Tradeoffs in Transactional Memory Virtualization

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TM Virtualization

- Transactional Memory (TM)
  - TM is a promising solution for parallel programming
  - Hardware TM delivers best performance
    - But, hardware resources are limited

- Virtualization of hardware TM systems
  - What if cache capacity is exhausted?
    - Space virtualization: cache overflow, paging, thread migration, …
  - What if a transaction is interrupted?
    - Time virtualization: interrupts, context switches, …
  - What if transactions are deeply nested?
    - Depth virtualization
  - It is crucial to address these issues properly for practical HTMs

Design Options for TM Virtualization

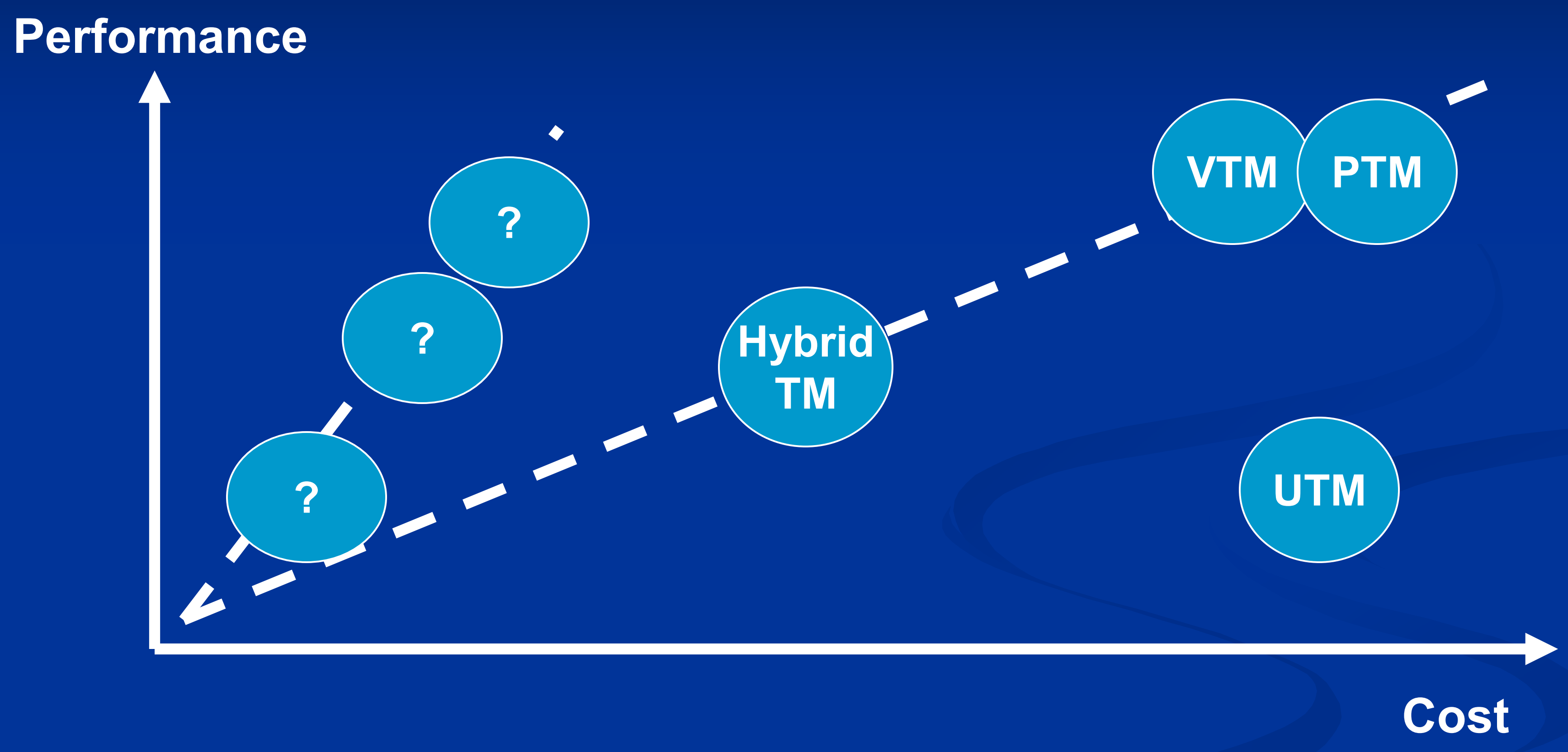
- TM is virtualized by overflowing transactions to VM
  - It is yet another TM system implementation
- Granularity of data management
  - Word Vs. cache-line Vs. page level
- Conflict detection strategy
  - Optimistic Vs. pessimistic
- Implementation approach
  - Hardware & firmware Vs. operating system Vs. user software
- See paper for detailed discussion on options

