Challenges and Opportunities for Systems Using CXL Memory

Emmett Witchel, UT Austin
Credit to many, including Zhiting Zhu, Newton Ni, Yibo Huang, Zhipeng Jia (Google), Yan Sun (UIUC), Nam Sung Kim (UIUC)
Once upon a time
In the beginning
Intel creates software guard extension (SGX) enclaves [2015]
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Haven [OSDI 14] places legacy apps in enclave with library OS
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from
ImageFX (Google)
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Panoply [NDSS 17], Komodo [SOSP 17], Occlum [ASPLOS 20], minimize TCB in enclave
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Hoard [ASPLOS 00] does scalable memory allocation.

IBM does a lock-free version of Hoard [PLDI04].
Hoard [ASPLOS 00] does scalable memory allocation from Copilot (MS)
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Apple adopts Hoard, cites ASPLOS paper in code [08]

from Copilot (MS)
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LLAMA [ASPLOS 20] uses machine learning to reduce fragmentation

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Spectre & Meltdown microarchitectural side channels are exploitable [2018]
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KPTI in Linux, Intel firmware patch [2018]
Spectre & Meltdown microarchitectural side channels are exploitable [2018]

from ImageFX (Google)
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from
ImageFX (Google)

Foreshadow [USENIX 18]
Augury [IEEE SP 22]
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Foreshadow [USENIX 18]
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from ImageFX (Google)
Spectre & Meltdown microarchitectural side channels are exploitable [2018] from ImageFX (Google)
Gustav Freytag’s pyramid [1863]

- Exposition
- Rising action
- Inciting incident
- Climax
- Falling action
- Denouement
The role of metacognition

- Metadata is data about data, e.g., a file’s modification timestamp
  - Metacognition is thinking about thinking
- Metacognition can provide insight and perspective
  - Can get you out of a rut
  - Even if useful, it is no crystal ball
Where is your work in the pyramid?

Open a field
Where is your work in the pyramid?

Provide superior alternative

Open a field
Where is your work in the pyramid?

- Provide superior alternative
- Solve long tail of problems
- Open a field
Where is your work in the pyramid?

- Provide superior alternative
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- Open a field
- Deploy and move on (closer)
Compute Express Link (CXL) memory

Memory becomes limiting resource

Pond, TPP [ASPLOS 23]

CXL standard finalized

???????
Talk outline

- CXL memory — saving costs
  - Disaggregation motivation
  - CXL memory is transparent
- CXL pods — increasing performance [CXL-SHM SOSP 23]
  - CXL memory is explicitly controlled by programmer
  - Unstructured / global coordination can be fast
- New challenges for CXL pods
  - Tolerating partial failures, why and how
What is a computer?

- [A computer must] store numbers passively—the results of various partial, intermediate calculations. The totality of these organs is called a “memory.”
  - John Von Neumann (1958)
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Physical racks vs. virtual machines

- Memory stranding in Azure cloud (from Pond [ASPLOS 23])
  - No free CPU cores but memory left
  - Up to 25% stranded memory at 95th percentile
- Untouched memory due to overprovisioning

Image credit: Pond [ASPLOS 23]
The dream of disaggregation

- So many compute nodes
- Memory and Storage
  - All the bandwidth you can buy
  - All the capacity you can buy
  - Low latency (physical limits)
- Optimized for cost savings
  - Flexible partitioning of resources
  - Transparent to applications
The reality of disaggregation

A hierarchy of layers

System software!
  ○ Virtual memory was invented for this
  ○ Prediction & migration

Works pretty well
  ○ Pond, TPP, etc.

Image credit: Timothy Prickett Morgan, The Next Platform
Questions remain

- Enough layers?
- Enough bandwidth?
- Low enough latency?
- Accurate prediction?
- Latency insensitive applications?
- Active area now

Image credit: Timothy Prickett Morgan, The Next Platform
Single-host software vs. distributed software

One Host

- Shared mutable state
- Centralized state
- Many efficient algorithms
- Limited concurrency
- Database
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**Distributed (many hosts)**
- Replicated state machines
- Scalable
- Fast failover
- Difficult to construct and maintain (performance)
- Key-value store
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CXL Pod
- Machines connected to CXL memory

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A tale of two climates

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**CXL Pod**
- Encapsulate complexity in data structures
- Low tail latency
- The “SQLite” of distributed systems

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CXL Pod

- Runs single-node SW
  - Fine-grain sharing CXL
  - Requires next HW standard
- Need support from
  - OS + memory allocator
- 16 hosts X 288 cores
  - 4,608 cores Sierra Forest
  - 7,200 MapReduce [04]
What will run on a CXL pod?

- An in-memory database
  - High performance
  - High availability, no downtime
  - Coordination by shared memory more efficient than
    - Partitioned state +
    - Distributed transactions over the network

- Long-running computation with lots of state
  - Computation is valuable enough to require fault tolerance
  - Check pointing state is slow
    - Consumes storage bandwidth
What are the requirements for a CXL pod?

