Semantic Data Placement for CXL Memory Systems

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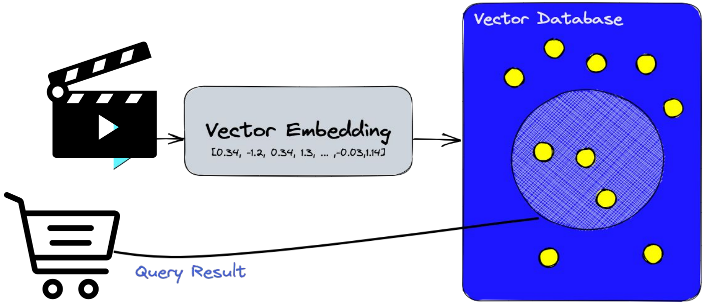
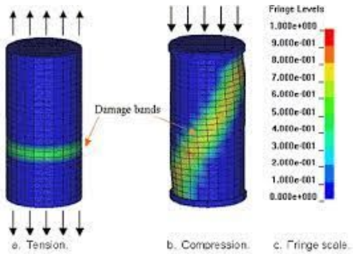
Vector Processing Applications



Vector Databases

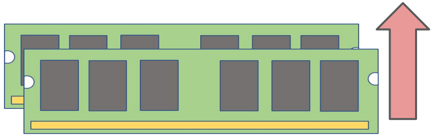


Simulations

CHATGPT

Large Language Models

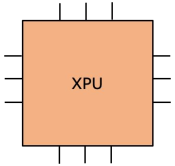
VPA Characteristics:



Memory-intensive

$$\vec{u} \cdot \vec{v}$$

Perform many vector operations

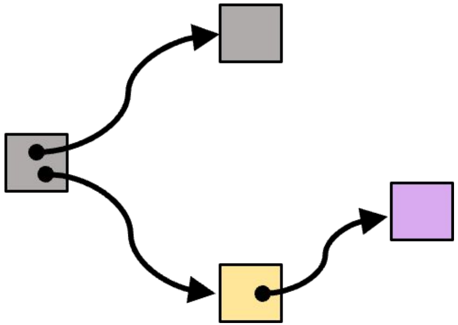


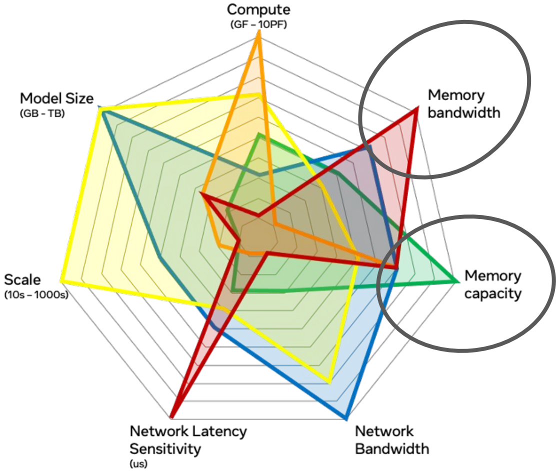
Use Accelerators

Image Credits: ONERA, U.S. DOT, Pinecone, OpenAI, Flaticon.com

Problem: Pressure on the Memory Hierarchy

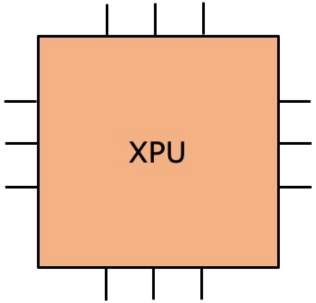
Application





Manoj Wadekar, Meta [FMS'24]

