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

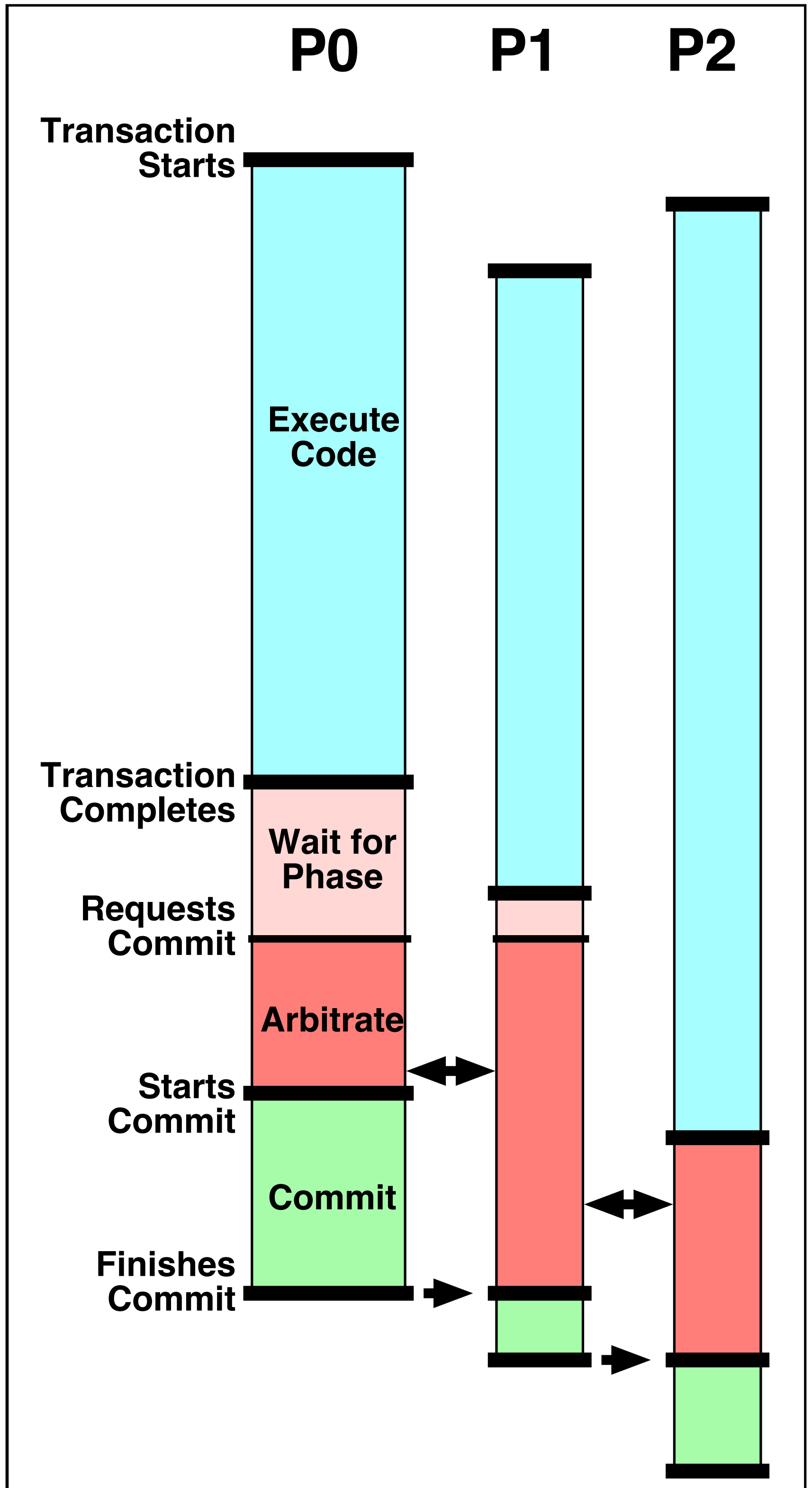
- Yes! Execute *transactions* all of the time
  - — Programmer-defined groups of instructions within a program

```
End/Begin Transaction        Start Buffering Results
   Instruction #1
   Instruction #2
   . . .
End/Begin Transaction        Commit Results Now (+ Start New 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 . . .

