Advancing AI in IoT Systems for Smart Health

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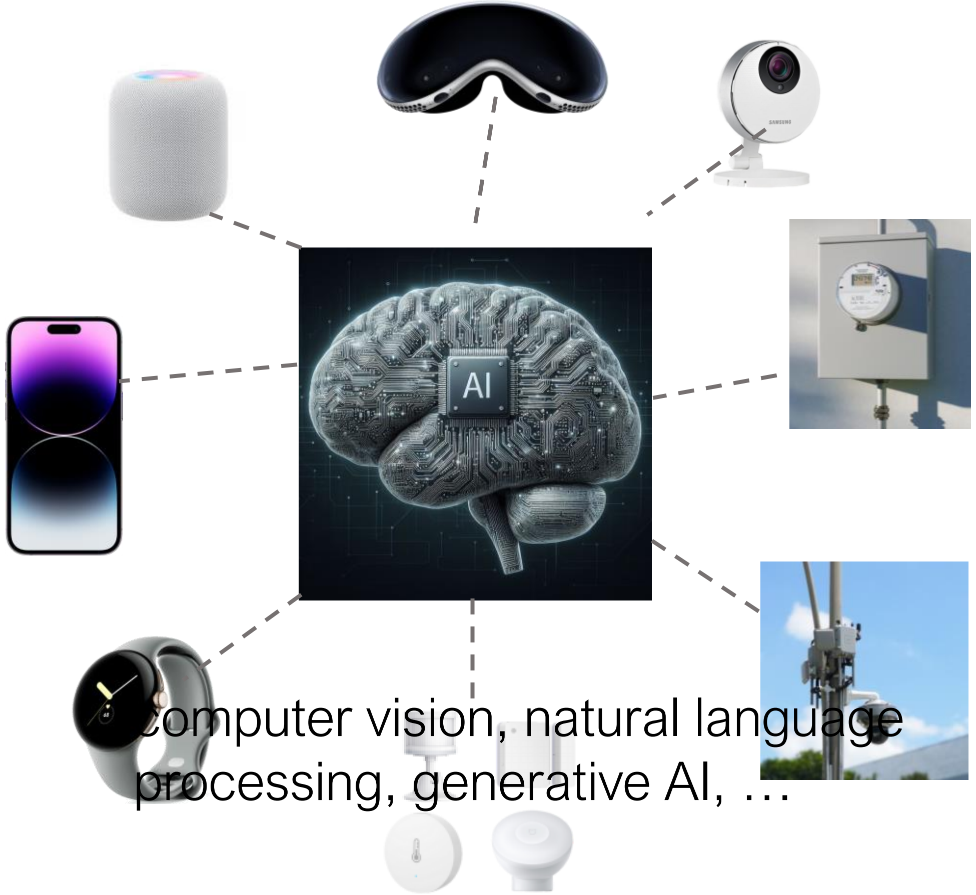
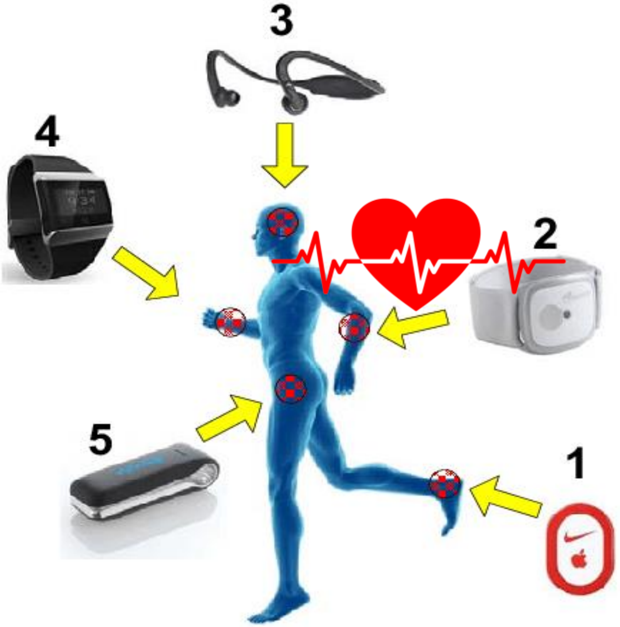
LOTS of IoT and Mobile Devices in Daily Life

- In-situ sensing and networked computing

On-Device AI for Smart Health



computer vision, natural language processing, generative AI, …



Smart Health

On-device AI for In-home and Community-based Health: *transfer reactive healthcare practice to* ***proactive, personalized, and seamless*** *healthcare and well-being.*

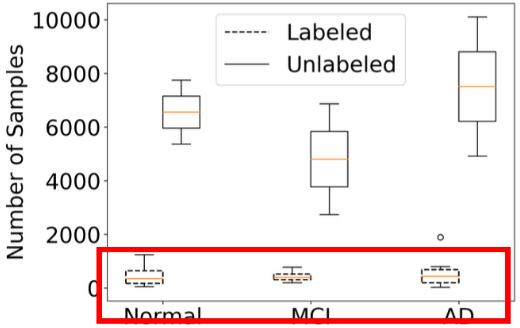
Outline

- **Embedded AI Systems**
- Smart Health

Understanding Real-World Challenges

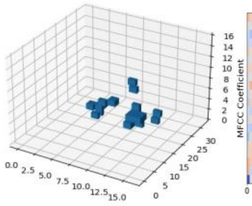
➢ Data Challenges

- Limited labeled data

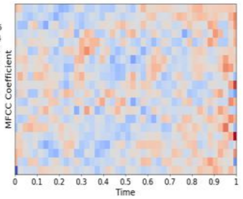


- Fusing heterogeneous modalities

Depth Image

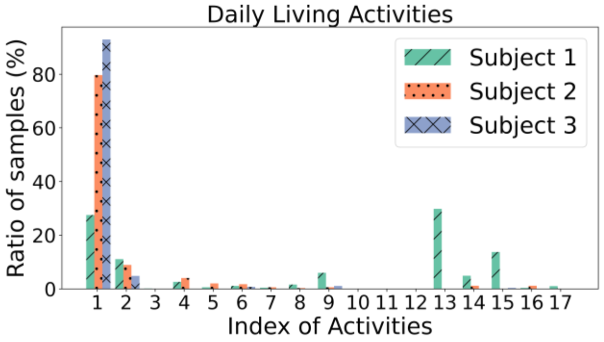


Radar Data



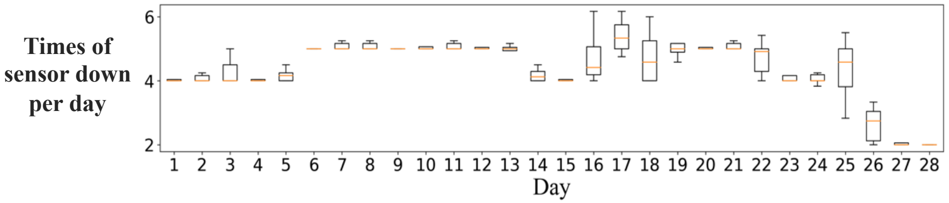
MFCC of Audio

- Non-i.i.d. distributions

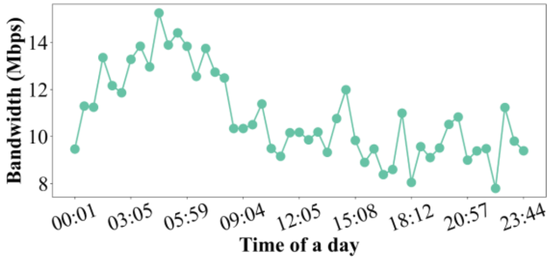


➢ System Challenges

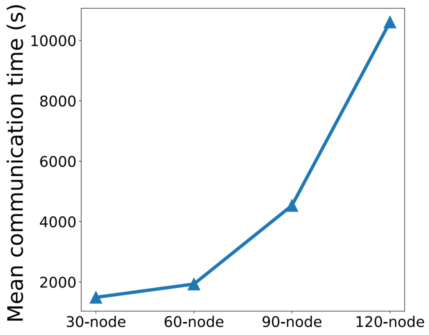
- Sensor dynamics



- Limited resources



- Scalability

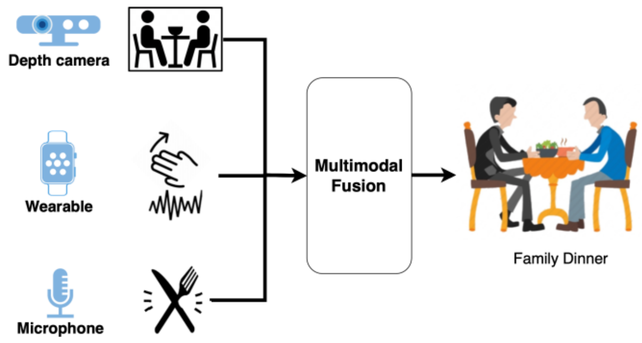


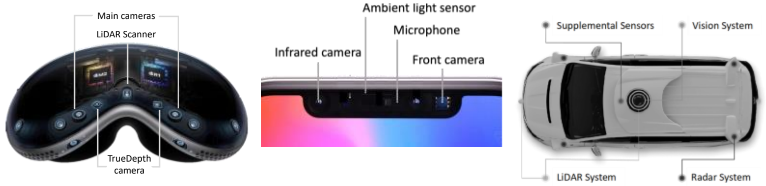
- How to harness **distributed and imperfect IoT data**?
- How to make the system more **scalable, resource-efficient and robust to real-world dynamics**?