Accelerator

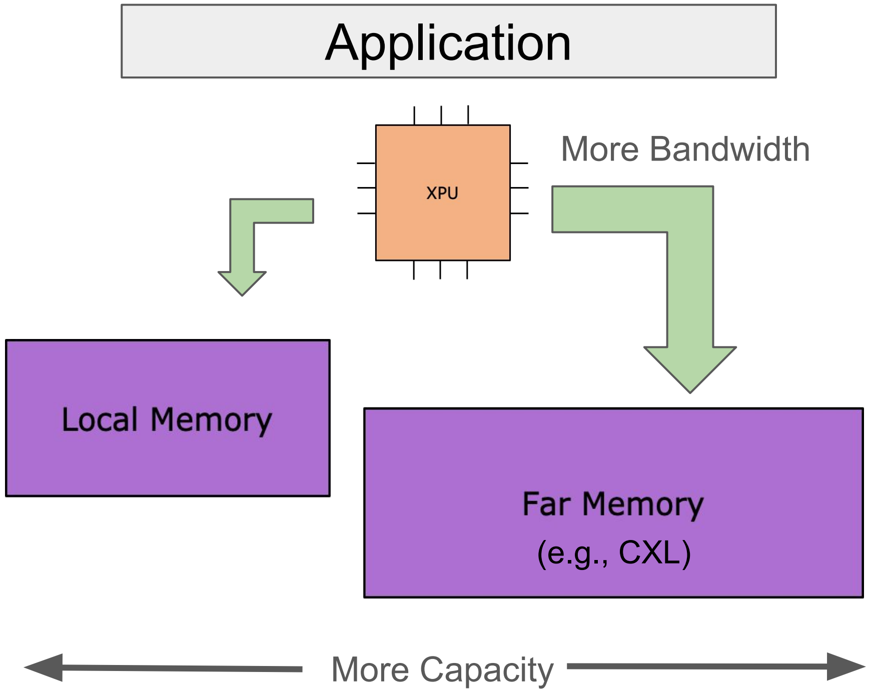


Needs large *memory capacity*

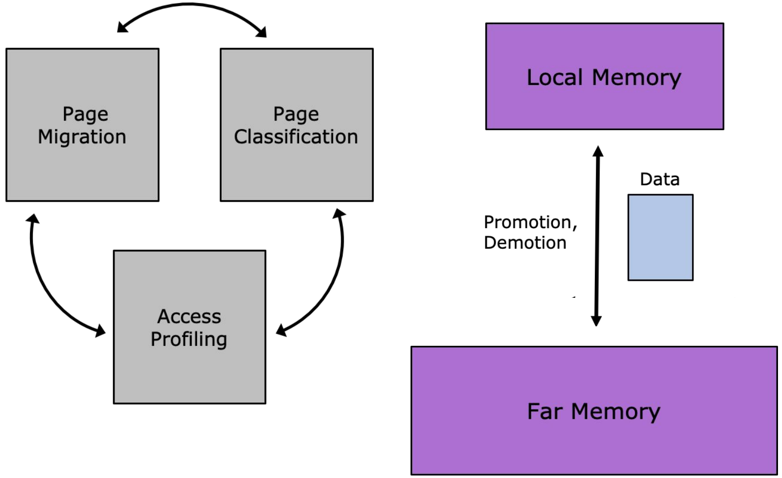
Wants high *memory bandwidth*

Issue: application working set >> accelerator memory capacity

Potential Solution: Memory Expansion

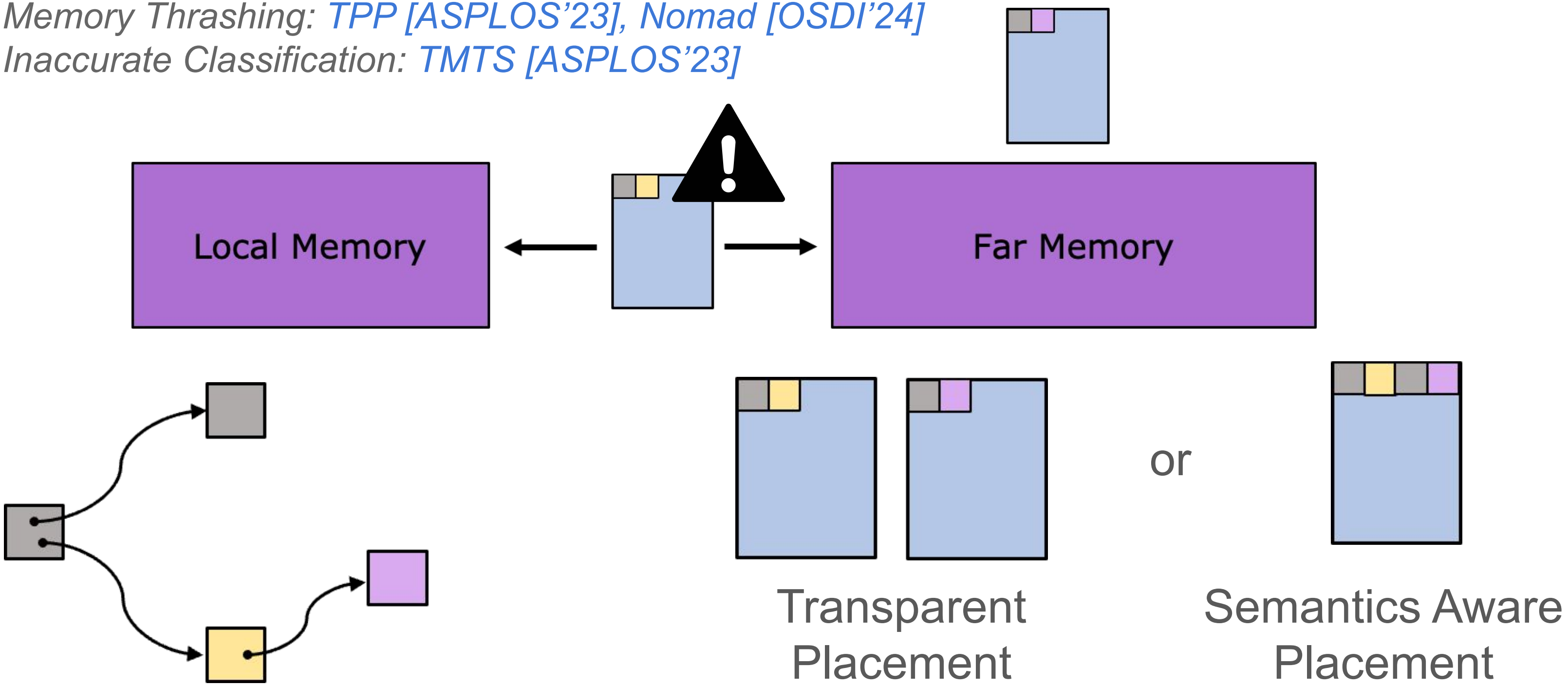


- **Manage additional memory with software-based memory tiering**
  - TPP [ASPLOS'23], Nimble [ASPLOS'19], HeMem [SOSP'21], TMTS [ASPLOS'23]



