HeteroSync: A Benchmark Suite for Fine-Grained Synchronization on Tightly Coupled GPUs

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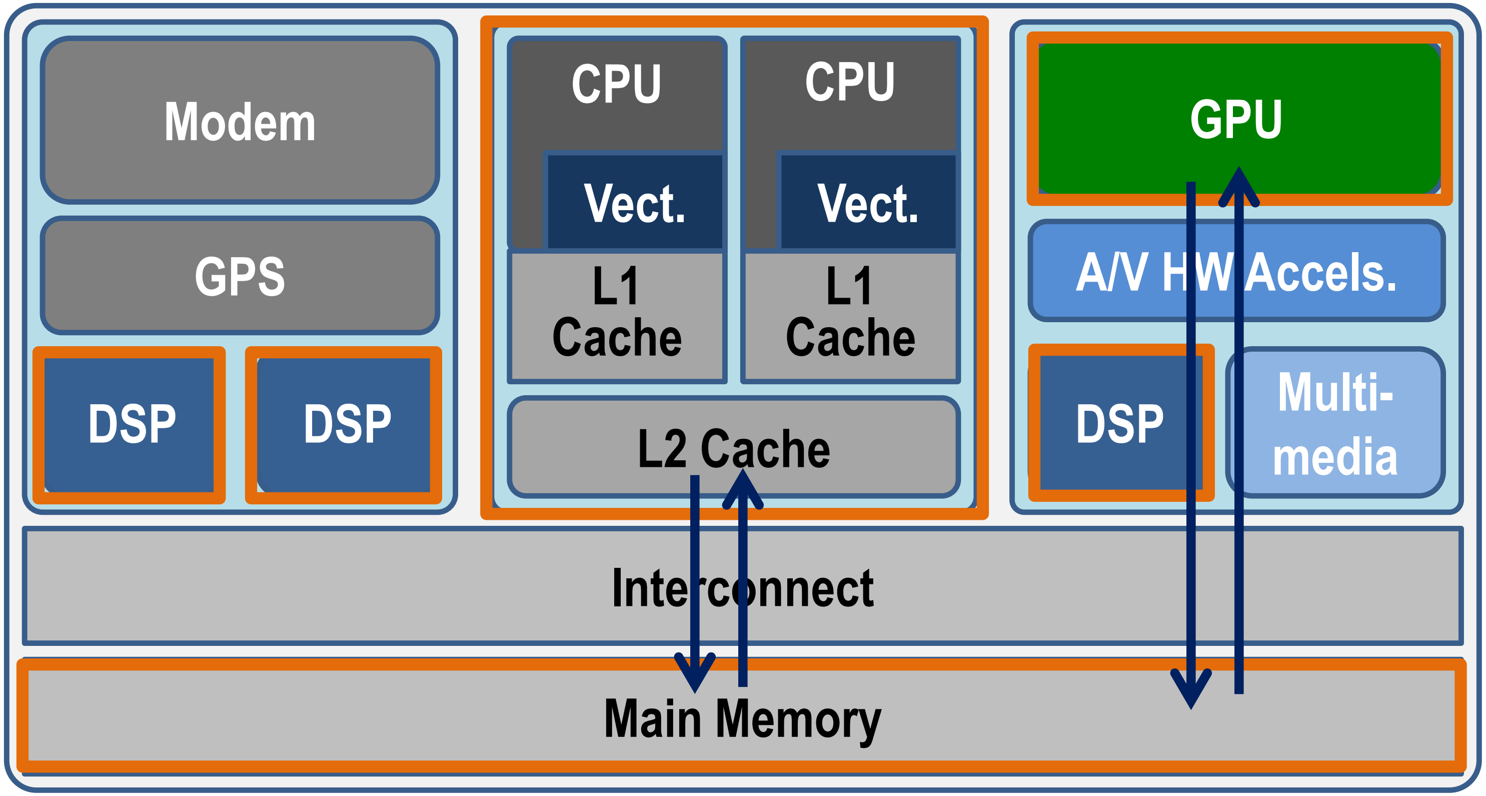
Traditional Heterogeneous SoC Memory Hierarchies



Discrete address spaces

Works well for streaming applications

Inefficient for applications with fine-grained synchronization

Motivation

- Tighter CPU-GPU integration – need better synch support
- Lots of heterogenous coherence, consistency research

QuickRelease HPCA'14	HRF ASPLOS '14
DeNovo MICRO '15	RemoteScopes ASPLOS '15
hLRC MICRO '16	hVIPS TACO '16
RAts ISCA '17	…

No standardization – which approach is best?

HeteroSync: new microbenchmark suite

HeteroSync

- **Fine-grained synchronization microbenchmarks**
  - Various mutex, semaphore, barrier algorithms
  - Relaxed atomics: event counters, split counters, seqlocks, …
- **Enable deep analysis of:**
  - Algorithm scalability
  - Scalability of different coherence and consistency schemes

Standard fine-grained synch microbenchmarks

Outline

- Motivation
- Background: Coherence & Consistency
- HeteroSync
- Results
- Conclusion

Atomics Background

- **Default: Data-race-free-0 (DRF0) [Adve ISCA '90]**
  - **Identify all races as synchronization accesses (C++: atomics)**

```
// each thread
for i = 0:n
    ...
    ADD R4, A[i], R1   synch (atomic)
    ADD R5, B[i], R1   synch (atomic)
    ...
```

  - **All atomics order data accesses**
  - **Atomics order other atomics**

  ⇒**Ensures SC semantics if no data races**

Atomics Background (Cont.)

