Eliminating Global Interpreter Locks in Ruby through Hardware Transactional Memory

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Global Interpreter Locks in Scripting Languages

- Scripting languages (Ruby, Python, etc.) everywhere. → Increasing demand on speed.

- Many existing projects for single-thread speed.
  - JIT compiler (Rubinius, ytljit, PyPy, Fiorano, etc.)
  - HPC Ruby
- Multi-thread speed restricted by global interpreter locks.
  - Only one thread can execute interpreter at one time.
    - ☺ No parallel programming needed in interpreter.
    - ☹ No scalability on multi cores.

Hardware Transactional Memory (HTM) Coming into the Market

- Improve performance by simply replacing locks with TM?
- Realize lower overhead than software TM by hardware.

IBM

Blue Gene/Q
2012

Sun Microsystems

Rock Processor
Cancelled

IBM

zEC12
2012

Intel

Transactional
Synchronization
eXtensions, 2013

Our Goal

- What will the performance of real applications be if we replace GIL with HTM?
  - Global Interpreter Lock (GIL)
- What modifications and new techniques are needed?

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- What will the performance of real applications be if we replace GIL with HTM?
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✓ Eliminate GIL in Ruby through zEC12's HTM
✓ Evaluate Ruby NAS Parallel Benchmarks

```
atomic { }
```

zEC12

Related Work

- Eliminate Python's GIL with HTM
  - ☹ Micro-benchmarks on non-cycle-accurate simulator [Riley et al. ,2006]
  - ☹ Micro-benchmarks on cycle-accurate simulator [Blundell et al., 2010]
  - ☹ Micro-benchmarks on Rock's restricted HTM [Tabba, 2010]
- Eliminate Ruby and Python's GILs with fine-grain locks
  - JRuby, IronRuby, Jython, IronPython, etc.
  - ☹ Huge implementation effort
  - ☹ Incompatibility in multithreaded execution of class libraries

✓ Eliminate the GIL in Ruby …
✓ through HTM on a real machine …
✓ and evaluate it using non-micro-benchmarks.
✓ Small implementation effort
✓ No incompatibility problem in the class libraries

Outline

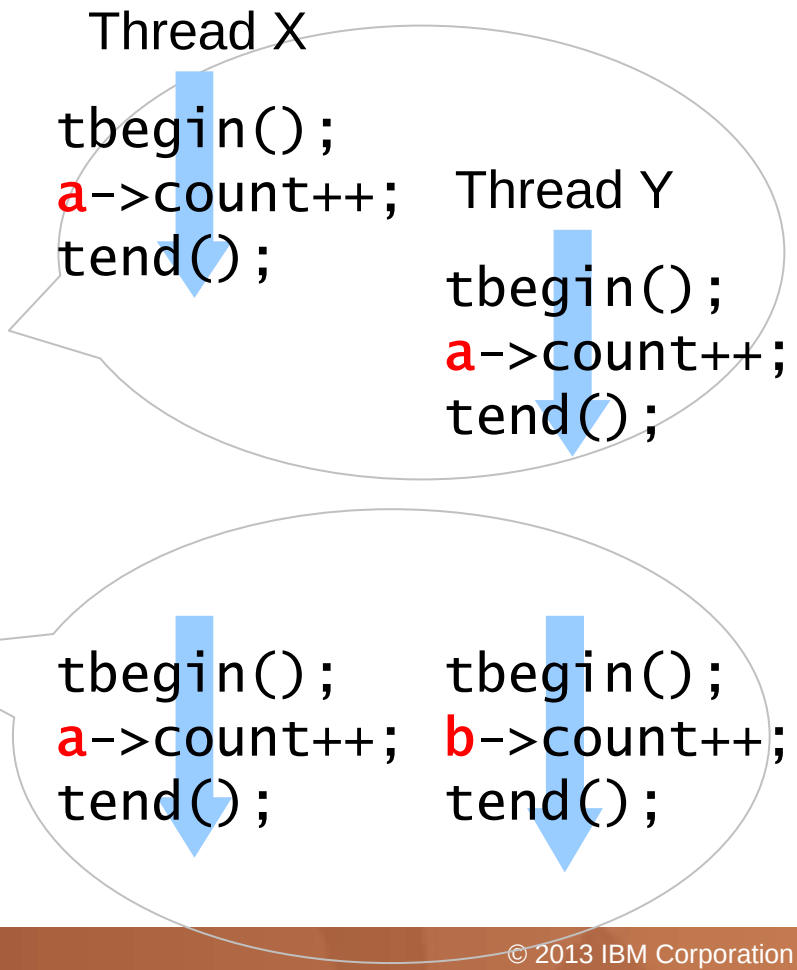
- Motivation
- Transactional Memory
- GIL in Ruby
- Eliminating GIL through HTM
- Experimental Results
- Conclusion

Transactional Memory

```
lock();
a->count++;
unlock();
```

```
tbegin();
a->count++;
tend();
```

- At programming time
  - Enclose critical sections with transaction begin/end instructions.
- At execution time
  - Memory operations within a transaction observed as one step by other threads.
  - Multiple transactions executed in parallel as long as their memory operations do not conflict.
    → Higher parallelism than locks.



HTM in zEC12

```
TBEGIN
if (cc!=0)
  goto abort handler
...
...
TEND
```

- Instruction set
  - TBEGIN: Begin a transaction
  - TEND: End a transaction
  - TABORT, NTSTG, etc.
- Micro-architecture
  - Hold read set in L1 and L2 caches (~2MB)
  - Hold write set in L1 cache and store buffer (8KB)
  - Conflict detection using cache coherence protocol
- Roll back to immediately after TBEGIN in the following cases:
  - Read set and write set conflict
  - Read set and write set overflow
  - Restricted instructions (e.g. system calls)
  - External interruptions, etc.