Limitations of Memory Tiering

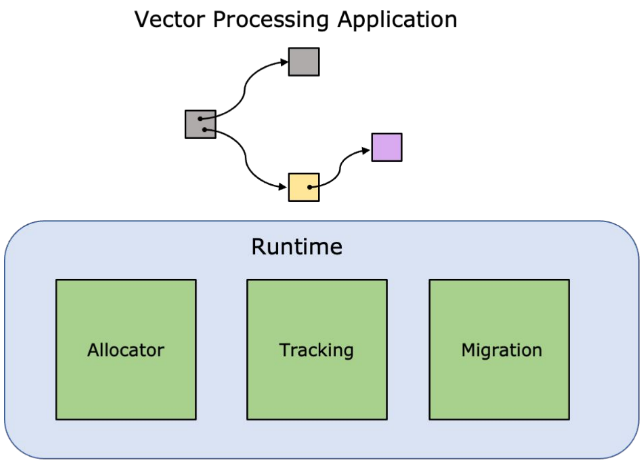
- *Data Amplification: AIFM [OSDI’20], DiLoS [Eurosys’23]*
- *Memory Thrashing: TPP [ASPLOS’23], Nomad [OSDI’24]*
- *Inaccurate Classification: TMTS [ASPLOS’23]*

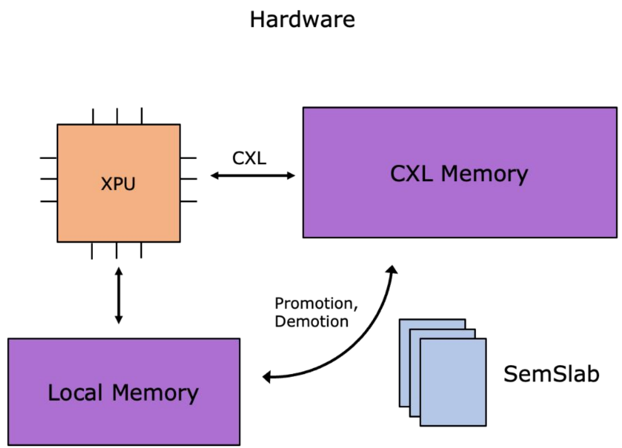


Research Question

What is the impact of a semantics-aware tiered memory system on resource utilization and application performance in heterogeneous systems?