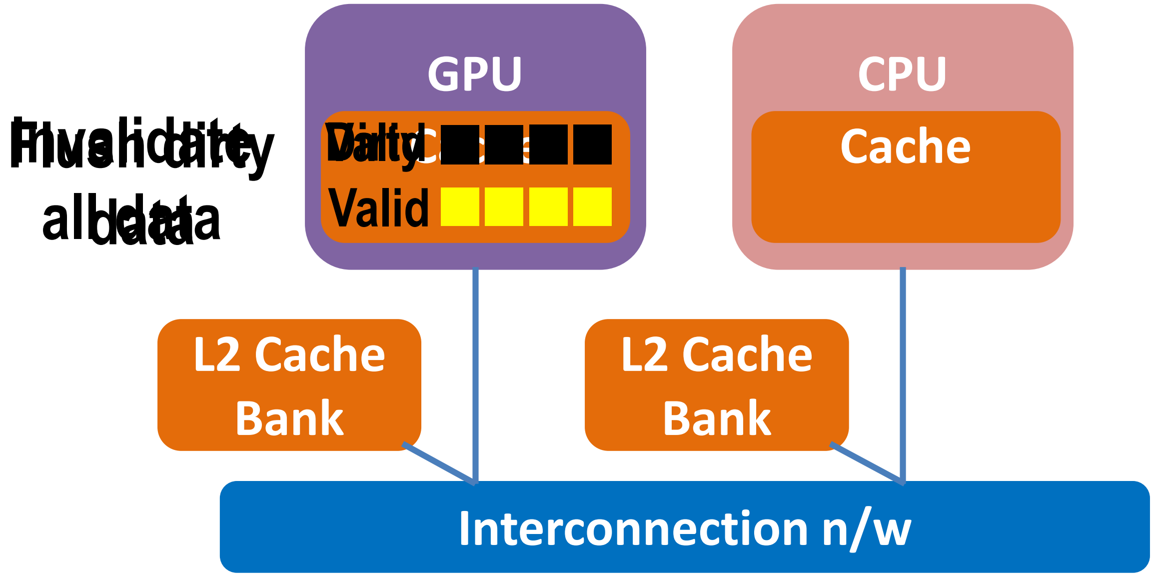
- Default: Data-race-free-0 (DRF0) [Adve ISCA ‘90]
  - All atomics order data
  - All atomics order other atomic accesses

  ⇒Ensures SC semantics if no data races
- Relaxed atomics [Boehm PLDI ‘08]
  + Do not order data or other atomics

  ⇒But can violate SC and no formal specification
- Data-race-free-relaxed (DRFrlx) [Sinclair ISCA ‘17]

  ⇒SC-centric semantics + efficiency

GPU Coherence with DRF

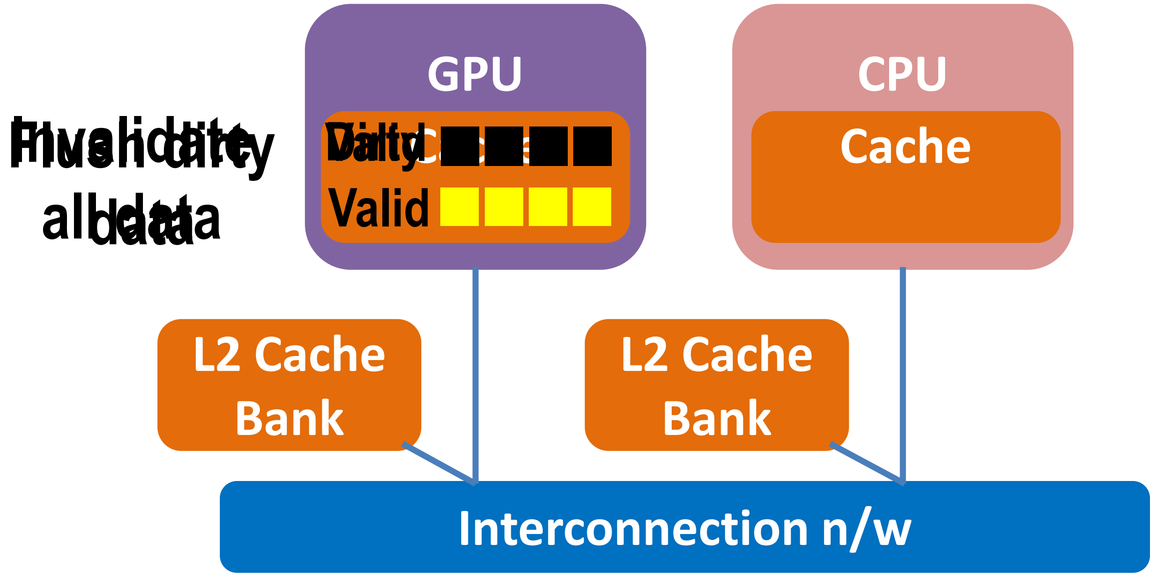



```
// each thread
for i = r[tid]:r[tid+1]
    LOCK
    LD R1, A[i];
    LD R2, B[i];
    R3 ← Math(R1, R2);
    ST B[i], R3;
    UNLOCK
```

