Heuristics for Profile-driven Method-level Speculative Parallelization

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Speculative Multithreading

- Speculatively parallelize an application
  - Uses speculation to overcome ambiguous dependencies
  - Uses hardware support to recover from misspeculation
  - Promising technique for automatically extracting parallelism from programs
- Problem: Where to put the threads?

Method-Level Speculation

- Idea: Use method boundaries as speculative threads
  - Computation is naturally partitioned into methods
  - Execution often independent
  - Well-defined interface
- Extract parallelism from irregular, non-numerical applications

Method-Level Speculation Example

```
main()
{
  work_A;

  foo();

  work_C; // reads *q
}
```

```
foo()
{
  work_B; // writes *p
}
```

Method-Level Speculation Example

```
main()
{
  work_A;
  foo() {
    work_B; // writes *p
  }
  work_C; // reads *q
}
```

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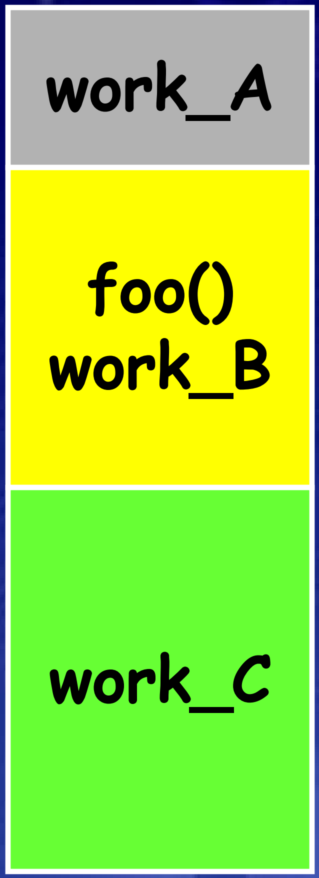

Sequential execution

Method-Level Speculation Example

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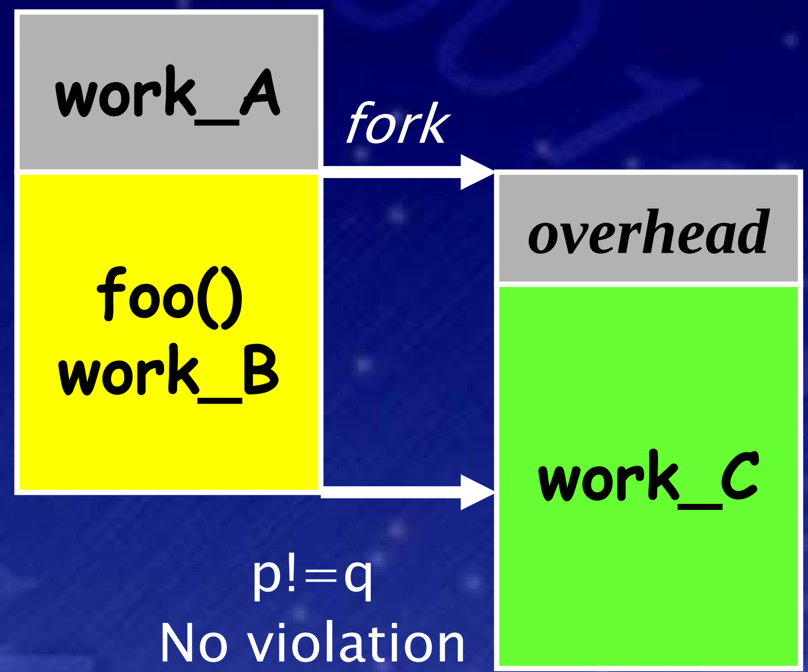