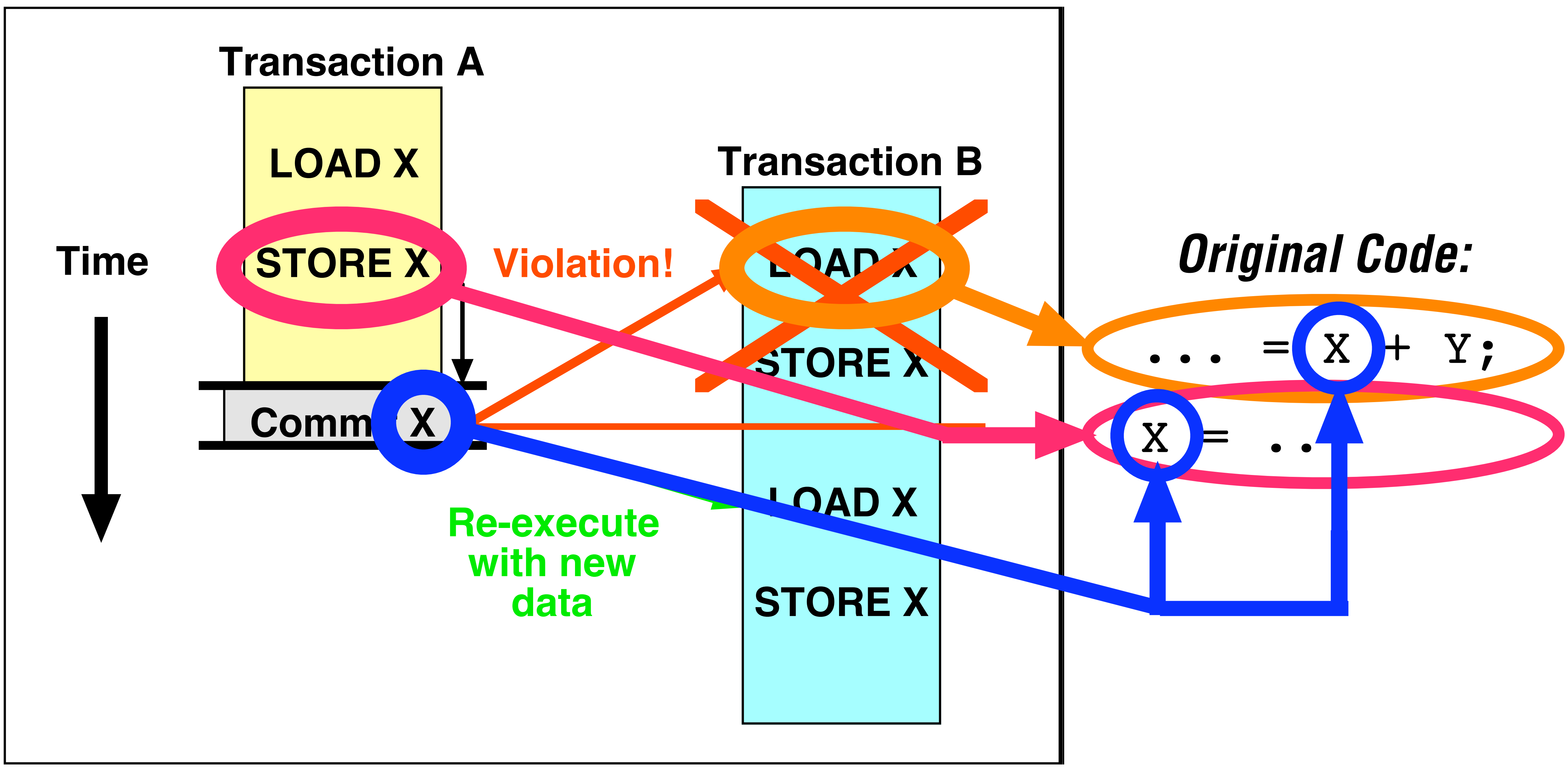
The TCC Cycle

- 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!

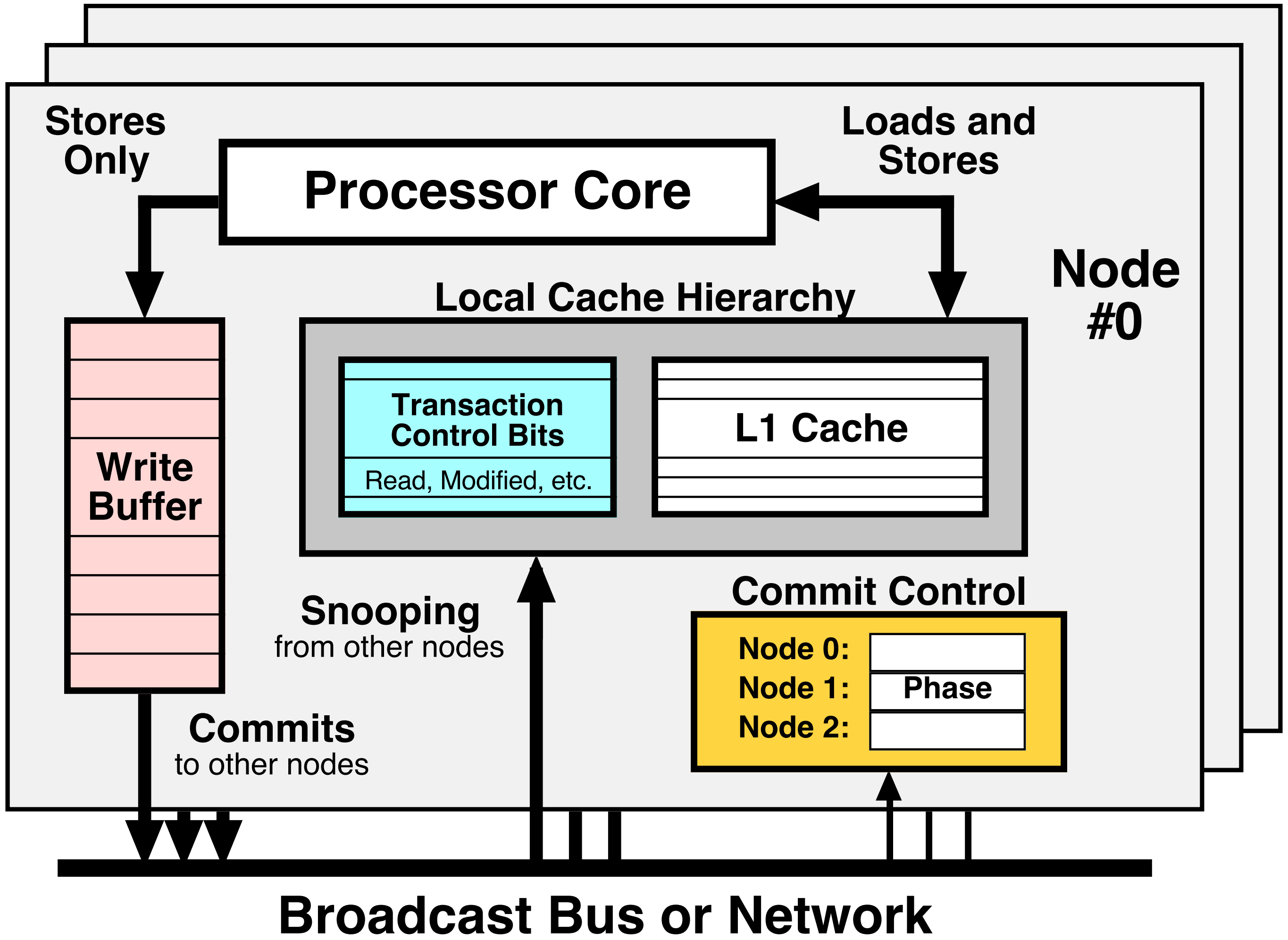


Transactional Memory

- 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!



Sample TCC Hardware



- 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

Programming with TCC