- **With data-race-free (DRF) memory model**
  - No data races; synchs must be explicitly distinguished
  - Synchronization accesses (atomics) go to last level cache (LLC)
  - Synchronization points are expensive, preclude reuse

Simple but inefficient coherence, simple consistency

GPU Coherence with HRF

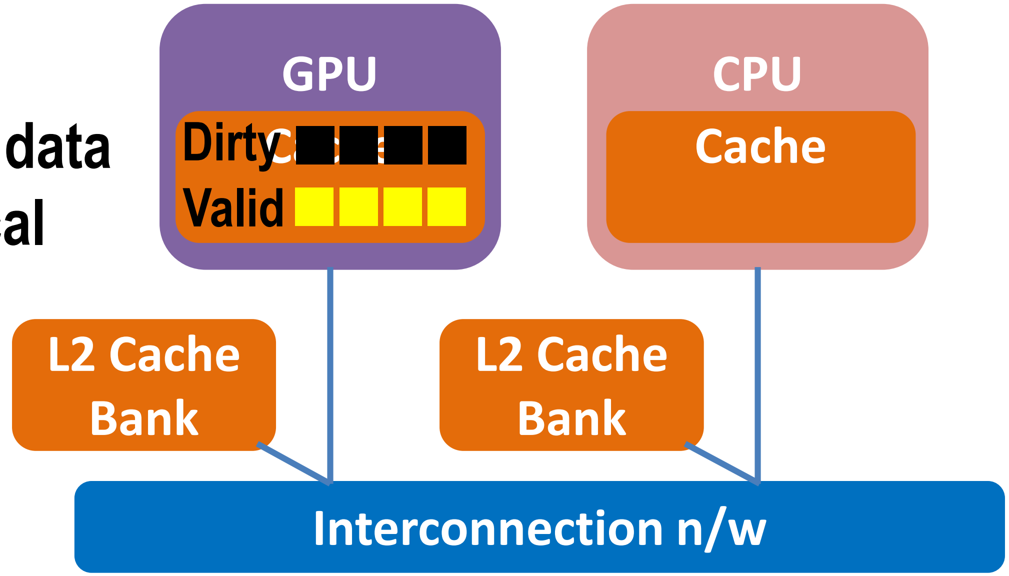



```
// each thread
for i = r[tid]:r[tid+1]
    LOCK           global
    LD R1, A[i];
    LD R2, B[i];
    R3 ← Math(R1, R2);
    ST B[i], R3;
    UNLOCK         global
```

- New memory model: Heterogeneous-race-free (HRF) [ASPLOS ‘14]
  – Adds scoped synchronization

