Language-level Transactions for Modular Reliable Systems

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Outline

- Problems with traditional software development
  - lock ordering
  - proper atomicity
  - fault-tolerance
  - priority inversion
- Language-level Transactions
- How?
  - Software implementation
  - Hardware implementation
  - Both!
- Conclusions

Programming Reliable Systems (is hard)

Conventional Locking: Ordering

- **When more than one object is involved in a critical region, deadlocks may occur!**
  - **Thread 1 grabs A then tries to grab B**
  - **Thread 2 grabs B then tries to grab A**
  - **No progress possible!**
- **Solution: all locks ordered**
  - **A before B**
  - **Thread 1 grabs A then B**
  - **Thread 2 grabs A then B**
  - **No deadlock**

Conventional Locking: Ordering

- **Maintaining lock order is a lot of work!**
- **Programmer must choose, document, and rigorously adhere to a global locking protocol for each object type**
  - **development overhead!**
- **All symmetric locked objects must include lock order field, which must be assigned uniquely**
  - **space overhead!**
- **Every multi-object lock operation must include proper conditionals**
  - **which lock do I take first? which do I take next?**
  - **execution-time overhead!**
- ***No exceptions!***

Multi-object atomic update

- Programmer's mental model of locks can be faulty
- **Monitor synchronization**: associates locks with objects
- Promises modularity: locking code stays with encapsulated object implementation
- Often breaks down for multiple-object scenarios
- End result: **unreliable software, broken modularity**

A problem with multiple objects

```
public final class StringBuffer ... {
  private char value[ ];
  private int count;
  ...
  public synchronized StringBuffer append(StringBuffer sb) {
    ...
A:int len = sb.length();
    int newcount = count + len;
    if (newcount > value.length)
      expandCapacity(newcount);
    // next statement may use state len
B:sb.getChars(0, len, value, count);
    count = newcount;
    return this;
  }
  public synchronized int length() { return count; }
  public synchronized void getChars(...) { ... }
}
```

Fault-tolerance

- Locks are irreversible
- When a thread fails holding a lock, the system will crash
  - it's only a matter of time before someone else attempts to grab that lock
- What are the proper semantics for exceptions thrown within a critical region?
  - data structure consistency not guaranteed
- Asynchronous exceptions?

Priority Inversion

- Well-known problem with locks
- Described by Lampson/Redell in 1980 (Mesa)
- Mars Pathfinder in 1997, etc, etc, etc
- Low-priority task takes a lock needed by a high-priority task -> the high priority task must wait!
- Clumsy solution: the low priority task must become high priority
- What if the low priority task takes a long time?

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Language-level Transactions

- Locks are the wrong model for expressing synchronization!
- Atomicity is a more natural (and modular) way to specifying the system
- Let's use transactions to implement atomic regions
- What sort of transactions do we want?

Transactions (definition)

- A transaction is a sequence of loads and stores that either commits or aborts
- If a transaction commits, all the loads and stores appear to have executed atomically
- If a transaction aborts, none of its stores take effect
- Transaction operations aren't visible until they commit or abort
- Simplified version of traditional ACID database transactions (no durability, for example)

Non-blocking synchronization

- Although transactions can be implemented with mutual exclusion (locks), we are interested only in non-blocking implementations.
- In a non-blocking implementation, the failure of one process cannot prevent other processes from making progress. This leads to:
  - Scalable parallelism
  - Fault-tolerance
  - Safety: freedom from some problems which require careful bookkeeping with locks, including priority inversion and deadlocks
- Little known requirement: limits on trans. suicide

Making StringBuffer atomic

```
public final class StringBuffer ... {
  private char value[ ];
  private int count;
  ...
  public synchronized StringBuffer append(StringBuffer sb) {
    ...
A:int len = sb.length();
    int newcount = count + len;
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      expandCapacity(newcount);
    // next statement may use state len
B:sb.getChars(0, len, value, count);
    count = newcount;
    return this;
  }
  public synchronized int length() { return count; }
  public synchronized void getChars(...) { ... }
}
```

