amounts of data
- **Connectivity**
  - Disconnection to the cloud

  ....
- **Privacy!**
  - Sensitive data transferred to the cloud

Edge Computing



Edge Computing S&P Challenges

Attacks/Threats

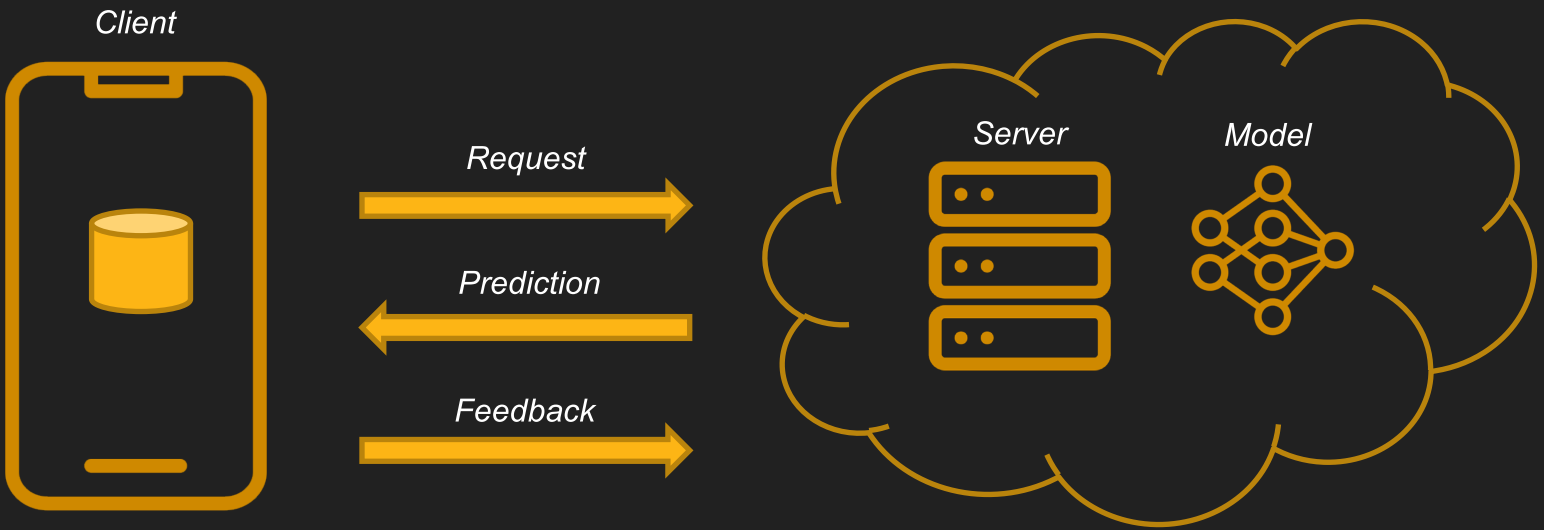
- Malicious Hardware/Software Injection
- Jamming Attacks
- Distributed Denial of Service (DDoS) Attacks
- Physical Attacks or Tampering
- Eavesdropping or Sniffing
- Non-Network Side-Channel Attacks
- Routing Information Attacks
- Forgery Attacks
- Unauthorized Control Access
- Different Privacy Leakages
- …

Countermeasures

- Side-Channel Signal Analysis
- Trojan Activation Methods
- Policy-Based Mechanisms
- Securing Firmware Update
- Reliable Routing Protocols
- Intrusion Detection System (IDS)
- Cryptographic Schemes
- Secure Data Aggregation
- MPC
- DP
- …

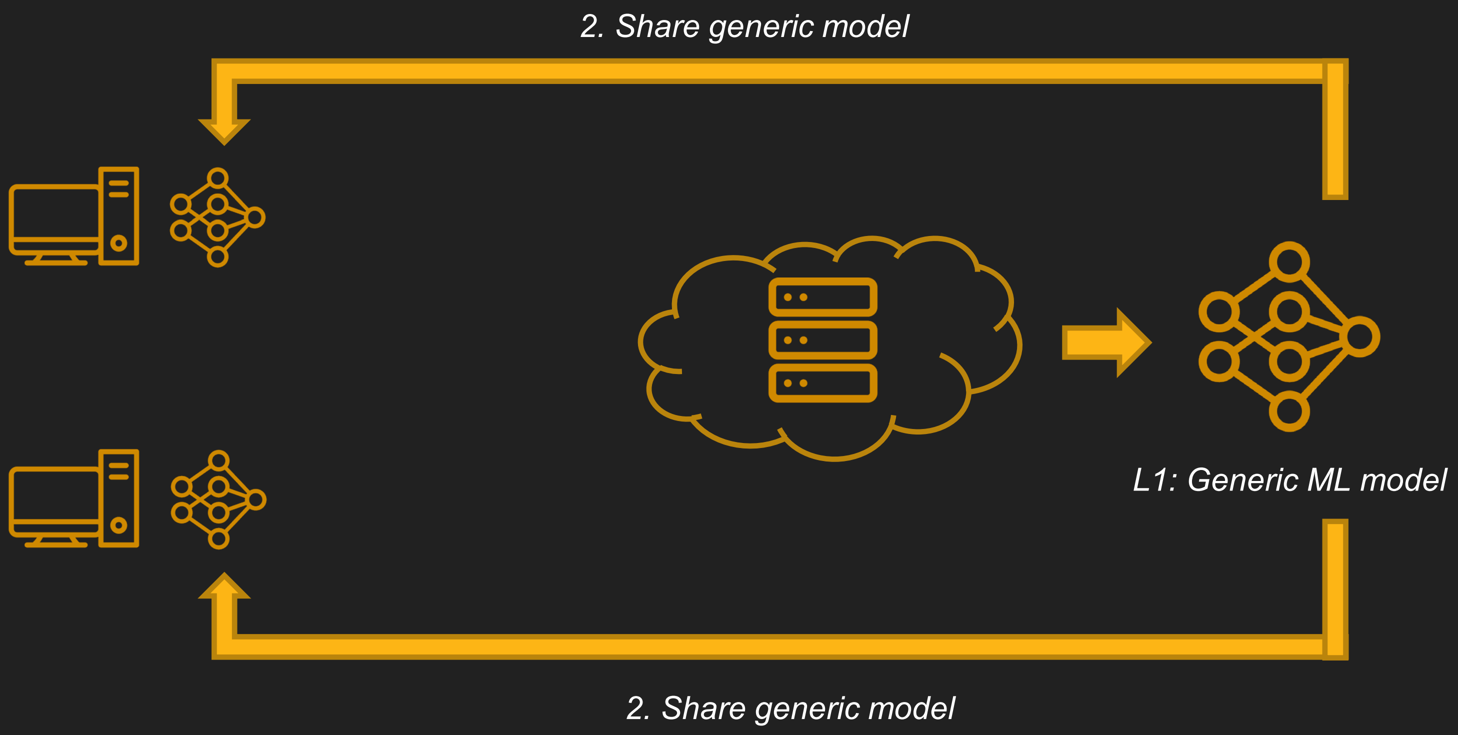
Alwarafy, Abdulmalik, et al. "A survey on security and privacy issues in edge-computing-assisted internet of things." IEEE Internet of Things Journal 8.6 (2020): 4004-4022.

