Programming with Transactional Coherence and Consistency (TCC)

“all transactions, all the time”

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The Need for Parallelism

- **Uniprocessor system scaling is hitting limits**
  - Power consumption increasing dramatically
  - Wire delays becoming a limiting factor
  - Design and verification complexity is now overwhelming
  - Exploits limited instruction-level parallelism (ILP)

- **So chip multiprocessors are the future**
  - Inherently avoid many of the design problems
    - Replicate small, easy-to-design cores
    - Localize high-speed signals
  - Exploit thread-level parallelism (TLP)
    - But can still use ILP within cores
  - But now we must force programmers to use threads
    - And conventional shared memory threaded programming is primitive at best . . .
The Trouble with Multithreading

• Multithreaded programming requires:
  — Synchronization through barriers, condition variables, etc.
  — Shared variable access control through locks . . .

• Locks are inherently difficult to use
  — Locking design must balance performance and correctness
    ◆ Coarse-grain locking: Lock contention
    ◆ Fine-grain locking: Extra overhead, more error-prone
  — Must be careful to avoid deadlocks or races in locking
  — Must not leave anything shared unprotected, or program may fail

• Parallel performance tuning is unintuitive
  — Performance bottlenecks appear through low level events
    ◆ Such as: false sharing, coherence misses, …

• Is there a simpler model with good performance?
TCC: Using Transactions

- Yes! Execute transactions all of the time
  - Programmer-defined groups of instructions within a program

  ```
  End/Begin Transaction
  Instruction #1
  Instruction #2
  ...
  End/Begin Transaction
  ```

  - Can only “commit” machine state at the end of each transaction
    - **To Hardware:** Processors update state *atomically* only at a coarse granularity
    - **To Programmer:** Transactions encapsulate and replace locked “critical regions”

  - Transactions run in a *continuous* cycle . . .
The TCC Cycle

- Speculatively execute code and buffer

- Wait for commit permission
  - “Phase” provides commit ordering, if necessary
    - Imposes programmer-requested order on commits
  - Arbitrate with other CPUs

- Commit stores together, as a block
  - Provides a well-defined write ordering
    - To other processors, all instructions within a transaction “appear” to execute atomically at transaction commit time
  - Provides “sequential” illusion to programmers
    - Often eases parallelization of code
  - Latency-tolerant, but requires high bandwidth

- And repeat!
Transactional Memory

- What if transactions modify the same data?
  - First commit causes other transaction(s) to “violate” & restart
  - Can provide programmer with useful (load, store, data) feedback!

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Original Code:

```plaintext
... = X + Y;
X = ...

x
```

Diagram:

- Transaction A
  - LOAD X
  - STORE X
  - Commit X

- Transaction B
  - LOAD X
  - STORE X
  - Violation!

- Re-execute with new data

Time
— Write buffer (~16KB) + some new L1 cache bits in each processor
  ◆ Can also double buffer to overlap commit + execution
— Broadcast bus or network to distribute commit packets atomically
  ◆ Snooping on broadcasts triggers violations, if necessary
— Commit arbitration/sequencing logic
— *Replaces* conventional cache coherence & consistency: ISCA 2004
1. Break sequential code into *potentially* parallel transactions
   — Usually loop iterations, after function calls, etc.
   — Similar to threading in conventional parallel programming, but:
     ◆ We do not have to verify parallelism in advance
     ◆ Therefore, much easier to get a parallel program running *correctly*!

2. Then specify *order* of transactions as necessary
   — *Fully Ordered*: Parallel code obeys sequential semantics
   — *Unordered*: Transactions are allowed to complete in any order
     ◆ Must verify that unordered commits won’t break correctness
   — *Partially Ordered*: Can emulate barriers and other synchronization

3. Finally, optimize performance
   — Use violation feedback and commit waiting times from initial runs
   — Apply several optimization techniques
A Parallelization Example

• Let’s start with a simple histogram example
  — Counts frequency of 0–100% scores in a data array
  — Unmodified, runs as a single large transaction
    • 1 sequential code region

```c
int* data = load_data();
int i, buckets[101];
for (i = 0; i < 1000; i++)
{
    buckets[data[i]]++;
}
print_buckets(buckets);
```
Transaction Loops

- `t_for` transactional loop
  - Runs as 1002 transactions
    - 1 sequential + 1000 parallel, ordered + 1 sequential
  - Maintains sequential semantics of the original loop

```c
int* data = load_data();
int i, buckets[101];
t_for (i = 0; i < 1000; i++)
{
    buckets[data[i]]++;
}
print_buckets(buckets);
```
Unordered Loops