Making StringBuffer atomic

```
public final class StringBuffer ... {
  private char value[ ];
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  public atomic StringBuffer append(StringBuffer sb) {
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      expandCapacity(newcount);
    // next statement may use state len
B:sb.getChars(0, len, value, count);
    count = newcount;
    return this;
  }
  public atomic int length() { return count; }
  public atomic void getChars(...) { ... }
}
```

Solving the lock ordering problem

```
void pushFlow(Vertex v1, Vertex v2, double flow) {
  v1.excess -= flow; /* Move excess flow from v1 */
  v2.excess += flow; /* ...to v2 */
}
```

- Simple **network flow algorithm**
- “Flow” moved from node to node in the graph
- Updates to **two different objects**
- Serial version above requires a complicated parallel version when using locks

Solving the lock ordering problem

```
void pushFlow(Vertex v1, Vertex v2, double flow) {
  v1.excess -= flow; /* Move excess flow from v1 */
  v2.excess += flow; /* ...to v2 */
}

void pushFlow(Vertex v1, Vertex v2, double flow) {
  Object lock1, lock2;
  if (v1.id < v2.id) { /* avoid deadlock */
    lock1 = v1; lock2 = v2;
  } else {
    lock1 = v2; lock2 = v1;
  }
  synchronized (lock1) {
    synchronized (lock2) {
      v1.excess -= flow; /* Move excess flow from v1 */
      v2.excess += flow; /* ...to v2 */
    }
  }
}
```

Solving the lock ordering problem

```
void pushFlow(Vertex v1, Vertex v2, double flow) {
  v1.excess -= flow; /* Move excess flow from v1 */
  v2.excess += flow; /* ...to v2 */
}
```

```
void pushFlow(Vertex v1, Vertex v2, double flow) {
  atomic {
    v1.excess -= flow; /* Move excess flow from v1 */
    v2.excess += flow; /* ...to v2 */
  }
}
```

- **Specifying desired atomicity property directly is much simpler for the programmer!**

Addressing reliability, fault tolerance, and priority inversion

- A proper implementation of the transaction mechanism allows **constant-time abort**
  - Allows us to solve priority inversion by aborting the low-priority thread!
- Atomicity properties are **modular** – no global lock ordering required
- A **reasonable semantics for exceptions**: critical region aborted/undone. No dangling locks.
- Failure of one thread will not cause the system to fail!

Programming Reliable Systems (is hard)