Example Domain: Machine Learning



Federated Learning

Federated Learning



Federated Learning

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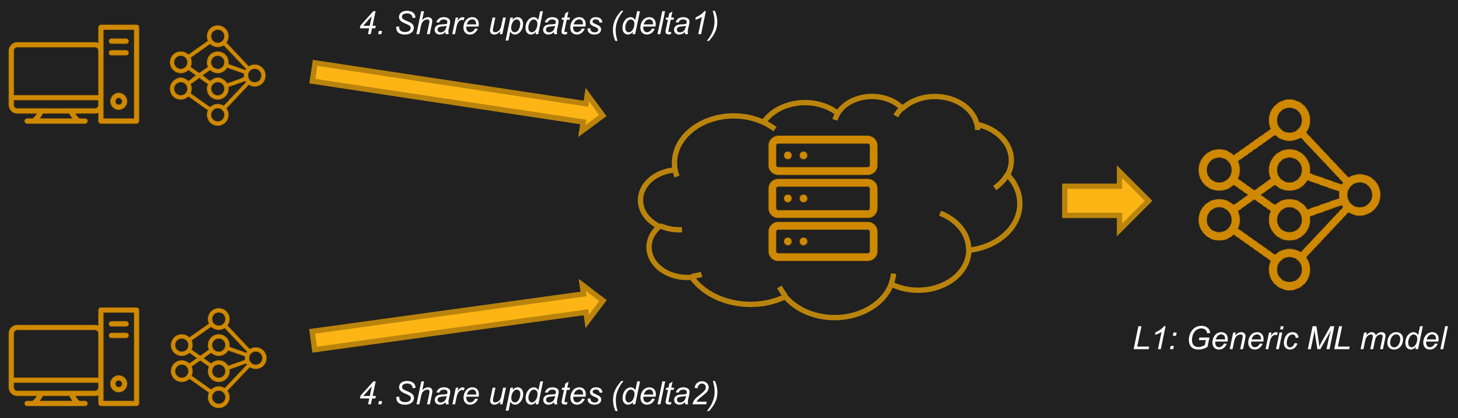

Federated Learning

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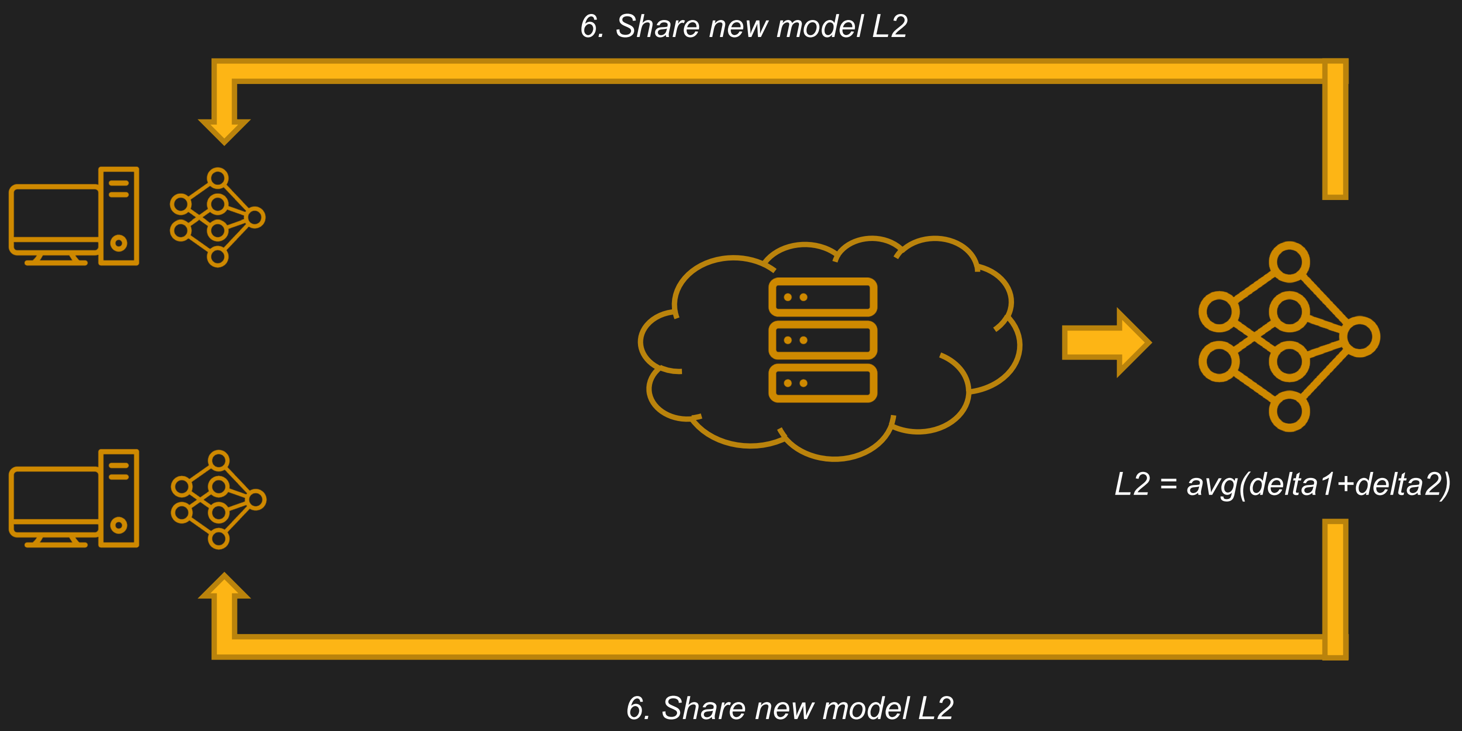


Limits of Federated Learning

- **FL does not apply to all ML applications**
- Model might be too large for clients
- Client data might not be relevant
  - E.g., might not be clean!
- Clients might not label data
  - Problem for supervised techniques

Core Challenges

- Challenge 1: **Expensive Communication**
- Challenge 2: **Systems Heterogeneity**
- Challenge 3: **Statistical Heterogeneity**
- Challenge 4: **Privacy Concerns**

Li, Tian, et al. "Federated learning: Challenges, methods, and future directions." IEEE Signal Processing Magazine 37.3 (2020): 50-60.

Challenge 1: Expensive Communication

- **Communication is a critical bottleneck!**
    - Send model updates from/to clients and server
- Massive number of devices (e.g., millions of smartphones)
- Slower network communication
- **Key ideas:**
    - Reduce total number of communication rounds
    - Reduce size of transmitted messages per round

Li, Tian, et al. "Federated learning: Challenges, methods, and future directions." IEEE Signal Processing Magazine 37.3 (2020): 50-60.

Challenge 2: Systems Heterogeneity

- Storage, computational, and communication capabilities of devices may differ
  - Variability in hardware (CPU, memory), network connectivity (3G, 4G, 5G, Wi-Fi), and power (battery level)

- Devices might be unreliable
  - They might disconnect/stop at any round

- **Key ideas:**
  - Anticipate a low amount of participation
  - Tolerate heterogeneous hardware
  - Be robust to dropped devices in the network.

Li, Tian, et al. "Federated learning: Challenges, methods, and future directions." IEEE Signal Processing Magazine 37.3 (2020): 50-60.

Challenge 3: Statistical Heterogeneity

- Devices frequently generate and collect data in a non-identically manner
- Number of data points across devices vary significantly
- Conflict with independent and identically distributed assumptions
- Challenging to learn a global model in this setting

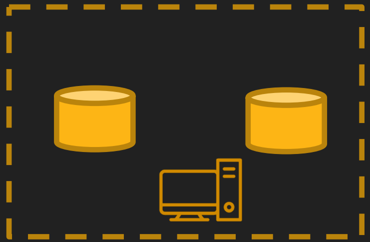
Li, Tian, et al. "Federated learning: Challenges, methods, and future directions." IEEE Signal Processing Magazine 37.3 (2020): 50-60.