Embedded AI Systems

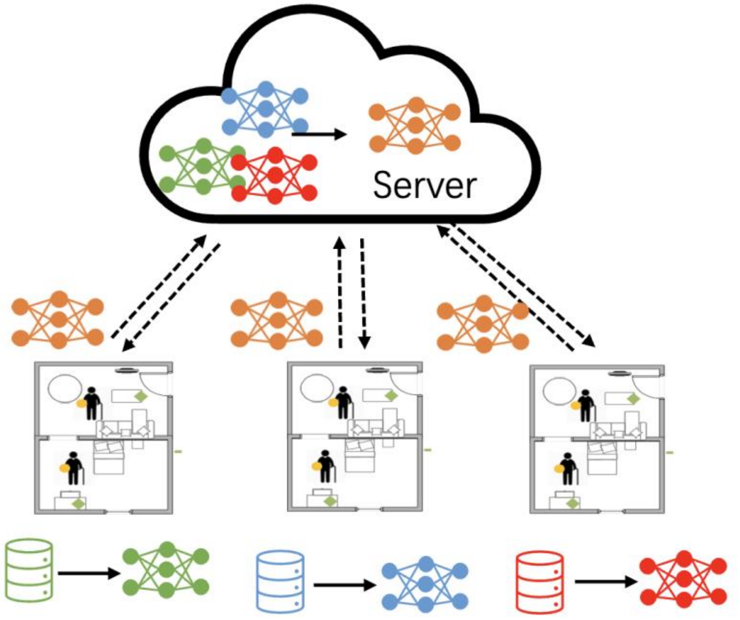
➢ Tackling real-world data and system challenges

➢ Multimodal Learning

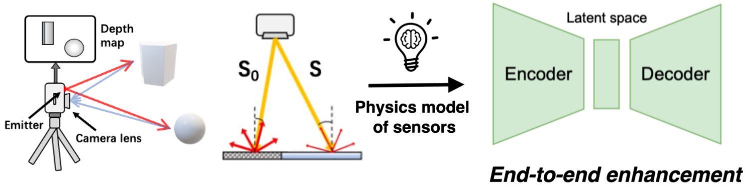


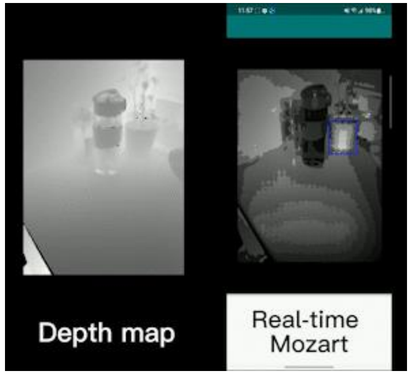


➢ Distributed (Federated) Learning



➢ Physics-Strengthened AI





Harness **distributed and imperfect data**

- MMBind (SenSys'25): foundational dataset
- Cosmo (MobiCom'22): small labeled data

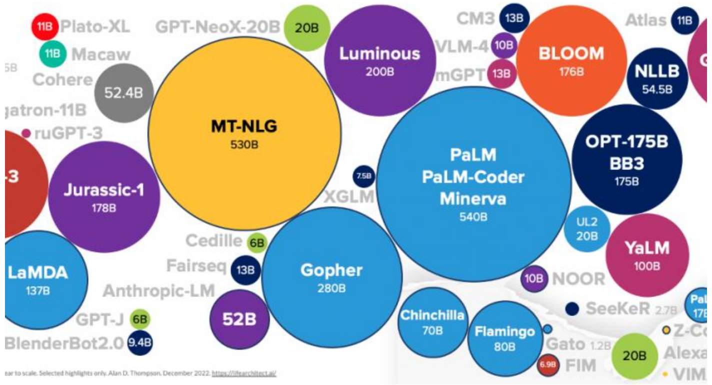
Address **data and resource heterogeneity**

- Harmony (MobiSys'23): modality heterogeneity
- ClusterFL (MobiSys'21): scalability

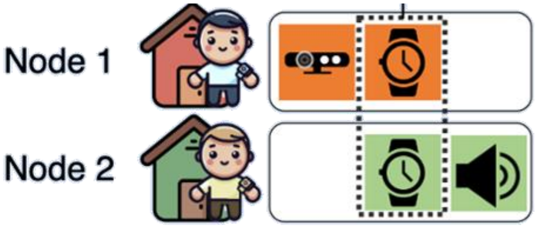
Enhance sensing quality

- Mozart (MobiSys'23 **Best Paper**)
- UltraDepth (SenSys'21)

Multimodal Learning with Distributed and Incomplete Data



Big Data in CV and NLP



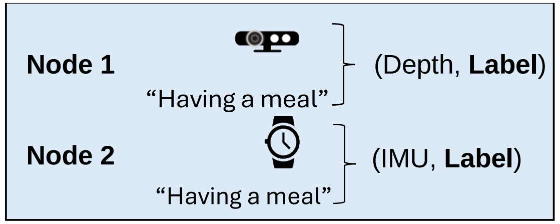
Setting	Dataset	Modality	Nodes (Subjects)	Class	Sample
Cross Node (Intra Dataset)	UTD	Acc, Gyro, Skeleton	4/2/2	27	864
	MMFi	Depth, Radar, Skeleton, WiFi	20/10/20	27	1,080
	PAMAP2	Acc, Gyro, Mag	4/2/2	30	9,611
	SUN-RGBD	Image, Depth, SemSeg	N/A	5	4,620
Cross Dataset (Activity)	MotionSense	Acc, Gyro	24	6	12,636
	Shoaib-right	Acc, Mag	10	7	4,500
	Shoaib-left	Acc, Mag	10	7	4,500
	Shoaib-wrist	Acc, Mag	10	7	4,500
	RealWorld	Acc, Gyro, Mag	15	8	21,663
Cross Dataset (Gesture)	GR4DHCI	Skeleton, IR	16	7	7,339
	DHG	Skeleton, Depth	20	14	2,800
	Briareo	Skeleton, Depth, IR	40	12	1,440

Small and Distributed Data in IoT

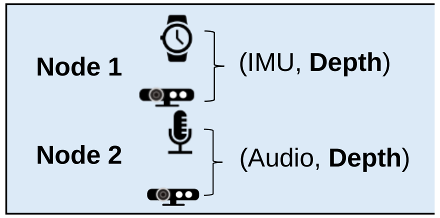
Multimodal Learning with Distributed and Incomplete Data

➢ Key Question:

- Can we learn joint multimodal embeddings with **distributed and incomplete data in IoT**?



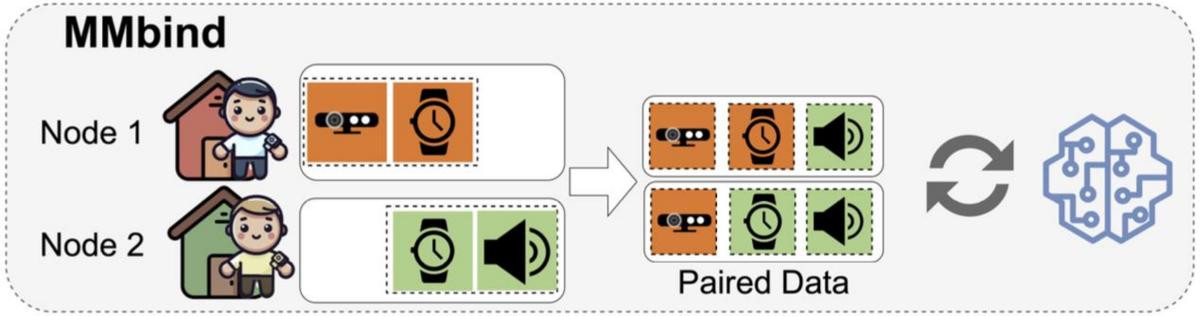
$D1=(x_1, \mathbf{y})$,
$D2=(x_2, \mathbf{y})$