GPU Coherence with HRF

Keep data local

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// each thread
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    LOCK          global
    LD R1, A[i];
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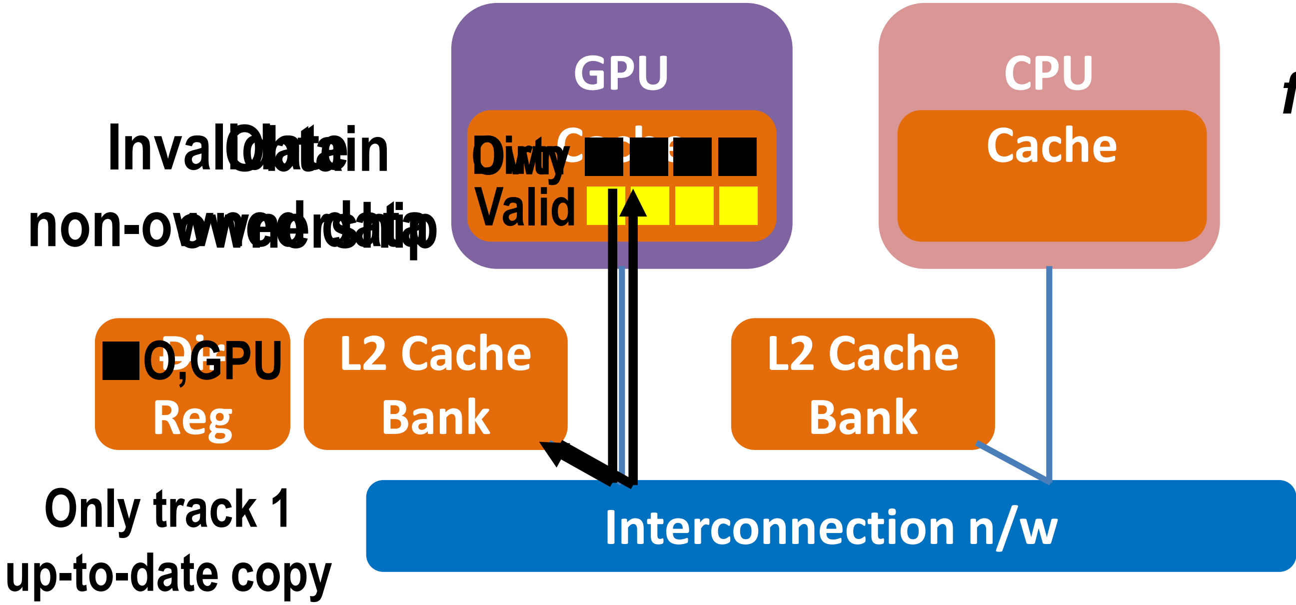
    ST B[i], R3;
    UNLOCK        global
```

- New memory model: Heterogeneous-race-free (HRF)
  - Adds scoped synchronization
  - No overhead for locally scoped synchronizations
- But higher programming complexity

More efficient coherence, complex consistency

DeNovo Coherence with DRF



for i = r[tid]:r[tid+1]
LOCK
LD R1, A[i];
LD R2, B[i];
R3 ← Math(R1, R2);
ST B[i], R3;
UNLOCK

- Reuse dirty data across synch points – more data reuse
- Synchronization accesses can be performed at L1 – synch reuse

Efficient coherence, simple consistency

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- HeteroSync
  - Synchronization Primitives Microbenchmarks
  - Relaxed Atomics Microbenchmarks
- Results
- Conclusion

Synchronization Primitives Microbenchmarks

- SyncPrims microbenchmarks [Stuart CoRR ’11]:
  - Originally studied synchronization primitive latency
  - Focus: performance of atomic operations
  - Less Focus: overheads of proper synchronization