Challenge 4: Privacy Concerns

- FL is a step towards protecting data generated on each device by sharing model updates…
- …but! updates can reveal sensitive information
- **Key ideas:**
  - Anonymization?
  - Multi-Party Computation?
  - Differential Privacy?

Li, Tian, et al. "Federated learning: Challenges, methods, and future directions." IEEE Signal Processing Magazine 37.3 (2020): 50-60.

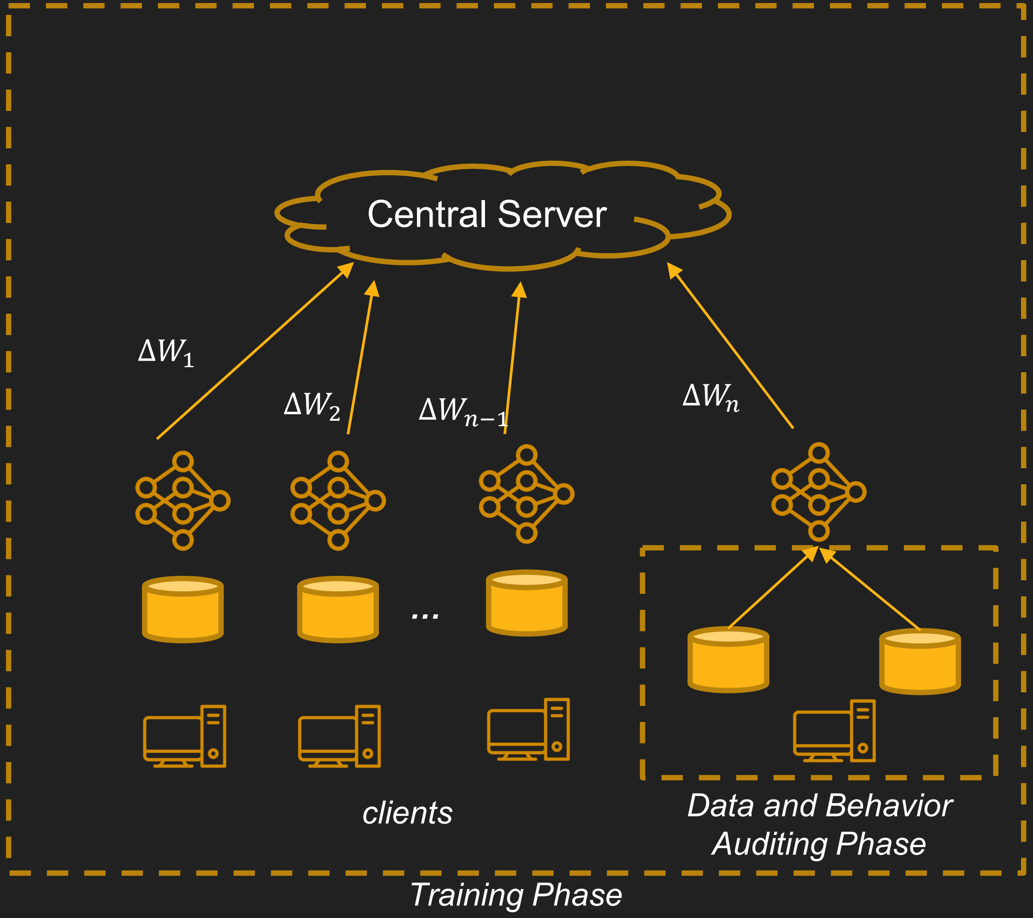
FL Privacy/Security Attacks



Data and Behavior Auditing Phase

Liu, Pengrui, Xiangrui Xu, and Wei Wang. "Threats, attacks and defenses to federated learning: issues, taxonomy and perspectives." Cybersecurity 5.1 (2022): 1-19.

FL Privacy/Security Attacks



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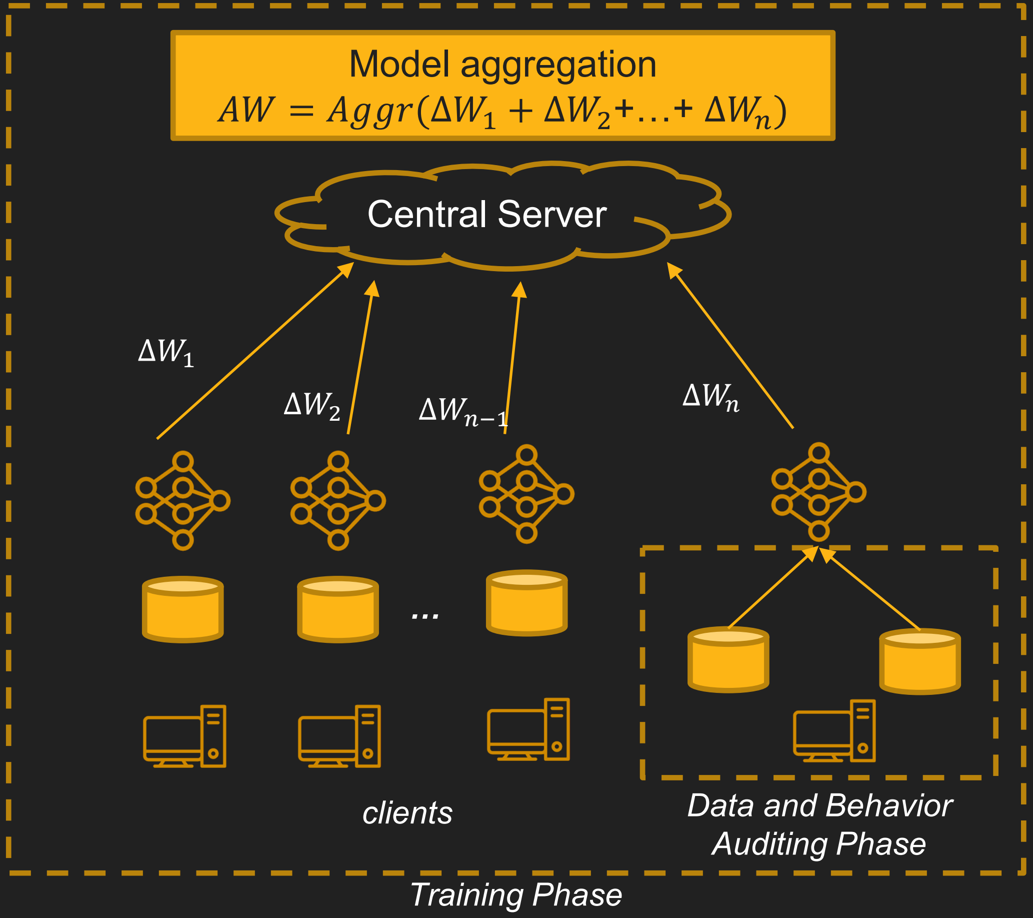

