Scalable and Robust Hyperdimensional Computing with Brain-Like Neural Adaptation

ACM Student Research Competition @ ICCAD 2023

Junyao Wang

Department of Computer Science,

University of California, Irvine

https://sites.uci.edu/junyaowang/

Why Hyperdimensional Computing (HDC) ?

- Popular **machine learning (ML)** algorithms
  - Require intensive computations over multiple time periods
  - Often exceed the computational capabilities of today's edge devices
- **Hyperdimensional computing (HDC)** has been introduced
  - Project low-dimensional inputs to hypervectors in high-dimensional space ($\mathcal{D} \approx$ 10k)
  - Resource-efficient, fast convergence, ultra-robust

Cerebellum

Cerebellum works with sparse high-dimensional representations.

Robustness

Brains can work with multiple noisy inputs.

Efficient

Brains work at around as low as 20W of energy.

High-Dimensional

Basic elements are hypervectors.

Holographic Encoding

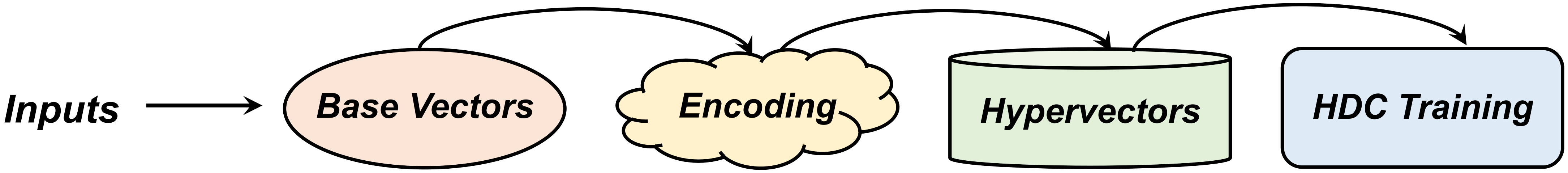
Info of every feature is on all the dimensions of the hypervectors.

Well-trackable Algebra

Well-defined and highly-parallel operations.