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  - fault-tolerance
  - priority inversion
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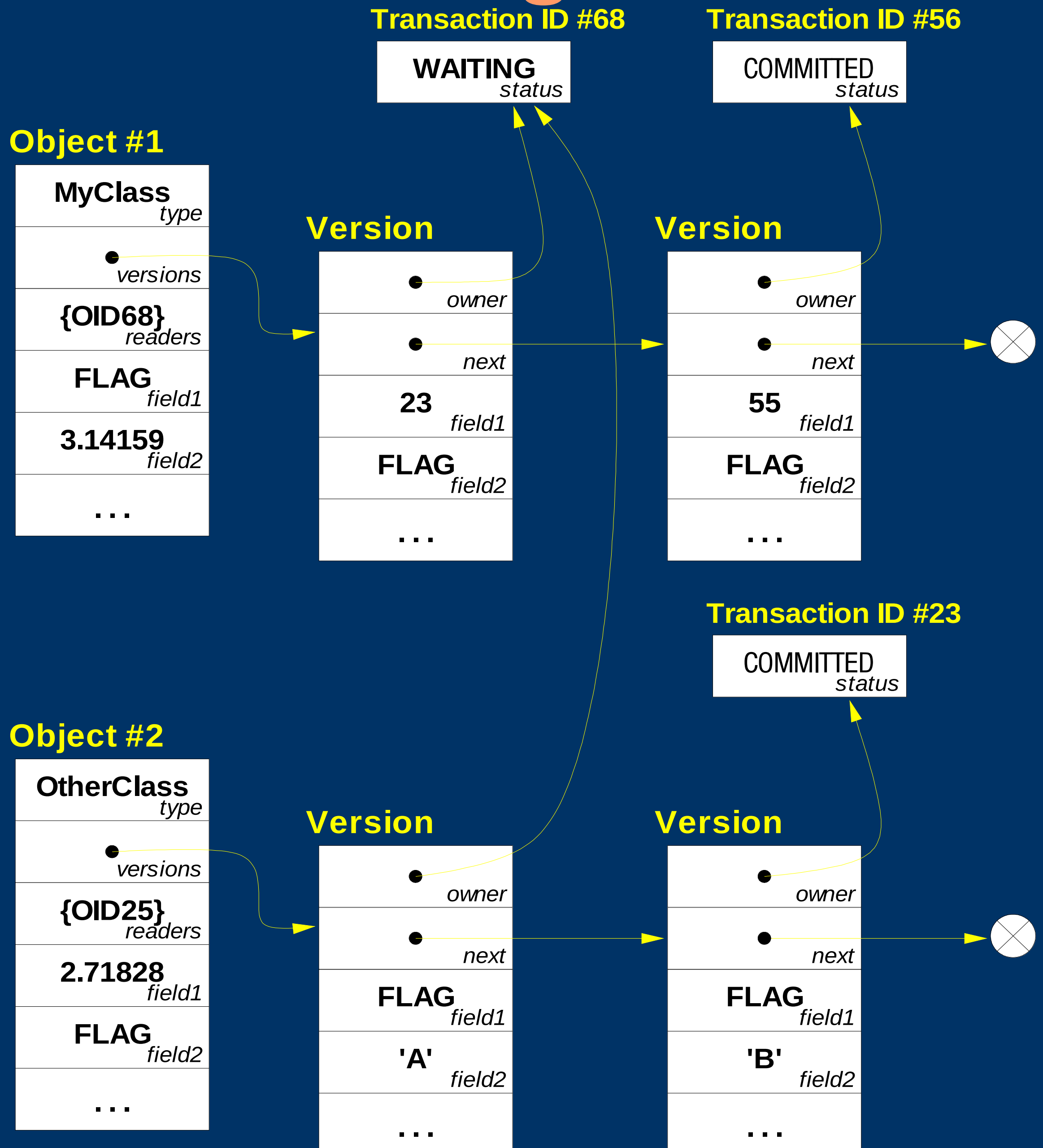
Software Transaction Implementation

- **Goals:**
  - Non-transactional operations should be fast
  - Reads should be faster than writes
  - Minimal amount of object bloat
- **Solution:**
  - Use special `FLAG` value to indicate "location involved in a transaction"
  - Object points to a linked list of **versions**, containing values written by (in-progress, committed, or aborted) transactions
  - Semantic value of `FLAG`ged field is: "value of the first version owned by a committed transaction on the version list"
  - Values which are "really" FLAG are handled with an escape mechanism

Transactions using version lists



Performance

- Non-transactional code only needs to check whether a memory operand is `FLAG` before continuing.
  - On superscalar processors, there are plenty of extra functional units to do the check
  - The branch is extremely predictable
  - This gives only a few % slowdown
- Once `FLAG`ged, transactional code operates directly on the object's "version"
- Creating versions can be an issue for large arrays; use "functional array" techniques

Non-blocking algorithms are hard!

- In published work on Synthesis, a non-blocking operating system implementation, three separate races were found:
  - One **ABA problem** in LIFO stack
  - One **likely race** in MP-SC FIFO queue
  - One **interesting corner case** in quaject callback handling
- It's hard to get these right! Ad hoc reasoning doesn't cut it.
- Non-blocking algorithms are too hard for the programmer
- Let's get it right **once** (and verify this!)

The Spin Model Checker

- Spin is a model checker for communicating concurrent processes. It checks:
  - Safety/termination properties
  - Liveness/deadlock properties
  - Path assertions (requirements/never claims)
- It works on finite models, written the Promela language, which describe infinite executions.
- Explores the entire state space of the model, including all possible concurrent executions, verifying that Bad Things don't happen.
- Not an absolute proof – pretty useful in practice
- Make systems reliable by concentrating complexity in a verifiable component

Spin theory

- Generates a **Büchi Automaton** from the Promela specification.
  - Finite-state machine w/ special acceptance conditions
  - Transitions correspond to executability of statements
- **Depth-first search of state space**, with each state stored in a hashtable to detect cycles and prevent duplication of work
  - If *x* followed by *y* leads to the same state as *y* followed by *x*, will not re-traverse the succeeding steps
- If memory is not sufficient to hold all states, may **ignore hashtable collisions**: requires one bit per entry. # collisions provides approximate coverage metric