Previous Work

- Hardware solutions
  - UTM [HPCA'05], VTM [ISCA'05], PTM [ASPLOS'06]
    - Primarily cache-line granularity
    - Hardware manages overflowed data and metadata in virtual memory
  - \+ Good performance for all workload cases
  - − Expensive, extra hardware mostly idle

- User software solutions
  - Hybrid TM [PPoPP'06 & ASPLOS' 06]
    - Primarily object level granularity
    - Software TM for virtualization, hardware TM for acceleration
  - \+ No additional hardware
  - − Two versions of code, lower performance in some cases

Virtualization Design Space



- Tradeoff: common-case performance Vs. HW/SW cost
- Overflows, interrupts, and deep nesting are rare [HPCA'06]

XTM: eXtended TM

- Goals
  - Virtualize all 3 dimensions of TM (space, time, depth)
  - Low HW cost and completely transparent to user SW
  - Does not slow down coexisting HW transactions
- Assumption
  - Overflows, interrupts, and deep nesting are rare [HPCA'06]
- Key idea: virtualization through the operating system
  - Builds upon existing VM support
  - Data versioning & conflict detection at page granularity
  - Similar to page-based software DSM systems
- 3 designs at different performance/cost points
  - XTM-base, XTM-g, XTM-e

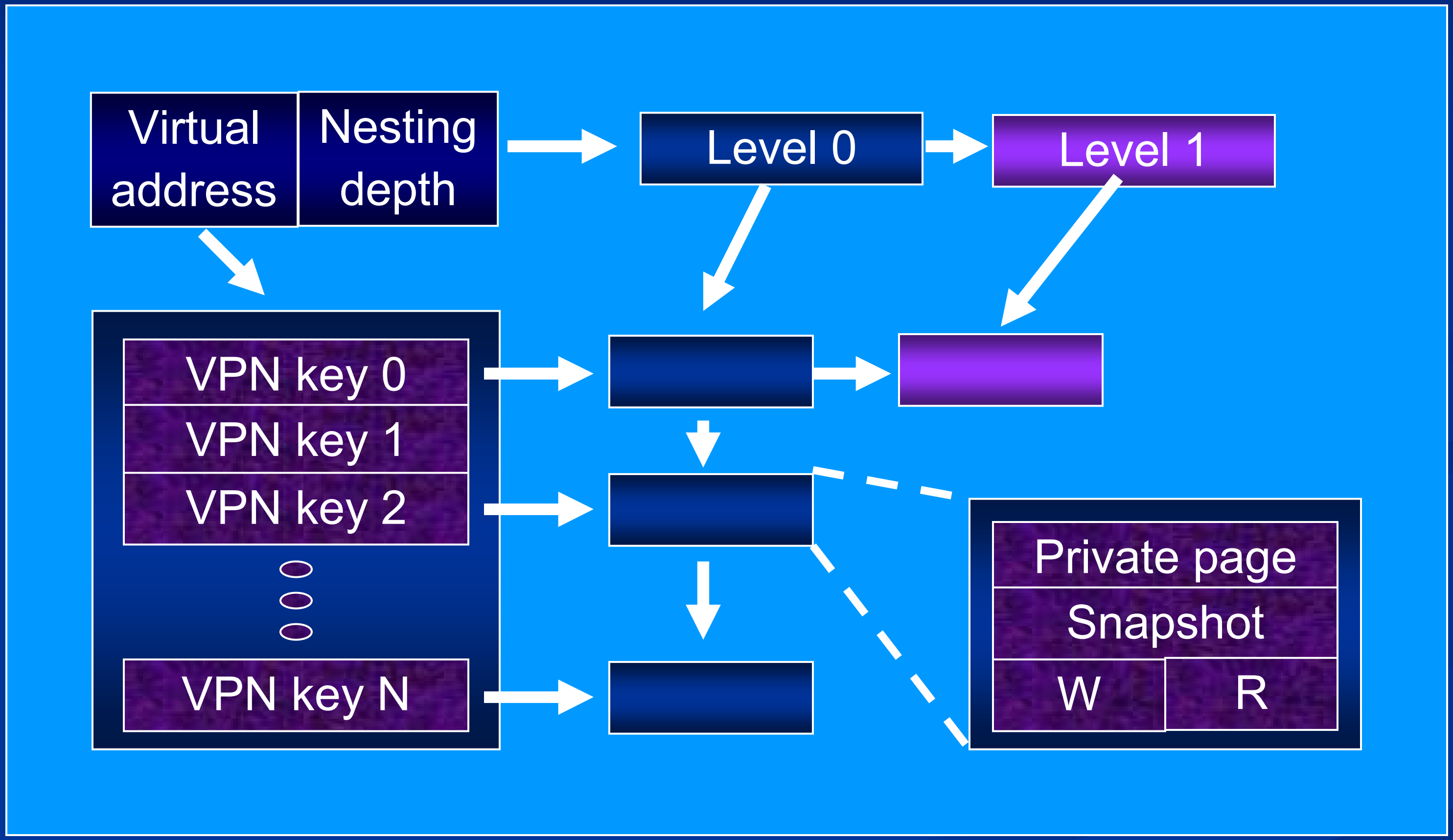
XTM-base Overview

- Basic operation
  - On HTM overflow, rollback and restart in SW mode
  - At the first access, create a copy of original (master) page
    - Change the address mapping to the copy (private page)
    - Transactional data in private page, committed data in master page
  - At commit, make the private page the new master page
  - All orchestrated by the operating system (no HW)
- Conflict detection: pessimistic Vs. optimistic
  - Pessimistic: use TLB shoot-downs to gain exclusive page access
  - Optimistic: use snapshots & diffs before XTM commit
    - No overhead for HW transactions
- See paper for forward progress guarantees for XTM