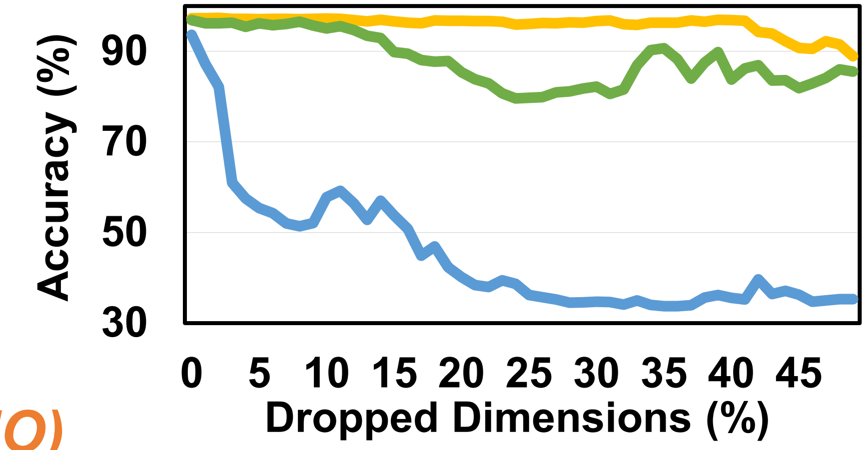
HDC Preliminaries

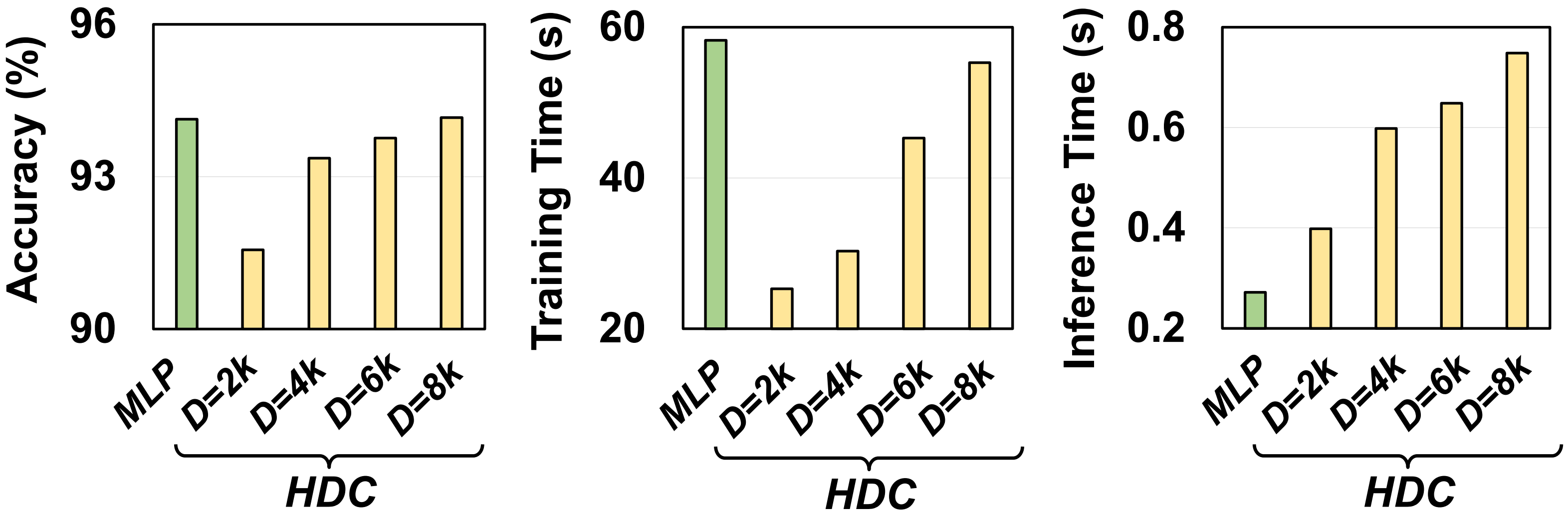
- **Encoding:**
  - Inspired by the high-dimensional information representation in human brains
- **Learning:**
  - Samples are bundled based on their similarities to the class hypervectors (distance to each other in high-dimensional space)

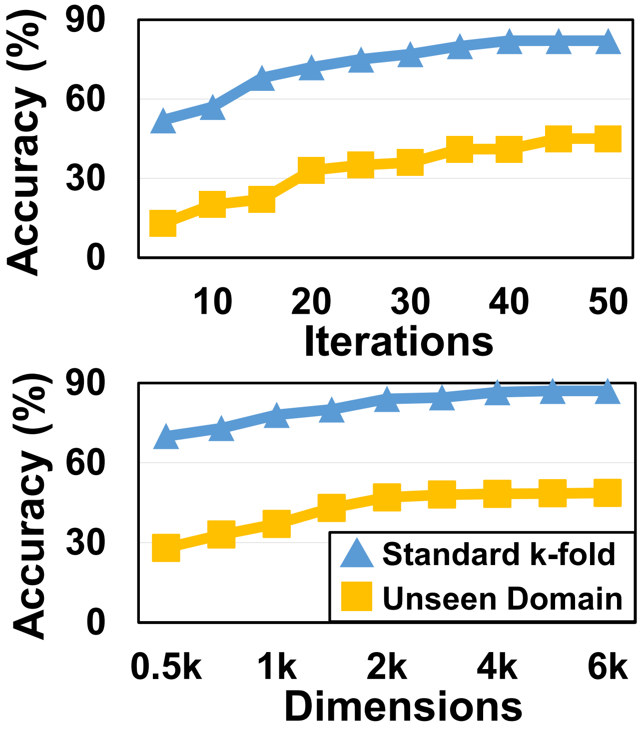


HDC Issues: Undesired Dimensions

- Are all the dimensions "useful"? ***(Work I, CyberHD)***
  - What if we lower the dimensionalities?
- Are all the dimensions "good"? ***(Work II, DistHD)***
  - Are there any dimensions misleading the result?
- Are all the dimensions "unbiased"? ***(Work III, DOMINO)***
  - **Distribution Shift:** when training (source domains) and testing (target domains) data come from different data distributions
  - Are there dimensions specifically contribute to the domain-specific information?