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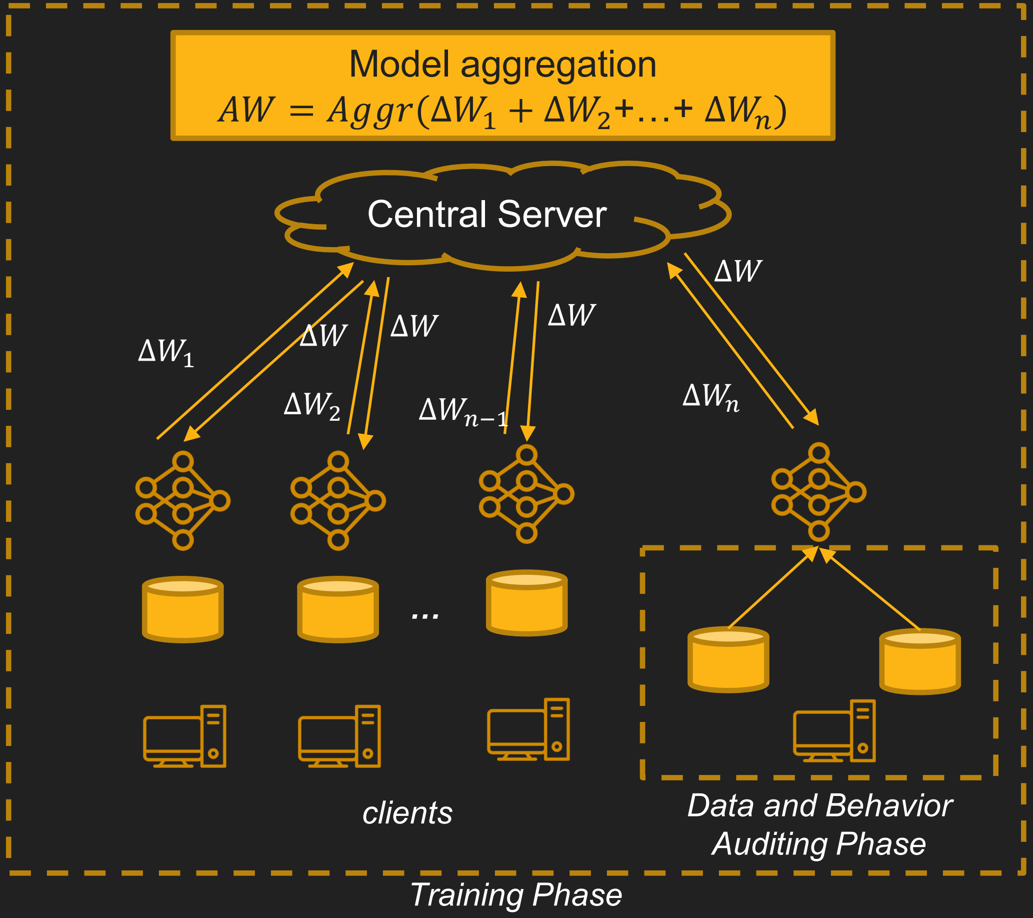

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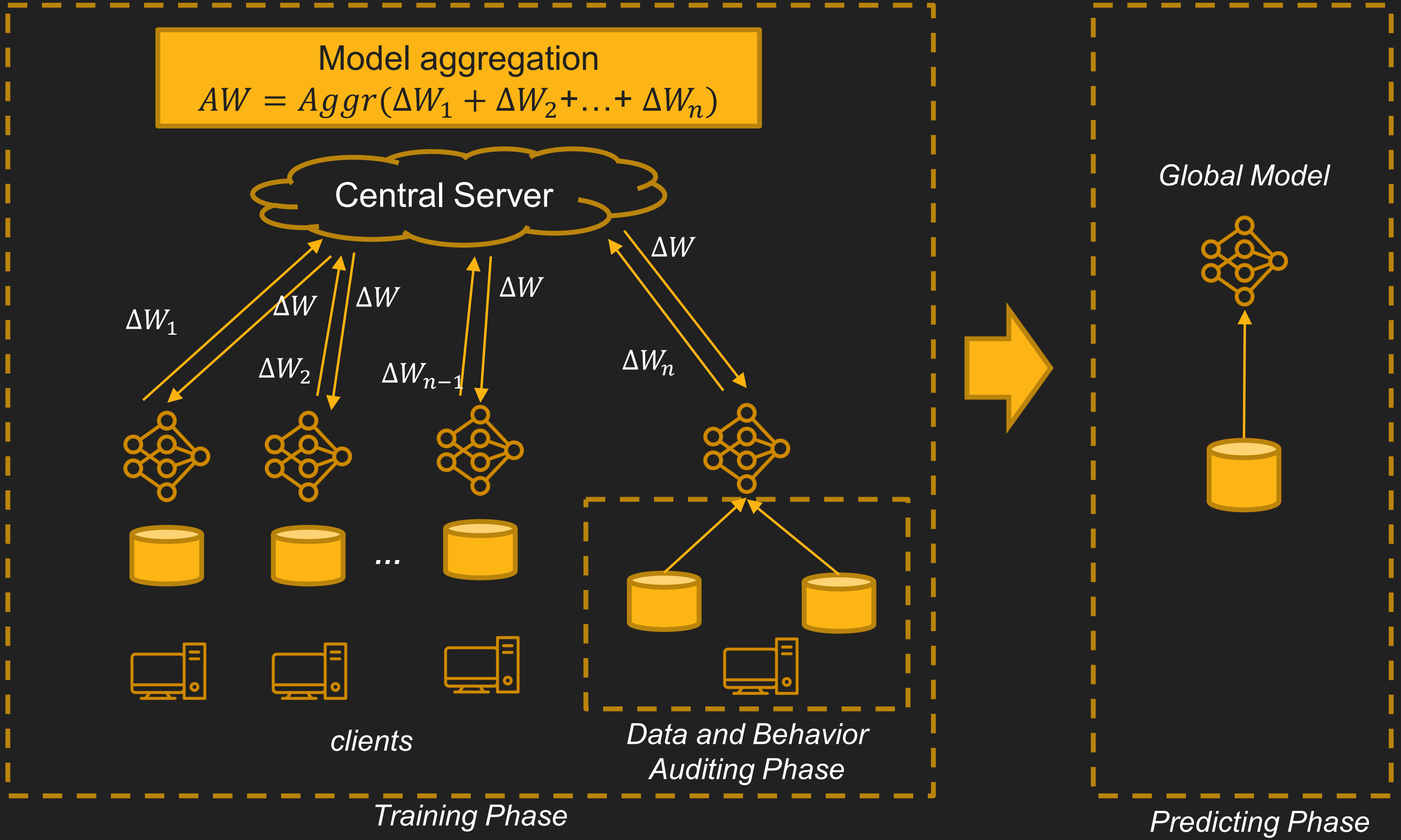