- Will I get hardware cache coherence across all CXL?
  - Uncertain at this time
  - Might require SRAM tags
    - Raising the cost
- What should HW provide SW?
Persistent memory: avoid extra instructions

- Before 2016, pcommit needed

```
MOV X1, 70 ; store 70 to X1
CLWB X1   ; flush X1 from cache
SFENCE
PCOMMIT  ; persist
SFENCE   ; ensure pcommit finished
```
Persistent memory: avoid extra instructions

```assembly
MOV X1, 70 ; store 70 to X1
CLWB X1    ; flush X1 from cache
SFENCE
```

- After 2016
  - pcommit deprecated
Persistent memory: avoid extra instructions

MOV X1, 70 ; store 70 to X1
SFENCE

- After 2020
  - Extended asynchronous DRAM Refresh (eADR)
  - No more cache flushing
- Analogy for CXL: global persistent flush (GPF)
  - No more performance sapping clwb!
Challenges of the CXL pod - partial failure

- Let’s say one OS reboots or one process dies
  - Do I have to restart all OSes (or all processes)?
  - Full restart is bad for availability
- Tolerating partial failure means
  - Application remains available during partial recovery
  - OS / process recovers and rejoins
- CXL pod fault model
  - Is it a shared memory multiprocessor or a distributed system?
  - Distributed systems should tolerate partial failures
What goes wrong on a partial failure?

- Shared data structures go in shared CXL
  - Shared data structures need synchronization
- OSes & applications have to synchronize on CXL memory
  - Spinlocks, futexes, mutexes, semaphores are not fault-tolerant
  - Die with a lock held $\Rightarrow$ Deadlock
- OS reboot is not a global quiescent point!
  - Can’t rebuild DRAM from PM on OS reboot [NOVA FAST 16]
- On recovery, restore state from where? Storage is slow
CXL pod partial failure model

- Make CXL memory persistent
  - Give it independent power supply
  - Protect integrity with ECC
    - Raising cost of module
- On a partial failure restore from CXL memory state
  - Applications remain available during recovery
- How do we synchronize and remain fault-tolerant?
Transactions to the rescue!

- Transactions are fault-tolerant
  - Persistent memory systems use them for memory allocation
- Problem for PM allocation

```c
void * ptr = persistent_alloc(1024)
make_persistent_root(ptr)
```
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Memory leak
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- Tolerating partial failures more pervasive than memory allocation
  - Let’s avoid mandating fully transactional programming model
  - Find efficient special-case solutions
Correctness under concurrency

- Concurrent safety by linearizability [Herlihy, Wing 1990]
  - Operations have linearization point between invocation & response
    - Respects real-time order
  - Reorder linearization points to be sequential
  - Sequential history is correct for sequential specification of object
- But linearizability says nothing about failures
  - Use durable linearizability [Izraelevitz 2016]
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Correctness under concurrency + partial failure

- Durable linearizability has limitations for partial failure
- Need detectable execution [Friedman 2018]
  - Need the ability to execute operations exactly once
    - Crash while enqueue object O into Q
    - On recovery did I enqueue?
    - Can look for O in Q, but another thread might have dequeued it
  - Recovery settles question of whether operation succeeded
- Need linearizability + detectable execution
Performance of OpenMPI broadcast microbenchmark

- OSU microbenchmark across 16 VMs
- Message passing / distributed system benchmark
- Memory is more efficient than network messages

<table>
<thead>
<tr>
<th></th>
<th>OpenMPI (μs)</th>
<th>CXL (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>p50</td>
<td>p99</td>
</tr>
<tr>
<td>64B</td>
<td>18.5</td>
<td>53.7</td>
</tr>
<tr>
<td>1MB</td>
<td>3120</td>
<td>3660</td>
</tr>
</tbody>
</table>
Promise for CXL and beyond

- Mathematically, there are too many problems
  - Technology identifies important ones
- What should HW provide SW?
  - Vital as HW stops scaling
  - Ease SW programming model
- What do we learn even if CXL fails?
  - Break down solutions
  - Use the parts in new systems
Why do we do research?
Why do we do research?

- Ego gratification
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  - Change the world
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- Aha moment, pursuit of truth
  - Ph.D: Academic degree that pushes boundaries of human knowledge in a specialized field through focused research for several years
  - Insight is hard to search for and hard to recognize
What is the nature of insight?

Credit: Good Will Hunting, A Beautiful Mind, Its Always Sunny in Philadelphia
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What is the nature of insight?
Insight arises within a group

● Research is a social activity
  ○ A research group
  ○ The research community

● The whole is greater than the sum of its parts
  ○ I write papers because I learn so much from writing them
  ○ My old papers are written by someone more knowledgeable than I

● Unreasonable levels of effort help
  ○ Dedication displaces normality
  ○ Synesthesia
Research for the long haul

- Study what you love and what you are good at
- Explore, but topics recur in popularity
- Find the right fit
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Every shrink, every career counselor, every Disney princess knows the answer: “Be yourself.” “Follow your heart.”

Only here's what I really, really want someone to explain to me. What if one happens to be possessed of a heart that can't be trusted?

--Donna Tartt, The Goldfinch
How do we remain a robust community?

- Number of submissions is way up
- Number of accepted papers is way up
- Size of program committees is way up

What do we do?

- One or two annual deadlines, not three
- History of paper reviews from previous conferences?
- Pay per submission (in cash, in reviews)
Research ethics

No matter what our place in life is, each human being possesses a fundamental inner freedom that cannot be compromised unless we let it. And that therefore imbues us with an innate demand for personal responsibility.

- Like Stories of Old
  - https://youtu.be/FDVR73qUSXU?si=Bd-bUzOuZ4-BXepE&t=1307
Many thanks

Zhiting Zhu
UT Austin

Newton Ni
UT Austin

Nam Sung Kim
UIUC

Zhipeng Jia
Google

Yibo Huang
UT Austin

Yan Sun
UIUC
Summary

- **CXL memory — saving costs**
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