• **t_for_unordered** transactional loop
  — Programmer/compiler must **verify** that ordering is not required
    ∗ If no loop-carried dependencies
    ∗ If loop-carried variables are **tolerant** of out-of-order update (like histogram buckets)
  — Removes sequential dependencies on loop commit
  — Allows transactions to finish out-of-order
    ∗ Useful for load imbalance, when transactions vary dramatically in length

```c
int* data = load_data();
int i, buckets[101];
t_for_unordered (i = 0; i < 1000; i++)
{
    buckets[data[i]]++;
}
print_buckets(buckets);
```
Conventional parallelization requires explicit locking

- Programmer must manually define the required locks
- Programmer must manually mark critical regions
  - Even more complex if multiple locks must be acquired at once
  - Completely eliminated with TCC!

```c
int* data = load_data();
int i, buckets[101];
LOCK_TYPE bucketLock[101];
for (i = 0; i < 101; i++)
    LOCK_INIT(bucketLock[i]);
for (i = 0; i < 1000; i++) {
    LOCK(bucketLock[data[i]]);
    buckets[data[i]]++;
    UNLOCK(bucketLock[data[i]]);
}
print_buckets(buckets);
```
Forked Transaction Model

- An alternative transactional API forks off transactions
  - Allows creation of essentially arbitrary transactions
- **An example**: Main loop of a processor simulator
  - Fetch instructions in one transaction
  - Fork off parallel transactions to execute individual instructions

```c
int PC = INITIAL_PC;
int opcode = i_fetch(PC);
while (opcode != END_CODE) {
    t_fork(execute, &opcode, EX_SEQ, 1, 1);
    increment_PC(opcode, &PC);
    opcode = i_fetch(PC);
}
```
Evaluation Methodology

• We parallelized several sequential applications:
  — From SPEC, Java benchmarks, SpecJBB (1 warehouse)
  — Divided into transactions using looping or forking APIs

• Trace-based analysis
  — Generated execution traces from sequential execution
  — Then analyzed the traces while varying:
    ◆ Number of processors
    ◆ Interconnect bandwidth
    ◆ Communication overheads
  — Simplifications
    ◆ Results shown assume infinite caches and write-buffers
      ❖ But we track the amount of state stored in them…
    ◆ Fixed one instruction/cycle
      ❖ Would require a reasonable superscalar processor for this rate
The Optimization Process

- Initial parallelizations had mixed results
  - Some applications speed up well with “obvious” transactions
  - Others don’t . . .

For 8P:
Unordered Loops

- Unordered loops can provide some benefit
  - Eliminates excess “waiting for commit” time from load imbalance

For 8P:
Privatizing Variables

• Eliminate spurious violations using *violation feedback*
  — Privatize associative reduction variables or temporary buffers
  — Remaining violations from *true* inter-transaction communication

For 8P:
Splitting Transactions

- Large transactions can be split *between* critical regions
  - For early commit & communication of shared data (equake)
  - For reduction of work lost on violations (SPECjbb)

For 8P:

- MolDyn
- SPECjbb
- art
- equake
- tomcatv

**Results**

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<th>Base</th>
<th>+ unordered</th>
<th>+ reduction</th>
<th>+ privatization</th>
<th>+ t_commit</th>
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- **Processing Activity**
  - **t_commit**
  - Privatization
  - Reduction
  - Unordered
  - Base

- **Speedup**
  - **Idle**
  - Violated
  - Waiting
  - Useful
  - Inner Loops
Merging Transactions

- Merging small transactions can also be helpful
  - Reduces the number of commits per unit time
  - Often reduces the commit bandwidth (avoids repetition)
Overall Results

- Speedups very good to excellent across the board
  - And achieved in hours or days, not weeks or months

- Scalability varies among applications
  - Low commit BW apps work in board-level and chip-level MPs
  - High commit BW apps require a CMP
    - Little difference between CMP and “ideal” in most cases
    - CMP BW limits some apps only on 32-way, 1-IPC processor systems
Conclusions

- TCC eases parallel programming
  - Transactions provide easy-to-use atomicity
    - Eliminates many sources of common parallel programming errors
  - Parallelization mostly just dividing code into transactions!
    - Plus programmer doesn’t have to verify parallelism

- TCC eases parallel performance optimization
  - Provides direct feedback about variables causing communication
    - Simplifies elimination of communication
  - Unordered transactions can allow more speedup
  - Splitting and merging transactions simpler than adjusting locks
  - Programmers can parallelize aggressively
    - Some infrequently violating dependencies can be ignored

- TCC provides good parallel performance
TCC
“all transactions, all the time”

More info at: http://tcc.stanford.edu