Chasing Away RAts: Semantics and Evaluation for Relaxed Atomics on Heterogeneous Systems

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“Everyone (thinks they) can cook” use relaxed atomics (RAts)

Correctness Health code violations:

Incorrect usage moth No formal definition  fly Not portable

Hard to debug  ant Out-of-thin-air values  ant
C++17 "specification" for relaxed atomics

- Races that don't order other accesses
- Implementations should ensure no “out-of-thin-air” values are computed that circularly depend on their own computation

“C++ (relaxed) atomics were the worst idea ever. I just spent days (and days) trying to get something to work. ... My example only has 2 addresses and 4 accesses, it shouldn’t be this hard. Can you help?”

- Email from employee at major research lab

Formal specification for relaxed atomics is a longstanding problem
Why Use Relaxed Atomics?

- But generally use simple, SW-based coherence
  - Cost of staying away from relaxed atomics too high!
Our Approach

• Previous work
  – Goal: formal semantics for all possible relaxed atomics uses
  – Unsuccessful despite ~15 years of effort

• Insight: analyze how real codes use relaxed atomics
  – What are common uses of relaxed atomics?
  – Why do they work?
  – Can we formalize semantics for them?
Contributions [ISCA ‘17]

- Identified common uses of relaxed atomics
  - Work queues, event counters, ref counters, seqlocks, …
- Data-race-free-relaxed (DRFrIx) memory model:
  - Sequentially consistent (SC) centric semantics + efficiency
- Evaluated benefits of using relaxed atomics
  - Up to 53% less cycles (33% avg), 40% less energy (20% avg)

Everyone can safely use RAts
• Motivation
• **Background**
• Data-race-free-relaxed
• Results
• Conclusion
Atomics Background

• Default: Data-race-free-0 (DRF0) [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
• Default: Data-race-free-0 (DRF0) [ISCA ‘90]
  – All atomics order data accesses
  – Atomics order other atomics
  ⇒ Ensures SC semantics if no data races

• Data-race-free-1 (DRF1): unpaired atomics [TPDS ‘93]
  + Unpaired atomics do not order data accesses
  – Atomics order other atomics
  ⇒ Ensures SC semantics if no data races

• Relaxed atomics [PLDI ‘08]
  + Do not order data or other atomics
  ⇒ But can violate SC and no formal specification
Outline

- Motivation
- Background
  - Data-race-free-relaxed
- Results
- Conclusion
Identifying Relaxed Atomic Use Cases

• Our Approach
  – What are common uses of relaxed atomics?
  – Why do they work?
  – Can we formalize semantics for them?

• Contacted vendors, developers, and researchers

How do relaxed atomics work in Event Counters?
Event Counter

- Threads concurrently update counters
  - Read part of a data array, updates its counter
• Threads concurrently update counters
  – Read part of a data array, updates its counter
  – Increments race, so have to use atomics
• Threads concurrently update counters
  – Read part of a data array, updates its counter
  – Increments race, so have to use atomics

Commutative increments: order does not affect final result

How to formalize?
• New relaxed atomic category: commutative
• Formalism:
  – Accesses are commutative
  – Intermediate values must not be observed
⇒ Final result is always SC

What about the other use cases?
<table>
<thead>
<tr>
<th>Use Case</th>
<th>Category</th>
<th>Semantics</th>
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</thead>
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<td>Work Queues</td>
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<td>SC</td>
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<tr>
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Evaluation Methodology

• 1 CPU core + 15 GPU compute units (CU)
  – Each node has private L1, scratchpad, tile of shared L2

• Simulation Environment
  – GEMS, Simics, Garnet, GPGPU-Sim, GPUWattch, McPAT

• Study DRF0, DRF1, DRFrlx w/ GPU & DeNovo coherence

• Workloads
  – Microbenchmarks for each use case
    • Relaxed atomics help a little (Avg: 10% cycles, 5% energy)
  – Benchmarks with biggest RAts speedups on discrete GPU
    • UTS, PageRank (PR), Betweenness Centrality (BC)
Relaxed Atomics Applications – Execution Time