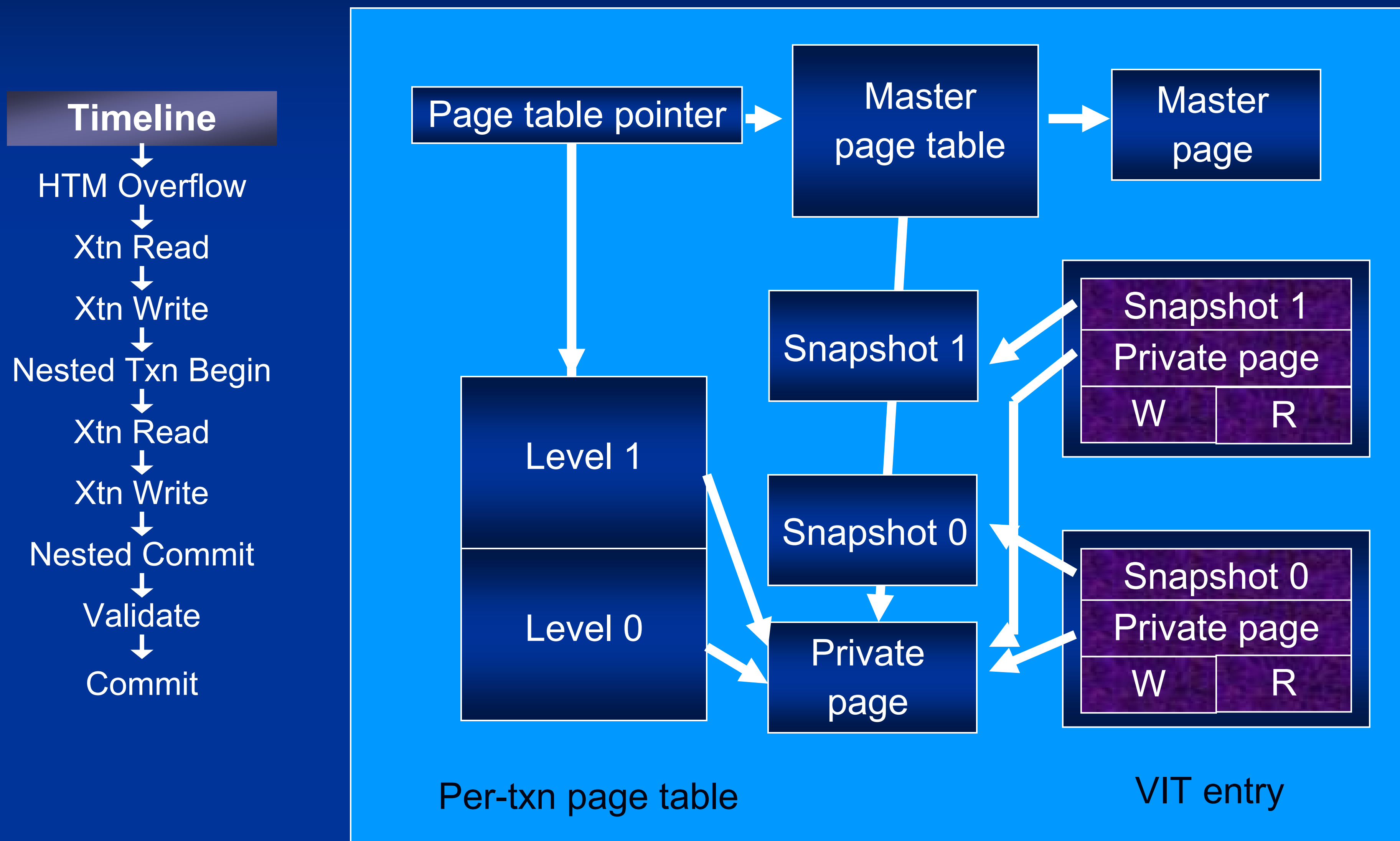
XTM-base Requirements

- Hardware
  - Required: overflow exception
  - Optional: fast page copy mechanism (DMA, SIMD, …)
- Data-structures (software)
  - Per-transaction page table
    - Contains only mappings to private pages, not master pages
    - Populated dynamically
  - Per-core virtualization information table (VIT)
    - Maintains metadata and the pointers to extra pages
  - Data-structures are pre-allocated to reduce overhead

Virtualization Information Table



XTM-base Example



XTM-g: Gradual Overflow

- XTM-base bottleneck: roll-back overhead on overflow

- Gradual overflow
  - On overflow, just flush one or a few pages to XTM
  - A portion of transactional data in private pages, the rest in the cache

- XTM commit
  - First validate both XTM and hardware TM data
  - Then commit the XTM and hardware TM data
  - Requires two-phase commit support [ISCA'06]

- Hardware requirements
  - Overflow bit to remember the pages that have overflowed
  - Per page-table entry, TLB entries, and cache lines