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

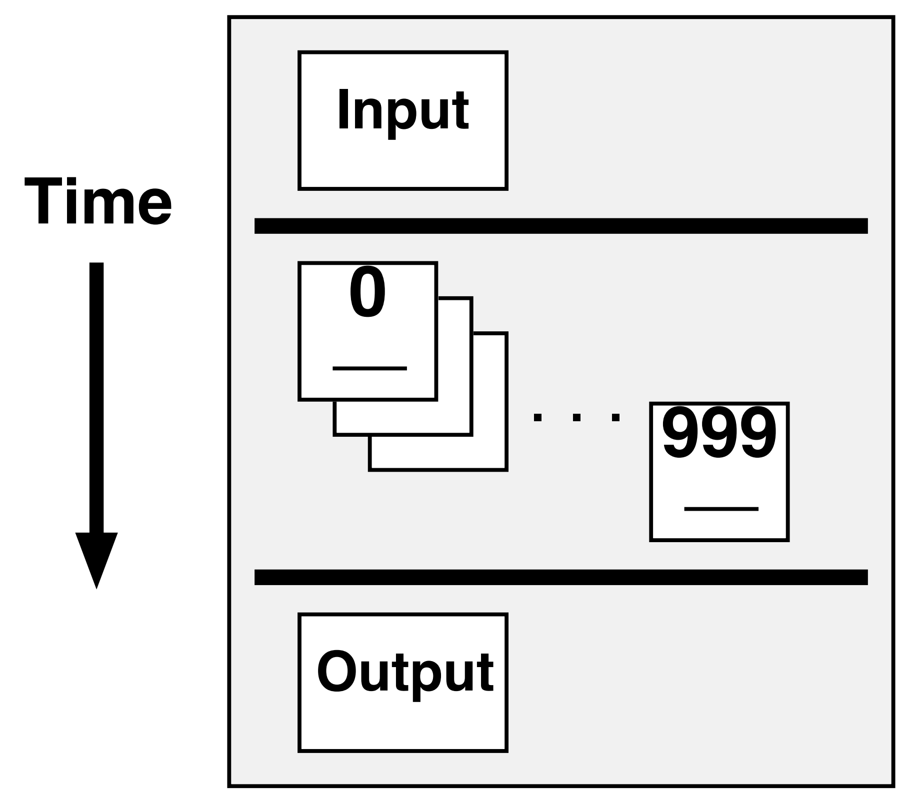
- Let's start with a simple histogram example
  - Counts frequency of 0–100% scores in a data array
  - Unmodified, runs as a single large transaction
    - 1 sequential code region

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

Transactional Loops

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