$D1=(x_1, \mathbf{x_2})$,
$D2=(\mathbf{x_2}, x_3)$

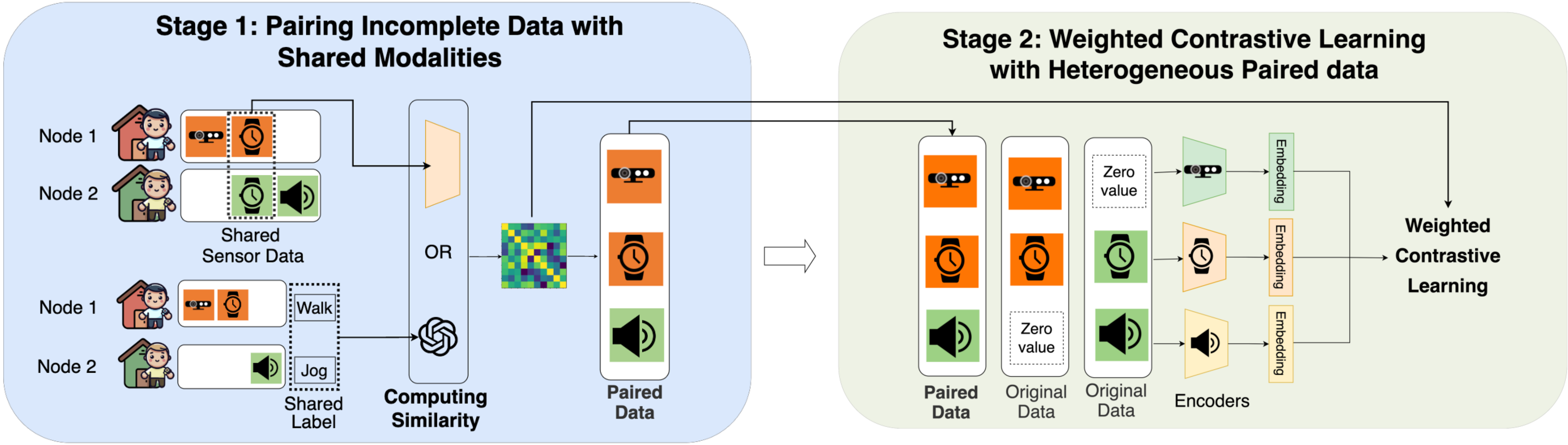
➢ Key Idea:

- Bind data from disparate sources and incomplete modalities with **the shared modality**
  - Shared modality: **sensor data or labels**



MMBind: System Overview

➢ **Construct Pseudo-Paired Data** ➢ **Learning with Heterogeneous Paired Data**



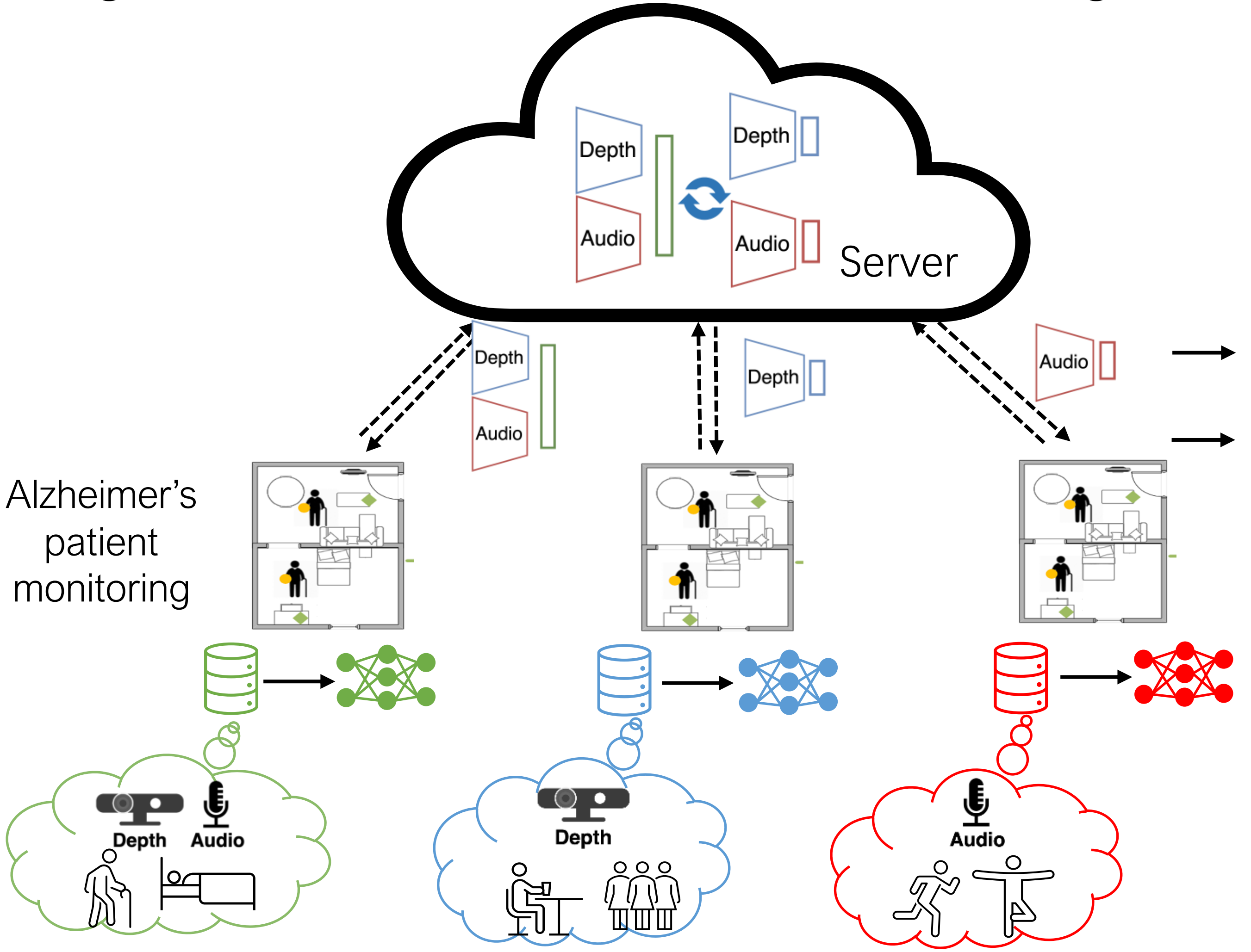
Imperfect paring

- Data of different modalities observing similar events can be effectively used for multimodal training.
  - Generate **a foundational multimodal dataset** for IoT applications

X. Ouyang, et al. MMBind: Unleashing the Potential of Distributed and Heterogeneous Data for Multimodal Learning in IoT. (SenSys '25)