    - No global data accesses
- Microbenchmarks:
  - Mutexes: Spin (with backoff), centralized ticket, ring buffer
  - Semaphores: Spin (with backoff)
  - Barriers: Centralized, decentralized barriers

Synchronization Primitives Microbenchmarks

- Updates [Sinclair MICRO '15]:
  - Global data accesses in critical sections
  - Synchronization loads and stores to enforce ordering
  - Two versions of each microbenchmark: local/global scope
  - Optimize algorithms

- Microbenchmarks:
  - Mutexes: Spin (with backoff), centralized ticket, ~~ring buffer~~ decentralized ticket
  - Semaphores: Spin (with backoff)
  - Barriers: Centralized, decentralized 2-level tree barriers + local exchange

Can vary data size, scope, synchronization primitive

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Relaxed Atomic (RAts) Microbenchmarks

- Contacted vendors, developers, and researchers
  - Common uses of relaxed atomics [Sinclair ISCA ‘17]:

Event Counters	Place events into bins
Seqlocks	Sequence number instead of mutex lock
Flags	Shared flag for inter-thread communication
Split Counters	Simultaneously update and get partial sums
Ref Counters	Track threads using an object; delete if none

Can vary data size, algorithm

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Evaluation Methodology

- 1 CPU core + 1-15 GPU compute units (CU)
  - Each node has private L1, scratchpad, tile of shared L2
- Simulation Environment
  - GEMS, Simics, Garnet, GPGPU-Sim
- HeteroSync microbenchmarks
  - SyncPrims: weak scaling
  - Relaxed Atomics: strong scaling

Configurations Studied

Studied GPU, DeNovo coherence with DRF0, DRFrlx, HRF

Abbreviation	Coherence	Consistency
GD0	GPU	DRF0
DD0	DeNovo	DRF0
GDR	GPU	DRFrlx
DDR	DeNovo	DRFrlx

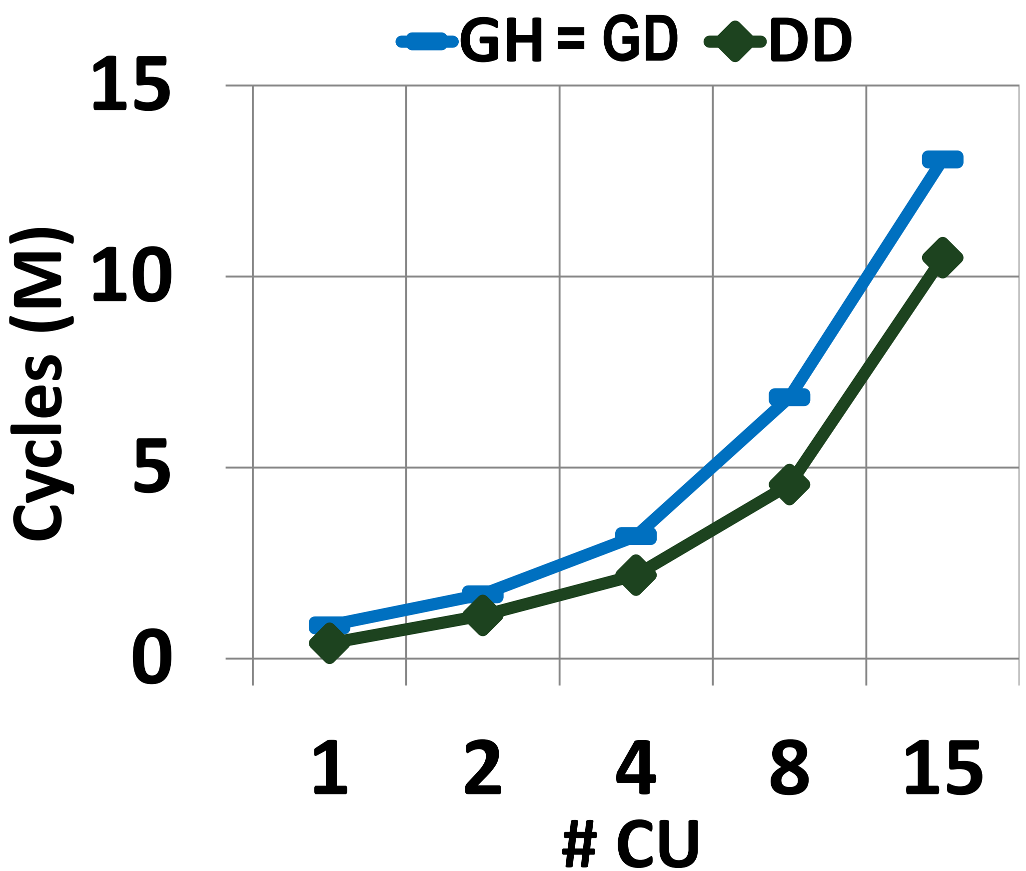
SyncPrims

Relaxed Atomics

Key Evaluation Questions

- How are coherence/consistency schemes impacted?
  - Do certain algorithms scale better than others?
  - How does an algorithm scale with local/global scope?
  - Do relaxed atomics impact scalability?

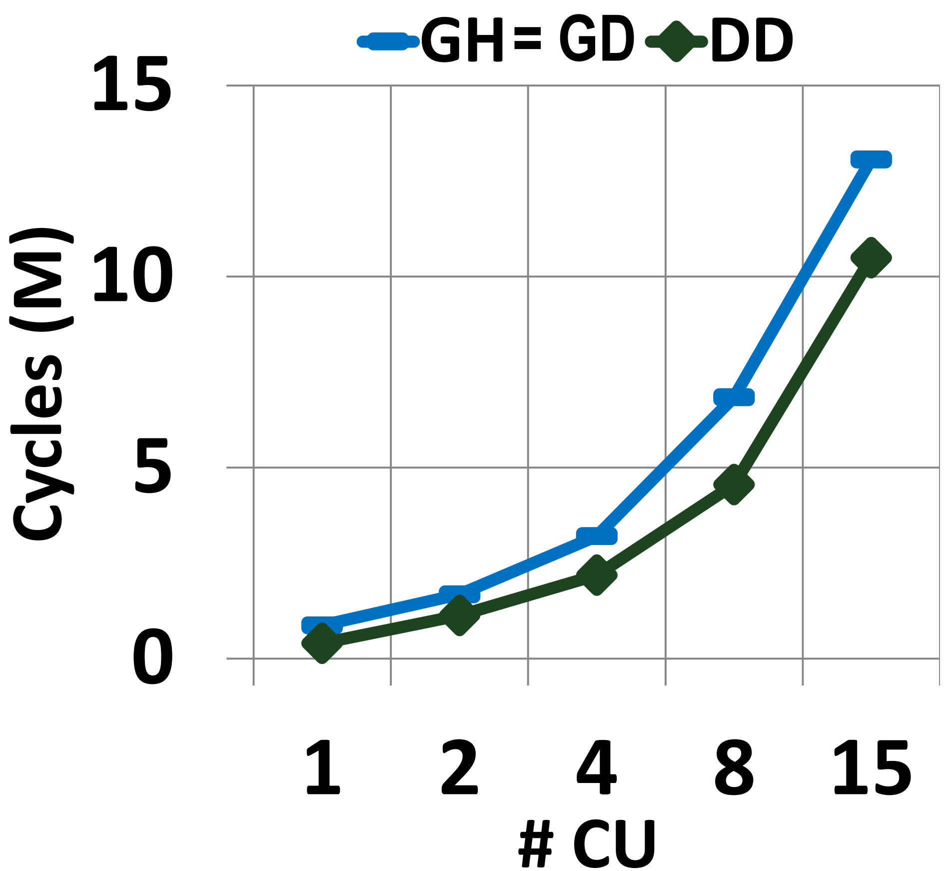
Centralized Ticket Lock Scalability (Global Scope)

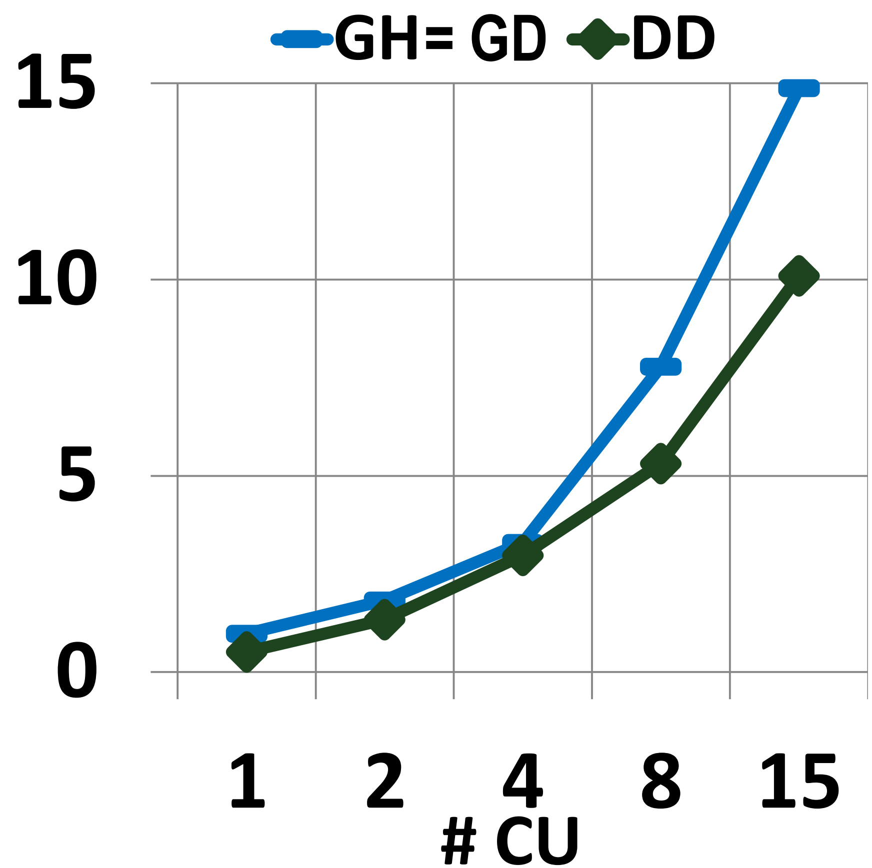


As CUs increase, execution time increases due to increased contention

DeNovo+DRF is able to reuse synch, so scales 20% better than GPU+HRF

Centralized vs. Decentralized (Global Scope)





As CUs increase, execution time increases due to increased contention

Decentralized ticket lock scales better than centralized with DeNovo+DRF

For decentralized, DeNovo+DRF scales 32% better than GPU+HRF