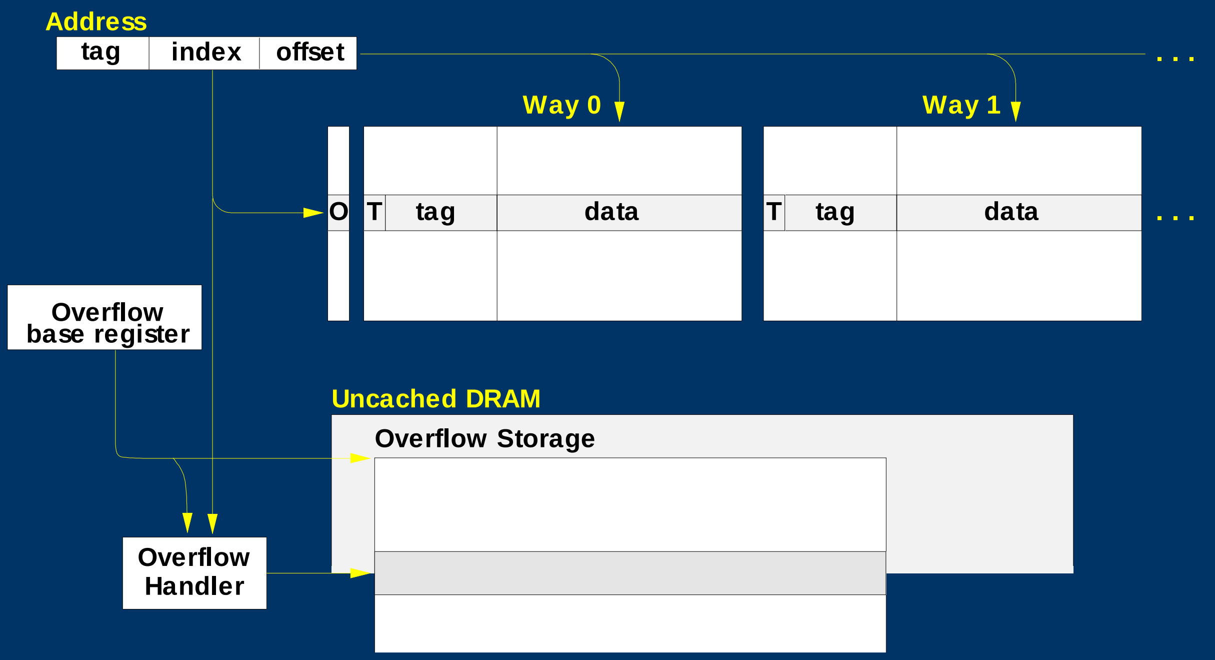
Verified Software Transactions

- Modelled the software transaction implementation in Promela
- Low-level model – every memory operation represented
- Spin used 16G of memory to exhaustively verify the implementation within a 6-version 2-object scope.

Hardware Implementation

- Following earlier work by Knight '86, Herlihy and Moss '92, '93
- Cache is used to store uncommitted transactional state (marked with a T bit)
- Main memory contains 'backup state'
- Cache-coherence protocol extended to coordinate transactions
- Our recent work (Ananian, Asanović, Kuszmaul, Leiserson, Lie HPCA 2005) overcomes transaction-size limitations in earlier designs
- Near-zero performance overhead.
  - Piggy-backs on existing cache coherency traffic