Distributed Model Training after Deployment

➢ Challenges of Multi-Modal Federated Learning



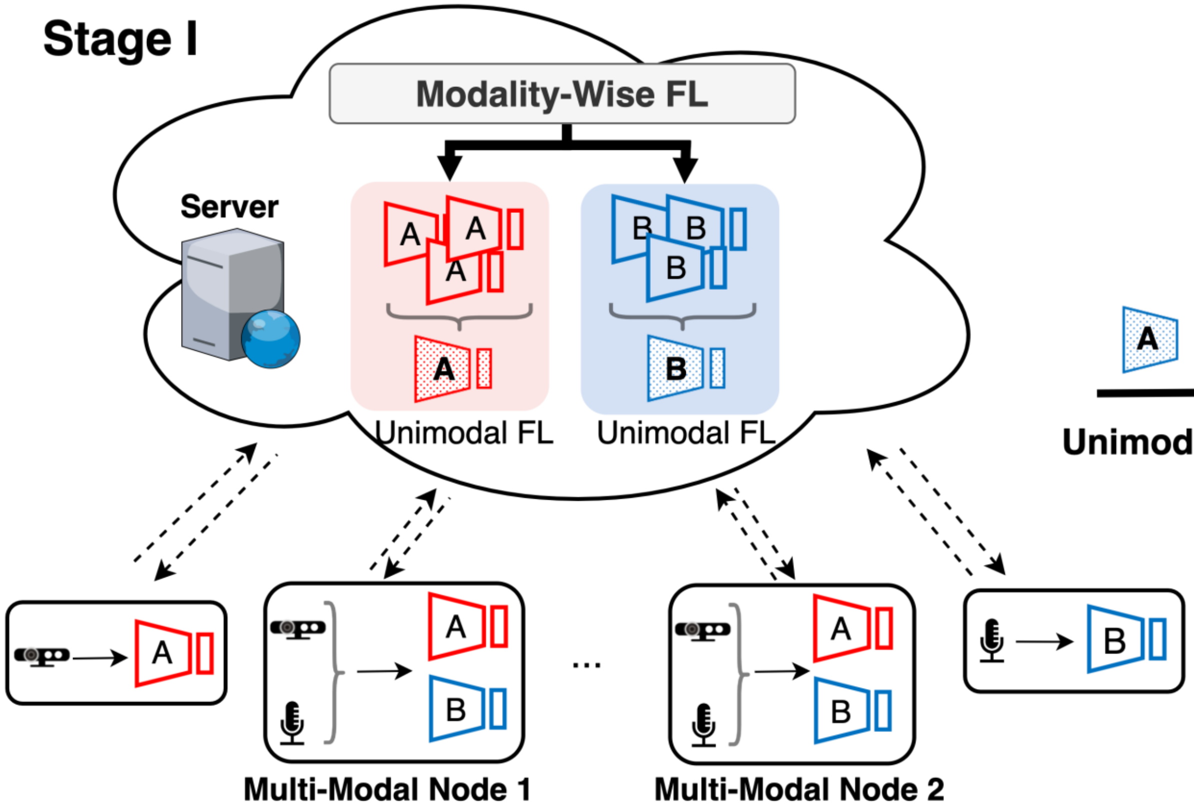
➢ Large model divergence

➢ Significant training latency

- Modality heterogeneity
- Distribution heterogeneity

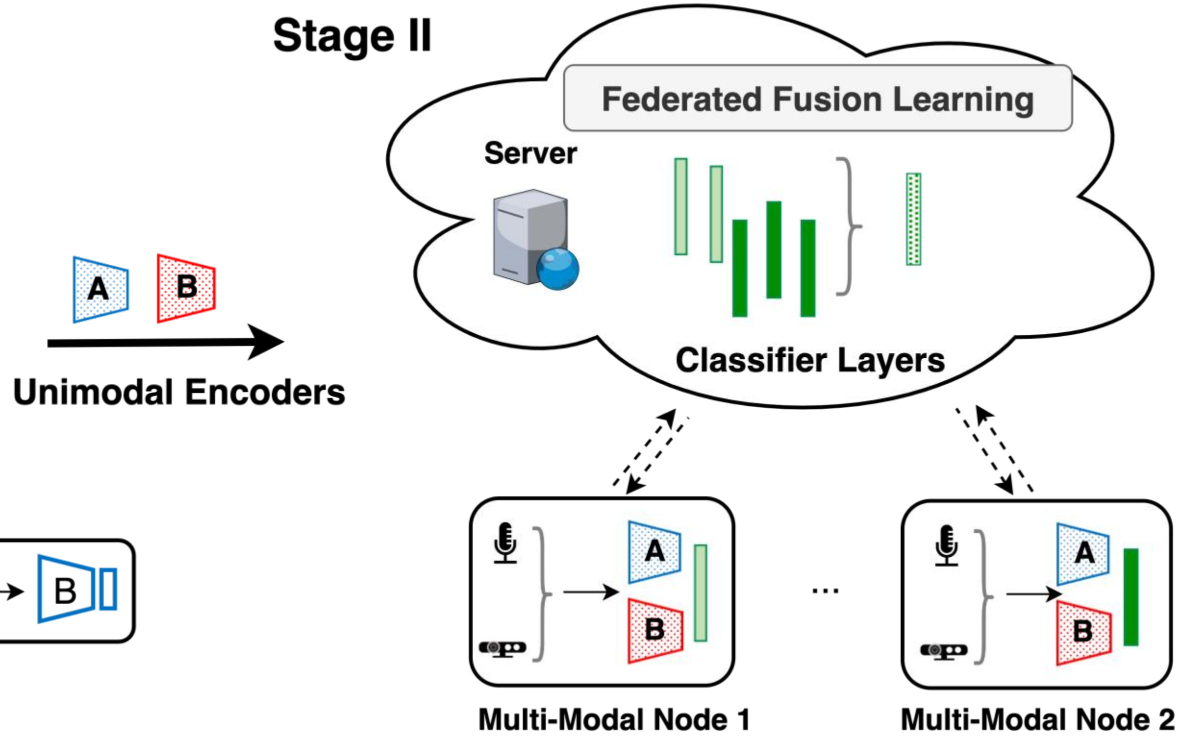
A Two-Stage Framework for Multi-Modal FL

➢ Modality-Wise Federated Learning



- Collaboratively train **unimodal encoders**

➢ Federated Fusion Learning

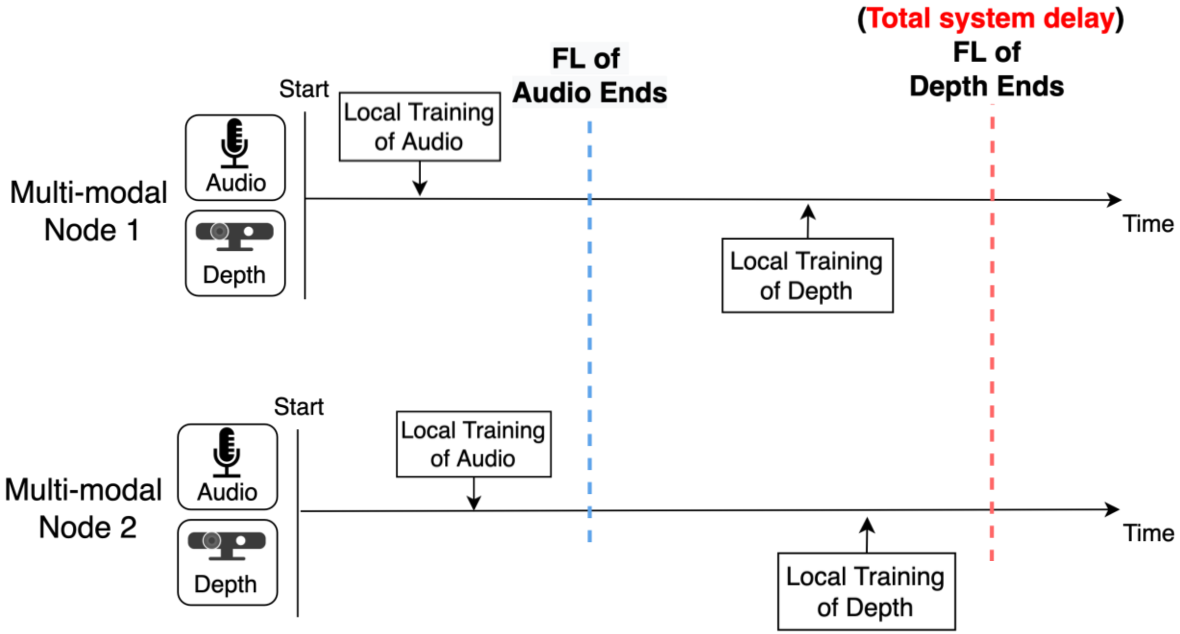


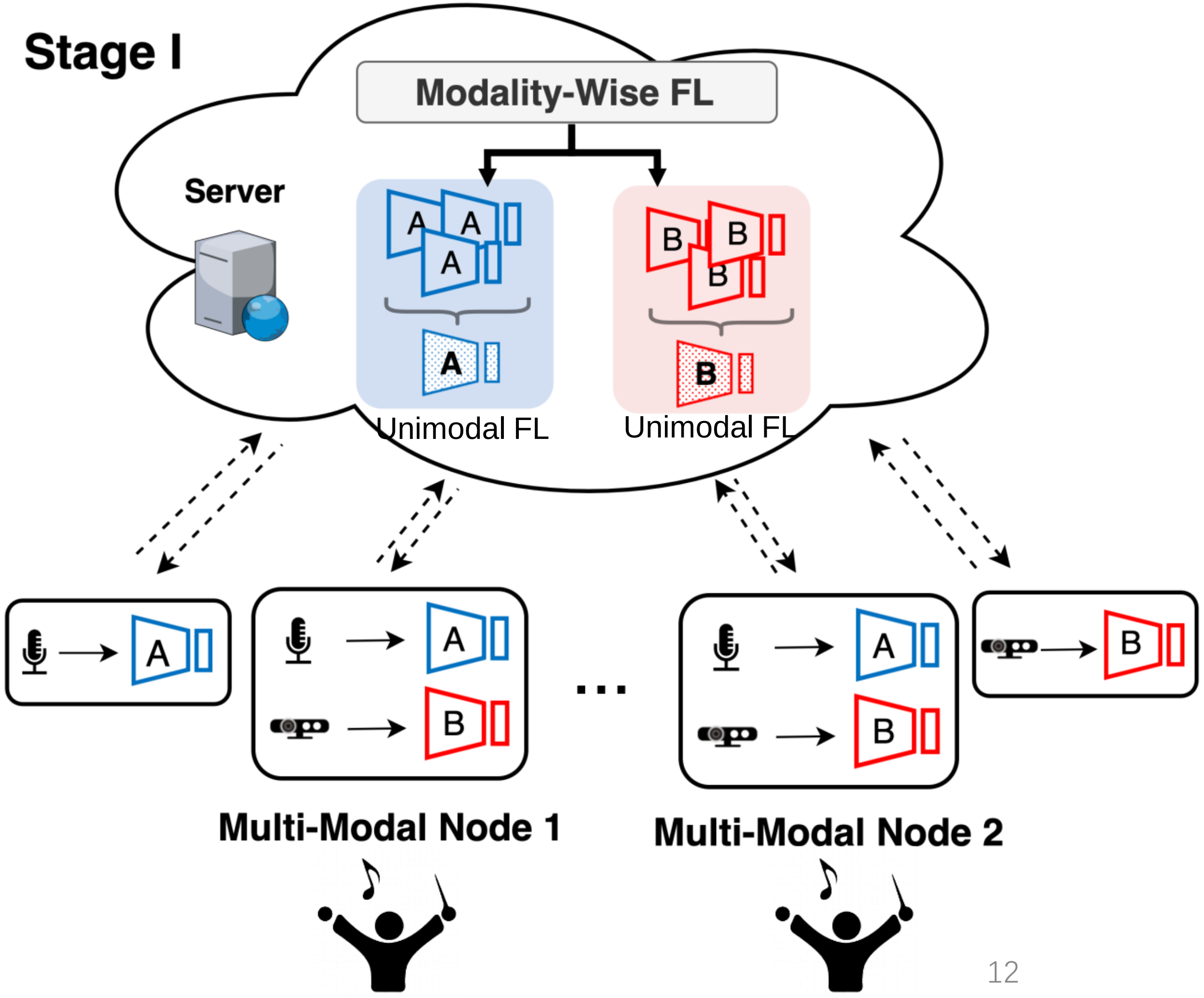
- Collaboratively train the **multi-modal classifier**