TLS execution – no violation

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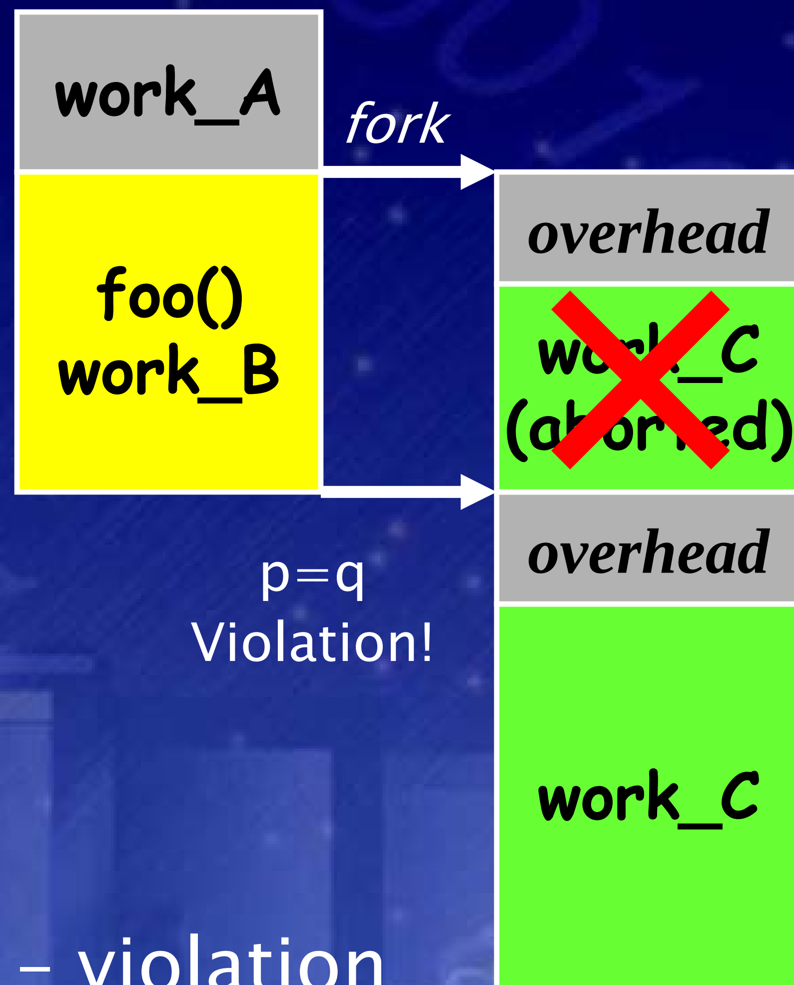
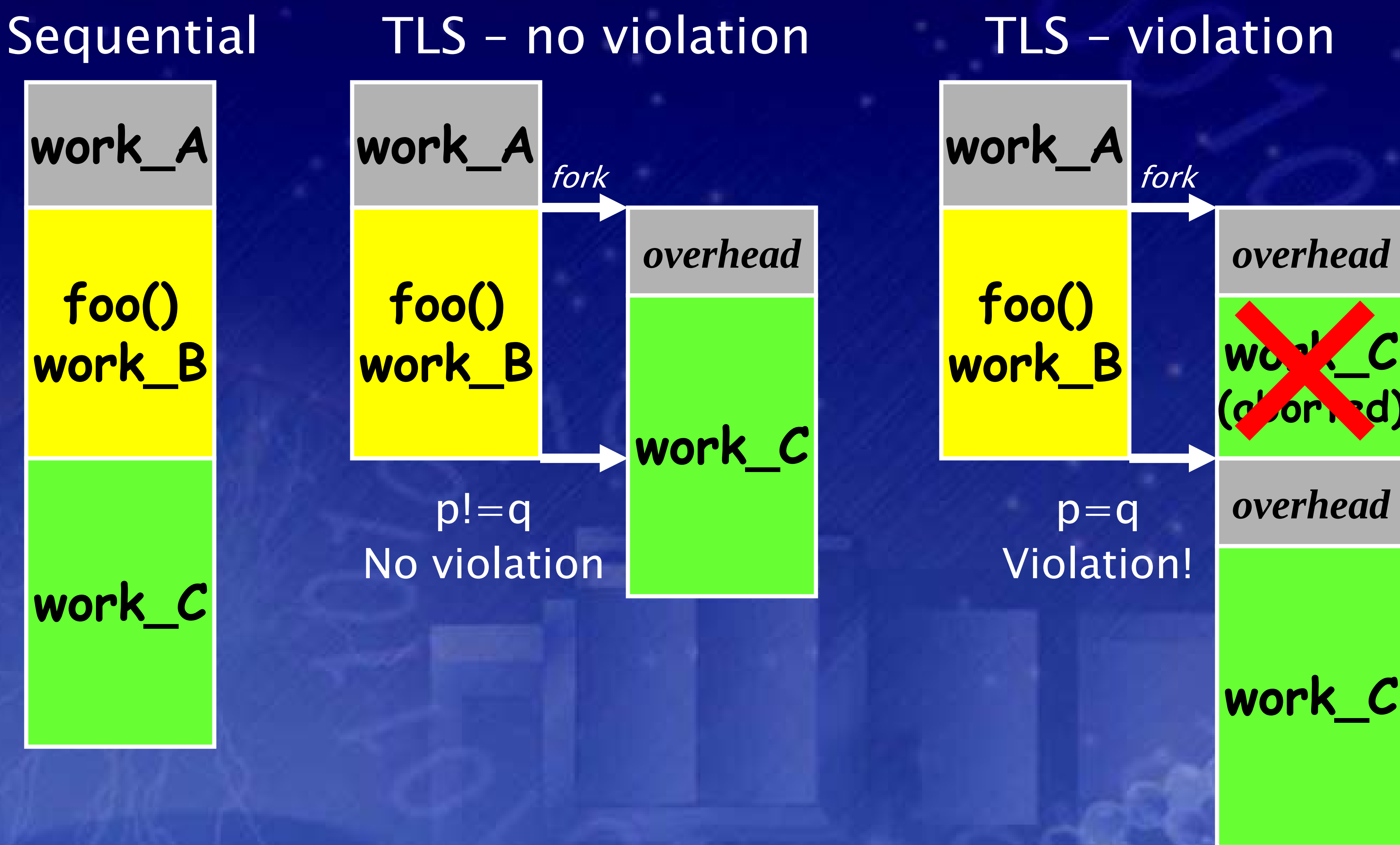
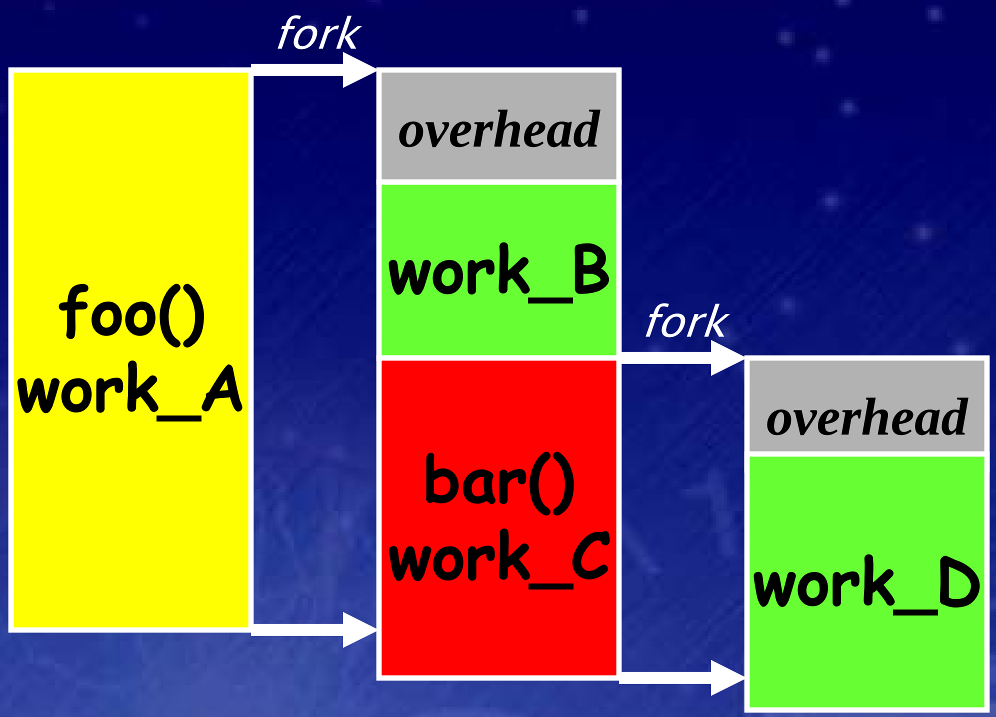