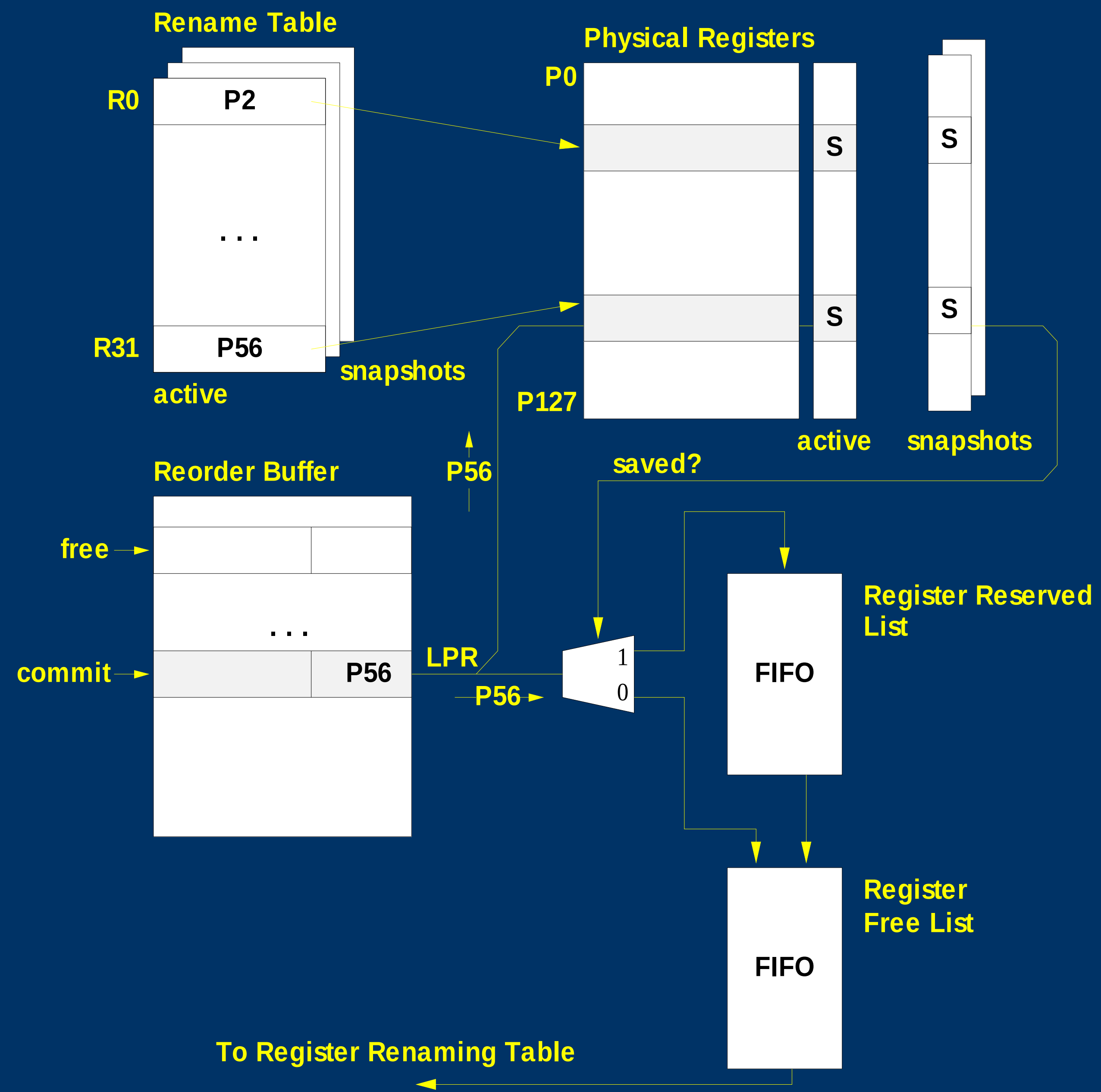
Hardware Transaction Cache Organization



- Each cache line gets a “T” bit indicating that this line is involved in a transaction
- On abort, “T” lines are invalidated
- On commit, the T bits are cleared
- Overflow mechanism

Register File Modifications

- Minor modifications to the processor rename table to support register restore after transaction abort.