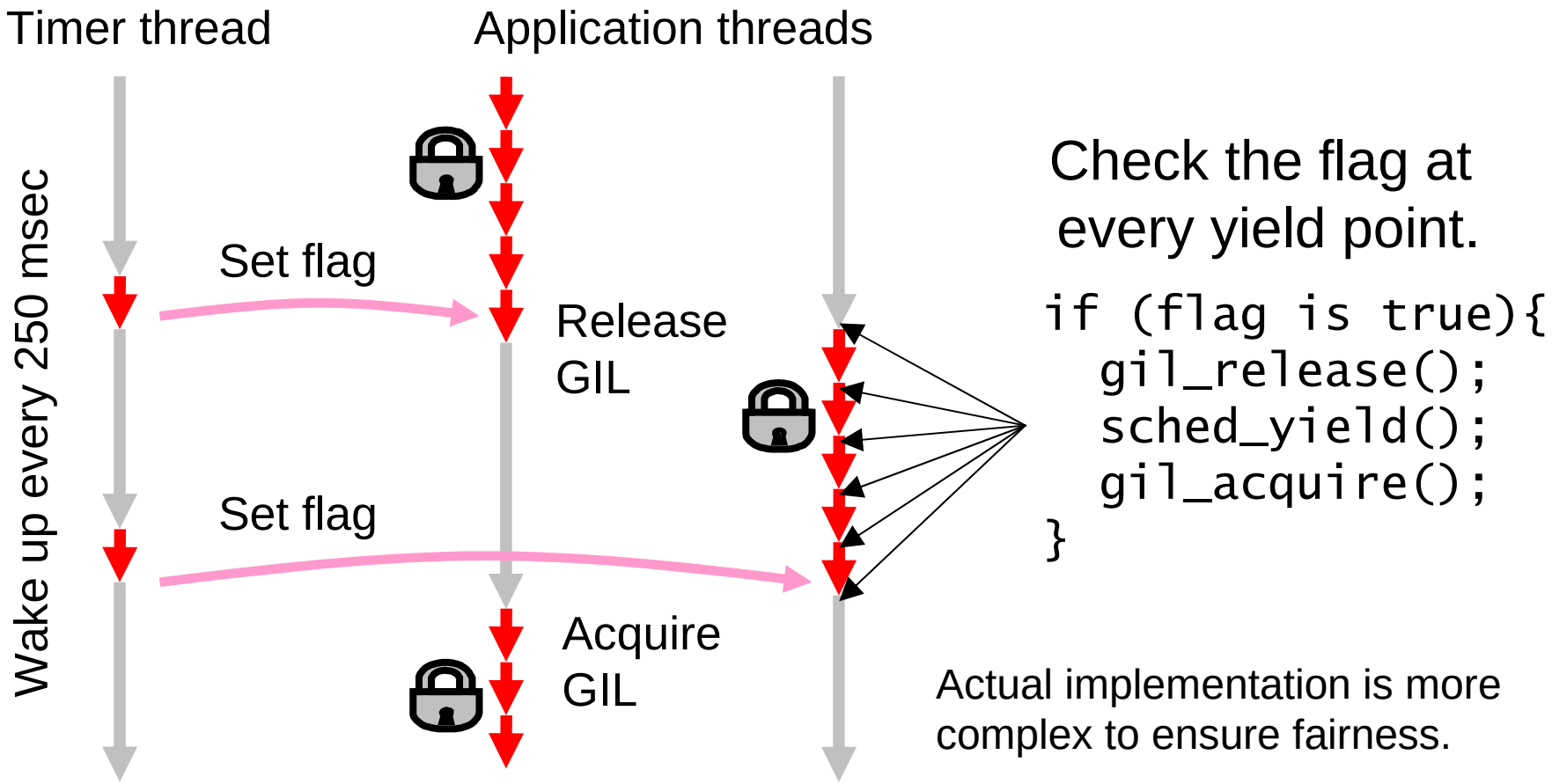
Ruby Multi-thread Programming and GIL based on 1.9.3-p194

- Ruby language
  - Program with Thread, Mutex, and ConditionVariable classes
- Ruby virtual machine
  - Ruby threads assigned to native threads (Pthread)
  - Only one thread can execute the interpreter at any give time due to the GIL.

- GIL acquired/released when a thread starts/finishes.
- GIL yielded during a blocking operation, such as I/O.
- GIL yielded also at pre-defined yield-point bytecode ops.
  - Conditional/unconditional jumps, method/block exits, etc.

How GIL is Yielded in Ruby

- It is too costly to yield GIL at every yield point.
  → Yield GIL every 250 msec using a timer thread.



Outline

- Motivation
- Transactional Memory
- GIL in Ruby
- Eliminating GIL through HTM
  - Basic Algorithm
  - Dynamic Adjustment of Transaction Lengths
  - Conflict Removal
- Experimental Results
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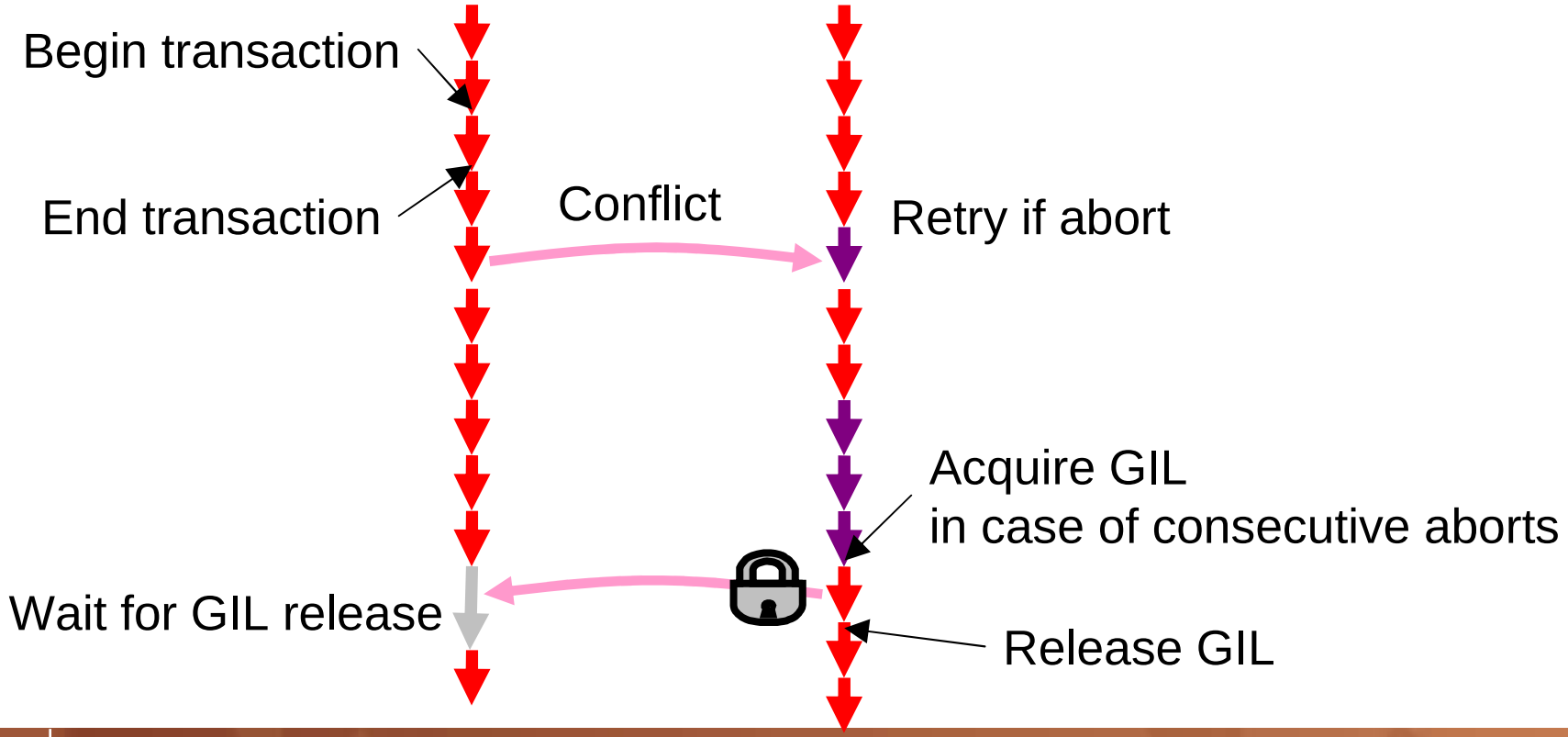
Eliminating GIL through HTM