Proposal: Semantic Data Placement





- Last time
  - Idea: Tiering for VPAs
- New Research
  - Refined ideas and system design
  - Work towards prototype
  - Identifying research challenges

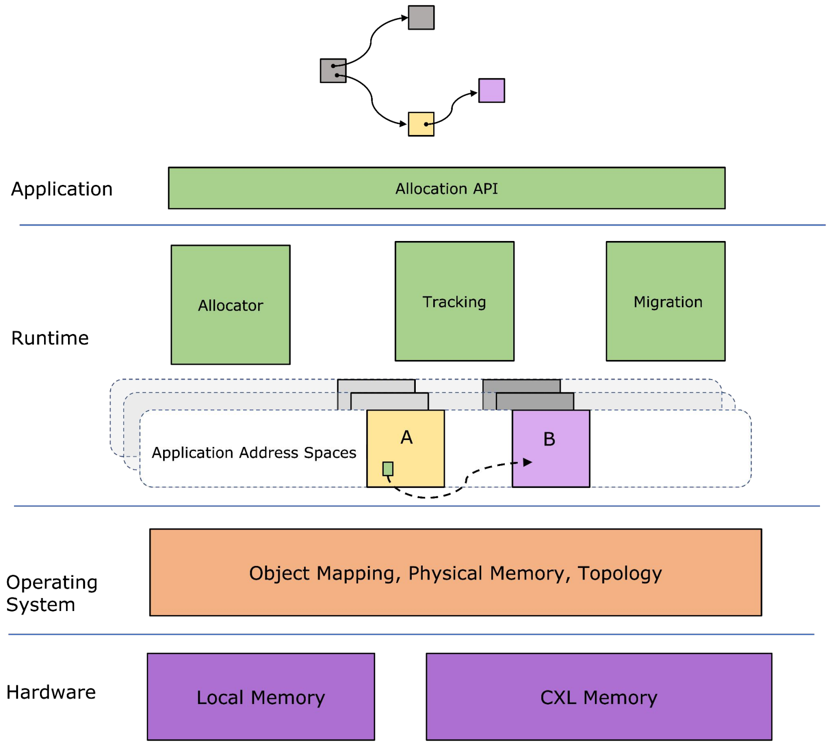
Research Challenges

- How can application semantics be used to reduce **memory bandwidth consumption** and improve memory **goodput**?
- What effect does semantic data placement have on application **performance** and **memory utilization**?
- How can we organize metadata for hotness tracking and other management functions to improve **scalability**?

System Architecture Overview

Our Proposed System:

Mnemonic Memory Tiers (M2T)



M2T’s Memory Allocation API: mnalloc

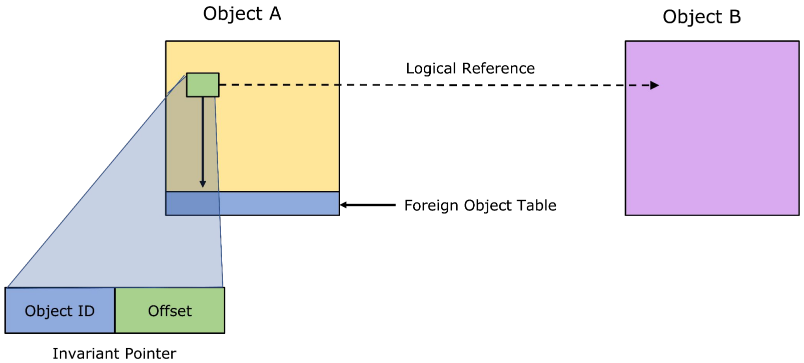
“Mnemonic Allocator”

```
mnalloc(size, PlacementDirective) → MemRef<T>
```