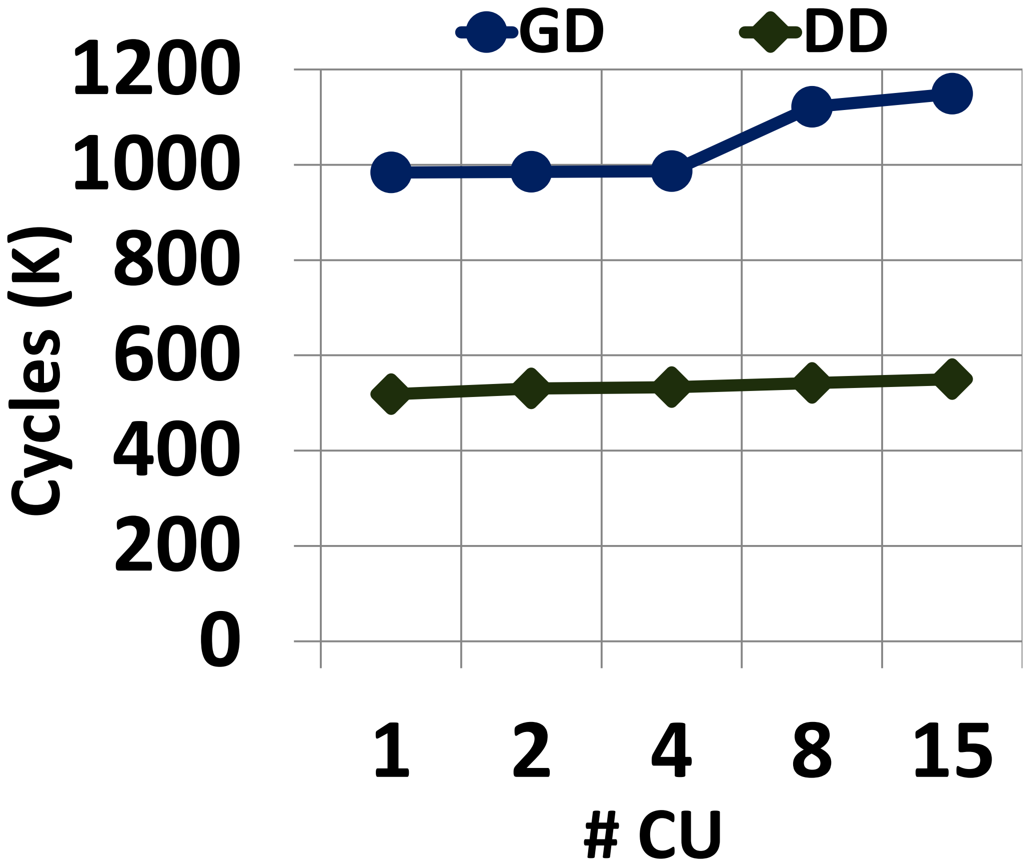
Key Evaluation Questions

- **How are coherence/consistency schemes impacted?**
  - **Do certain algorithms scale better than others?**

  Coherence protocol impacts which algorithm scales better

  - **How does an algorithm scale with local/global scope?**
  - **Do relaxed atomics impact scalability?**

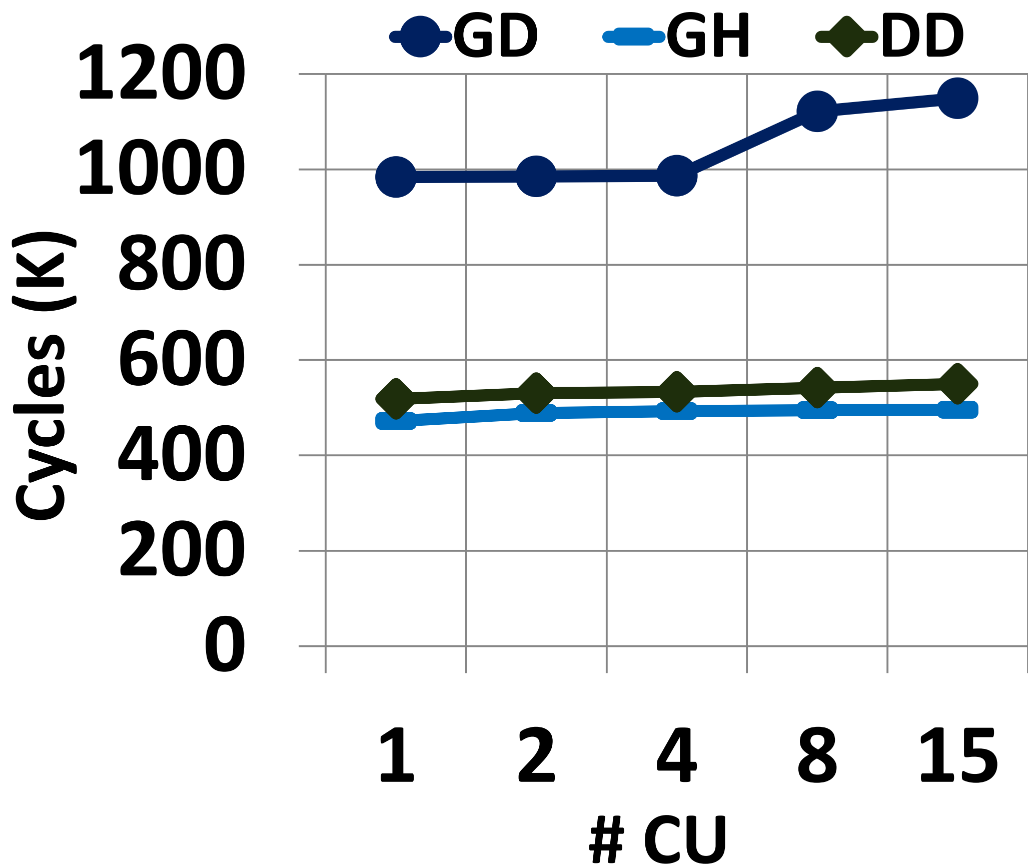
Decentralized Ticket Lock Scalability (Local Scope)



GPU+DRF cannot perform atomics locally, contention increases with # CUs

DeNovo+DRF exploits locality

Decentralized Ticket Lock Scalability (Local Scope)



GPU+DRF cannot perform atomics locally, contention increases with # CUs

DeNovo+DRF exploits locality

GPU+HRF also exploits locality, but increased programming complexity

Key Evaluation Questions

- How are coherence/consistency schemes impacted?
  - Do certain algorithms scale better than others?

  Coherence protocol impacts which algorithm scales better

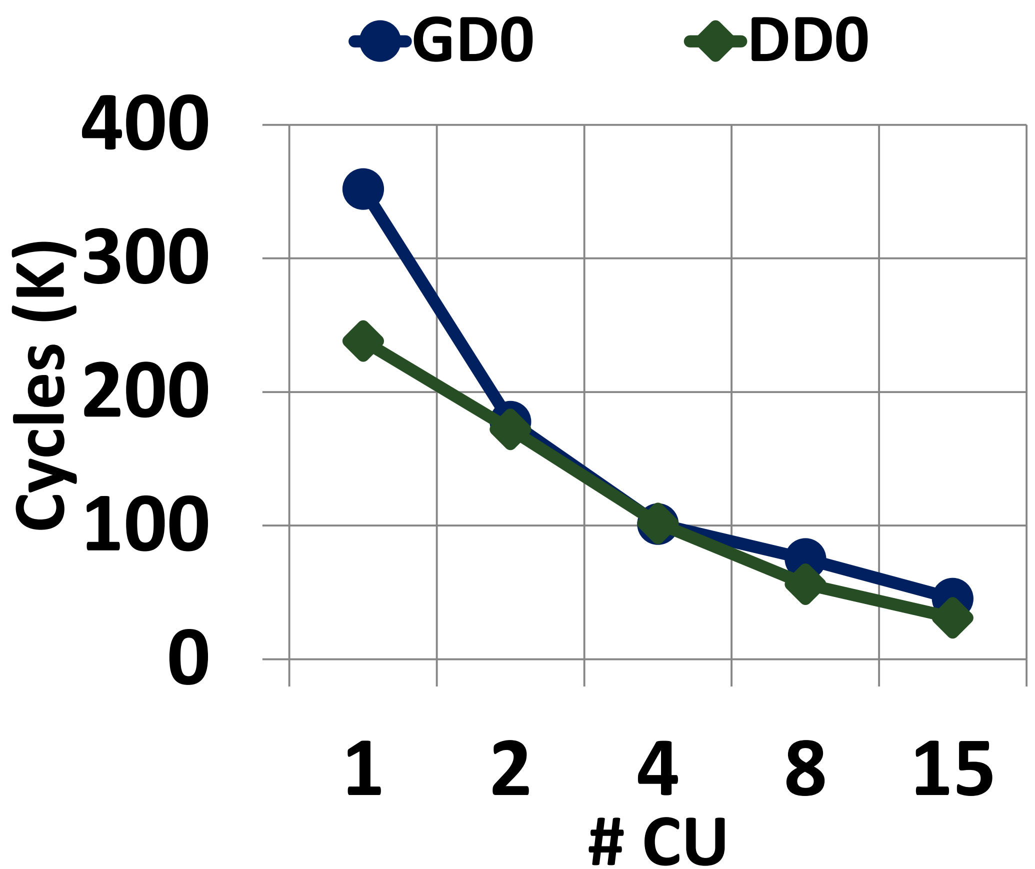
  - How does an algorithm scale with local/global scope?

  DeNovo+DRF provides best scalability with global scope

  GPU+HRF and DeNovo+DRF both scale well with local scope

  - Do relaxed atomics impact scalability?

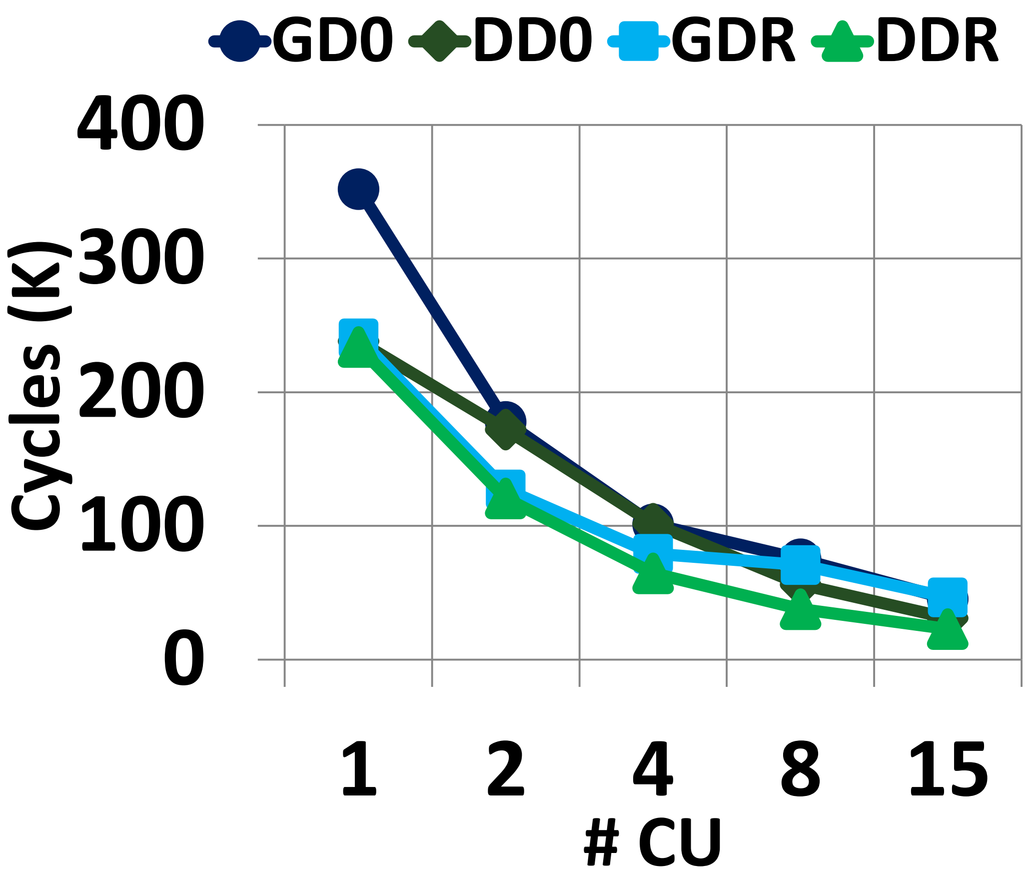
Split Counters Scalability



Execution time significantly reduced as work spread across more CUs

DeNovo+DRF0: tradeoff between increased reuse, remote accesses

Split Counters Scalability



Execution time significantly reduced as work spread across more CUs

DeNovo+DRF0: tradeoff between increased reuse, remote accesses

Relaxed atomics reduce execution time compared to DRF0

Key Evaluation Questions

- How are coherence/consistency schemes impacted?
  - Do certain algorithms scale better than others?

Coherence protocol impacts which algorithm scales better

  - How does an algorithm scale with local/global scope?

DeNovo+DRF provides best scalability with global scope

GPU+HRF and DeNovo+DRF both scale well with local scope

  - Do relaxed atomics impact scalability?

Relaxed atomics reduce execution time, but increase contention

Compare schemes and scalability with HeteroSync

Summary

- HeteroSync: fine-grained GPU synch microbenchmarks
  - Synchronization primitives: mutexes, semaphores, barriers
  - Relaxed atomics: event counters, split counters, seqlocks, …
  - Highly configurable
- Study algorithms, coherence, and consistency
  - Examine scalability of existing approaches
- Standard set of GPU microbenchmarks
  - Released soon: github.com/mattsinc/heterosync