- Execute as a transaction first.
  - Begins/ends at the same points as GIL's yield points.
- Acquire GIL after consecutive aborts in a transaction.



Beginning a Transaction

- Persistent aborts
  - Overflow
  - Restricted instructions
- Otherwise, transient aborts
  - Read-set and write-set conflicts, etc.
- Abort reason reported by CPU
  - Using a specified memory area

```
if (TBEGIN()) {
  /* Transaction */
  if (GIL.acquired)
    TABORT();
} else {
  /* Abort */
  if (GIL.acquired) {
    if (Retried 16 times)
      Acquire GIL;
    else {
      Retry after GIL release;
  } else if (Persistent abort) {
    Acquire GIL;
  } else { /* Transient abort */
    if (Retried 3 times)
      Acquire GIL;
    else
      Retry;
}}
Execute Ruby code;
```

Where to Begin and End Transactions?

- Should be the same as GIL's acquisition/release/yield points.
  - Guaranteed as critical section boundaries.

☹ However, the original yield points are too coarse-grained.

  - Cause many transaction overflows.

- Bytecode boundaries are supposed to be safe critical section boundaries.
  - Bytecode can be generated in arbitrary orders.
  - Therefore, an interpreter is not supposed to have a critical section that straddles a bytecode boundary.
  - ☹ Ruby programs that are not correctly synchronized can change behavior.

→ Added the following bytecode instructions as transaction yield points.

  - `getinstancevariable, getclassvariable, getlocal, send, opt_plus, opt_minus, opt_mult, opt_aref`
  - Criteria: they appear frequently or are complex.

Ending and Yielding a Transaction

Ending a transaction

```
if (GIL.acquired)
  Release GIL;
else
  TEND();
```

Yielding a transaction (transaction boundary)

```
if (--yield_counter == 0) {
  End a transaction;
  Begin a transaction;
}
```

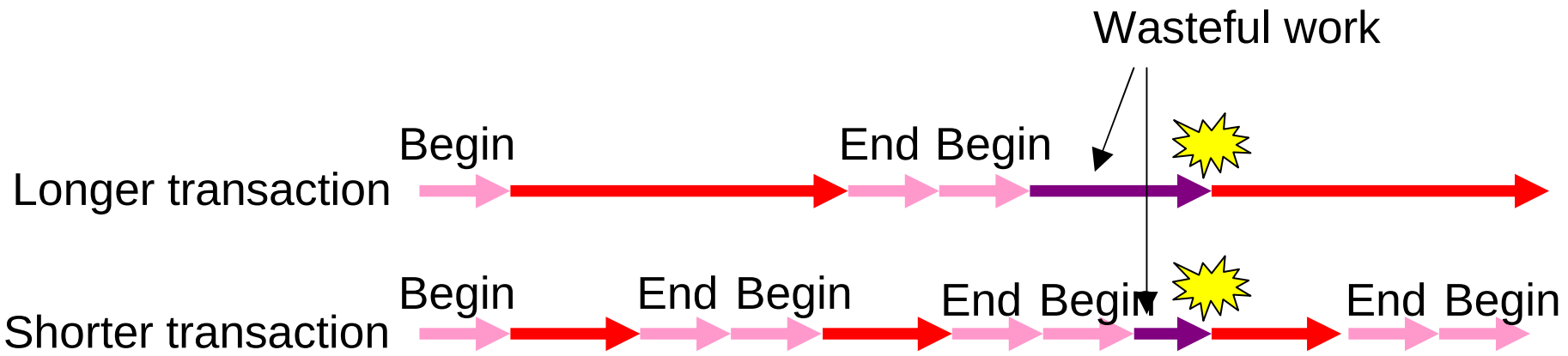
Dynamic adjustment of a transaction length

✓ Source code changes limited to only part of files
←→ Changes for fine-grain locking scattered throughout files

Tradeoff in Transaction Lengths

- No need to end and begin transactions at every yield point.
  = Variable transaction lengths with the granularity of yield points.

- Longer transaction = Smaller relative overhead to begin/end transaction.
- Shorter transaction = Smaller abort overhead
  - Smaller amount of wasteful work rolled-back at aborts
  - Smaller probability of size overflow



Dynamic Adjustment of Transaction Lengths

Adjust transaction lengths on a per-yield-point basis.

1. Initialize with a long length (255).
2. Calculate abort ratio at each yield point base on the following two numbers:
   - Number of transactions started from the yield point
   - Number of aborted transactions started from the yield point
3. If the abort ratio exceeds a threshold (1%), shorten the transaction length (x 0.75) and return to Step 2.
4. If a pre-defined number (300) of transactions started before the abort ratio exceeds the threshold, finish adjustment for the yield point.

5 Sources of Conflicts and How to Remove Them (1/2)

✓Source code needs to be changed for higher performance, but each change is limited to only a few dozen lines.

- Global variables pointing to the current running thread
  - Cause conflicts because they are written every time transactions yield
  - ✓Moved to Pthread's thread-local storage
- Updates to inline caches at the time of misses
  - Cache the result of hash table access for method invocation and instance-field access
  - Cause conflicts because caches are shared among threads.
  - ✓Implemented miss reduction techniques.

5 Sources of Conflicts and How to Remove Them (2/2)

- Manipulation of global free list when allocating objects
  - ✓Introduced thread-local free lists
    - When a thread-local free list becomes empty, take 256 objects in bulk from the global free list.
- Garbage collection
  - Cause conflicts when multiple threads try to do GC.
  - Cause overflows even when a single thread performs GC.
  - ✓Reduced GC frequency by increasing the Ruby heap.
- False sharing in Ruby's thread structures (rb_thread_t)
  - Added many fields to store thread-local information.
    → Conflicted with other structures on the same cache line.
  - ✓Assign each thread structure to a dedicated cache line.