- G0 = GPU coherence + DRF0
- G1 = GPU coherence + DRF1
- GRlx = GPU coherence + DRFlx
- D0 = DeNovo coherence + DRF0
- D1 = DeNovo coherence + DRF1
- DRlx = DeNovo coherence + DRFlx
Relaxed atomics reduce cycles up to ~50%
DeNovo increases reuse over GPU: 10% avg. for DRFrlx
Energy similar to execution time trends

DeNovo’s reuse reduces energy over GPU: 29% avg. for DRFrlx
Conclusion

- Cost of avoiding relaxed atomics too high
- Difficult to use correctly: no formal specification
- Insight: Analyze how real codes use relaxed atomics

DRFrlx: SC-centric semantics + efficiency

Everyone can safely use RAts
BACKUP
“If you think you understand quantum computers, it’s because you don’t. Quantum computing is actually harder than memory consistency models.”

- Luis Ceze, video in ISCA ‘16 Keynote

Memory consistency: gold standard for complexity

Relaxed atomics add even more complexity
Consistency is Complex

How hard are consistency models?

Memory consistency: gold standard for complexity
Atomics in Data-Race-Free-0 (DRF0)

- Default: DRF0 [ISCA ‘90]
  - All atomics order data accesses
  - Atomics order other atomics

⇒ Ensures SC semantics

Precludes data reuse and overlapping atomics
• Unpaired atomics do not order any data accesses
  + Avoids invalidations and flushes
    – Atomics order other atomics

⇒ Ensures SC semantics

Can reuse data but cannot overlap atomics
Relaxed Atomics

- Relaxed atomics do not order data or other atomics
  + Reorder, overlap with all other memory accesses

But can violate SC and no formal specification
• Threads simultaneously access counters
  – Some threads update their counter
  – Other threads read all counters to get the current partial sum
  – Counter accesses race, so must use atomics
• Can reorder, overlap relaxed atomics from same thread
  – Results may not be SC – programmers ok with approx values

• DRFrlx
  – Distinguish quantum atomics
    • Quantum atomic loads logically return approximate value
    – Program is DRFrlx if DRF1 and no races in new program
Cost of staying away too high!
Incorporating Other Use Cases Into DRFrlx

Work Queues

Seqlocks

Reference Counters

Flags

Split Counters
## Incorporating Other Use Cases Into DRFRlx

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Relaxed Atomics Microbenchmarks – Execution Time

- GD0 = GPU coherence + DRF0
- GD1 = GPU coherence + DRF1
- GDR = GPU coherence + DRFrlx
- DD0 = DeNovo coherence + DRF0
- DD1 = DeNovo coherence + DRF1
- DDR = DeNovo coherence + DRFrlx
Relaxed Atomics Microbenchmarks – Execution Time

Weakening the consistency model does not significantly improve perf
DRFrlx allows atomics to be overlapped (7% avg improvement for GPU)
Relaxed Atomics Microbenchmarks – Execution Time

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Weakening the consistency model does not significantly improve perf
DRFrlx allows atomics to be overlapped (7% avg improvement for GPU)
DeNovo exploits synch reuse, outperforms GPU (DRFrlx: 10% avg)
Relaxed Atomics Microbenchmarks – Energy

Energy trends somewhat similar to execution time

DRFrlx: DeNovo reduces energy by 4% over GPU
Weakening memory model helps a lot (up to 51% for GPU)
DRF1 increases data reuse (21% avg vs. GD0)
DRFrilx overlaps atomics (15% avg vs. GD1)
• New relaxed atomic type for each category
  – Formalize when an atomic falls into category
  – SC(-centric) semantics if use relaxed atomics correctly

Strongest (SC)

Unpaired
SC: Reorder unpaired with data accesses

Non-Ordering
SC: atomics do not order other accesses

Commutative
Final result always SC

Speculative
Final result always SC (retry violations)

Quantum
Isolate non-SC parts

Weakest (SC-centric)