X. Ouyang, et al. Harmony: Heterogeneous Multi-Modal Federated Learning through Disentangled Model Training. (MobiSys '23)

Reducing Training Latency

- ➢ Imbalanced Training Delays





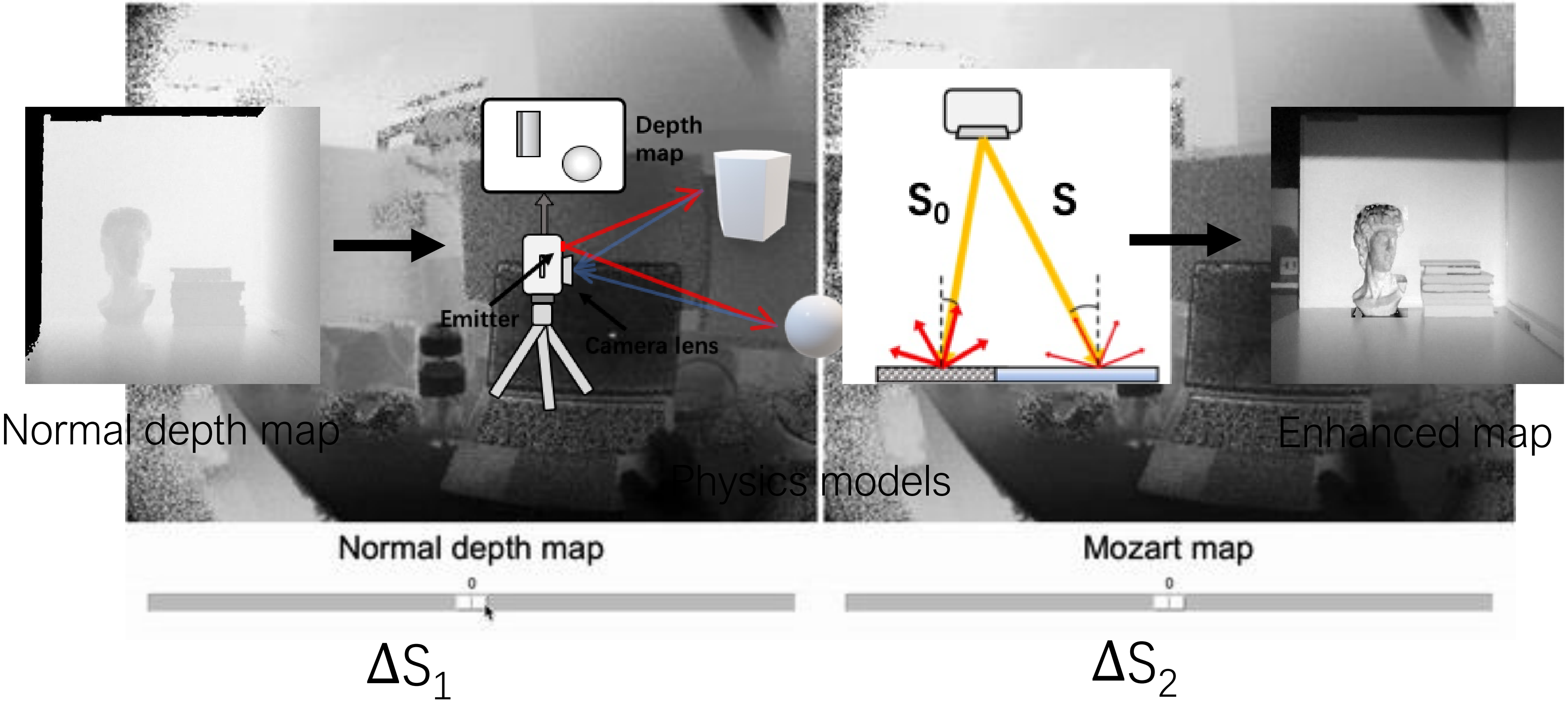
- ➢ Balance-Aware Resource Allocation

Less resources

More resources

Physics-Strengthened AI for Robust Sensing

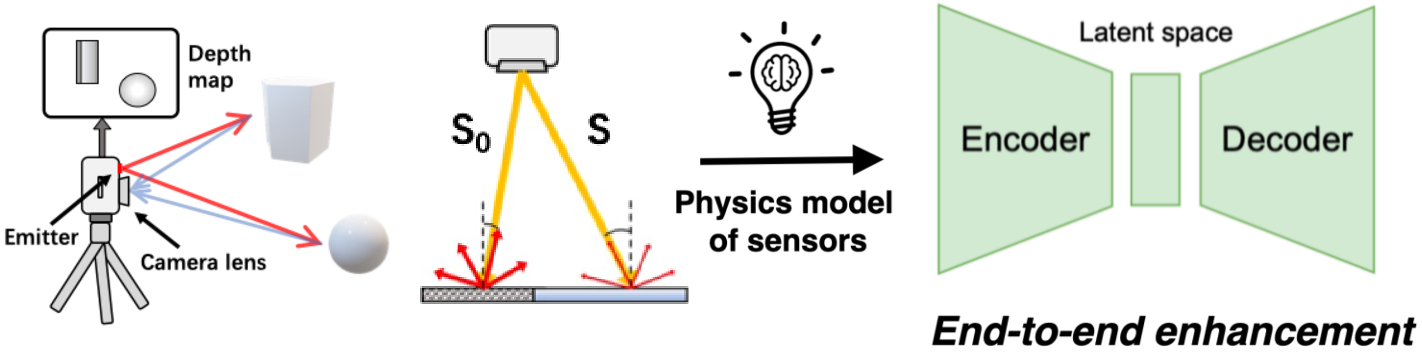
- Enhancing ToF Depth Sensing with Lambertian Reflection Model



Z. Xie*, X. Ouyang* (co-primary), et al. Mozart: A Mobile ToF System for Sensing in the Dark through Phase Manipulation (**MobiSys '23 Best Paper**).

Physics-Strengthened AI for Robust Sensing

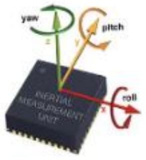
- Integrate First-principle Model with ML