TLS execution – violation

Method-Level Speculation Example



Nested Speculation




```
main()
{
   foo() {
     work_A;
   }
   work_B;
   bar() {
     work_C;
   }
   work_D;
}
```

Sequences of method calls can cause nested speculation.

This Talk: Choosing Speculation Points

- Which methods to speculate?
  - Low chance of violation
  - Not too short, not too long
  - Not too many stores
- Idea: Use profile data to choose good speculation points
  - Used for profile-driven and dynamic compiler
  - Should be low-cost but accurate
- We evaluated 7 different heuristics
  - ~80% effective compared to perfect oracle

Difficulties in Method-Level Speculation

- Method invocations can have varying execution times
  - Too short: Doesn't overcome speculation overhead
  - Too long: More likely to violate or overflow, prevents other threads from retiring
- Return values
  - Mispredicted return value causes violation

Classes of Heuristics

- Simple Heuristics
  - Use only simple information, such as method runtime
- Single-Pass Heuristics
  - More advanced information, such as sequence of store addresses
  - Single pass through profile data
- Multi-Pass Heuristics
  - Multiple passes through profile data

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Runtime Heuristic (SI-RT)

- Speculate on all methods with:
  - MIN < runtime < MAX
- Idea: Should be long enough to amortize overhead, but not long enough to violate
- Data required:
  - Average runtime of each method

Store Heuristic (SI-SC)

- Speculate on all methods with:
  - dynamic # of stores < MAX
- Idea: Stores cause violations, so speculate on methods with few stores
- Data required:
  - Average dynamic store count of each method