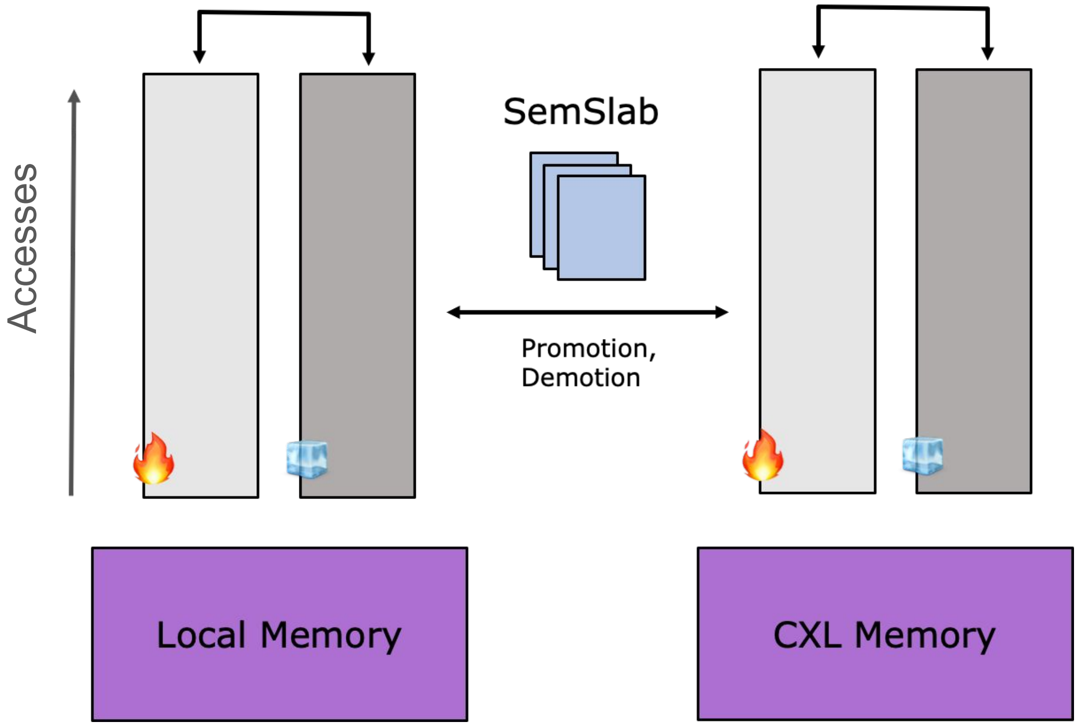
- **Encodes application semantics to the system**
  - Captures characteristics of a program from the perspective of its data
- **Similar approaches common in industry**
  - Google: TMTS [ASPLOS’23], Meta: TPP [ASPLOS’23]

M2T’s Memory Organization

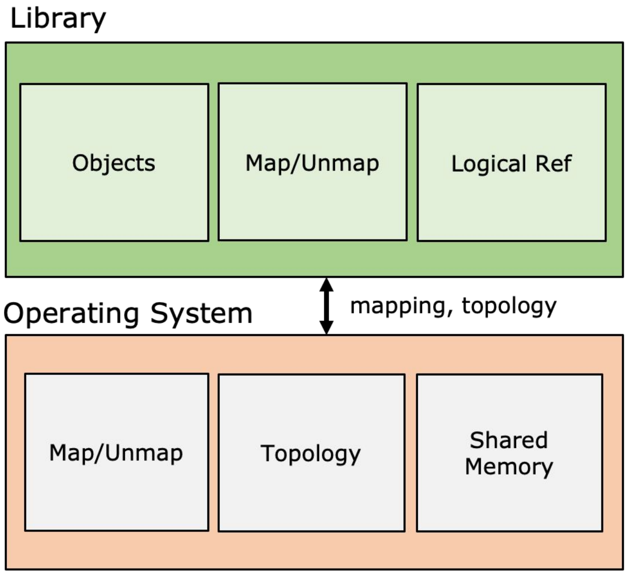
- **Adopt Twizzler’s Memory Model [ACT’20]**
  - Twizzler uses invariant pointers to memory objects as globally valid logical references
  - Software intercepts memory allocations and initial dereference only
- **Semantic Slabs (SemSlabs)**
  - Twizzler Memory Objects containing data allocated using **mnalloc**

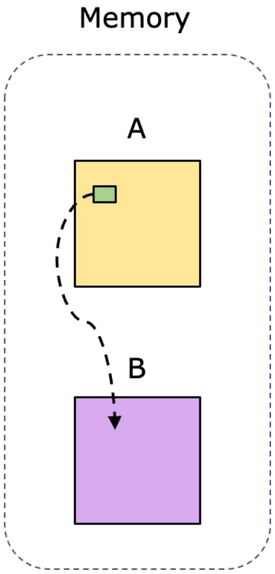


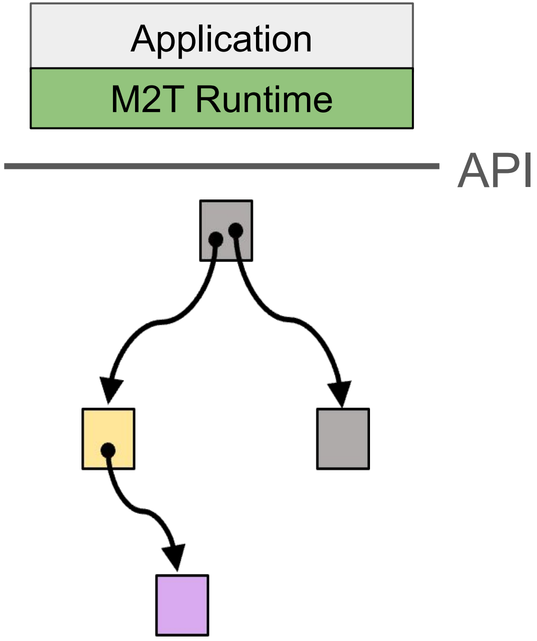
Tracking and Migration at SemSlab Granularity