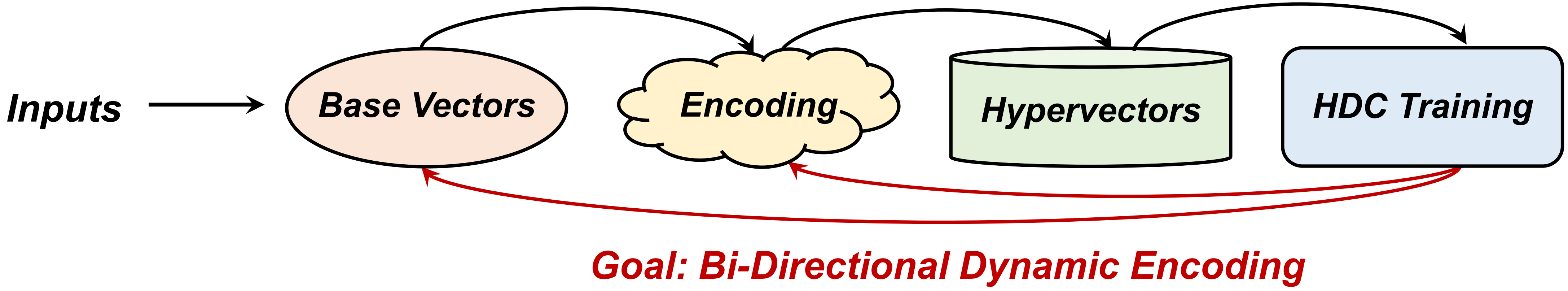






How to Solve the Issues? Let's Learn from Human Brains!

- **Issues stem from:**
  - **Static Encoder:** never updated during the entire training phase
- Neurons in human brains:
  - Dynamically regenerate all the time
  - Provide useful functionalities when accessing new information