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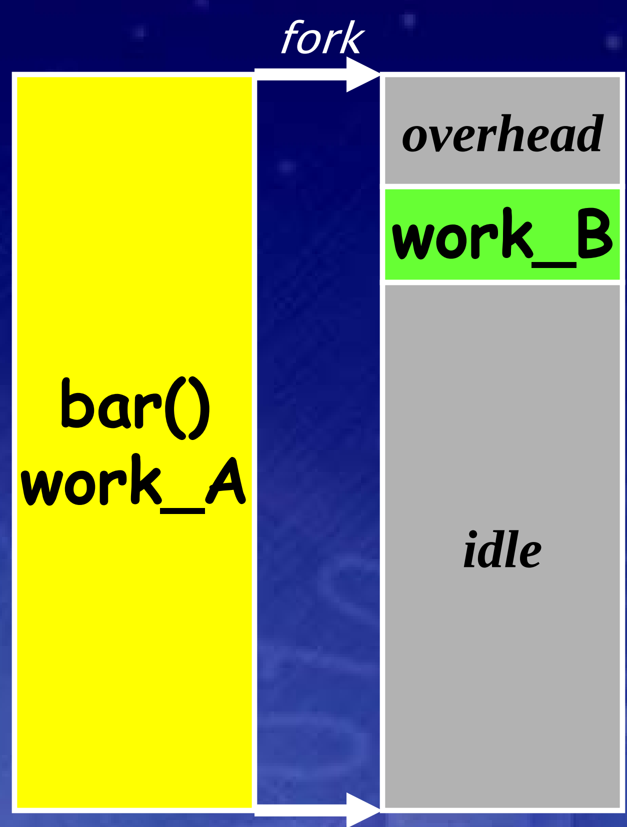
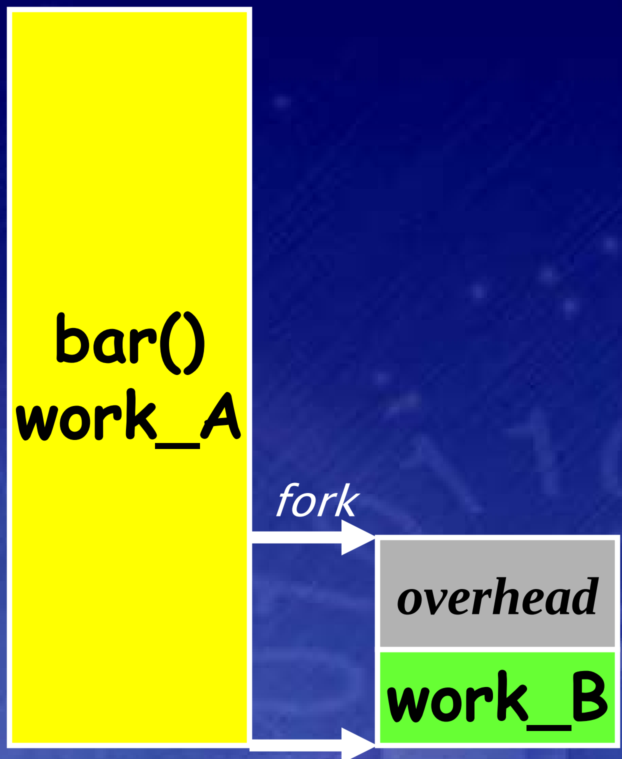
Stalled Threads




```
foo()
{
  bar() {
    work_A;
  }
  work_B;
}
```

Speculative threads may stall while waiting to become main thread.

Fork at intermediate points




```
foo()
{
  bar() {
    work_A;
  }
  work_B;
}
```

Fork at an intermediate point within a method to avoid violations and stalling

Best Speedup Heuristic (SP-SU)

- Speculate on methods with:
  - predicted speedup > THRES
- Calculate predicted speedup by:

$$\frac{\text{expected sequential run time}}{\text{expected parallel run time}}$$

- Scan store stream backwards to find fork point
  - Choose fork point to avoid violations and stalling

Most Cycles Saved Heuristic (SP-CS)

- Speculate on methods with:
  - predicted cycle savings > THRES
- Calculate predicted cycle savings by:

  sequential cycle count – parallel cycle count

- Place fork point such that:
  - predicted probability of violation < RATIO
- Uses same information as SP-SU

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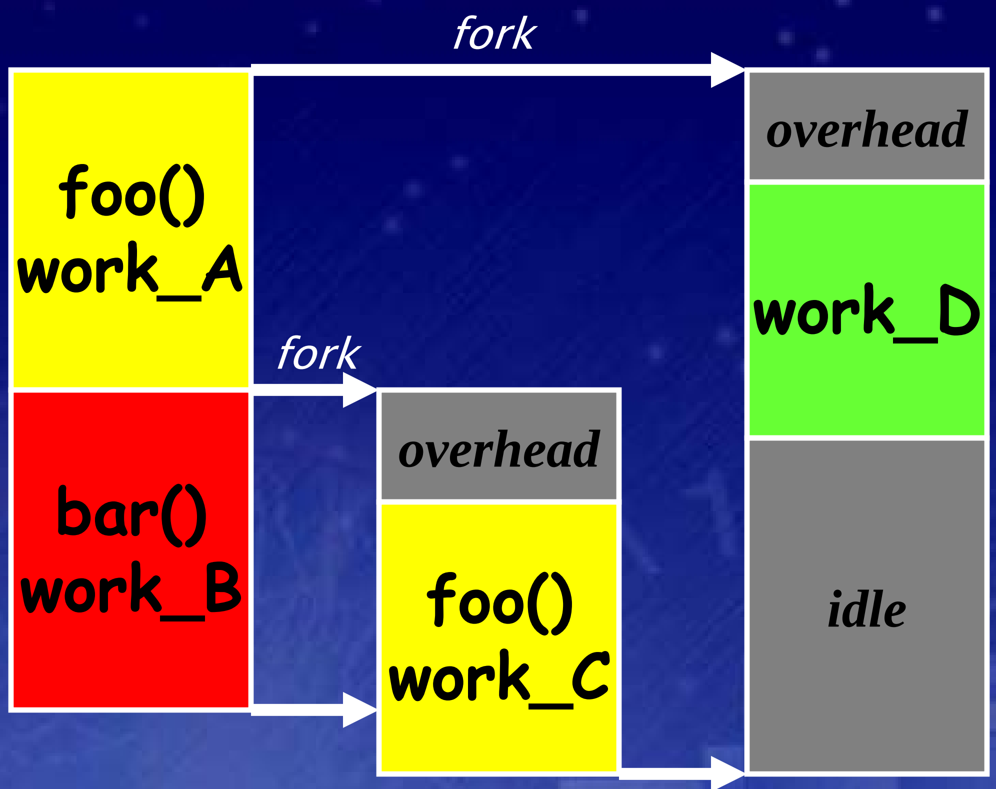
Nested Speculation




```
main()
{
   foo() {
      work_A;
      bar() {
         work_B;
      }
      work_C;
   }
   work_D;
}
```