```
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

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

Conventional Parallelization

- 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!

Define Locks →

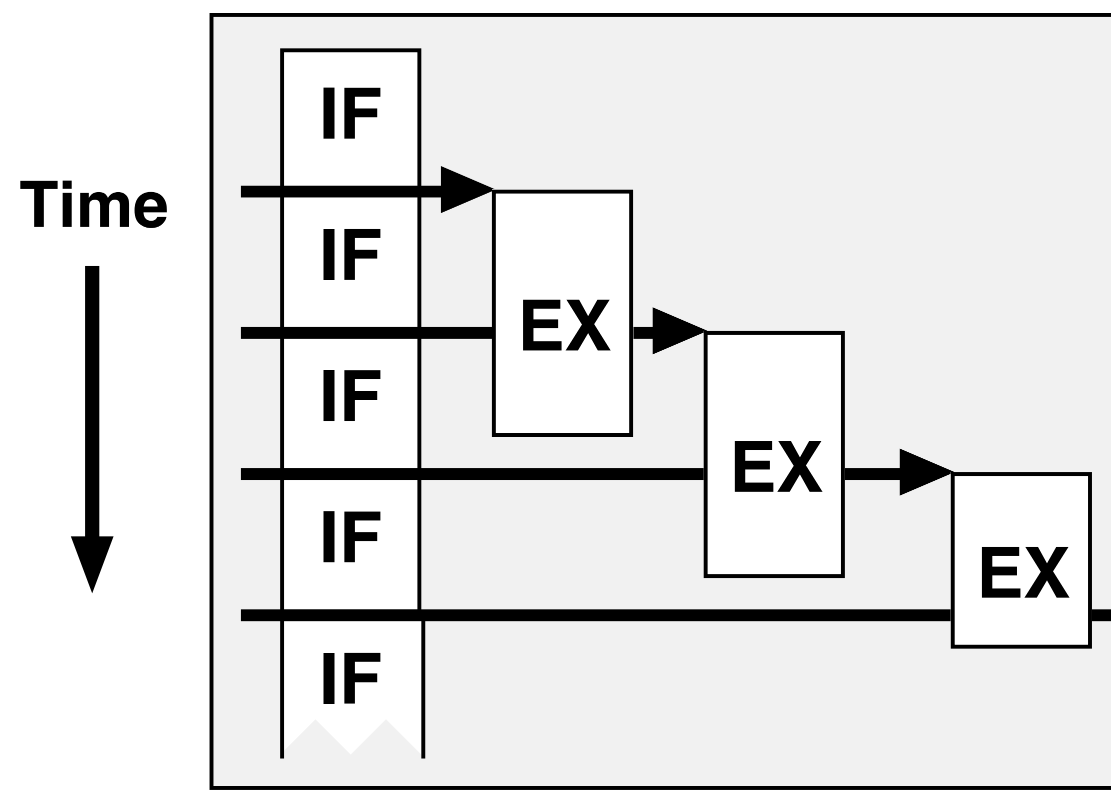
Mark Regions →

```
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

```
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

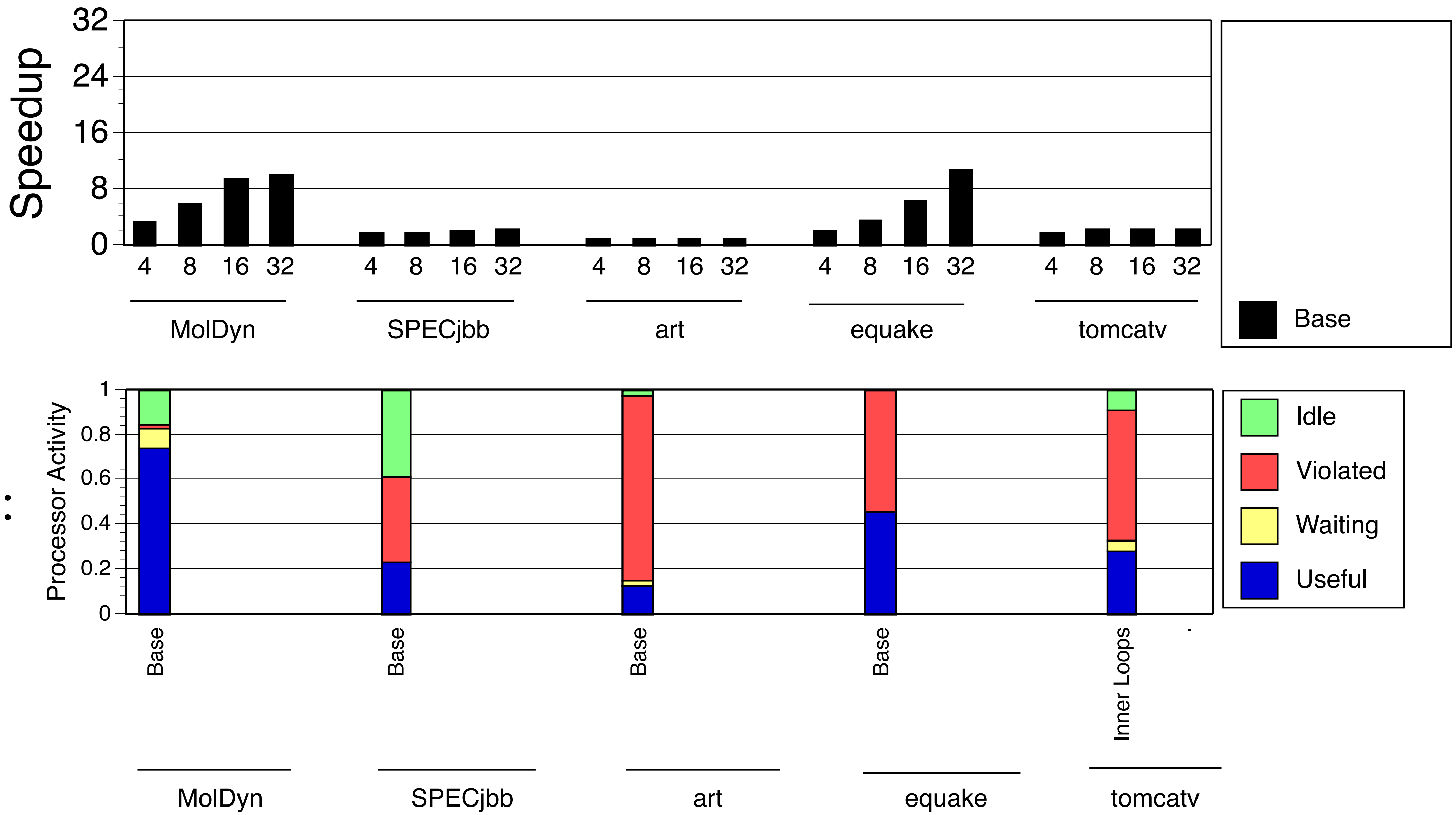
- We parallelized several sequential applications:
  - From SPEC, Java benchmarks, SpecJBB (1 warehouse)
  - Divided into transactions using looping or forking APIs