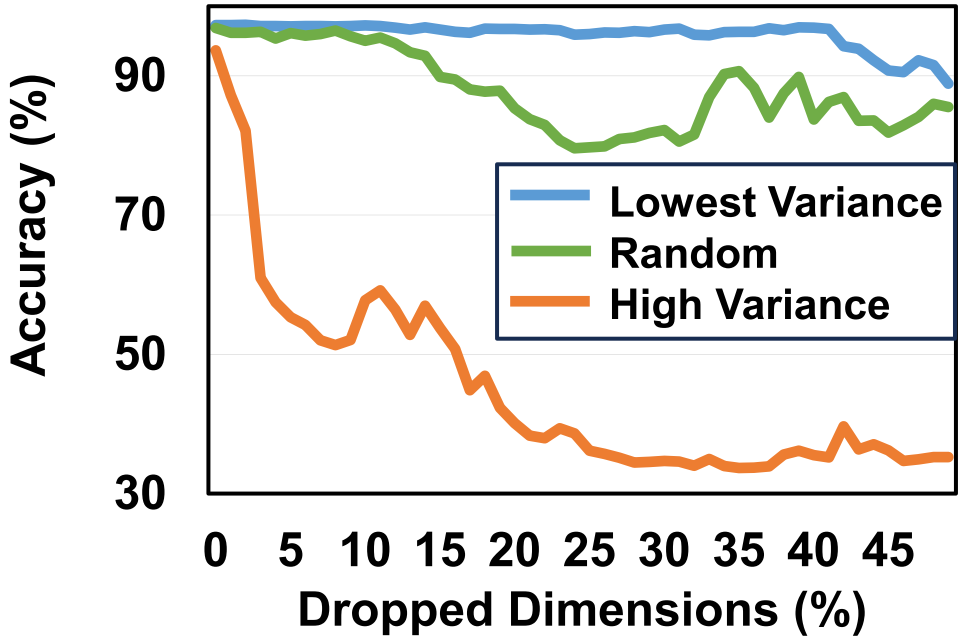


Our Hyperdimensional Training with Dynamic Encoding

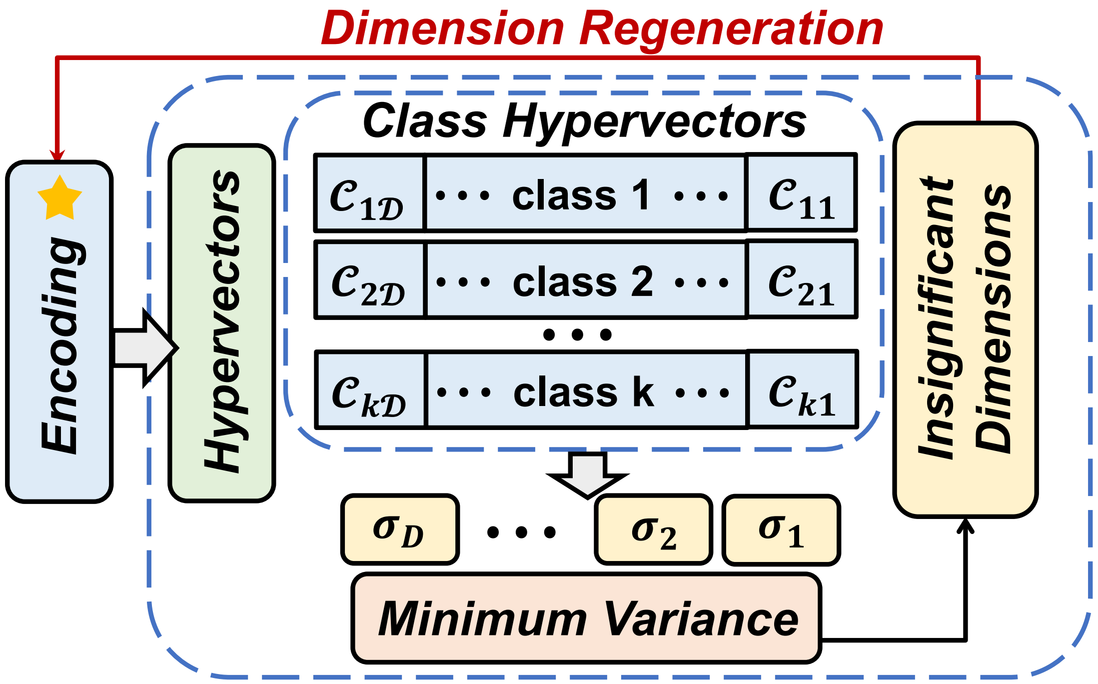
CyberHD: Regenerating Insignificant Dimensions

DAC'23 + IEEE IoT Journal'23

- An effective classifier has a strong capability to **distinguish patterns**, i.e., a testing sample has very differentiated similarity scores to each class
- Dimensions with similar values store common information across classes — playing minimal roles in classification tasks
- Comparable accuracy to SOTA HDC with **8.0× lower dimensionalities** with **1.85× speed up in training** and **15.29× speedup in inference**