- Enhancing Mobile Sensing

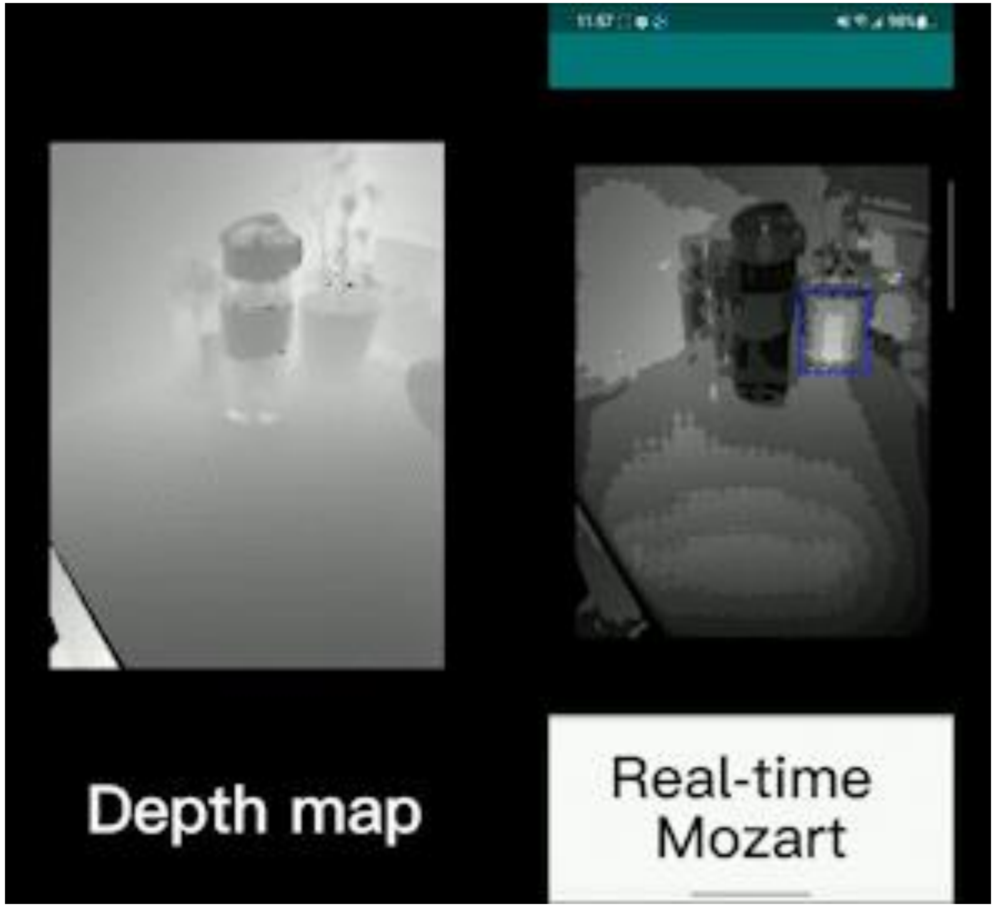
Microphone

mmWave Radar



IMU

PPG

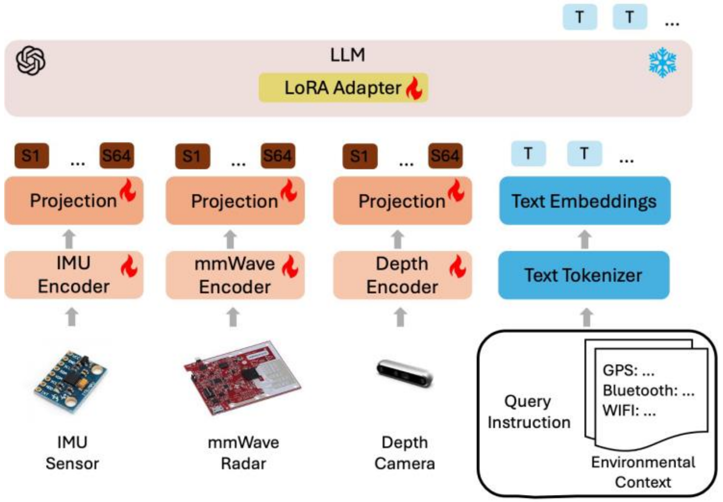


Z. Xie*, X. Ouyang* (co-primary), et al. Mozart: A Mobile ToF System for Sensing in the Dark through Phase Manipulation (**MobiSys '23 Best Paper**).

Embedded AI Systems

- Tackling real-world data and system challenges

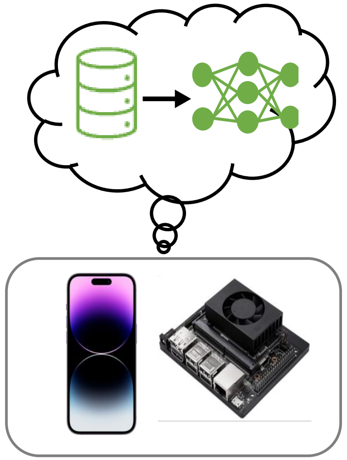
  - Ongoing Works



LLMs for sensing

Activity / Hour	Sleeping	Watching TV	…	Having a meal
00:00 - 01:00 am	✓			
⋮				
10:00 – 11:00 am		✓		
11:00 – 12:00 am				✓
⋮				

Weak labels

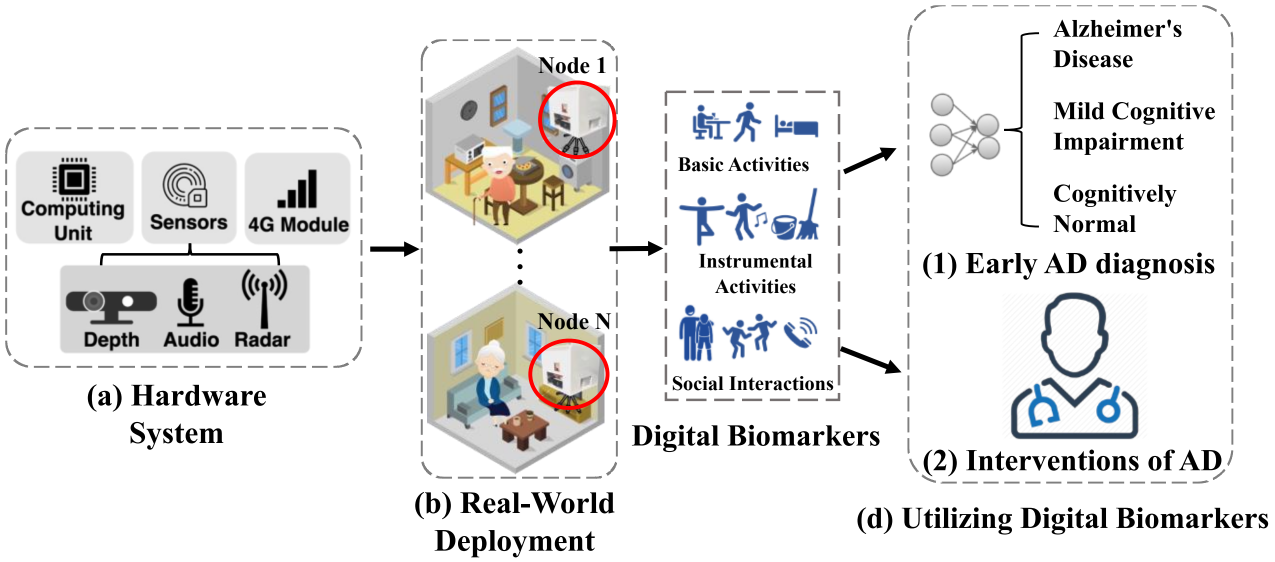


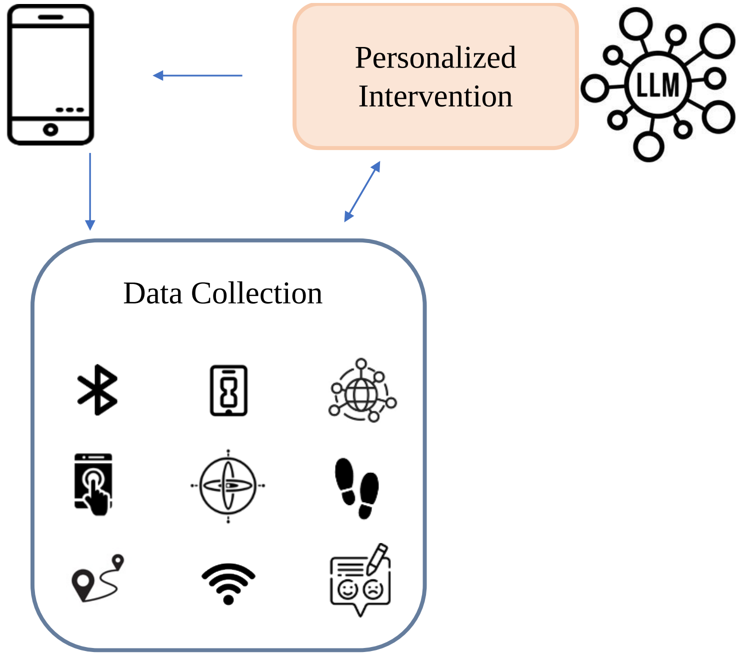
Efficient on-device inference

Outline

- ➢ Embedded AI Systems
- ➢ **Smart Health**

Smart Devices for In-home and Community-based Healthcare





➢ **Multimodal Sensor Systems for Alzheimer’s Monitoring**

➢ **LLM-Powered Mobile Intervention Systems**

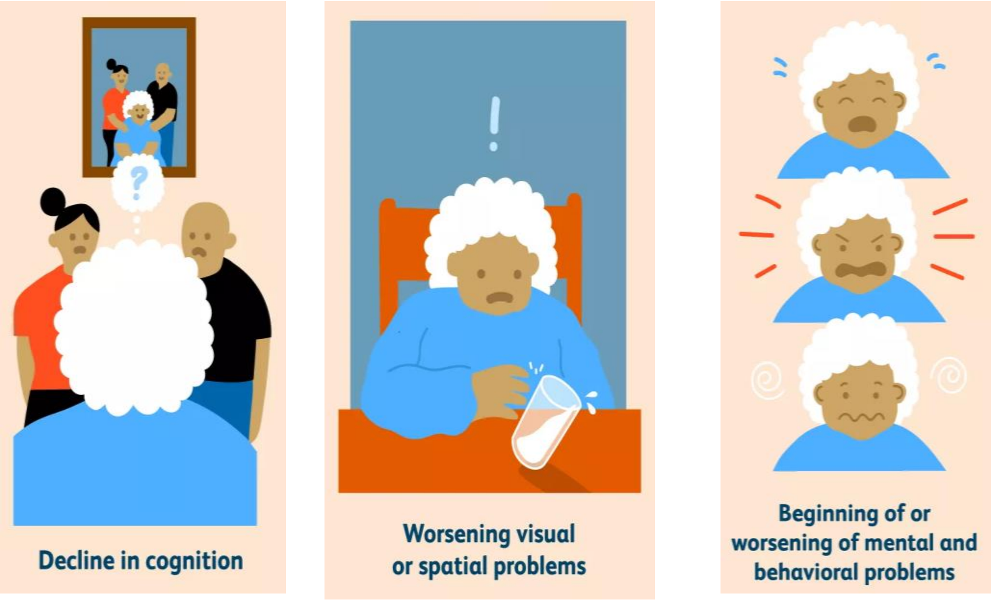
Alzheimer’s Disease (AD)

➢ A Global Health Challenge

Progressive

Degenerative

Irreversible



In 2024, over 55 million people worldwide had Alzheimer's disease, which costs over $13,00 billion for the managed healthcare system.