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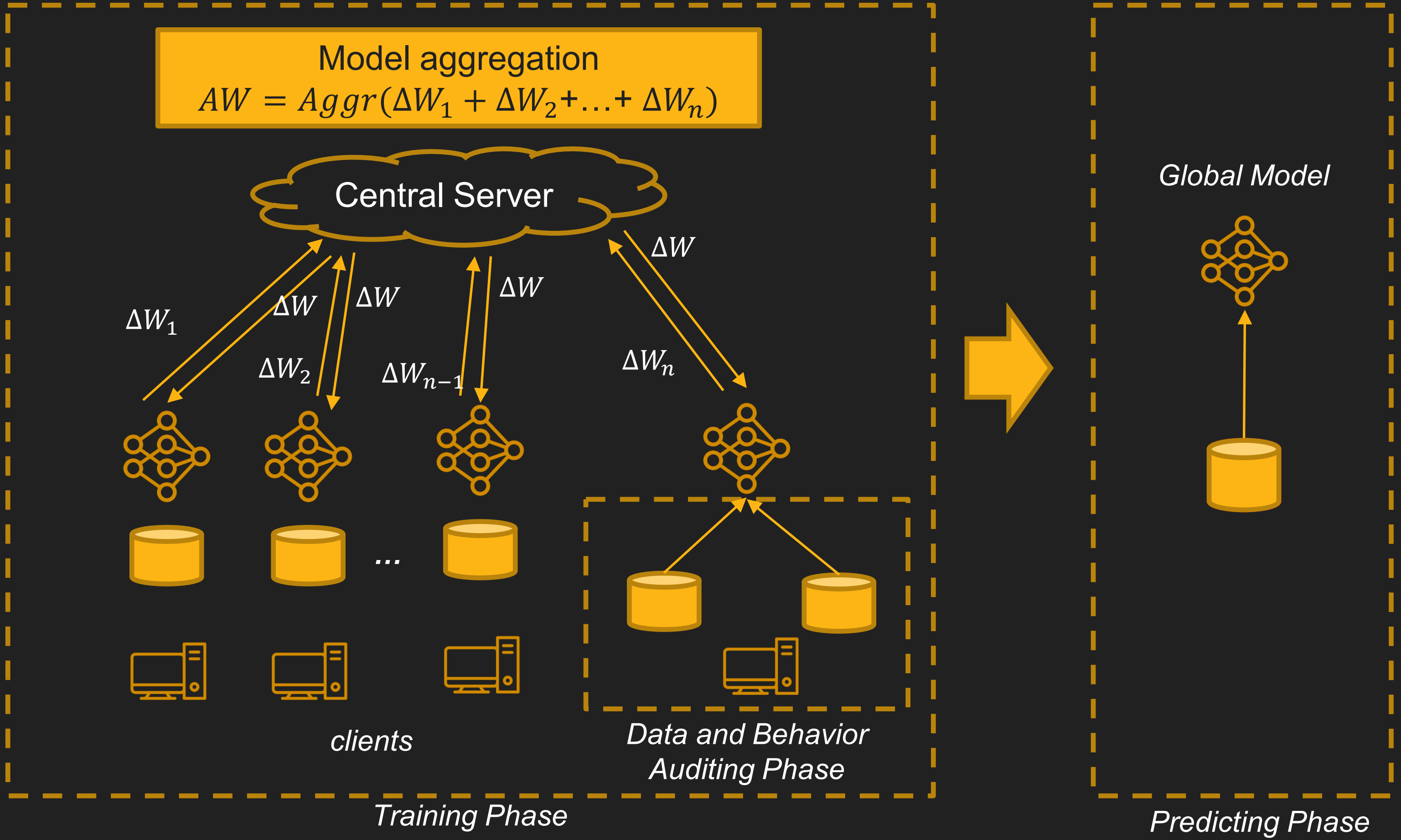

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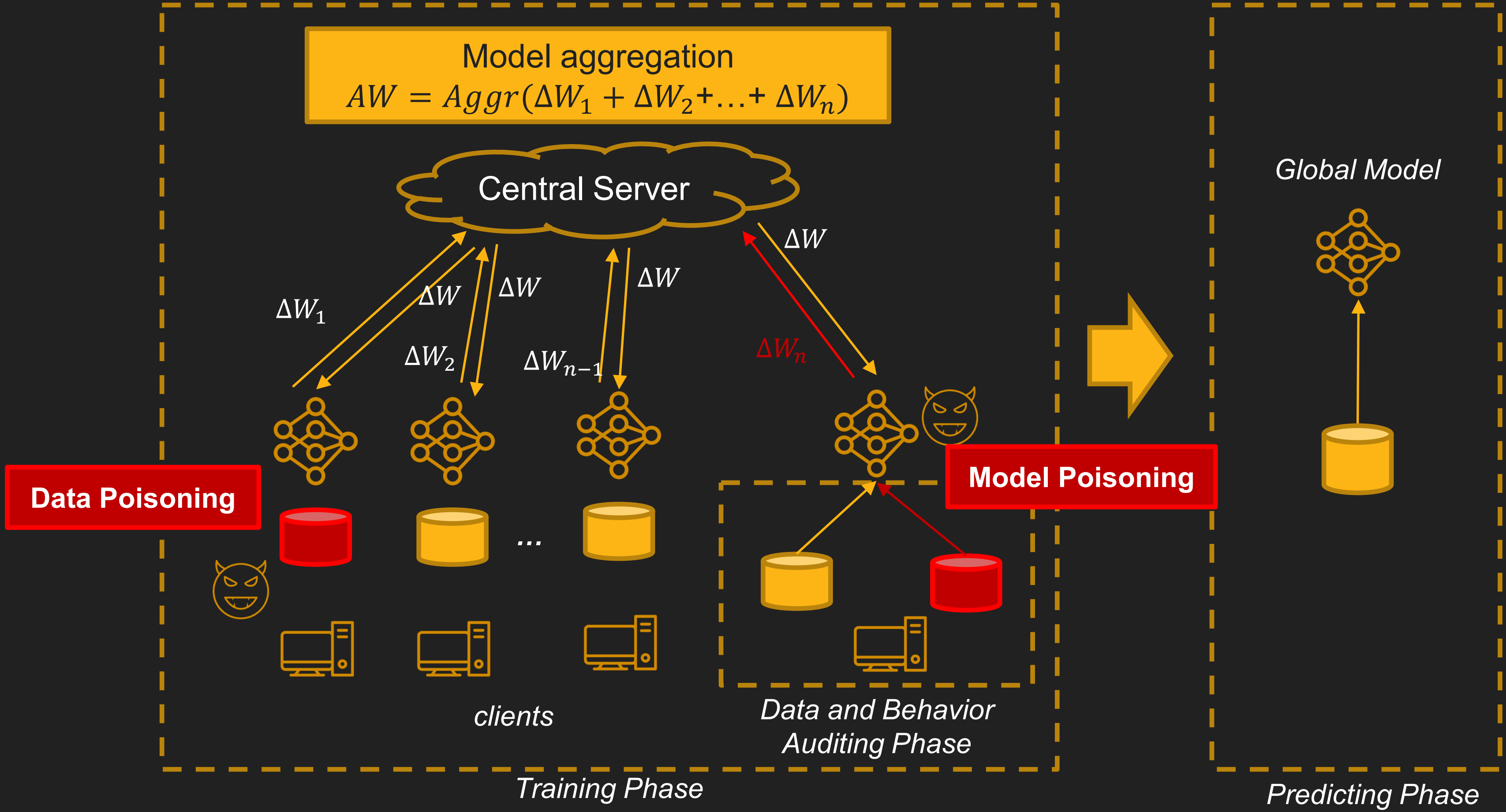