- 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

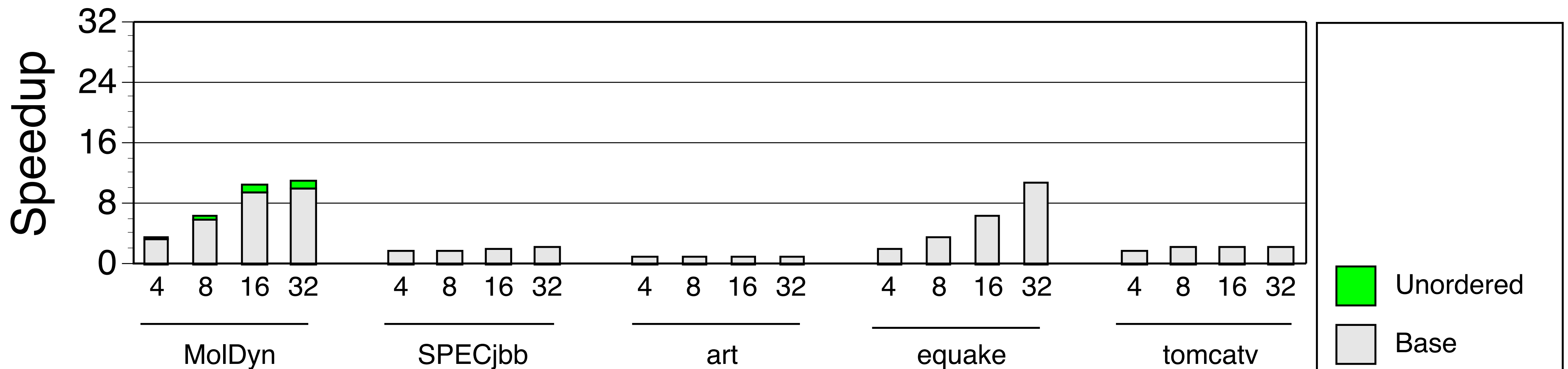
- Initial parallelizations had mixed results
  - Some applications speed up well with “obvious” transactions
  - Others don’t . . .

For 8P:



Unordered Loops

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



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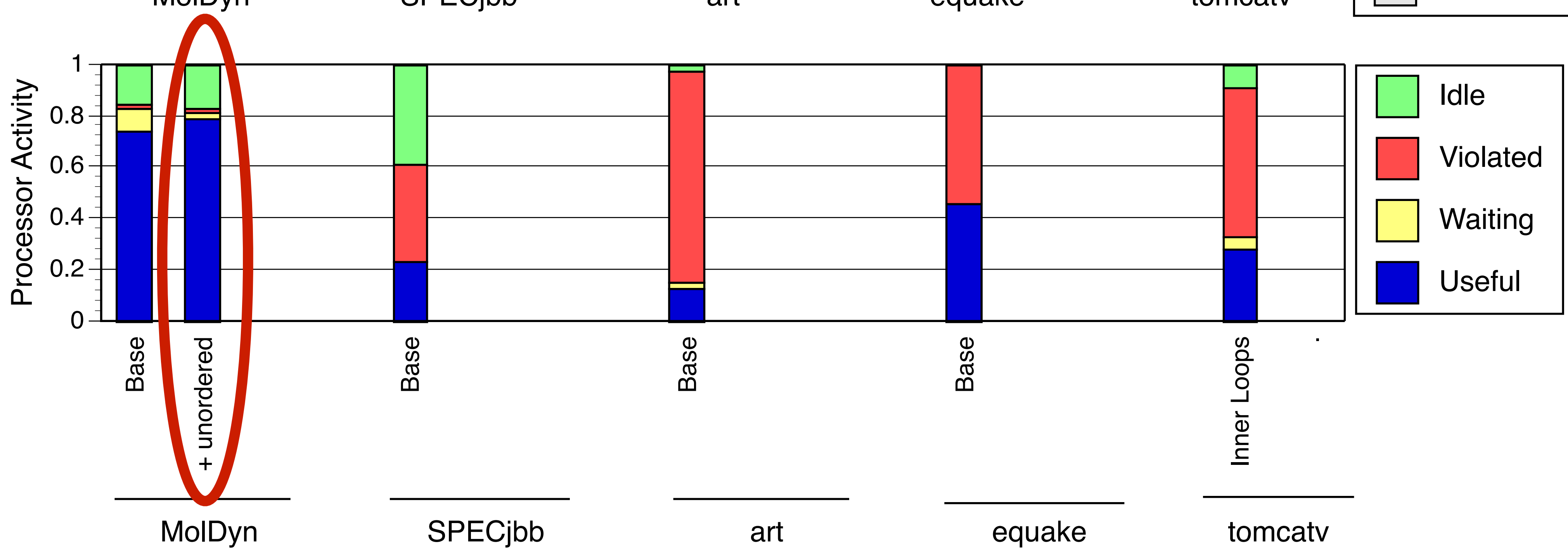