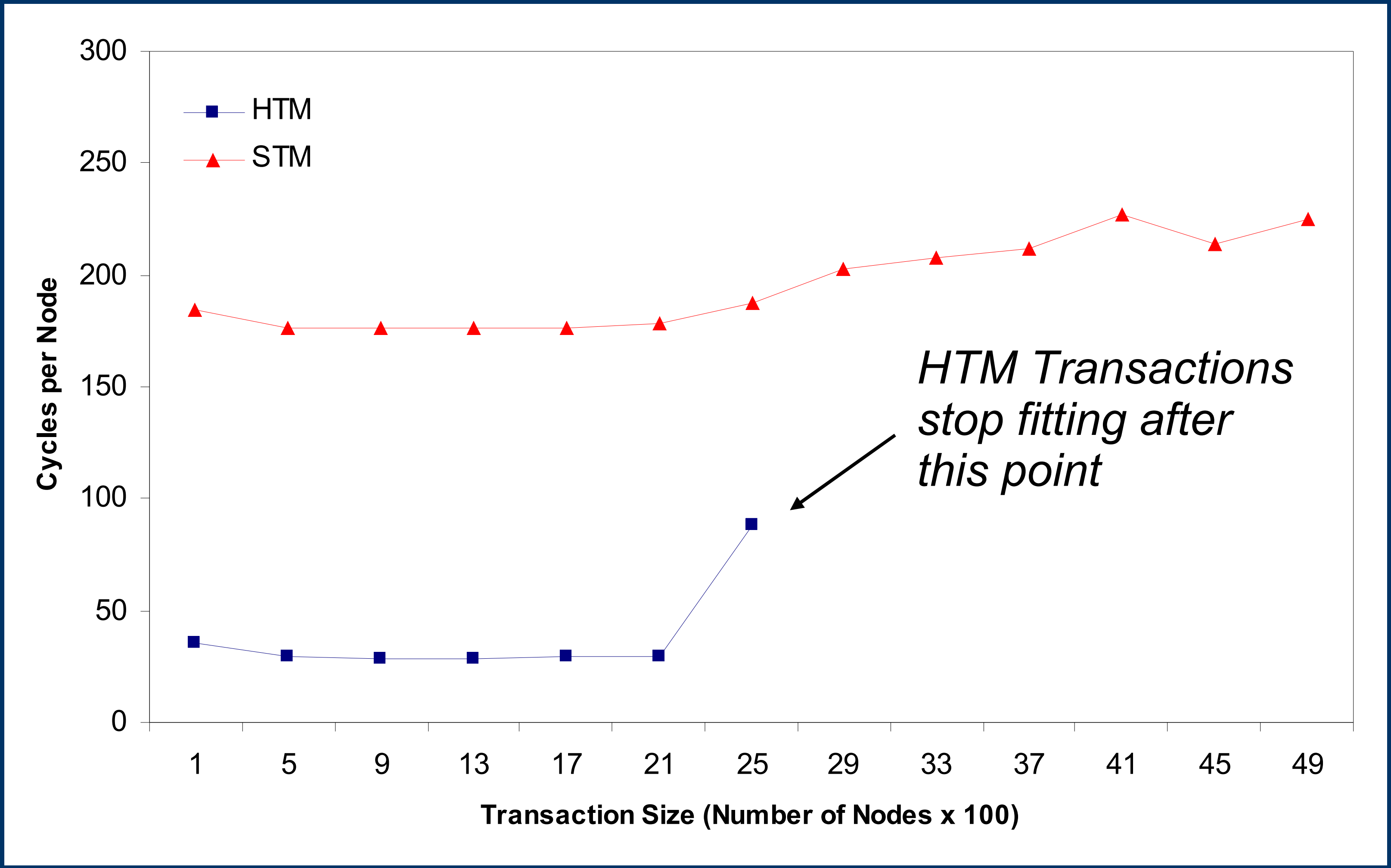


Hardware/Software Implementation

- Hardware transaction implementation is very fast! But it is limited:
  - Slow once you exceed Cache capacity
  - Transaction lifetime limits (context switches)
  - Limited semantic flexibility (nesting, etc)
- Software transaction implementation is unlimited and very flexible!
  - But transactions may be slow
- Solution: failover from hardware to software
  - Simplest mechanism: after first hardware abort, execute transaction in software
  - Need to ensure that the two algorithms play nicely with each other (consistent views)