XTM-e: Fine-grain Conflict Detection

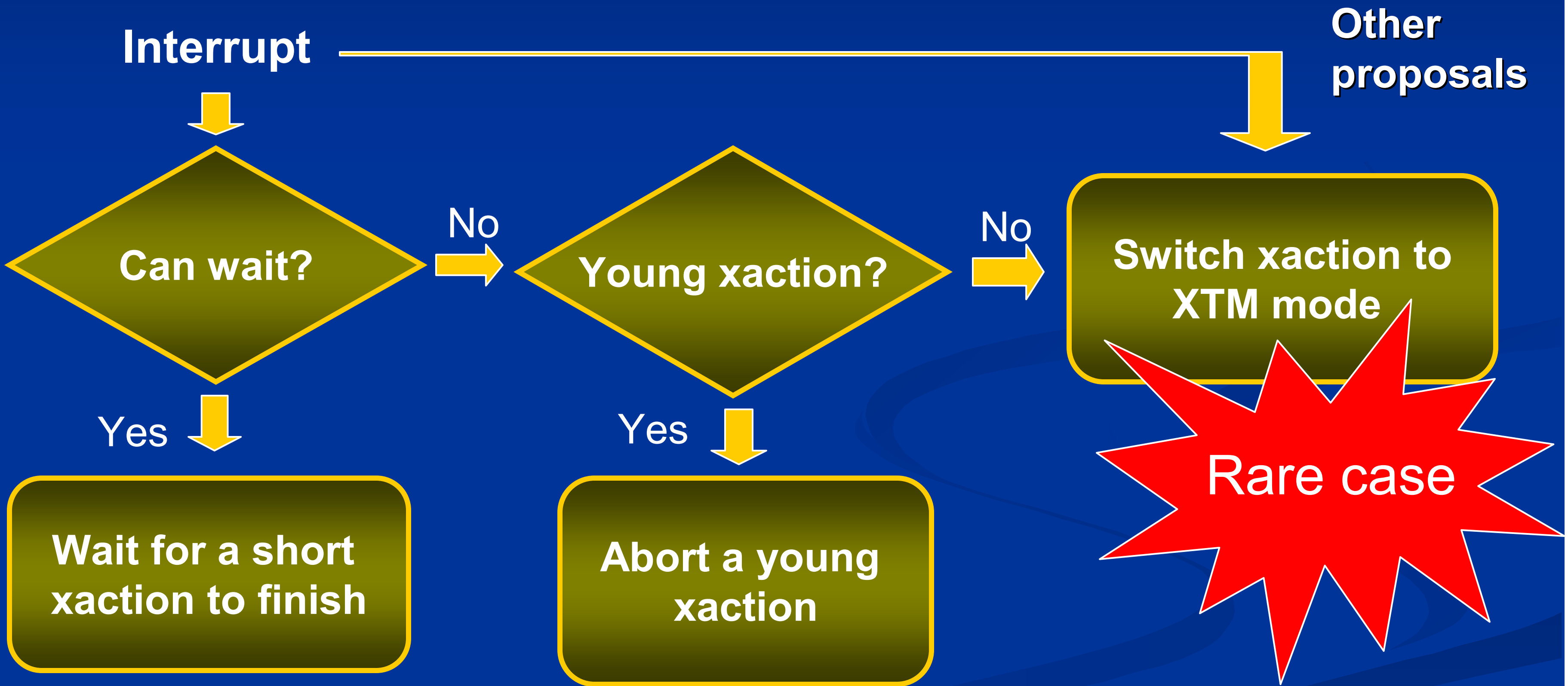
- XTM-g bottleneck: false sharing overhead at page level

- Fine-grain conflict detection
  - When flushing a cache line, record fine-grain metadata bits in VIT
    - Per cache line or per even per word
  - Use fine-grain information on validation
    - Validate only portions of each XTM page

- Requirements
  - SW: extra space in VIT entries for fine-grain metadata
  - HW: eviction buffer for metadata bits (performance enhancement)
    - Needed for cache lines that are reloaded and then evicted
    - Avoids SW handler invocation on each subsequent eviction
    - Buffer is flushed periodically