Platform-Specific Optimizations

- Performed spin-wait for a while at GIL contention.
  - Original GIL is acquired and released every ~250 msec.
  - Fallback GIL for HTM is acquired and released far more frequently.
    → Parallelism severely damaged if sleep in OS every time GIL is contended.
  - Some environments already include this optimization in Pthread implementation.
- Implemented our own `setjmp()` without a restricted instruction.
  - `setjmp()` in z/OS contains an address-space manipulation instruction.
  - It suffices to save general-purpose registers for Ruby's purpose.

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Experimental Environment

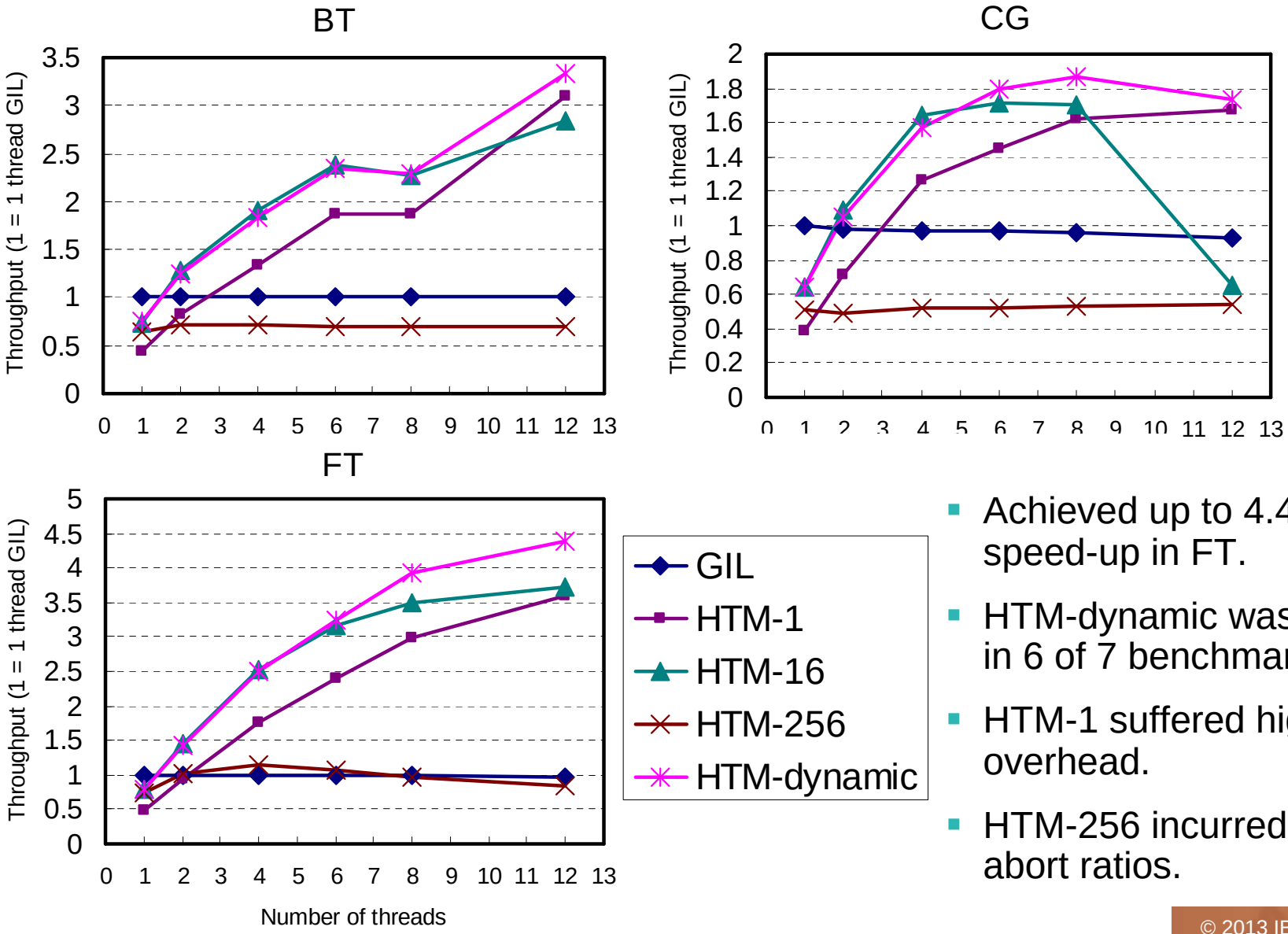
- Implemented in Ruby 1.9.3-p194.
- Ported to z/OS 1.13 UNIX System Services.
  - Not yet succeeded in building full-featured Ruby due to EBCDIC.
  - Instead, used miniruby, which supports core class libraries.
- Experimented on 12-core 5.5-GHz zEC12
  - 1 hardware thread on 1 core
- Configurations
  - GIL: Original Ruby
  - HTM-*n* (*n* = 1, 16, 256):
    Fixed transaction length (Skip *n-1* yield points)
  - HTM-dynamic:
    Dynamic adaptive transaction length

Benchmark Programs

- Two micro-benchmarks
  - Embarrassingly parallel programs running while and iterator loops.
  - 11-fold speed-ups over 1-thread GIL by HTM with 12 threads.
  - At least 5-14% single-thread overhead
- Ruby NAS Parallel Benchmarks (NPB) [Nose et al., 2012]
  - 7 programs translated from the Java version
  - Consist of single-threaded and multi-threaded sections

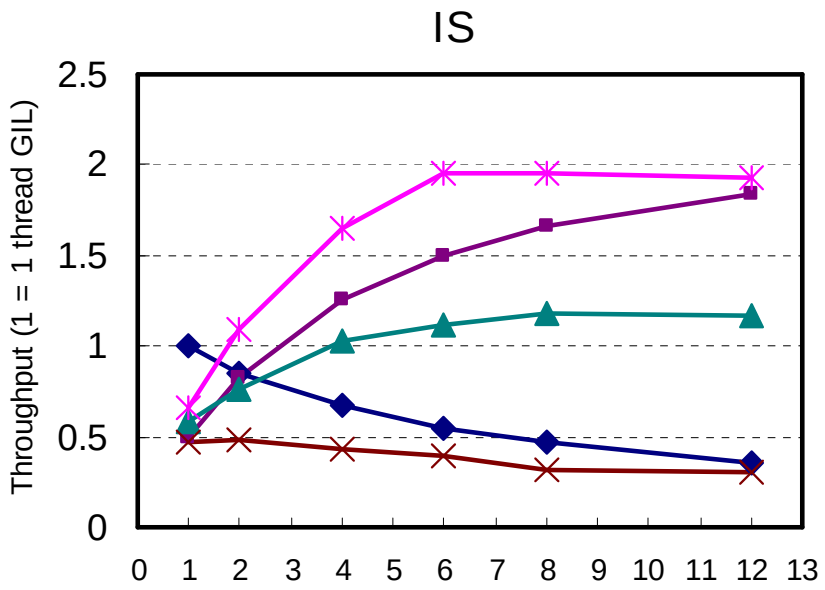
  → Inherent scalability limitation exists.
- Trying to measure Web-based workloads
  - Difficulties in EBCDIC support on z/OS, etc.