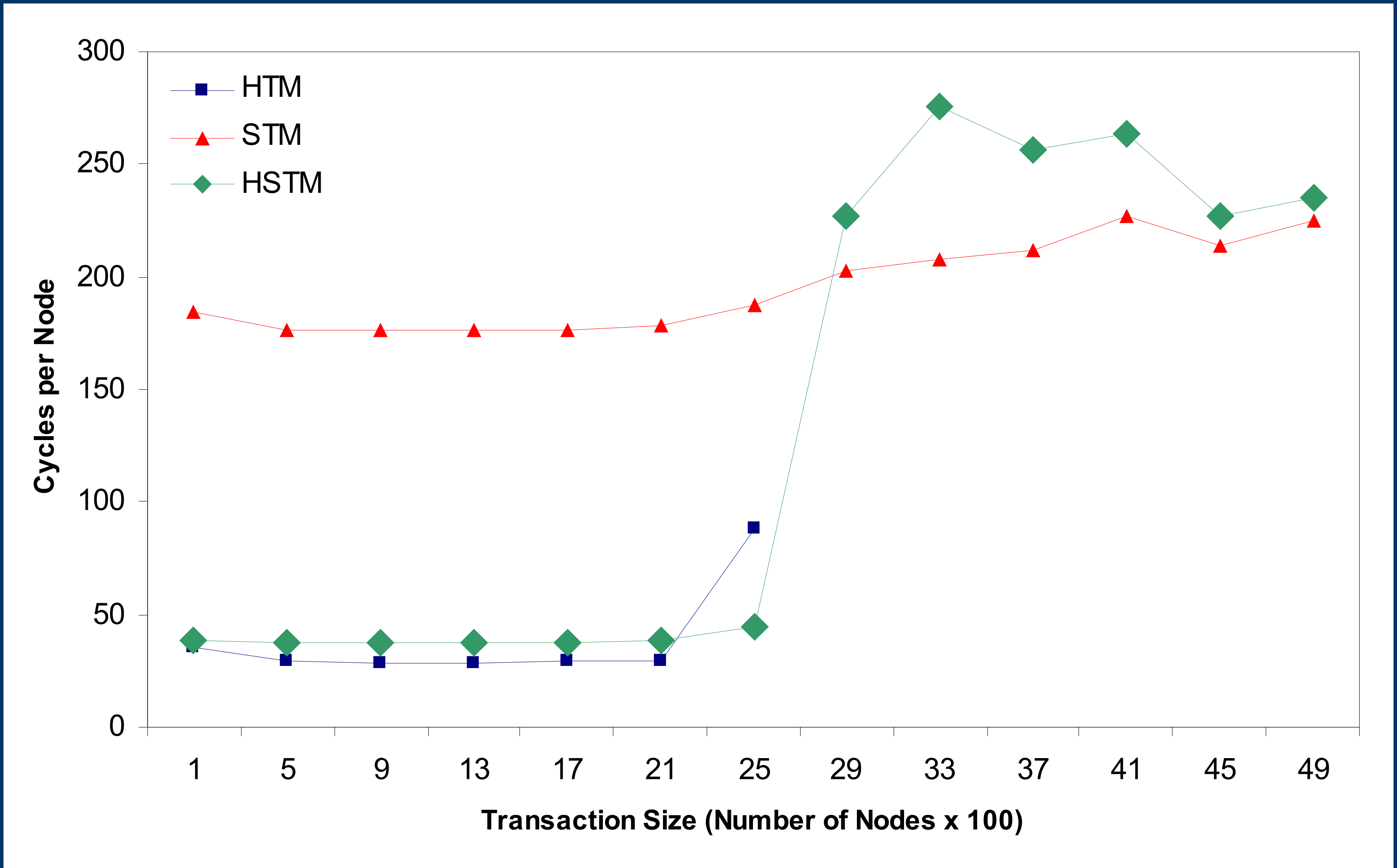
Overcoming HW size limitations

- Simple node-push benchmark
- As xaction size increases, we eventually run out of cache space in the HW transaction scheme



Overcoming HW size limitations

- Simple node-push benchmark
- Hybrid scheme best of both worlds!



Conclusions

- Language-level transactions provide a more-modular way to build reliable concurrent systems.
- Transactions can reduce software complexity and eliminate common programmer mistakes
- We've implemented a transaction mechanism for Java programs using software, hardware, and (in progress) joint approaches using the FLEX compiler infrastructure.
- Transactions can be efficient and practical to use!