Effectiveness of speculation choice depends on choices for caller methods!

Best Speedup Heuristic with Parent Info (MP-SU)

- Iterative algorithm:
  - Choose speculation with best speedup
  - Readjust all callee methods to account for speculation in caller
  - Repeat until best speedup < THRES
- Max # of iterations: depth of call graph

Most Cycles Saved Heuristic with Parent Info (MP-CS)

- Iterative algorithm:
  1. Choose speculation with most cycles saved and predicted violations < RATIO
  2. Readjust all callee methods to account for speculation in caller
  3. Repeat until most cycles saved < THRES
- Multi-pass version of SP-CS

Most Cycles Saved Heuristic with No Nesting (MP-CSNN)

- Iterative algorithm:
  - Choose speculation with most cycles saved and predicted violations < RATIO.
  - *Eliminate* all callee methods from consideration.
  - Repeat until most cycles saved < THRES.
- Disallows nested speculation to avoid double-counting the benefits
- Faster to compute than MP-CS

Experimental Results

Trace-Driven Simulation

- How to find the optimal parameters (THRES, RATIO, etc.) ?
- Parameter sweeps
  - For each benchmark
    - For each heuristic
      - Multiple parameters for each heuristic
- For cycle-accurate simulation: >100 CPU years?!
- Alternative: *trace-driven simulation*

Trace-Driven Simulation

1. Collect trace on Pentium III (3-way out-of-order CPU, 32K L1, 256K L2)
   - Record all memory accesses, enter/exit method events, etc.
2. Recalibrate to remove instrumentation overhead
3. Simulate trace on 4-way CMP hardware
   - Model shared cache, speculation overheads, dependencies, squashing, etc.

Spot check with cycle-accurate simulator: Accurate within ~3%

Simulated Architecture

- Four 3-way out-of-order CPUs
  - 32K L1, 256K shared L2
- Single speculative buffer per CPU
- Forking, retiring, squashing overhead: 70 cycles each
- Speculative threads can be preempted
  - Low priority speculations can be squashed by higher priority ones