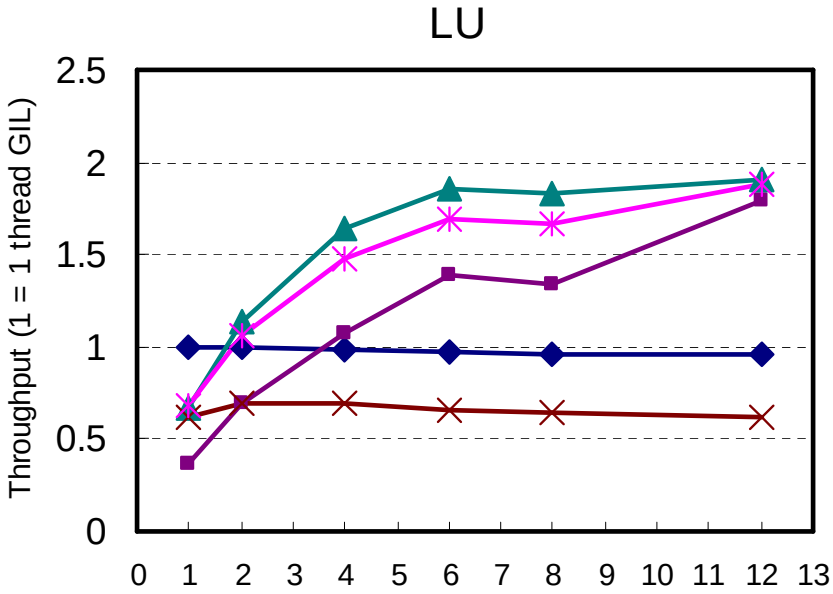
Throughput of Ruby NPB (1/2)

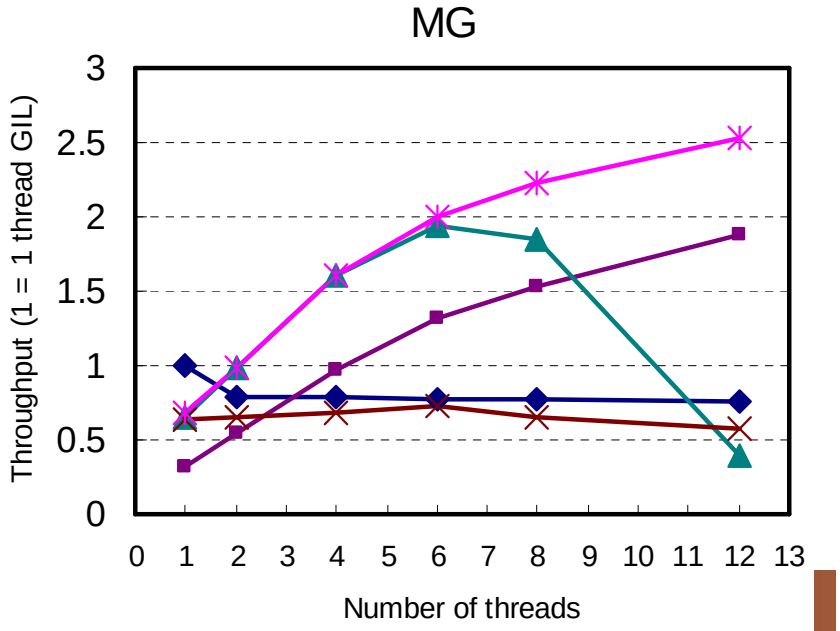


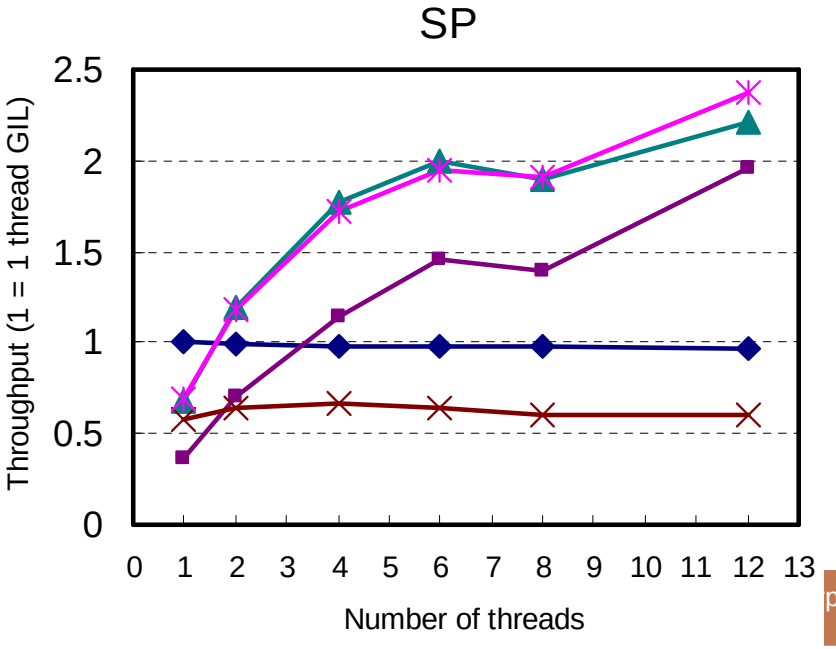
- Achieved up to 4.4-fold speed-up in FT.
- HTM-dynamic was the best in 6 of 7 benchmarks.
- HTM-1 suffered high overhead.
- HTM-256 incurred high abort ratios.