Privatizing Variables

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

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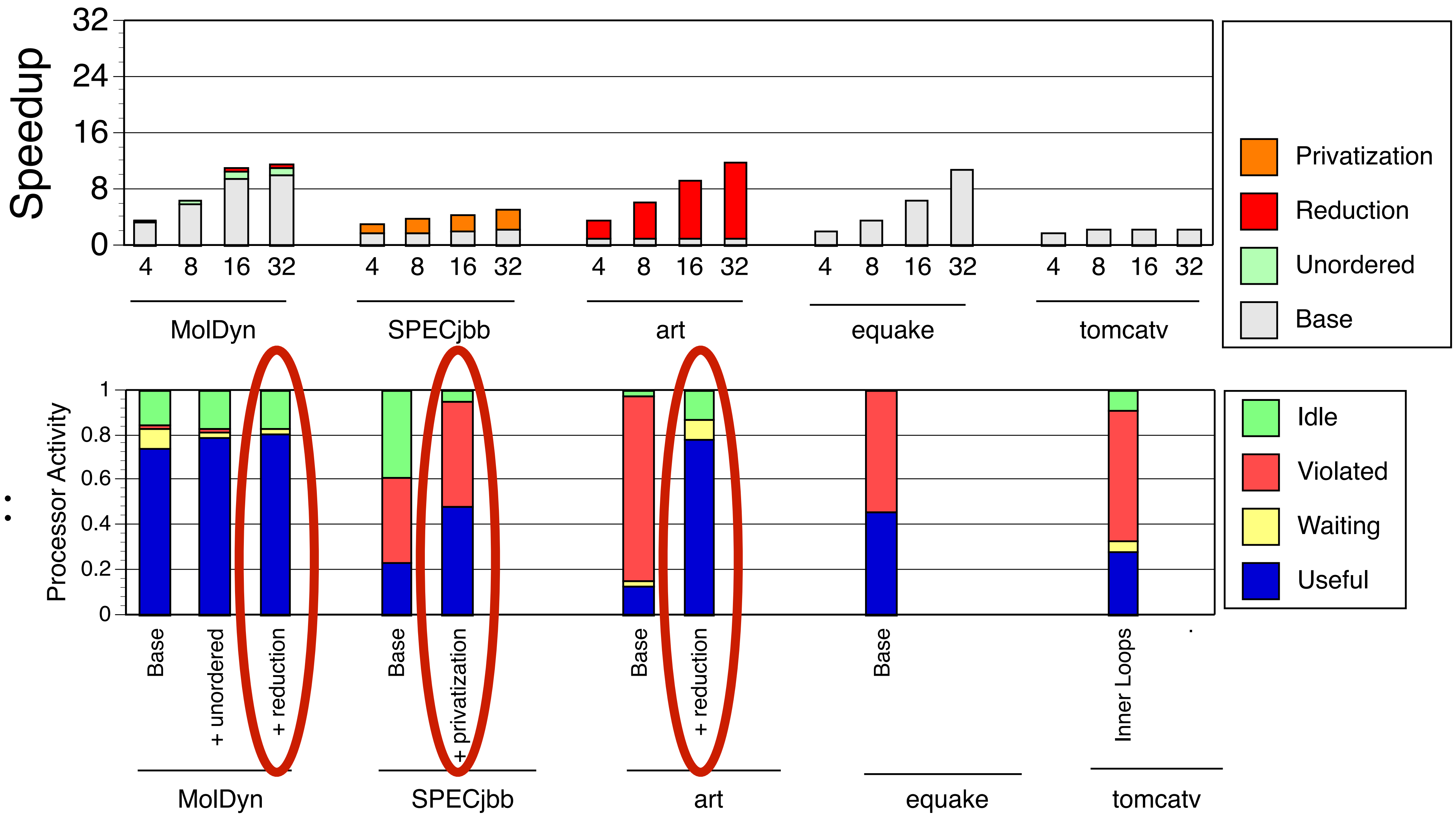
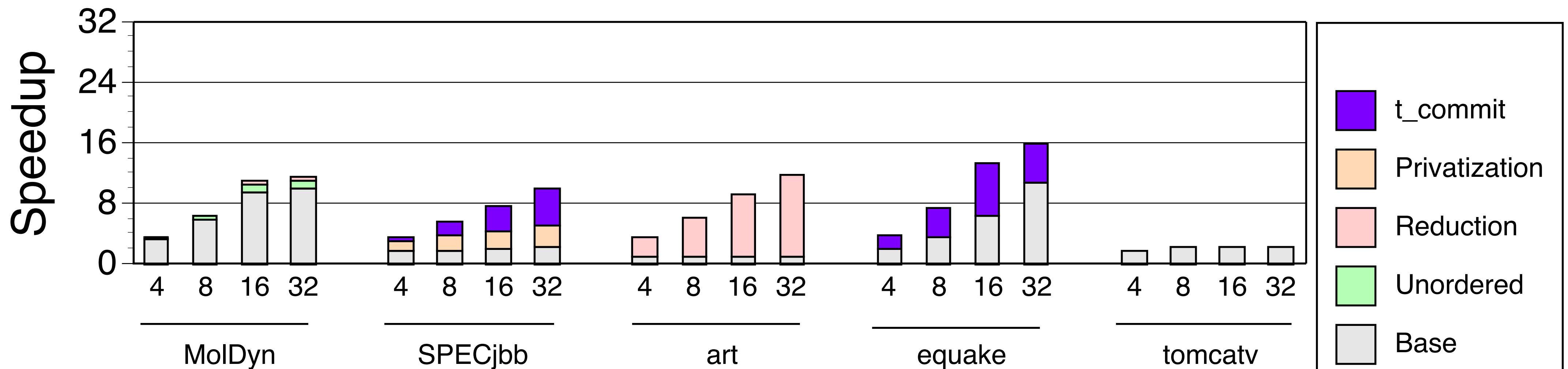