Time virtualization

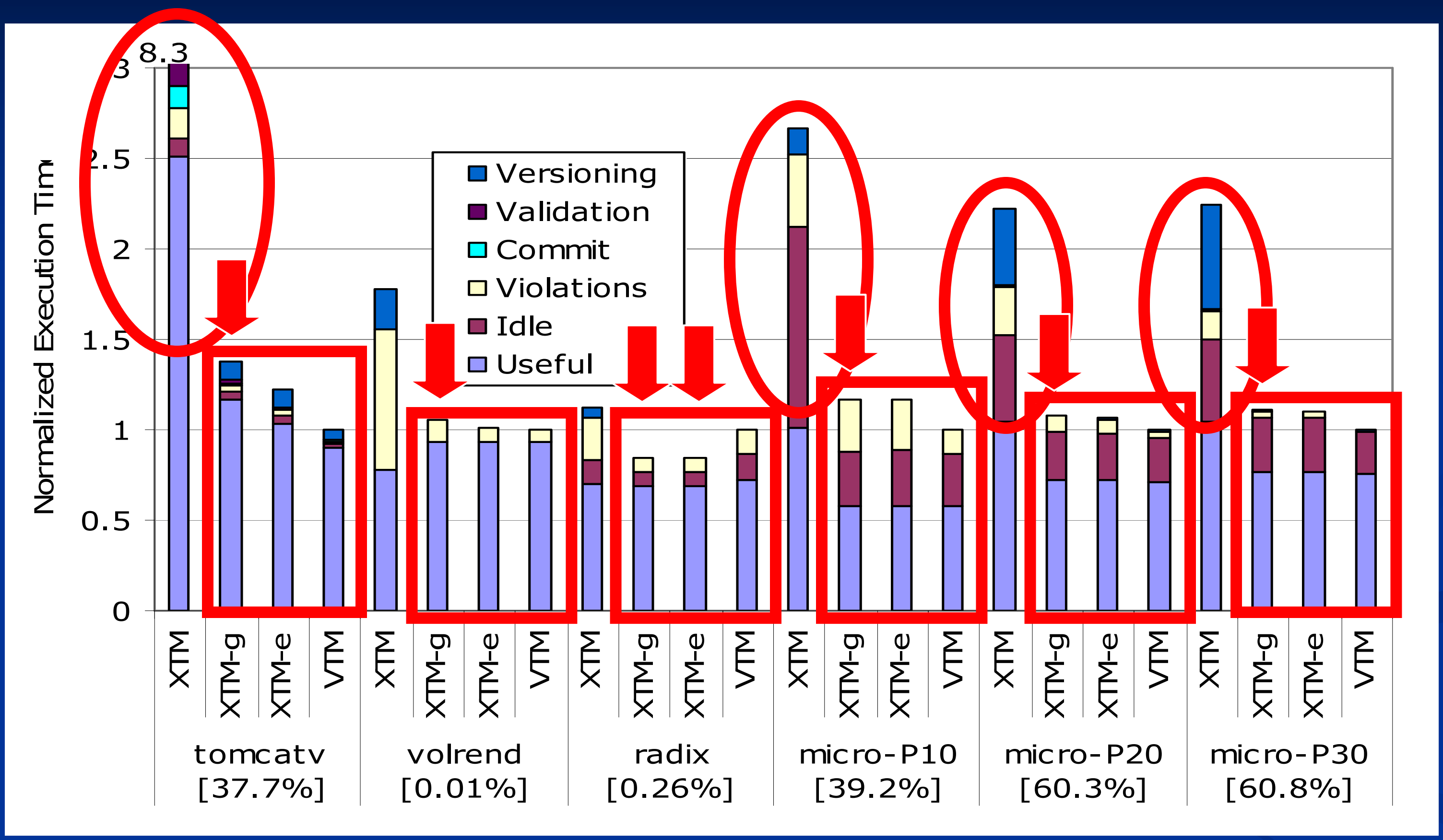
- Interrupt and context-switch procedure