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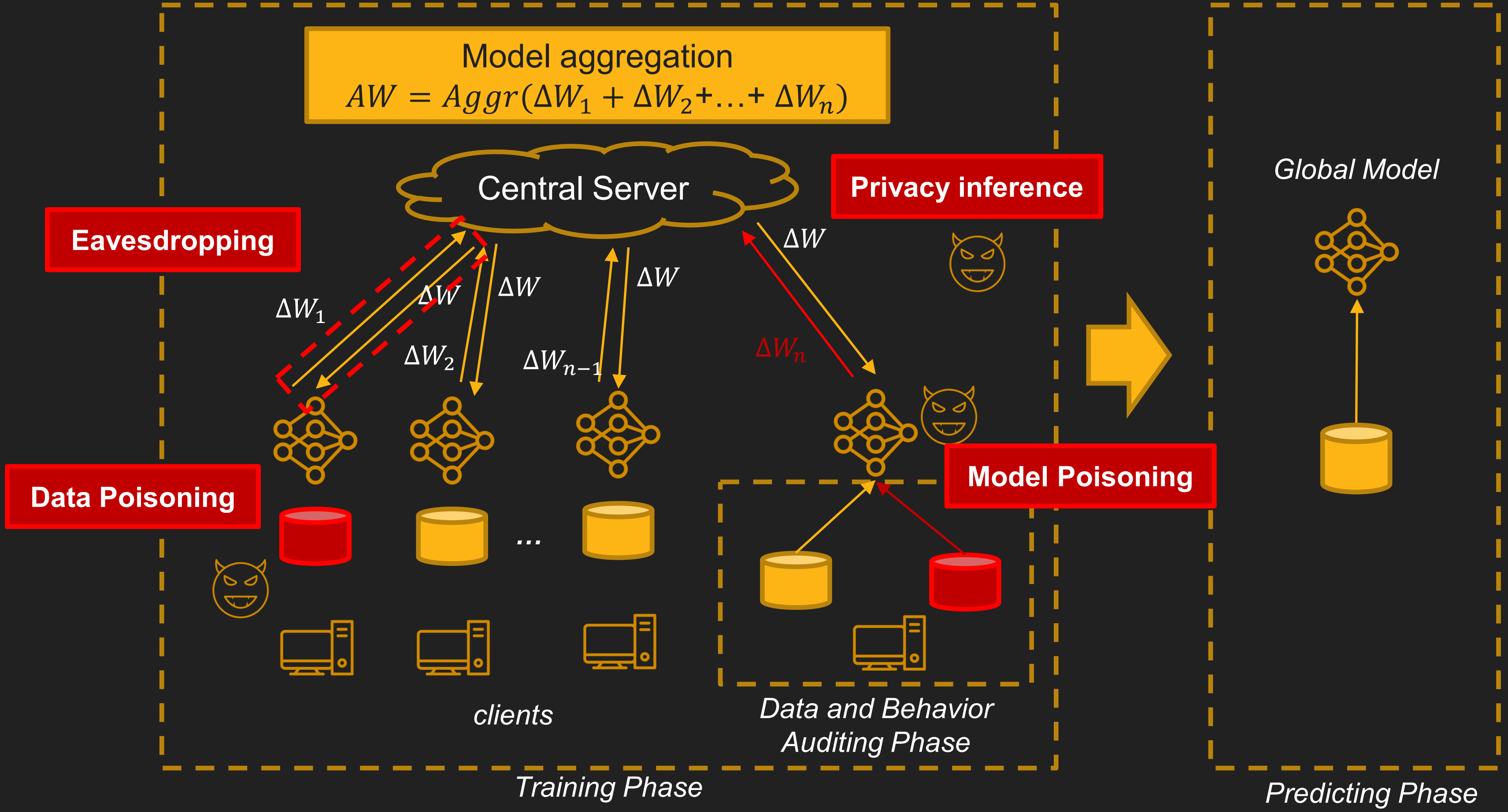

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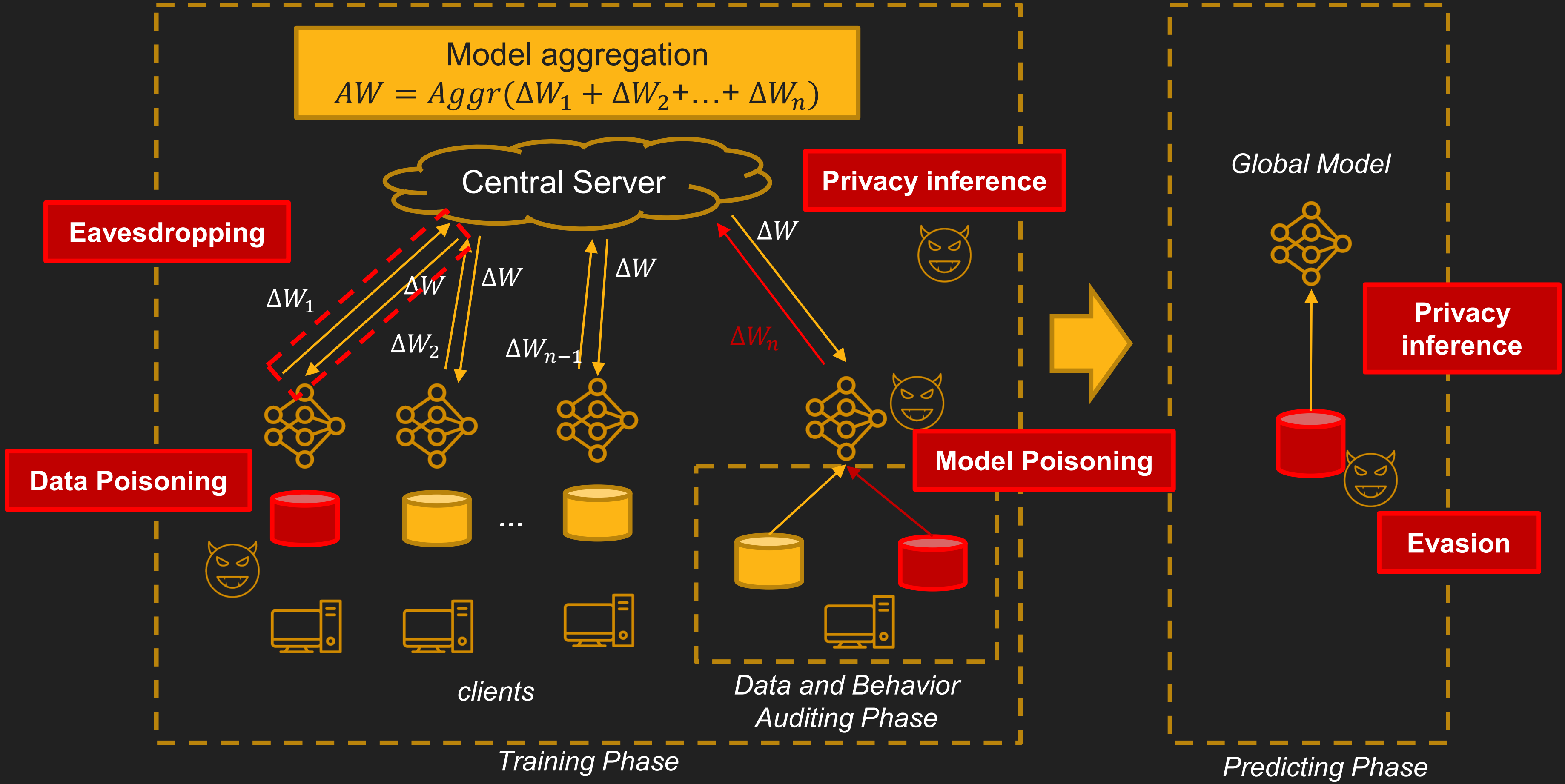

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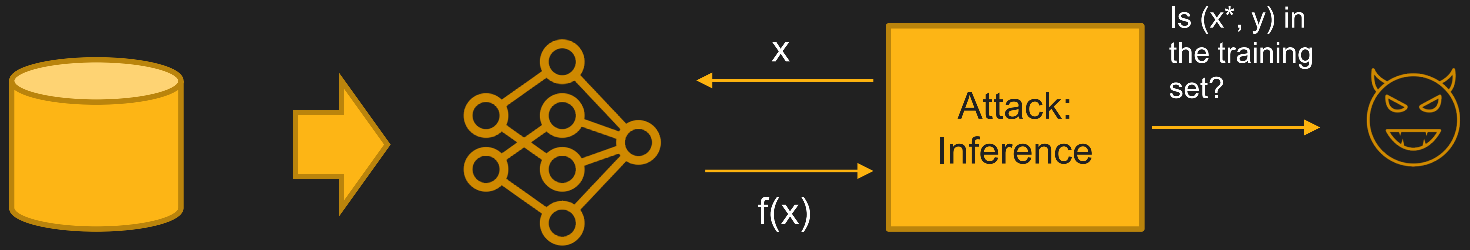
Privacy Attacks in ML

- **Privacy attacks / inference attacks** / **confidentiality attacks**
- Attacks against:
  - Training data
    - E.g., reveal the identity of patients whose data was used for training a model
  - ML model
    - E.g., reveal the architecture and parameters of a model that is used by an insurance company for predicting insurance rates
    - E.g., reveal the model used by a financial institution for credit card approval
- Main categories:
  - **Membership inference attack**
  - **Feature inference attack**
  - **Model extraction attack**

Liu, Bo, et al. "When machine learning meets privacy: A survey and outlook." ACM Computing Surveys (CSUR) 54.2 (2021): 1-36.