Throughput of Ruby NPB (2/2)



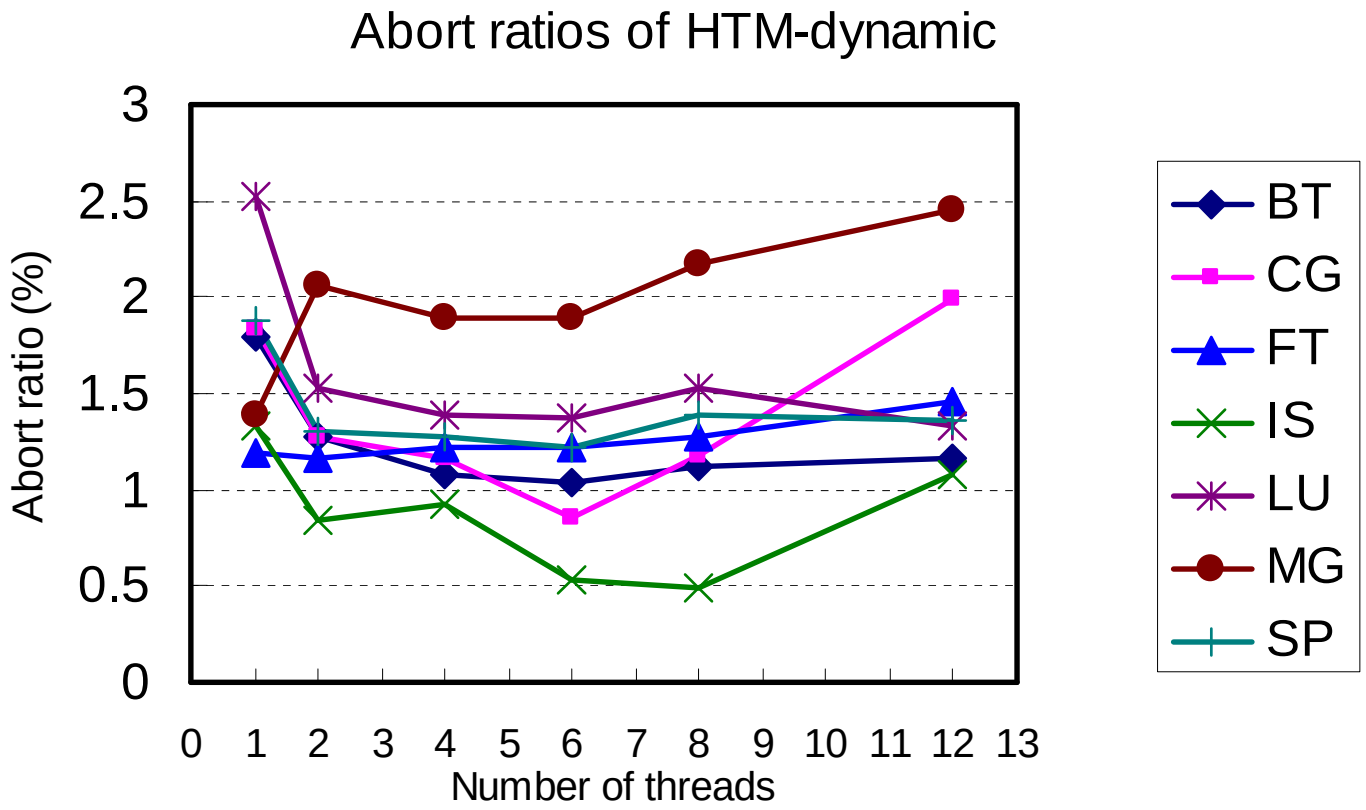






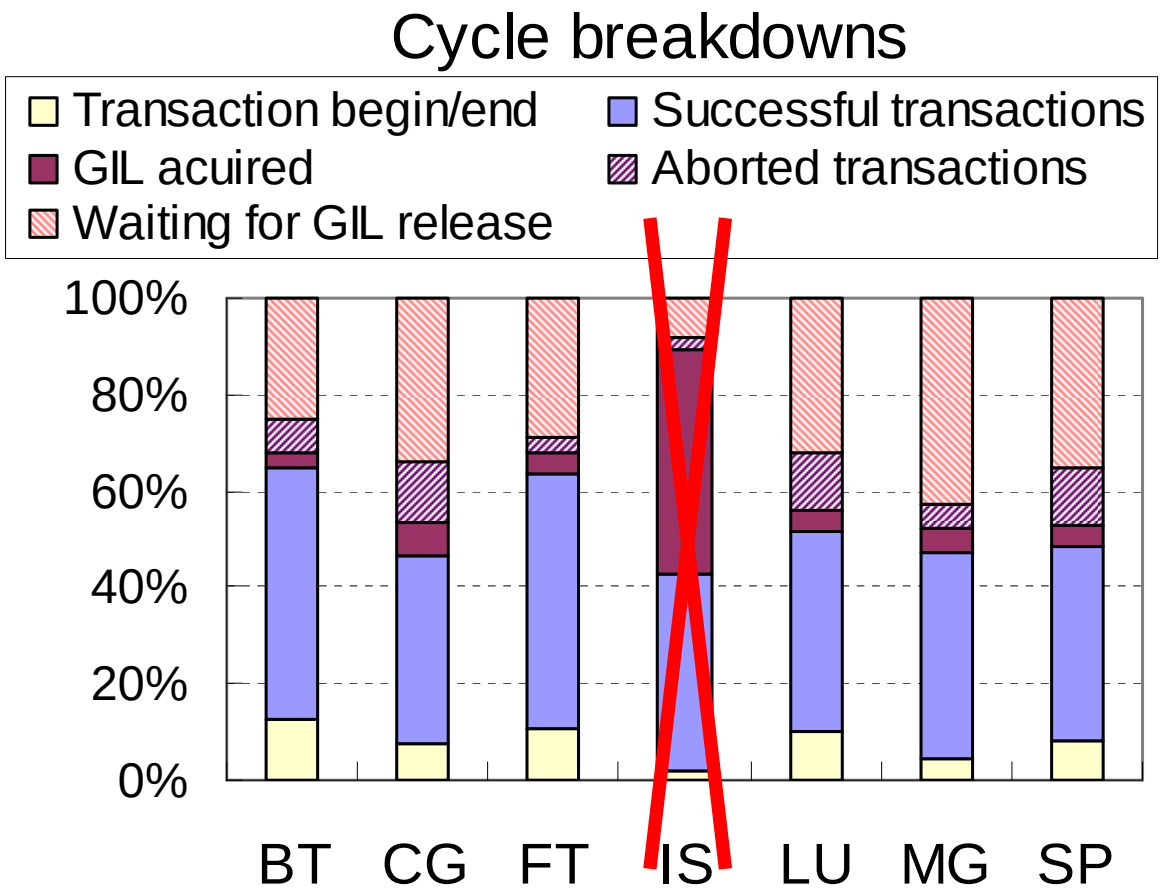
Abort Ratios

- Transaction lengths well adjusted by HTM-dynamic with 1% as a target abort ratio.
- No correlation to the scalabilities.