Evaluation

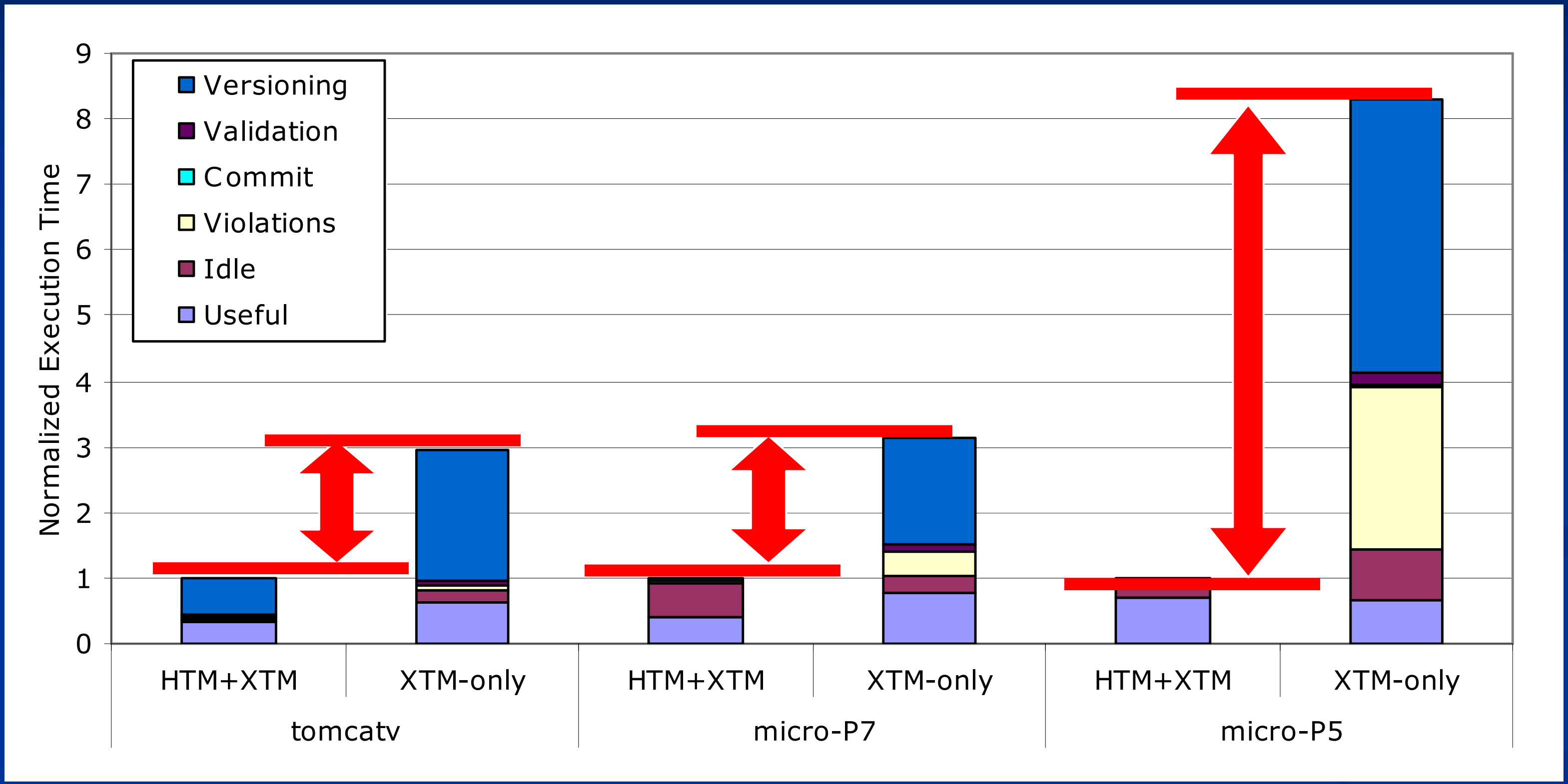
- Execution-driven hardware TM simulator (TCC)
  - XTM series and VTM are compared
  - 32KB cache for transactional buffering
- Applications
  - SPLASH-2, SPEC, and micro-benchmarks
  - **Important**: many applications did not invoke XTM at all
    - XTM introduces no HW cost or overhead for them
- Experiments
  - Overall performance analysis
  - XTM-only transactional memory
  - More results in the paper
    - Memory pressure, sensitivity to cache size, time virtualization evaluation, …

Performance Analysis



- XTM-base showed 3x to 8x slowdown for applications with frequent overflow
  - It causes no overhead for most applications that don't overflow
- XTM-g presents a good cost/performance tradeoff point
  - 20% faster to 50% slower than VTM

XTM-only Transactional Memory?



- There is a clear performance gap between HTM + XTM and XTM-only
  - It is 3x to 8x slower than hardware TM
- Hardware support is important for transactional memory

Conclusions

- TM is a promising solution for parallel programming
- Hardware TM delivers a good performance
  - Challenges for HTM : overflows, interrupts, deep nesting, …
  - TM virtualization is a crucial component for practical HTMs
- XTM: virtualization through the operating system
  - Virtualizes TM space, time, and depth
  - Low HW cost and completely transparent to user SW
  - proposes 3 designs of different tradeoff points
    - XTM-base: SW only solution
    - XTM-g: eliminates rollback overhead with Overflow bit
    - XTM-e: eliminates false sharing with more HW support
- We hope that this work helps build practical HTM systems

Questions?

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