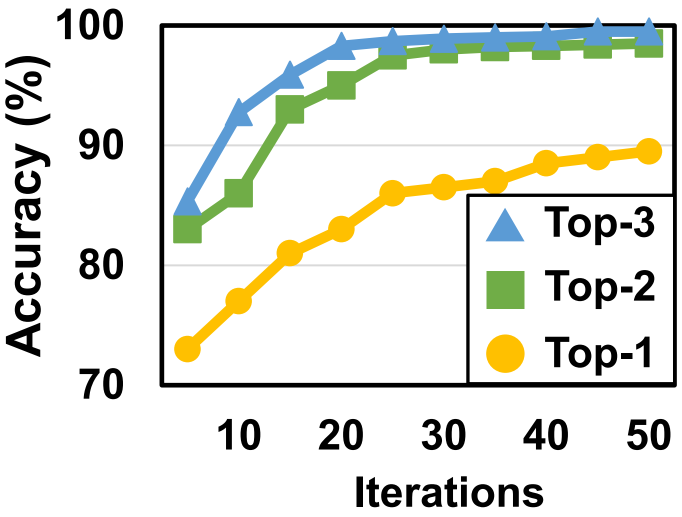
Impact of Dimension Reduction

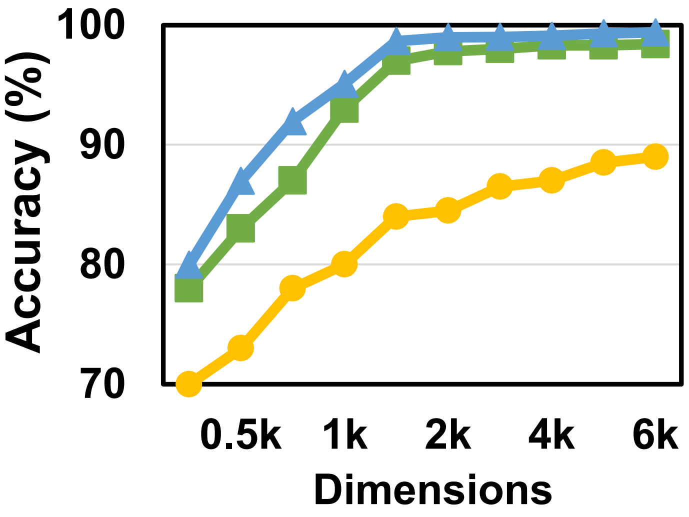


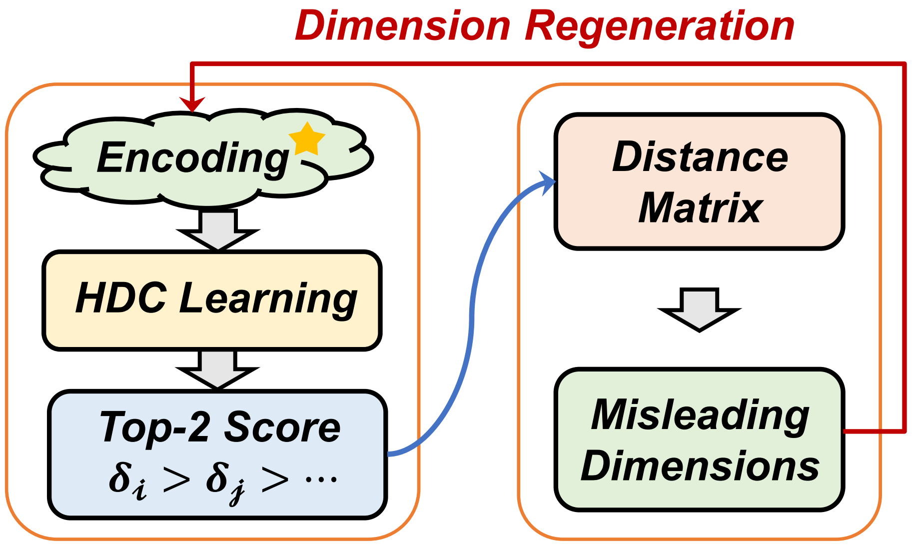
Regenerating Insignificant Dimensions

DistHD: Regenerating Misleading Dimensions

- HDC shows considerably higher accuracy and faster convergence for top-2 classification than top-1 classification
- We identify and regenerate misleading dimensions — those dimensions closest to the incorrect class hypervectors and farthest from the correct ones
- **8.0 × lower dimensionalities** and **2.12% higher accuracy** compared to the SOTA HDC, along with **5.97× speedup in training** and **8.09× speed up in inference**