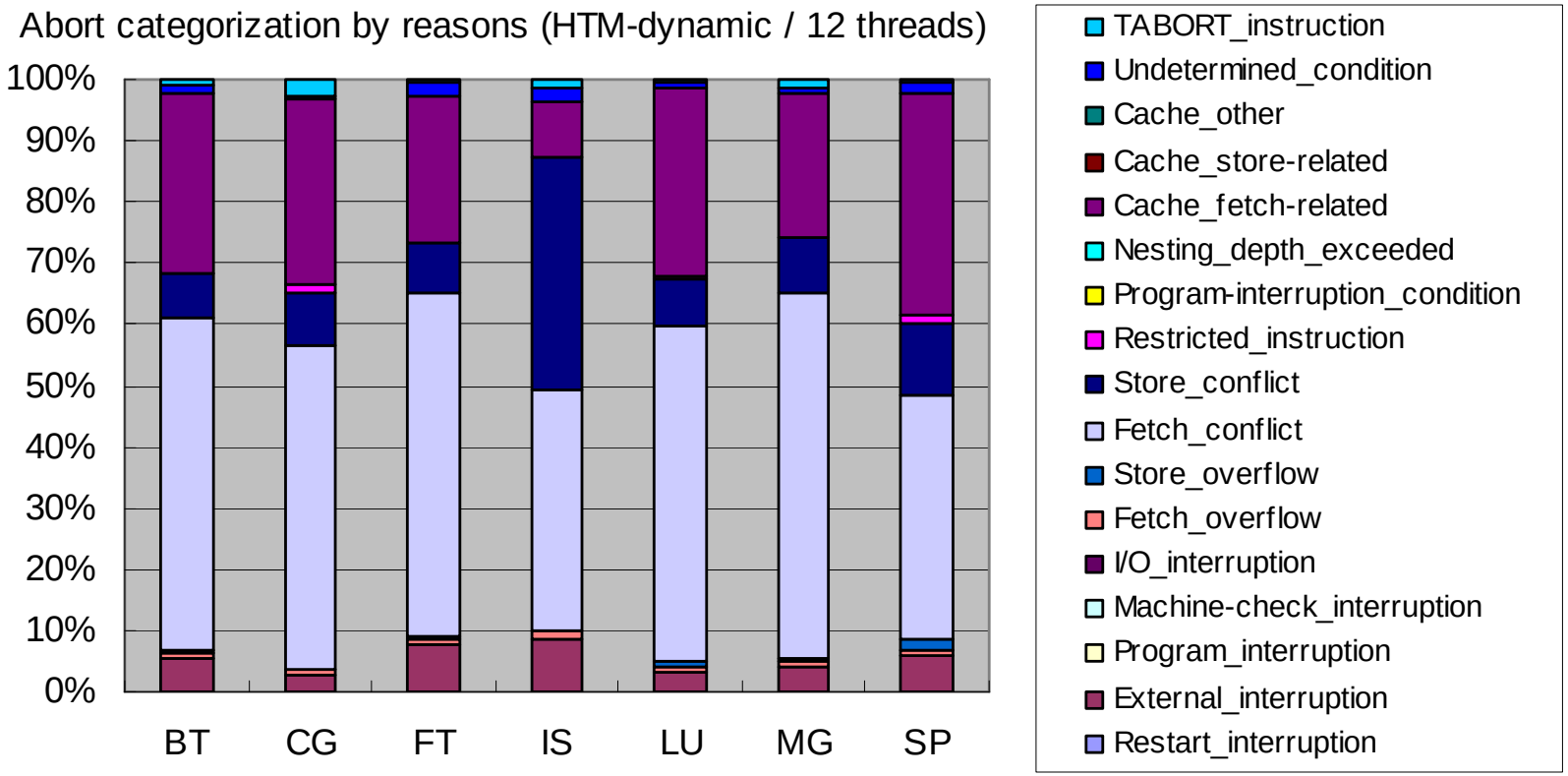
Cycle Breakdowns

- No correlation to the scalabilities.
  - Result of IS is not reliable because 79% of its execution was spent in initialization, outside of the measurement period.



Categorization by Abort Reasons

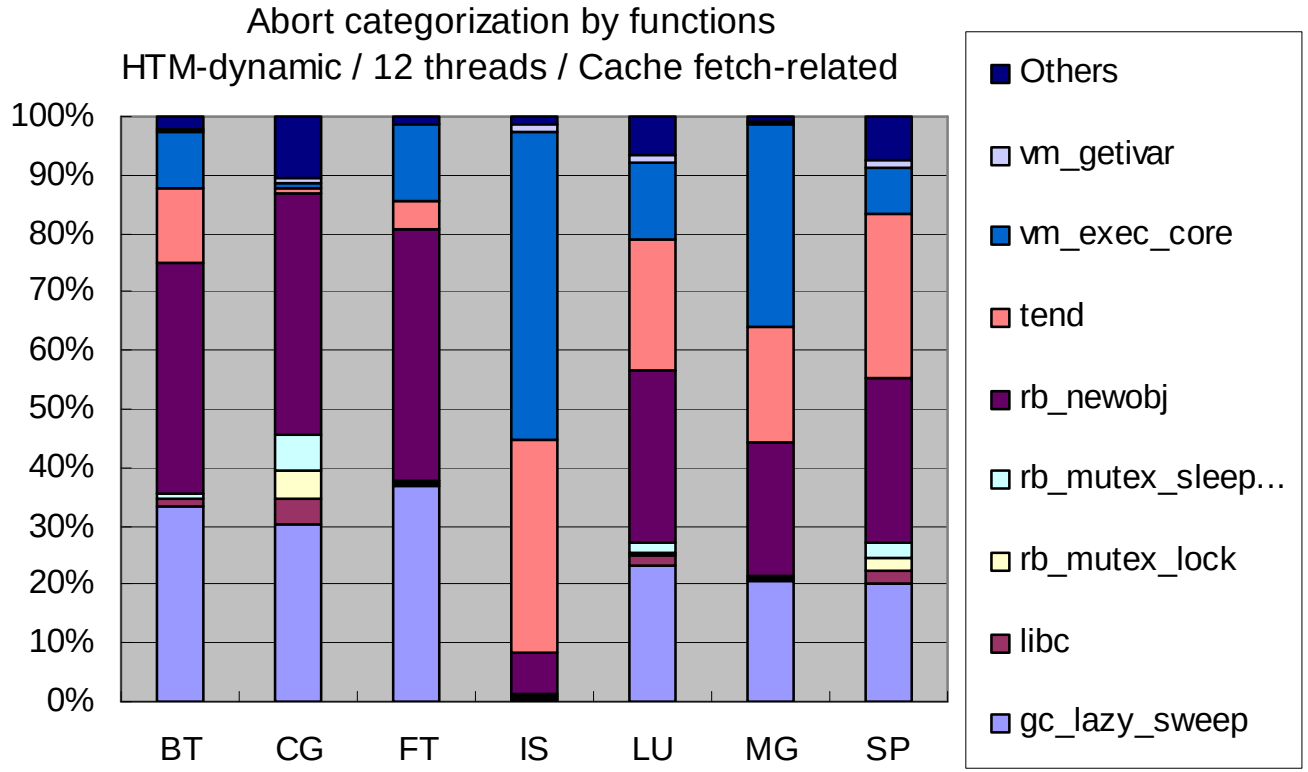
- Conflicts at read set accounted for most of the aborts.
  - Cache fetch-related + Fetch conflict