Application Integration



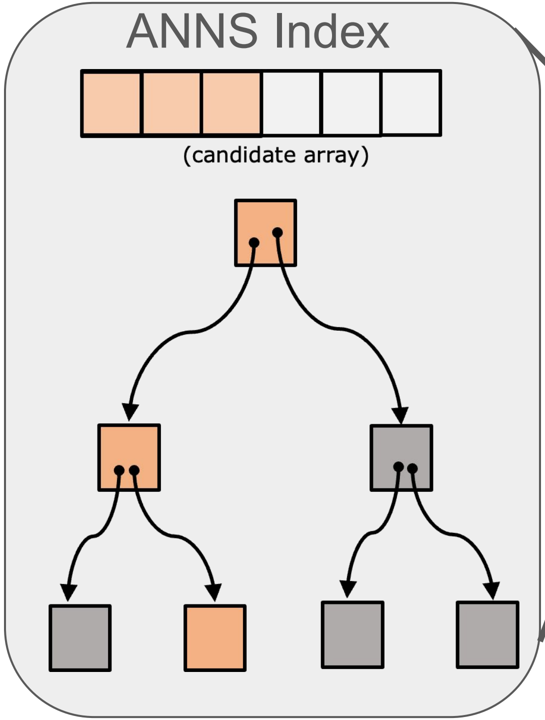




Applications link to the M2T runtime

Data Structure interface remains the same

Example: Scaling RAG Pipelines



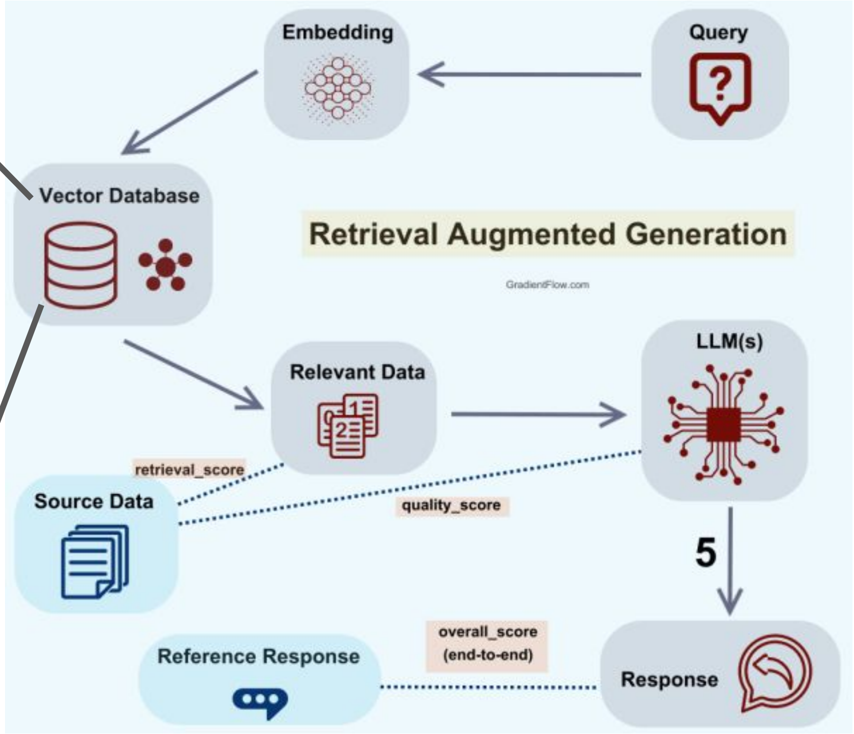
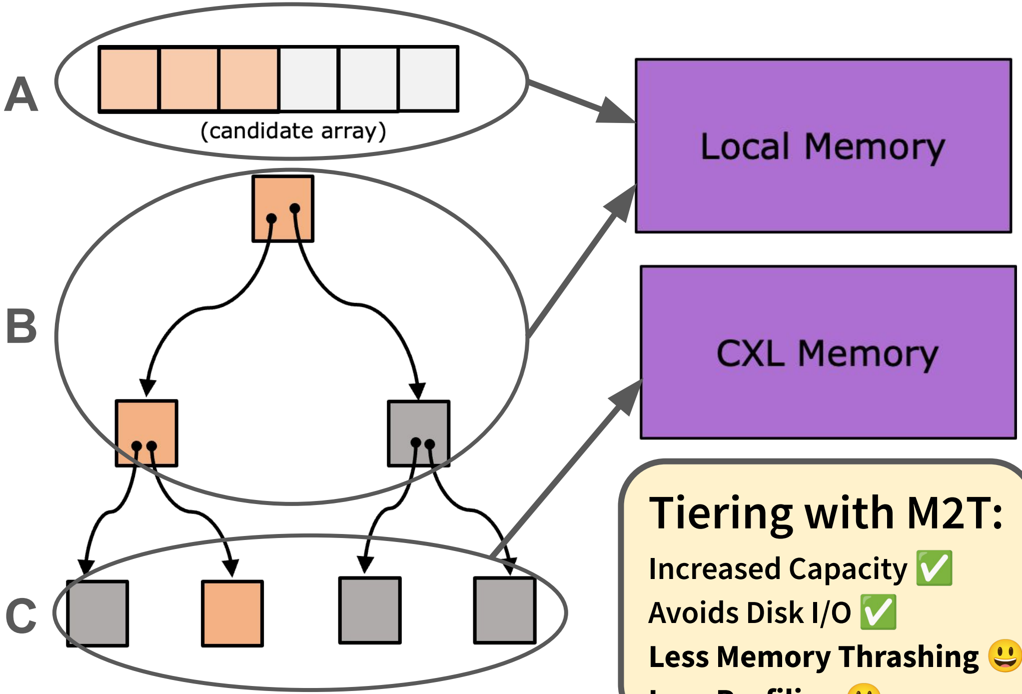