Splitting Transactions

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



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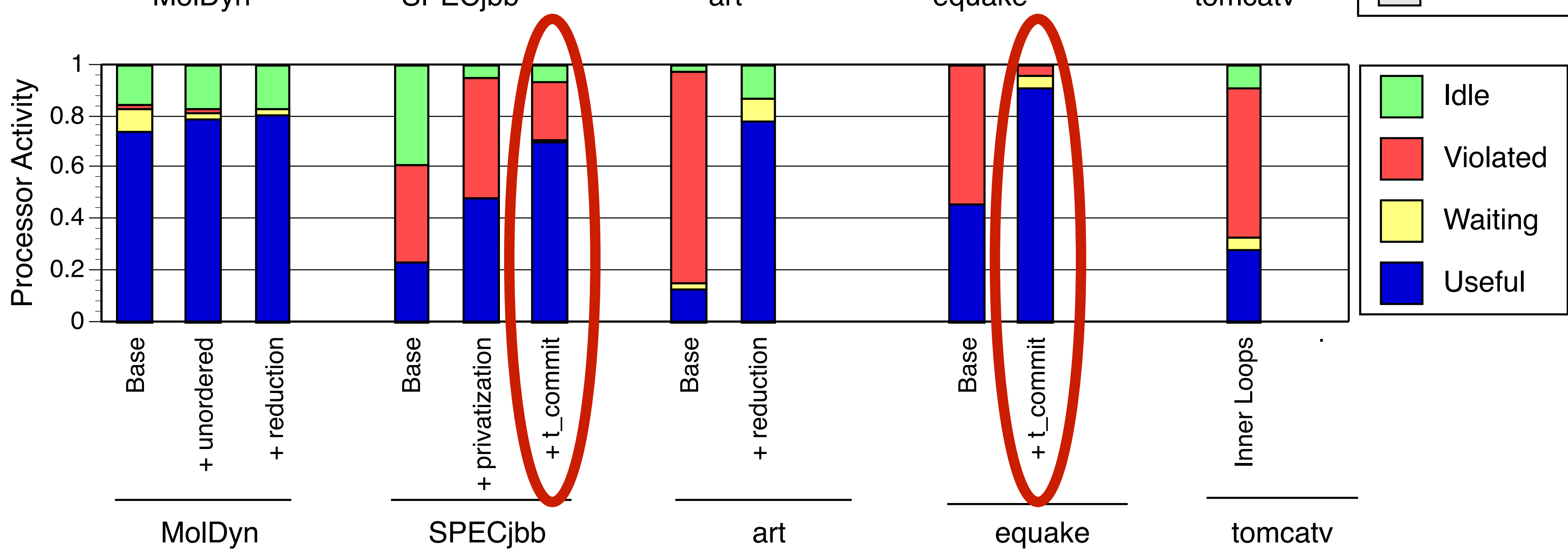
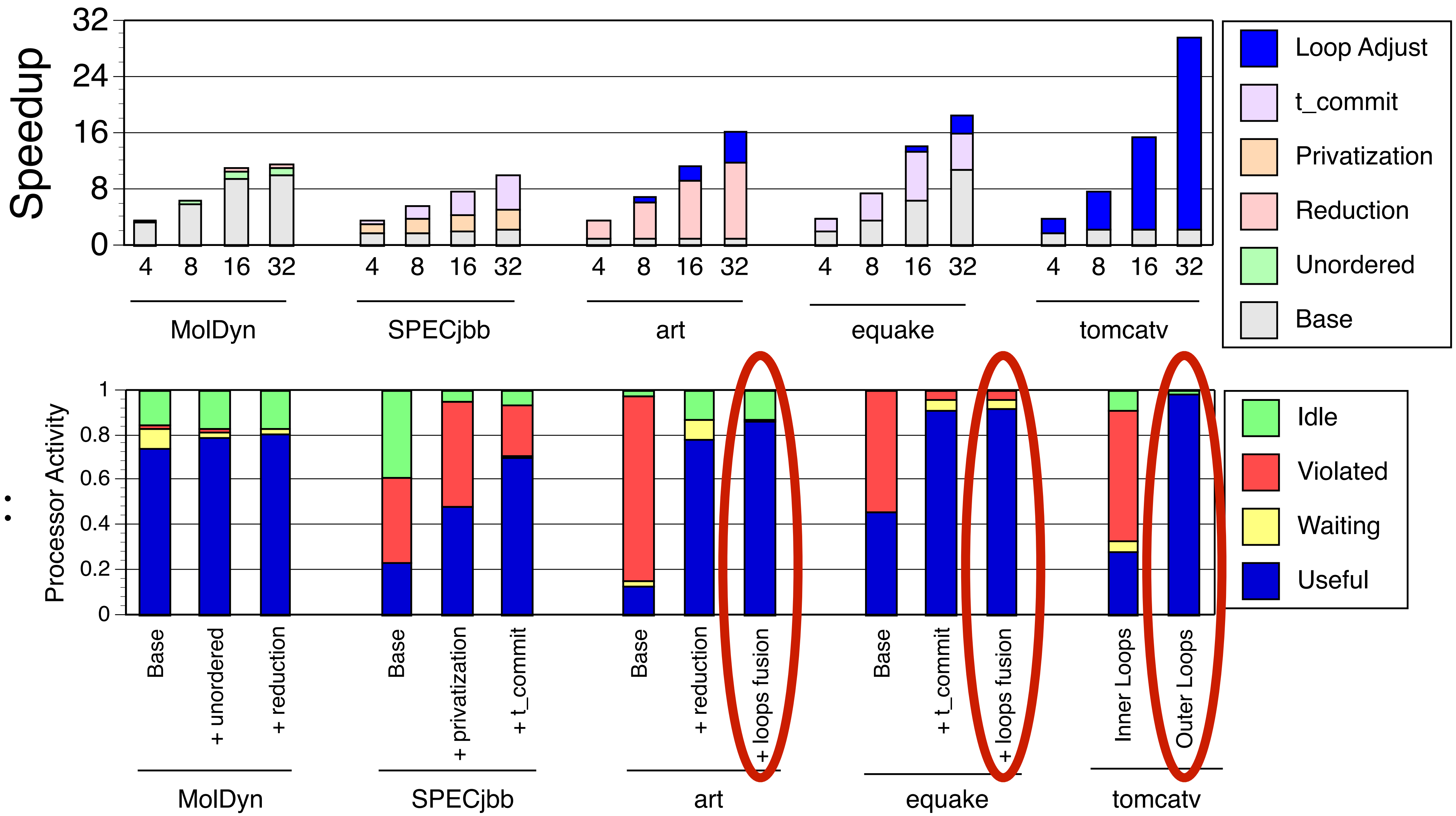