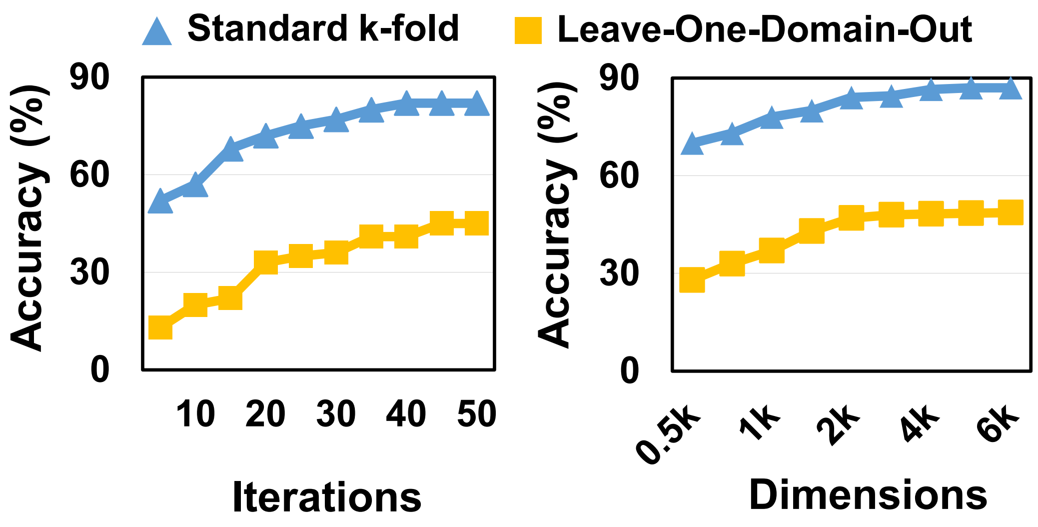


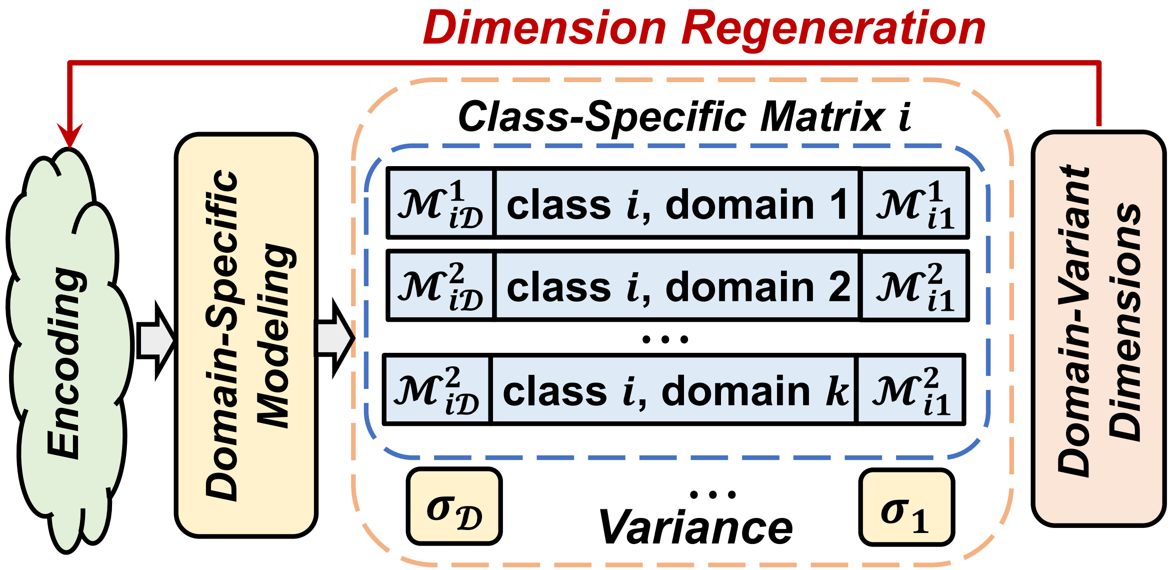




DOMINO: Regenerating Biased Dimensions

- **Distribution Shift:** A fundamental problem in data-driven ML
  - The excellent performance relies on a critical assumption — the training and inference data come from the same distribution, **but this can be easily violated in reality.**
  - **Domain Generalization:** extract domain-invariant features across known domains
- Regenerate dimensions that highly correlated to domain-specific information
- **2.04% higher accuracy** than SOTA DNN-based domain generalization techniques, **16.34× faster training** and **2.89× faster inference**





Result & Contributions

- My publications during the first year of my PhD:
  - ***Junyao Wang***, Arnav Vaibhav Malawade, Junhong Zhou, Shih-Yuan Yu, Mohammad Abdullah Al Faruque, *RS2G: Data-Driven Scene-Graph Extraction and Embedding for Robust Autonomous Perception and Scenario Understanding*, IEEE/CVF Winter Conference on Applications of Computer Vision (**WACV**), 2024
  - ***Junyao Wang***, Luke Chen, Mohammad Al Faruque, *DOMINO: Domain-Invariant Hyperdimensional Classification for Multi-Sensor Time Series Data*, IEEE/ACM International Conference on Computer-Aided Design (**ICCAD**), 2023.
  - ***Junyao Wang***, Haocheng Xu, Yonatan Achamyeleh, Sitao Huang, Mohammad Abdullah Al Faruque, *HyperDetect: A Real-Time Hyperdimensional Solution For Intrusion Detection in IoT Networks*, **IEEE Internet of Things Journal**, 2023
  - ***Junyao Wang***, Sitao Huang, Mohsen Imani, *DistHD: A Learner-Aware Dynamic Encoding Method for Hyperdimensional Classification*, the 60th Annual Design Automation Conference (**DAC**), 2023
  - ***Junyao Wang***, Haning Chen, Mariam Issa, Mohsen Imani, *Late Breaking Results: Scalable and Efficient Hyperdimensional Computing for Network Intrusion Detection*, the 60th Annual Design Automation Conference (**DAC**), 2023.
- I have worked on multiple real-world applications
  - Autonomous Vehicles
  - Multi-Sensor Human Activity Recognition
  - Cybersecurity

THANK YOU!

Scalable and Robust Hyperdimensional Computing with Brain-Like Neural Adaptation

ACM Student Research Competition @ ICCAD 2023

Junyao Wang
Department of Computer Science,
University of California, Irvine
https://sites.uci.edu/junyaowang/