Image Credits: https://gradientflow.com/techniques-challenges-and-future-of-augmented-language-models/

Transparent Memory Tiering:

Increased Capacity ✅
Avoids Disk I/O ✅
Memory Thrashing 🙁
Profiling Overhead 🙁

Example: Scaling RAG Pipelines



Tiering with M2T:

Increased Capacity ✅
Avoids Disk I/O ✅
Less Memory Thrashing 😃
Less Profiling 😃

Application Code:

```
A  let carr = mnalloc(Placement::None);
   ...
   let root = mnalloc(Placement::Hot);
B  let root_data = mnalloc(Placement::Hot);
   let root_neighbor = mnalloc(Placement::Hot);
   let root_neighbor = mnalloc(Placement::Hot);
   ...
   let leaf =
        mnalloc(Placement::LatencyInsensitive);
C  let leaf_data =
        mnalloc(Placement::LatencyInsensitive);
```

What semantics can we express?

- **Developers use `mnalloc` to steer how M2T places data**
- **Memory objects placed based on associated semantics**
  - Temperature → Hot, Cold
  - Objects are “related”: NextTo(r)
  - Performance Insensitive → LatencyInsensitive, BwInsenstive
- `PlacementDirective` **could be determined automatically**
  - compiler techniques: Mira [SOSP’23], TrackFM [ASPLOS’24]
  - analyzing the call stack: TMC [SoCC’23], 2PP [PACT’15]

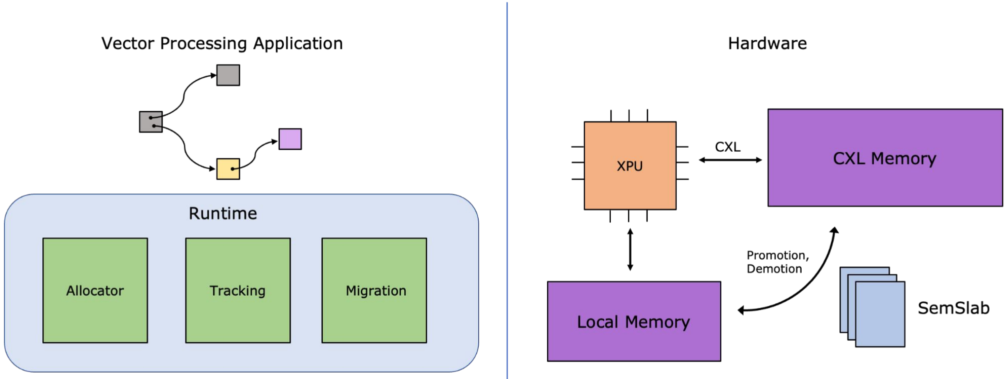
Goals for 2024-2025

CRSS

- **Implement a proof-of-concept M2T runtime**
- **Modify applications to use** `mnalloc`
  - Initial focus on vector indexes and Vector DB's
  - Applicable to HPC, simulation, graph processing, DBMS, and kv-stores
- **Evaluate the impact of semantic data placement**
  - On application performance?
  - On memory utilization?