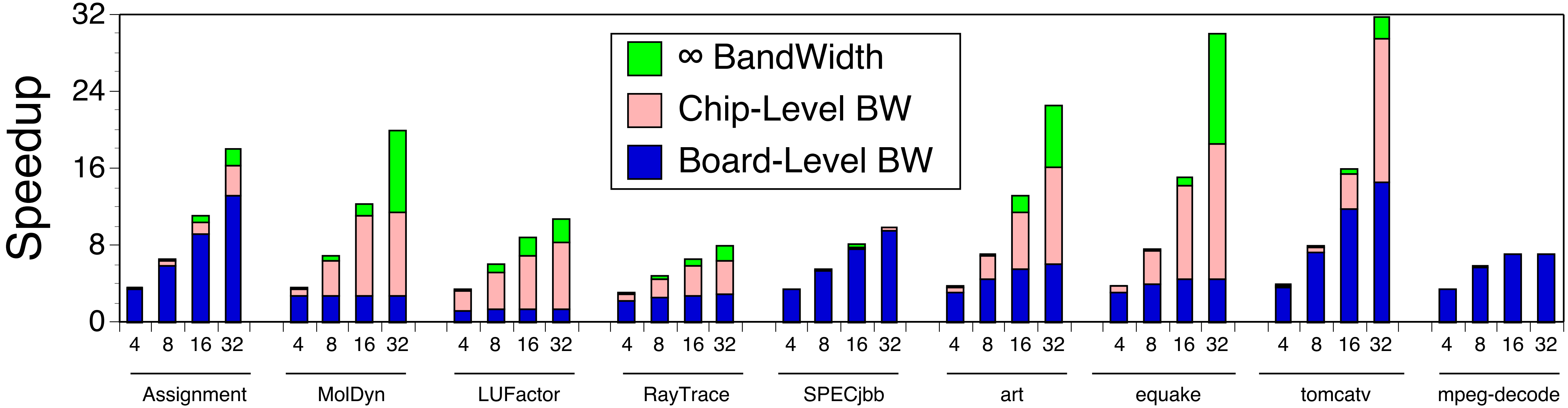
Merging Transactions

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

For 8P:



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

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