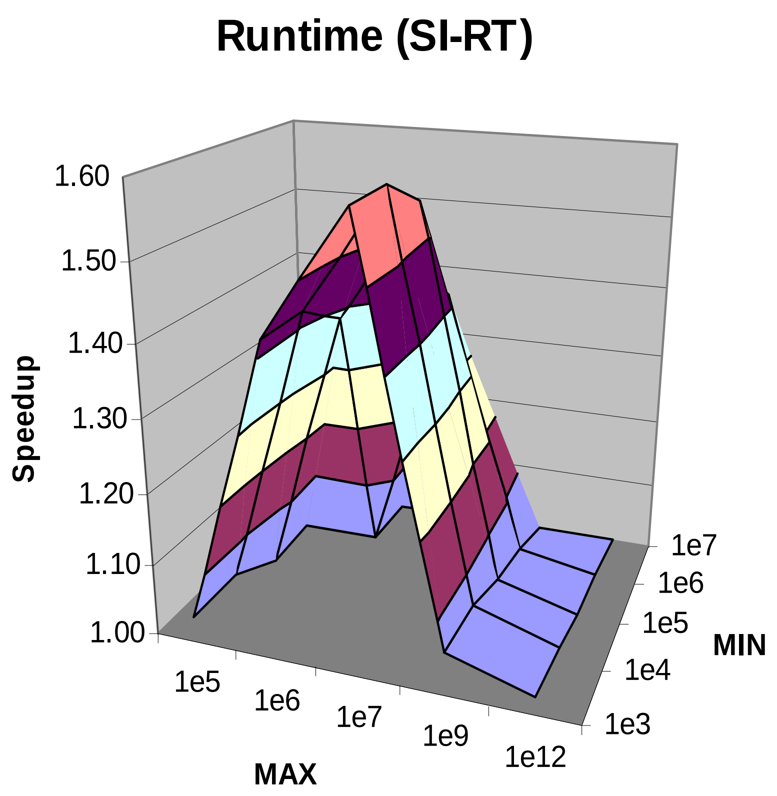
The Oracle

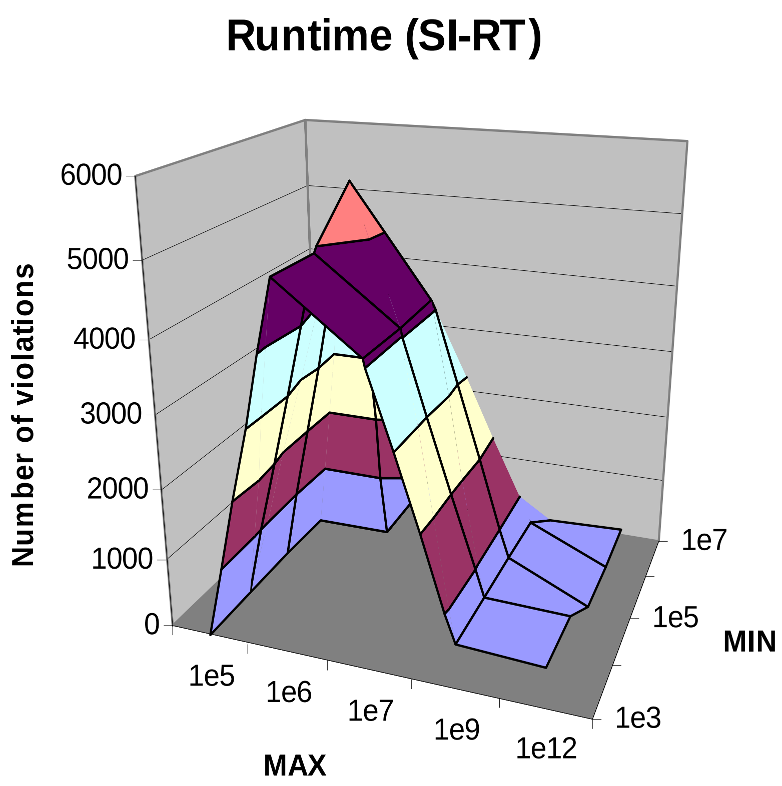
- A “Perfect” Oracle
  - Preanalyzes entire trace
  - Makes a separate decision on every method invocation
  - Chooses fork points to never violate
  - Zero overhead for forking or retiring threads
- *Upper-bound on performance of any heuristic*

Benchmarks

- SpecJVM
  - compress: Lempel-Ziv compression
  - jack: Java parser generator
  - javac: Java compiler from the JDK 1.0.2
  - jess: Java expert shell system
  - mpeg: Mpeg layer 3 audio decompression
  - raytrace: Raytracer that works on a dinosaur scene
- SPLASH-2
  - barnes: Hierarchical N-body solver
  - water: Simulation of water molecules