Conclusion

- **Vector Processing Applications need robust system architectures**
    - to manage their growing memory footprint efficiently
    - CXL memory expansion provides a path forward
- **Semantic data placement potentially impacts**
    - application performance
    - system resource utilization



Thank You

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Questions?

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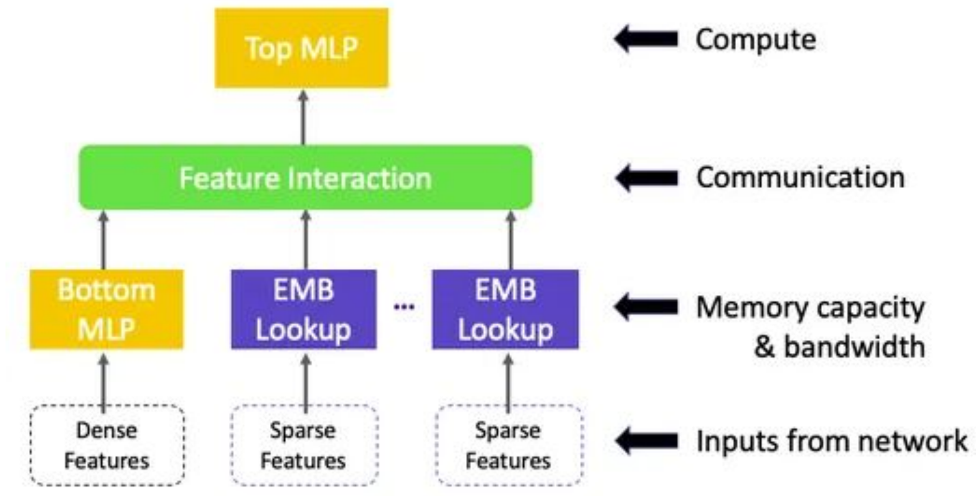
Backup Slides

Simple Example: Using M2T to build a Linked List

```
struct Node {
  next: InvPtr<Node>,
  data: u64
}

let mut a = mnalloc::<Node>(Placement::None);

*a = Node::new(42);

let mut b = mnalloc::<Node>(Placement::NextTo(a));

*b = Node::new(101);

a.next.assign(b);
```

Use Case: DLRM Inference Embedding Offload




```
let itemEmbedding =
mnalloc(size,LowLatency)
```

Local Memory

```
let userEmbedding =
mnalloc(size,BwInsenstive)
```

CXL Memory

Image Credits: Nishant Kumar, "Deep Learning Recommendation Models (DLRM): A Deep Dive". Medium.

Towards Low Overhead Tracking

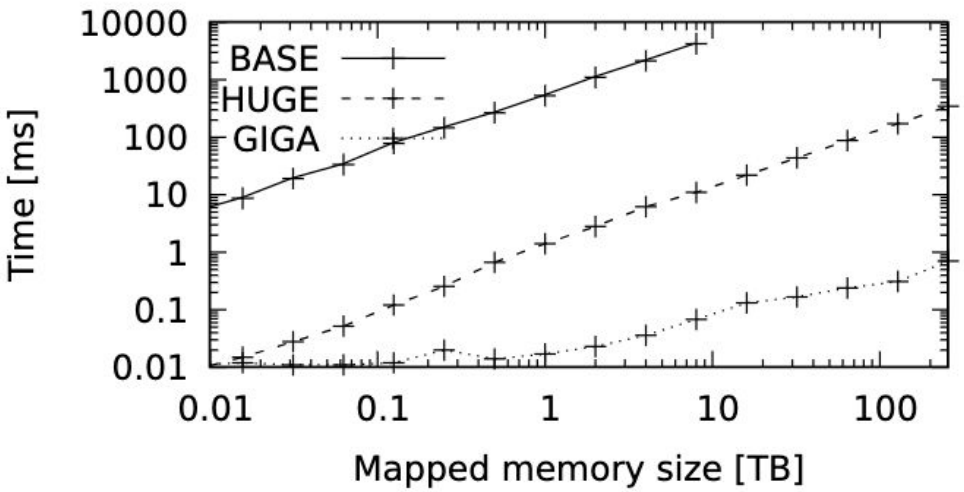


Figure 3: Page table scan time.

Amanda Raybuck, et al HeMem: Scalable Tiered Memory Management for Big Data Applications and Real NVM. SOSP 2021.