About 1/9 people aged 65 and older have Alzheimer’s.

➢ Current Diagnosis Approaches

Screening test

Interview

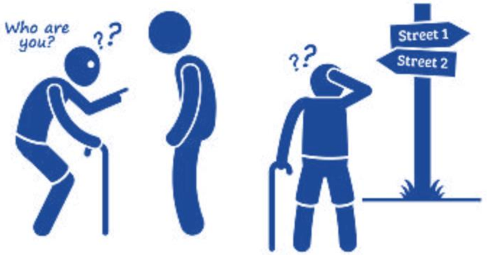
MRI test

- Intrusive and labor-intensive
- About 75% undiagnosed worldwide

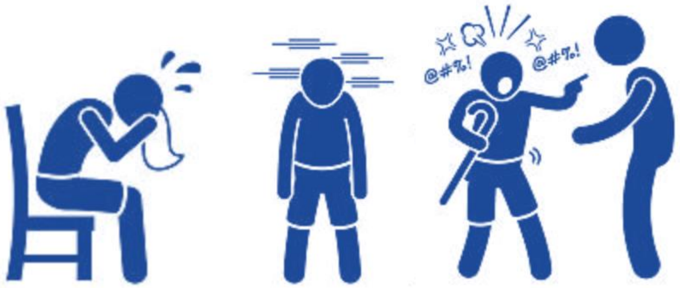
Digital Biomarkers for Early AD Diagnosis

➢ Leverage AI and sensor devices to capture **physiological, behavioral and lifestyle** symptoms of AD in natural living environments.

Activities of Daily Living



Cognition



Behavioral and Psychological Symptoms of Dementia (BPSD)

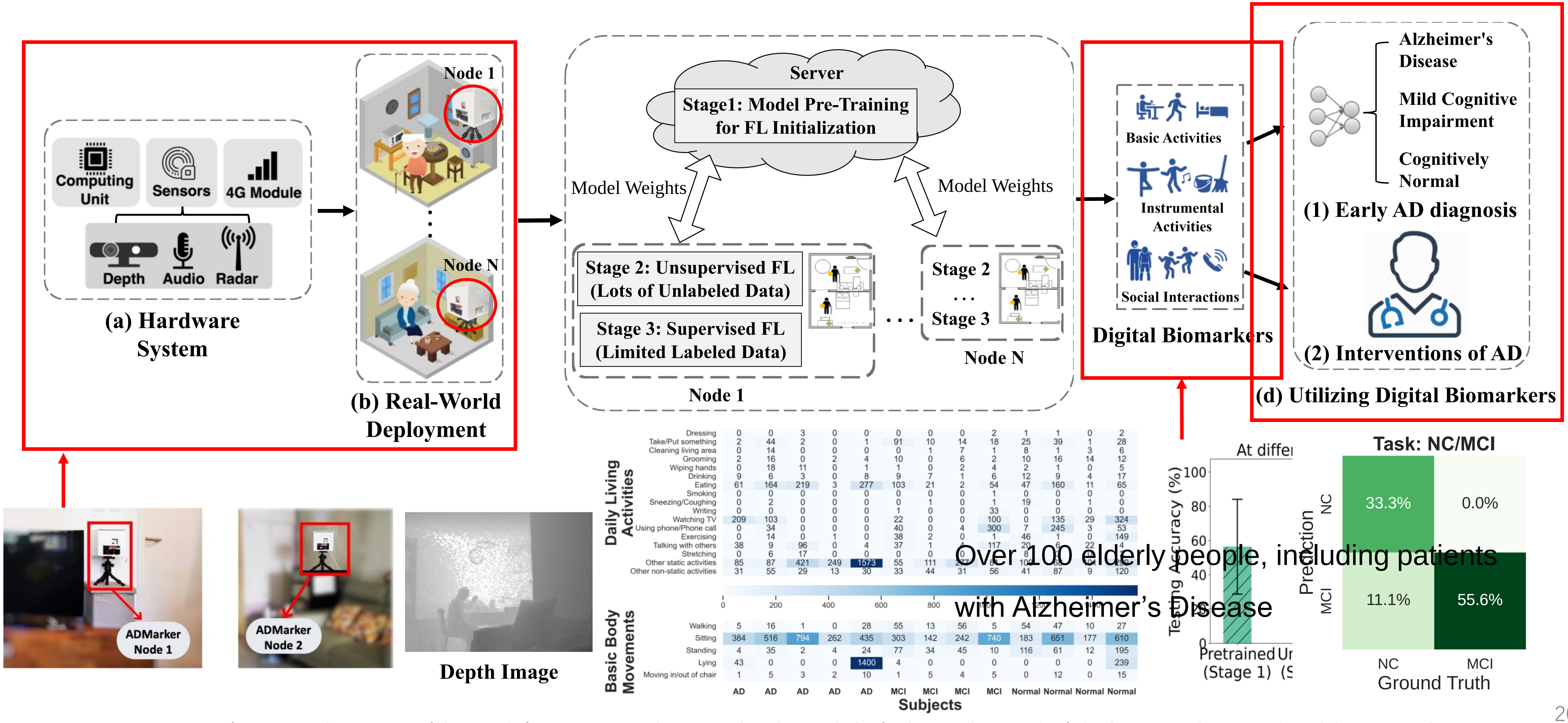
Social Interaction

- Multi-dimensional
- Complex and dynamic

Need multiple sensor modalities

ADMarker: System Oerview

- An end-to-end system for detecting **multi-dimensional AD digital biomarkers** in home environments.



Over 100 elderly people, including patients with Alzheimer's Disease

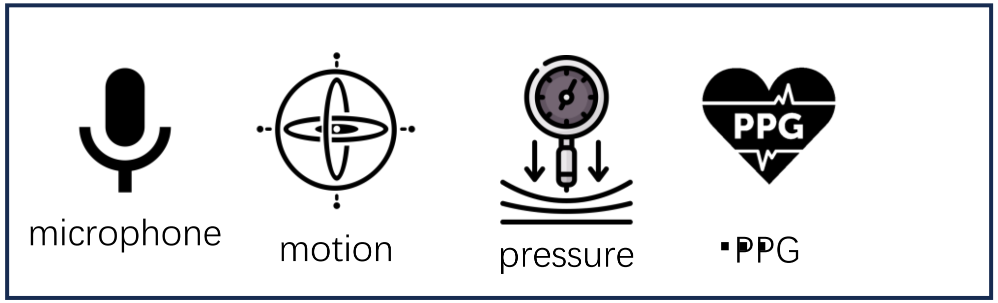
X. Ouyang, et. al. ADMarker: A Multi-Modal FL System for Monitoring Digital Biomarkers of Alzheimer's Disease. (MobiCom '24)

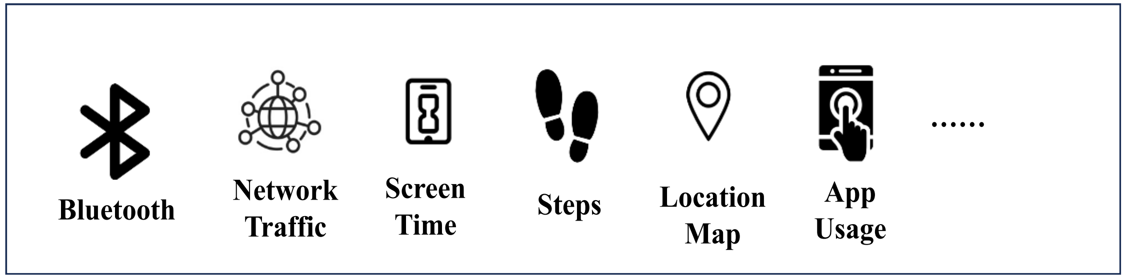
A Real-World Demo

In collaborations with CUHK Prince of Wales Hospital and HKU for AD behavior monitoring.