Membership Inference Attack

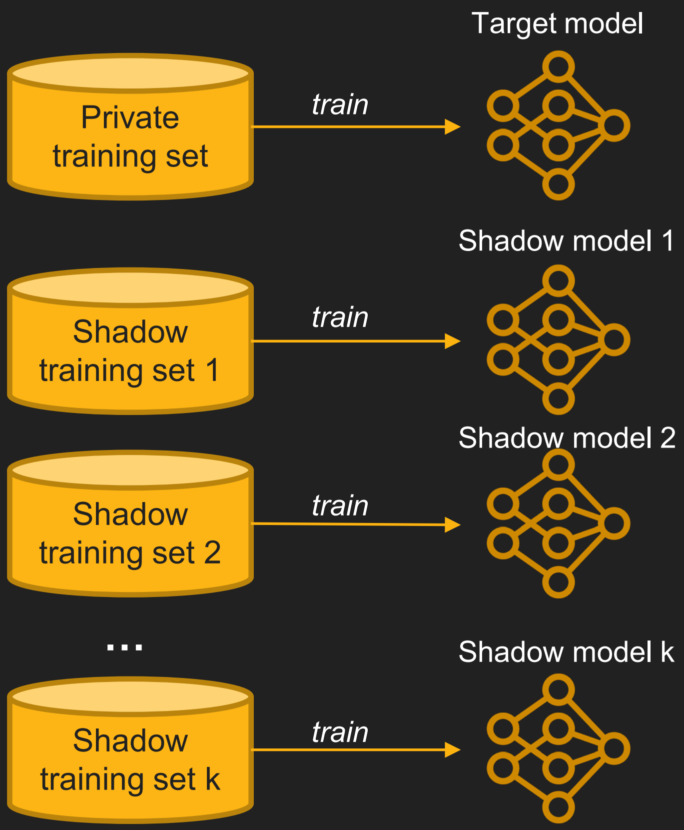
- **Adversarial goal:** determine whether or not an individual data instance is part of the training dataset for a model
- The attack typically assumes black-box query access to the model
- Attacks on both supervised classification models and generative models (GANs, VAEs) have been demonstrated



Liu, Bo, et al. *"When machine learning meets privacy: A survey and outlook." ACM Computing Surveys (CSUR) 54.2 (2021): 1-36.*

MIA: Shadow Training Attack

- **Threat model:**
  - Adversary has black-box query access to the target model
  - Goal: infer whether input samples were part of its private training set
- Shadow training approach:
  - Create several shadow models to substitute the target model
  - Each shadow model is trained on a dataset that has a similar distribution as the private training dataset of the target model



Shokri, Reza, et al. "Membership inference attacks against machine learning models." 2017 IEEE symposium on security and privacy (SP). IEEE, 2017.

Feature Inference Attack

- **Adversarial goal:** recreate certain features of data instances or statistical properties of the training dataset for the model
- A.k.a. **attribute inference**, **reconstruction**, or **data extraction attack**
- Attacks developed to:
  - Recover partial information about the training data (such as sensitive features of the dataset, or typical representatives for specific classes in the dataset) or full data samples
  - Recreating dataset properties that were not encoded in the (**property inference attack**)
    - E.g., extract information about the ratio of men and women in a patient dataset, despite that gender information was not provided for the training records

Liu, Bo, et al. "When machine learning meets privacy: A survey and outlook." ACM Computing Surveys (CSUR) 54.2 (2021): 1-36.

FIA: Model Inversion Attack

- Creates prototype examples for the classes in the dataset
- Authors demonstrated an attack against a DNN model for face recognition
- Given a person's name and white-box access to the model, the attack reverse-engineered the model and produced an averaged image of that person

Recovered image using attack

Image of the person used for training

Fredrikson, Matt, Somesh Jha, and Thomas Ristenpart. "Model inversion attacks that exploit confidence information and basic countermeasures." 22nd ACM CCS. 2015.

Attacks Against Distributed Learning

- Attacks can be **passive** (the adversary collects the updates) and **active** (the adversary shares information to impact the training procedure)

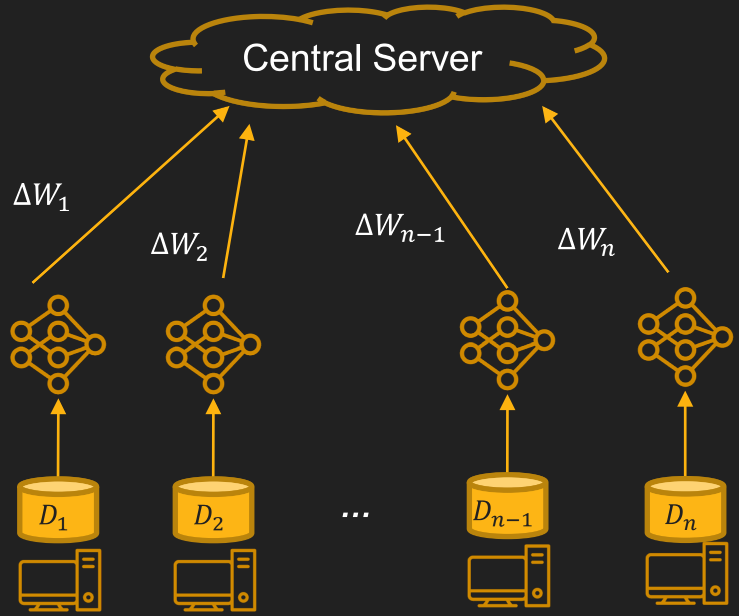
- Some (of many) examples:
    - **Membership inference attack** [1] : One of the clients is a malicious attacker that reveals if other participants used a data record for training
    - **Property inference attacks** [2]: Reveal whether training data with certain properties were used by the other participants
    - **Training data reconstruction attack** [3]: Use GAN model to reconstruct class representative samples from the local dataset used by the other participants

[1] Nasr et al. "Machine learning with membership privacy using adversarial regularization." ACM CCS. 2018.
[2] Melis et al. "Exploiting unintended feature leakage in collaborative learning." IEEE SP. 2019.
[3] Hitaj et al. "Deep models under the GAN: information leakage from collaborative deep learning." ACM CCS. 2017.

Mitigation Strategies?