Heuristic Parameter Tuning





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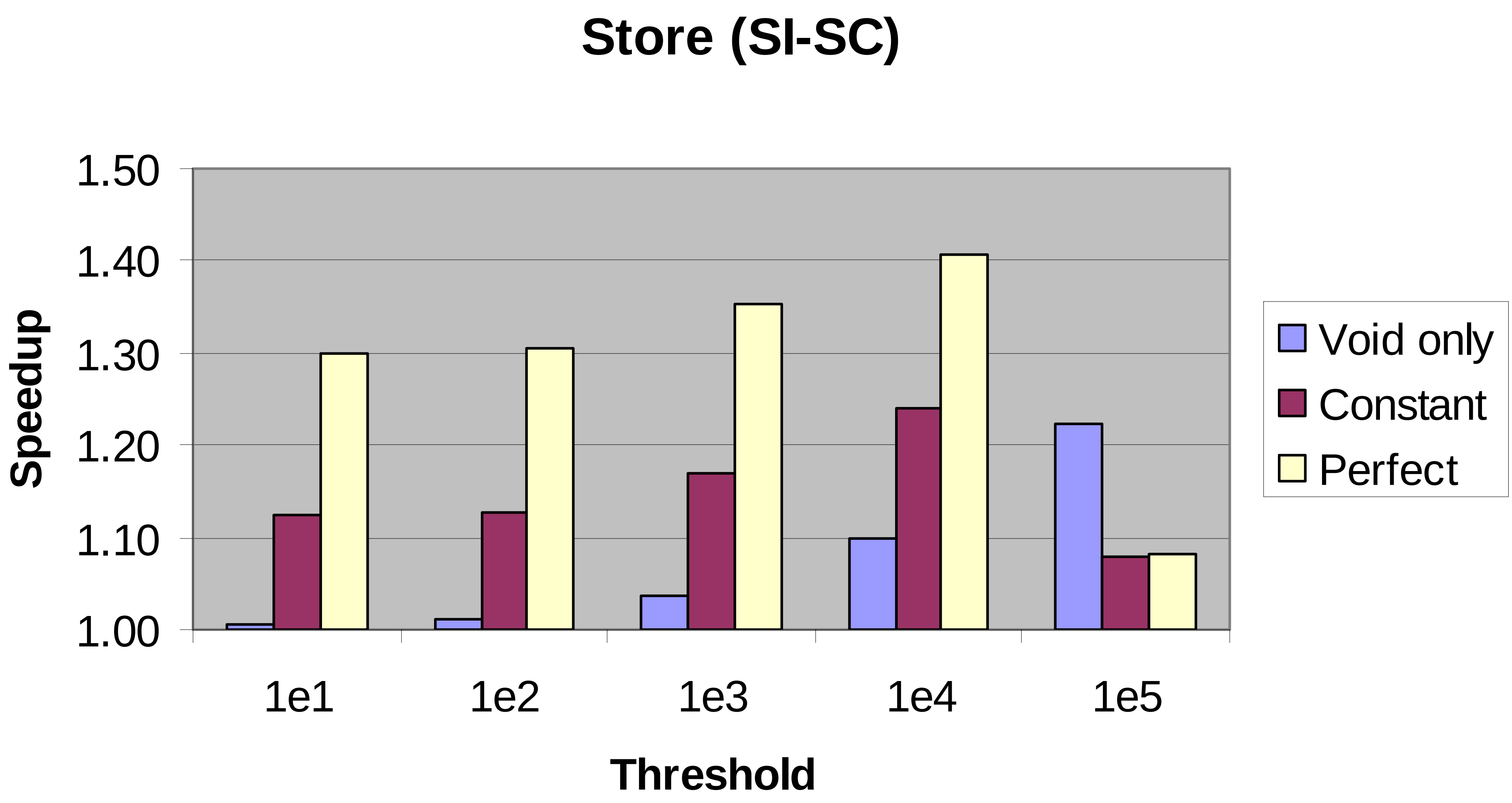

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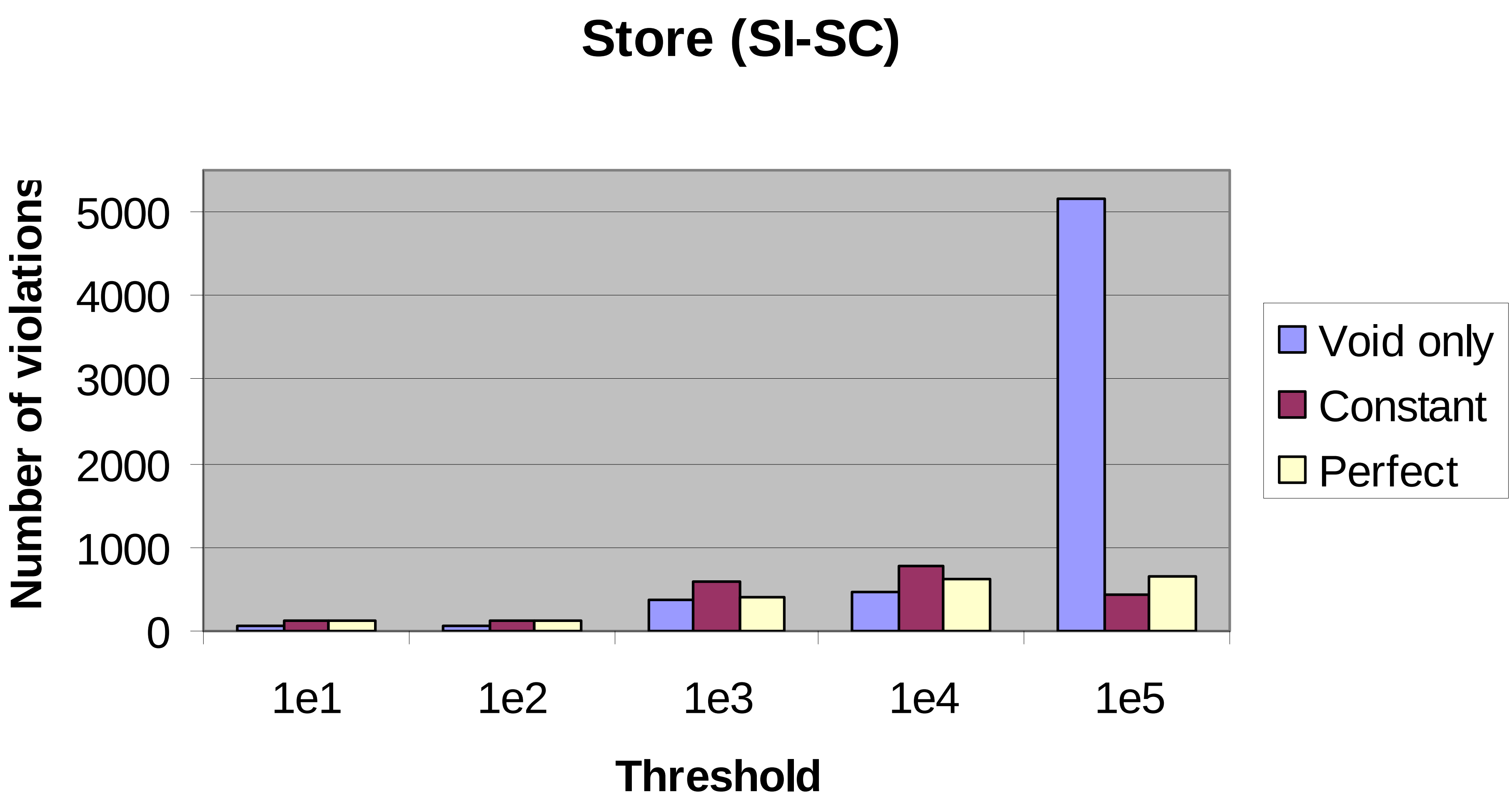