LLM-Powered Mobile Sensing for Personalized Intervention

➢ Mobile devices





Multimodal sensor data

User context information

➢ Large language models (LLMs)

ChatGPT

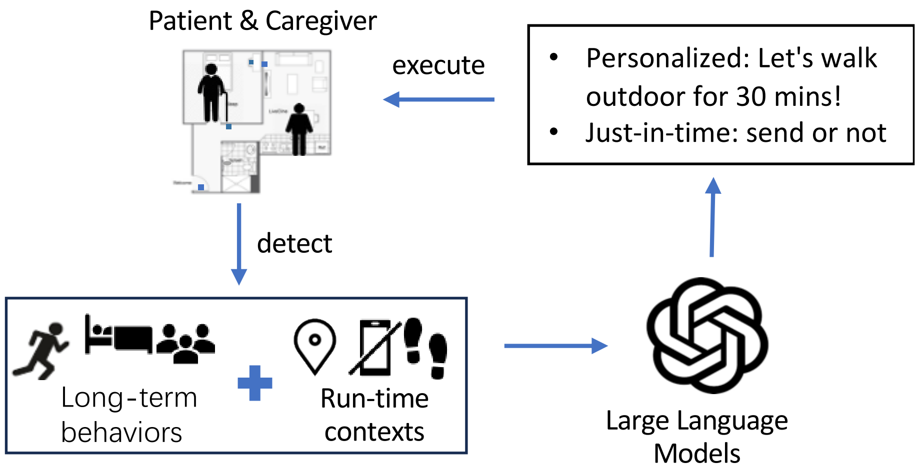
deepseek

Chat with DeepSeek AI

- **Reasoning** ability: interpret heterogeneous information to enable complex sensing tasks
- **Generative** ability: personalized user suggestion/recommender

LLM-Assisted Mobile Sensing for Personalized Intervention

➢ Deliver Personalized and Just-in-Time Intervention



- **Personalized**:
  - E.g., frequent reminder for physically inactive users
- **Just-in-time**:
  - no reminders when “working” or “sleeping”

System Overview

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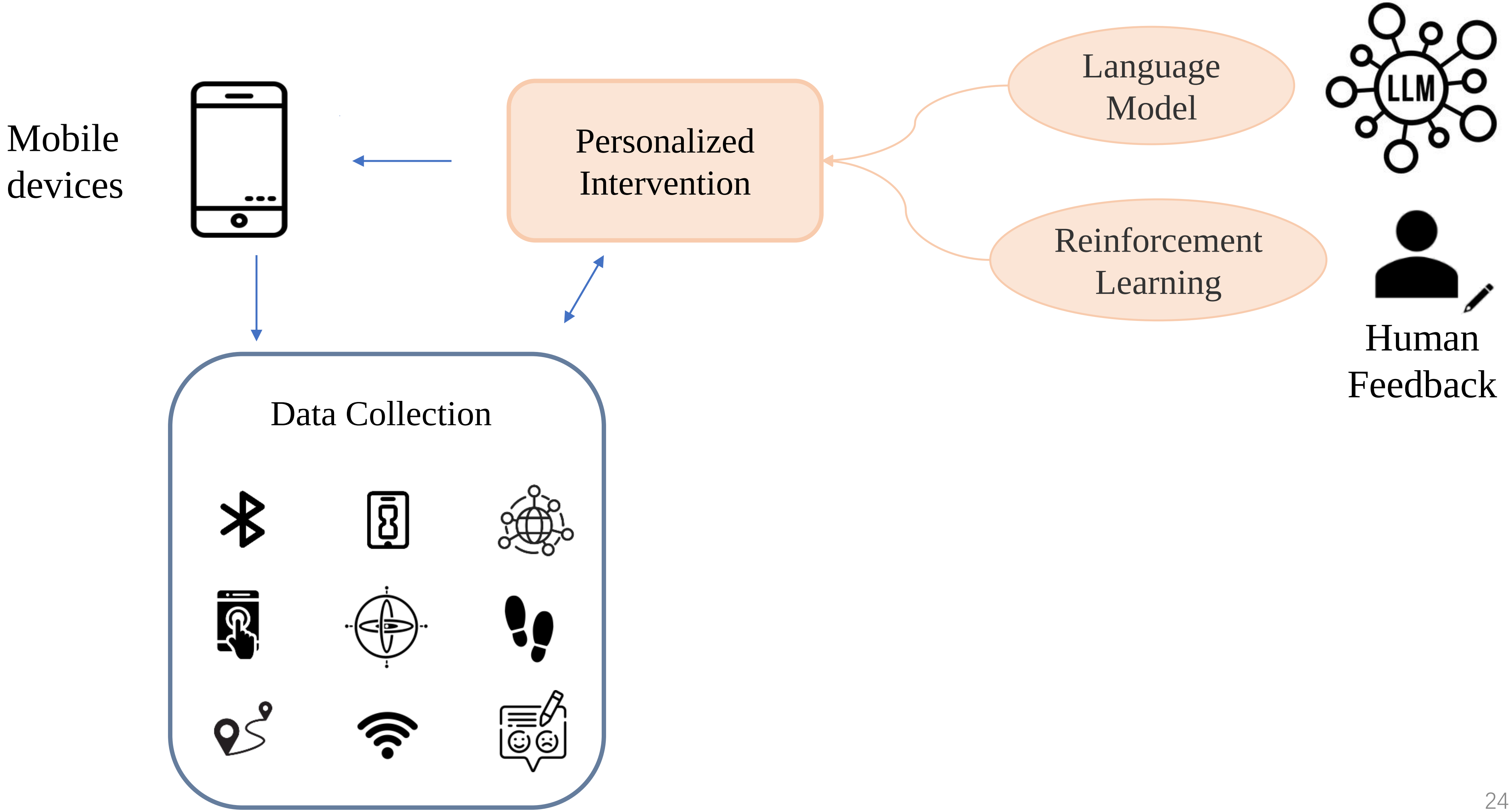

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Demo

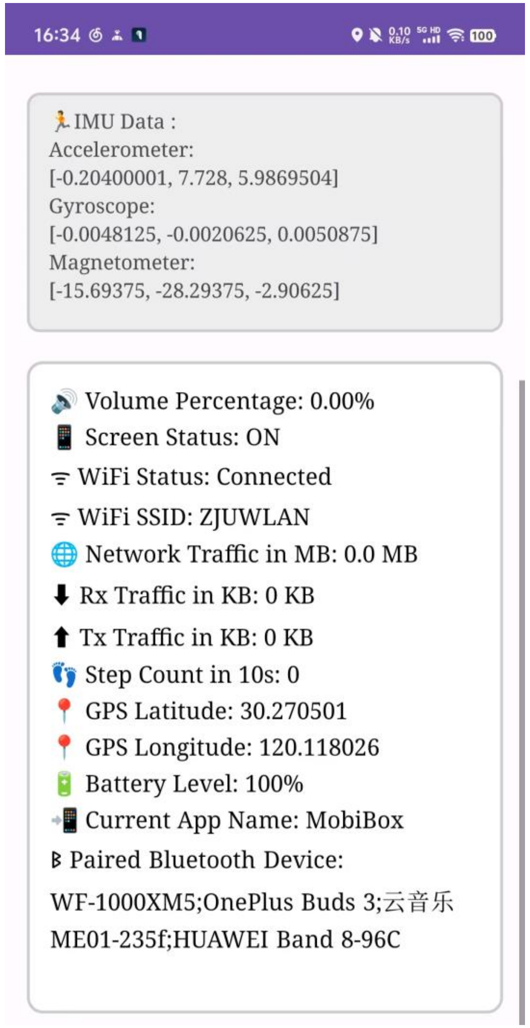
➢ MobiBox APP

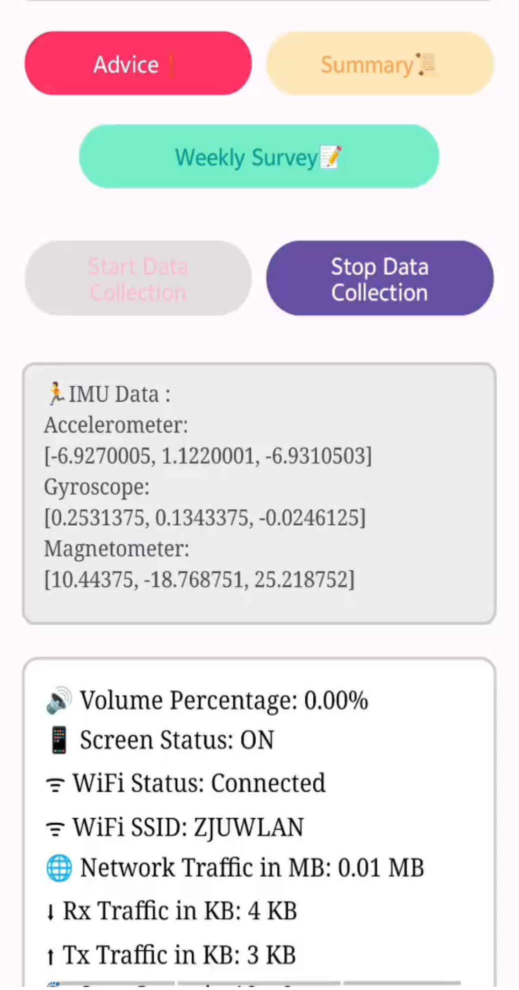
➢ Data Collection

IMU (Accelerometer / Gyroscope / Magnetic), GPS, Screen & App Usage, Battery Status, Bluetooth connection, Network Traffic, Step Count, Wi-Fi Connections.

➢ Daily & Weekly Activity Summary

➢ Bump-up **Intervention Suggestion**





In collaborations with CUHK and HKU for AI-powered dementia intervention.

Summary

- Embedded AI systems
  - Tackling real-world data and system challenges

- Building and deploying end-to-end AIoT systems for smart health
  - Working with interdisciplinary teams and medical researchers

Thanks!

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