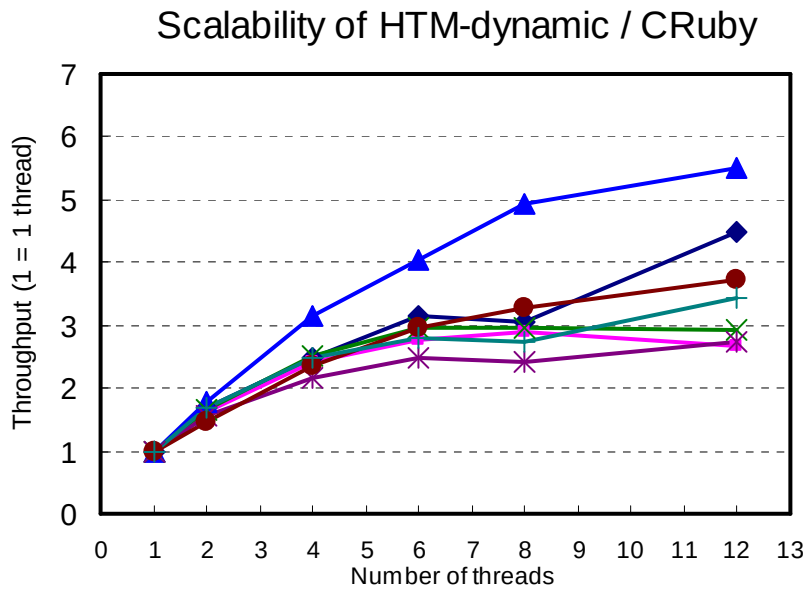
Categorization by Functions Aborted by Fetch Conflicts

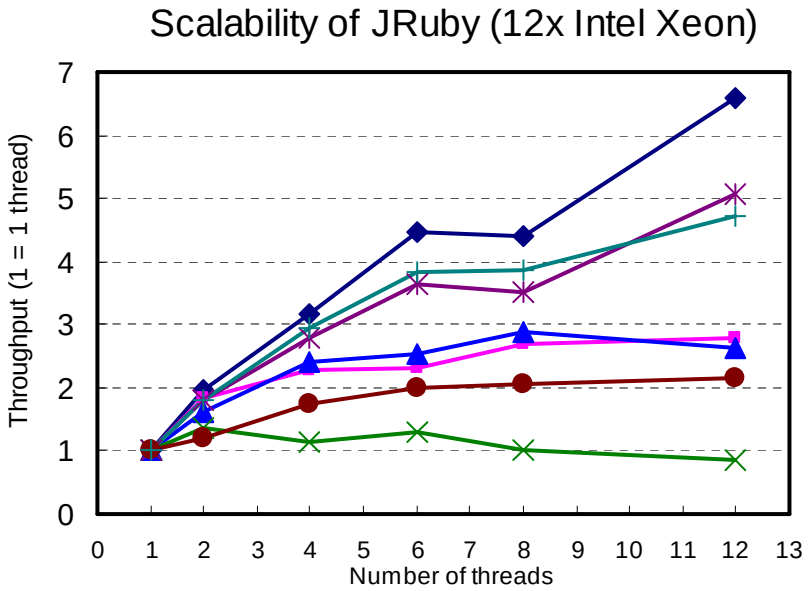
- Half of the aborts occurred in manipulating the global free list (rb_newobj) and lazy sweep in GC (gc_lazy_sweep).
  - A lot of Float objects allocated.

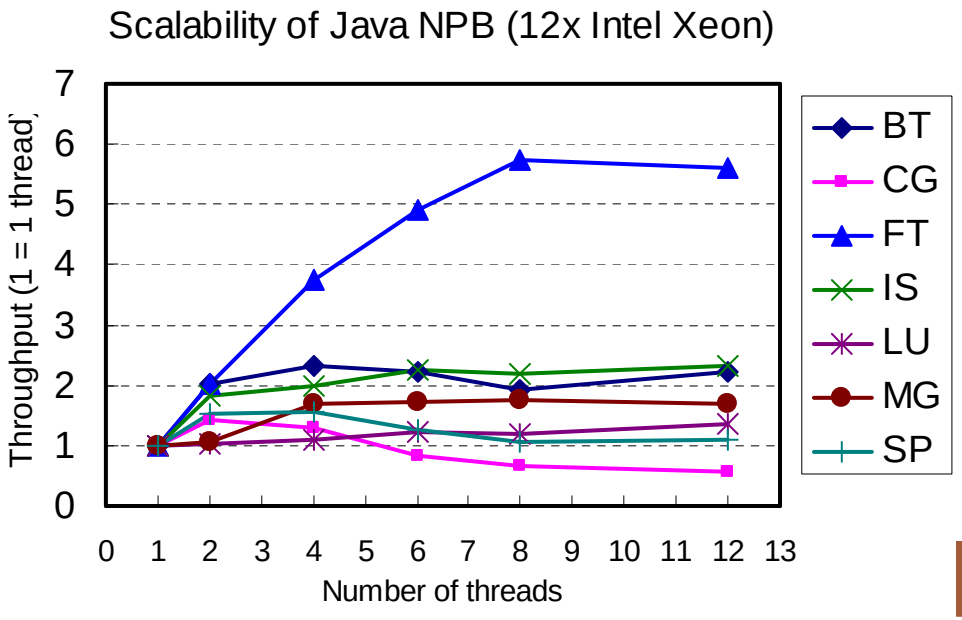
  → To be fixed in Ruby 2.0 with Flonum?



Comparing Scalabilities of CRuby, JRuby, and Java







- CRuby (HTM) was similar to Java (almost no VM-internal bottleneck).

→ Scalability saturation in CRuby (HTM) is inherent in the applications.

- JRuby (fine-grain locking) behaved differently from CRuby (HTM).
- On average, HTM achieved the same scalability as fine-grain locking.

Single-thread Overhead

- Single-thread speed is important too.

- With 1 thread, use the GIL instead of HTM.

→ 5-14% overhead in the micro-benchmarks even with this optimization.

- Sources of the overhead:
  - Checks at the yield points
  - Newly added yield points
  - Slow access to Pthread's thread-local storage (z/OS specific)

Conclusion

- What was the performance of real applications when GIL was replaced with HTM?
  - Up to 4.4-fold speed-up with 12 threads.
- What was required for that purpose?
  - Modified only a couple of source code files to replace the GIL with HTM.
  - Changed up to a few dozens of lines to remove each conflict.
  - Proposed dynamic transaction-length adjustment.

✓ Using HTM is an effective way to outperform the GIL with only small source code changes