Model aggregation

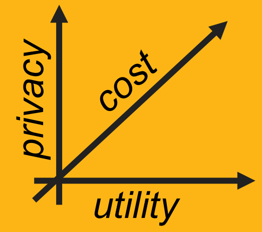
$AW = Aggr(\Delta W_1 + \Delta W_2 + \ldots + \Delta W_n)$

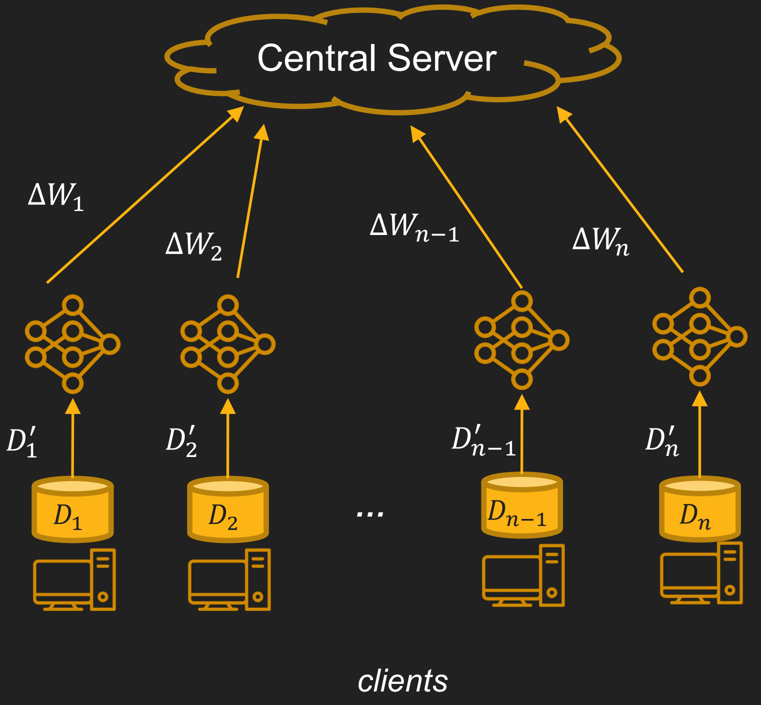


clients

Federated Learning + Anonymization

Pros and Cons?



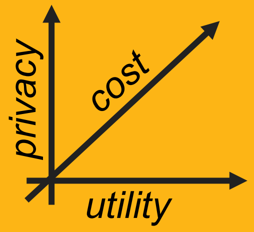


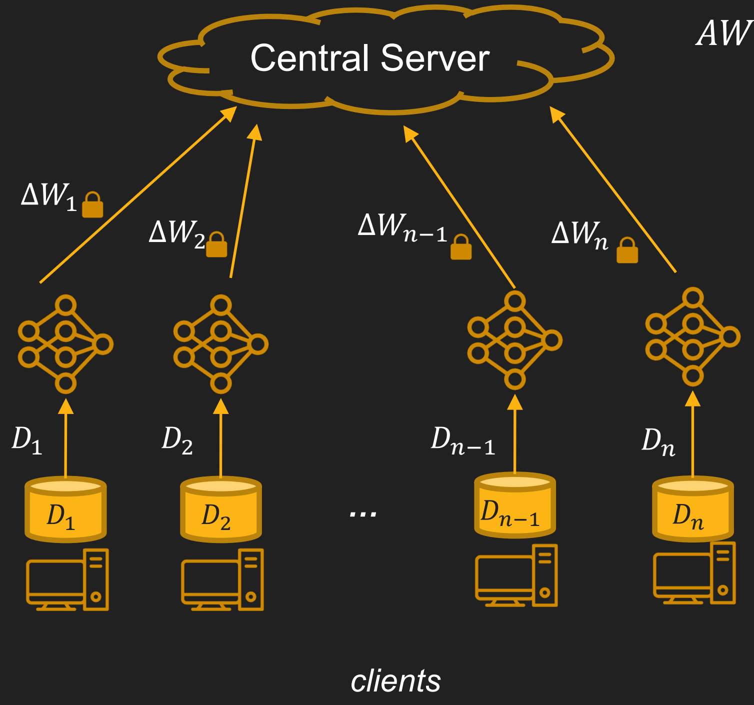
Anonymize training data (e.g., remove identifiers, generalize sensitive data)

Song, Mengkai, et al. "Analyzing user-level privacy attack against federated learning." IEEE Journal on Selected Areas in Communications 38.10 (2020): 2430-2444.
Choudhury, Olivia, et al. "A syntactic approach for privacy-preserving federated learning." ECAI 2020. IOS Press, 2020. 1762-1769.

Federated Learning + MPC

Pros and Cons?





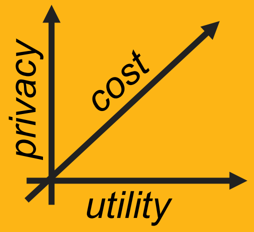
$$AW = Aggr(\Delta W_1 + \Delta W_2 + \ldots + \Delta W_n)$$

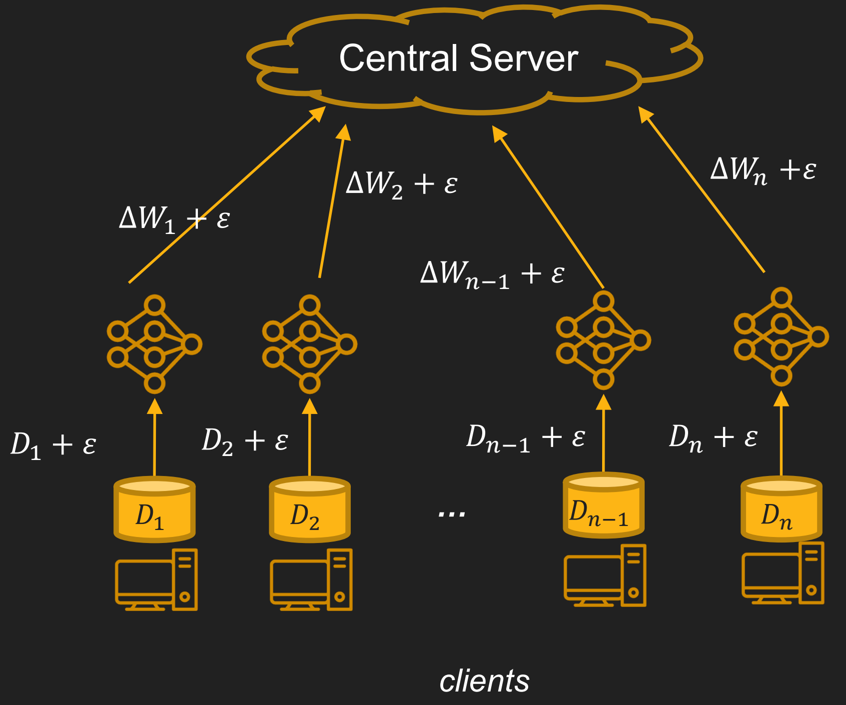
Secret share model updates

Bonawitz, Keith, et al. "Practical secure aggregation for privacy-preserving machine learning." ACM CCS. 2017.
Gao, Dashan, et al. "Privacy-preserving heterogeneous federated transfer learning." IEEE Big Data. 2019.
Mohassel, Payman, and Yupeng Zhang. "Secureml: A system for scalable privacy-preserving machine learning." IEEE SP. 2017.

Federated Learning + Differential Privacy

Pros and Cons?





Add DP noise to model updates

Add DP noise to training data

Geyer, Robin C., Tassilo Klein, and Moin Nabi. "Differentially private federated learning: A client level perspective." arXiv preprint arXiv:1712.07557 (2017).
Hao, Meng, et al. "Towards efficient and privacy-preserving federated deep learning." ICC 2019-2019 IEEE ICC. 2019.
Abadi, Martin, et al. "Deep learning with differential privacy." ACM CCS. 2016.

Conclusions

- **Cloud computing** has benefits but many **drawbacks**
  - Latency, bandwidth, connectivity, **privacy**!
- **Edge computing** can **mitigate** some of the **drawbacks**
  - E.g., minimize the amount of individuals data transferred to cloud by performing local computations
- **Federated learning** is a popular example of **edge computing for ML**
- While this is **helps in protecting privacy**, **attacks are still possible!**
- Need to **integrate PETs in Edge Computing / Federated Learning**

Group Activity

- Think about your group project (or any other application)
- If you use a client/server architecture…
  - What can you learn at the client?
  - What cannot you learn at the client?
  - What data would you need to transfer to server?