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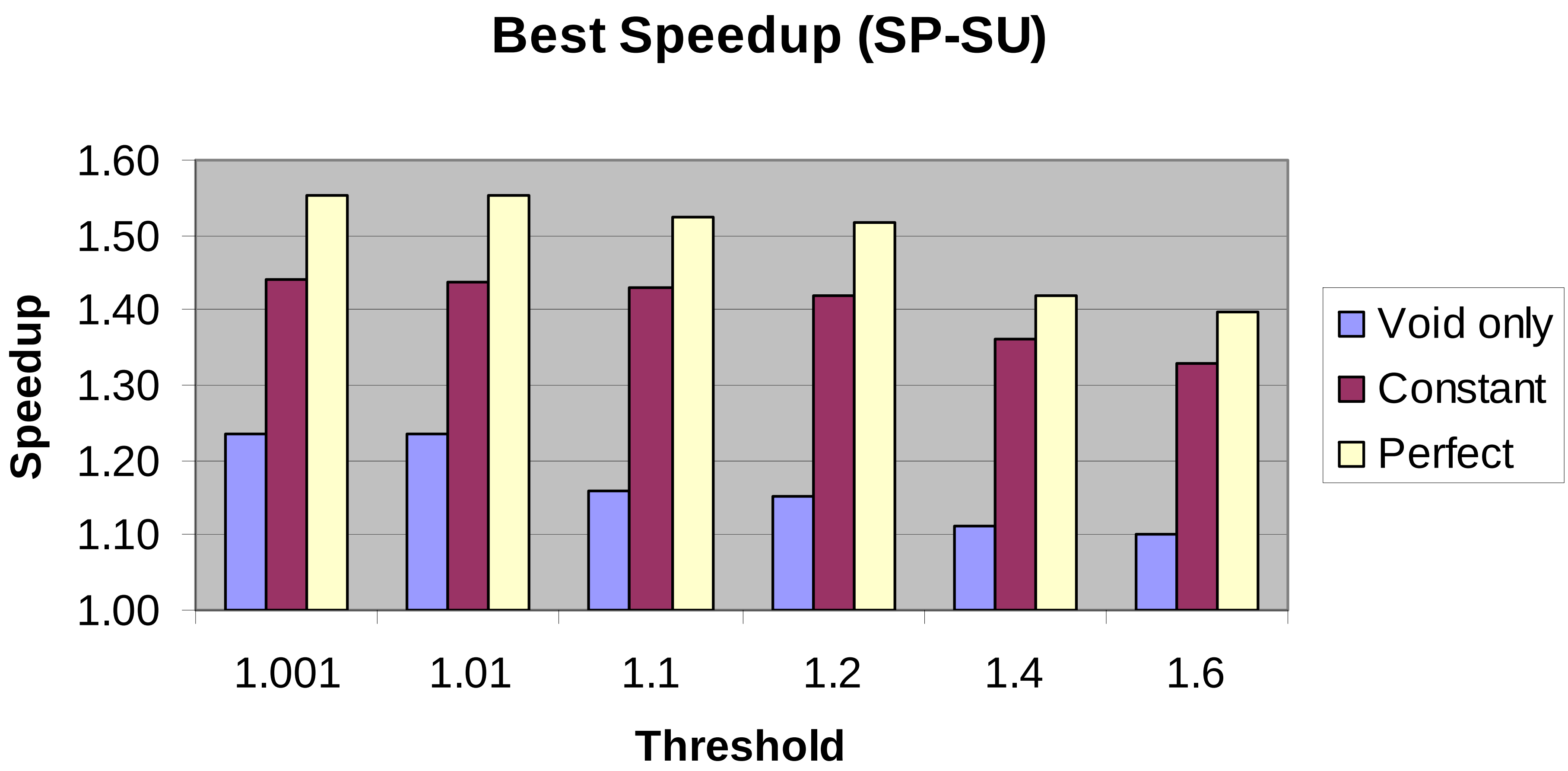

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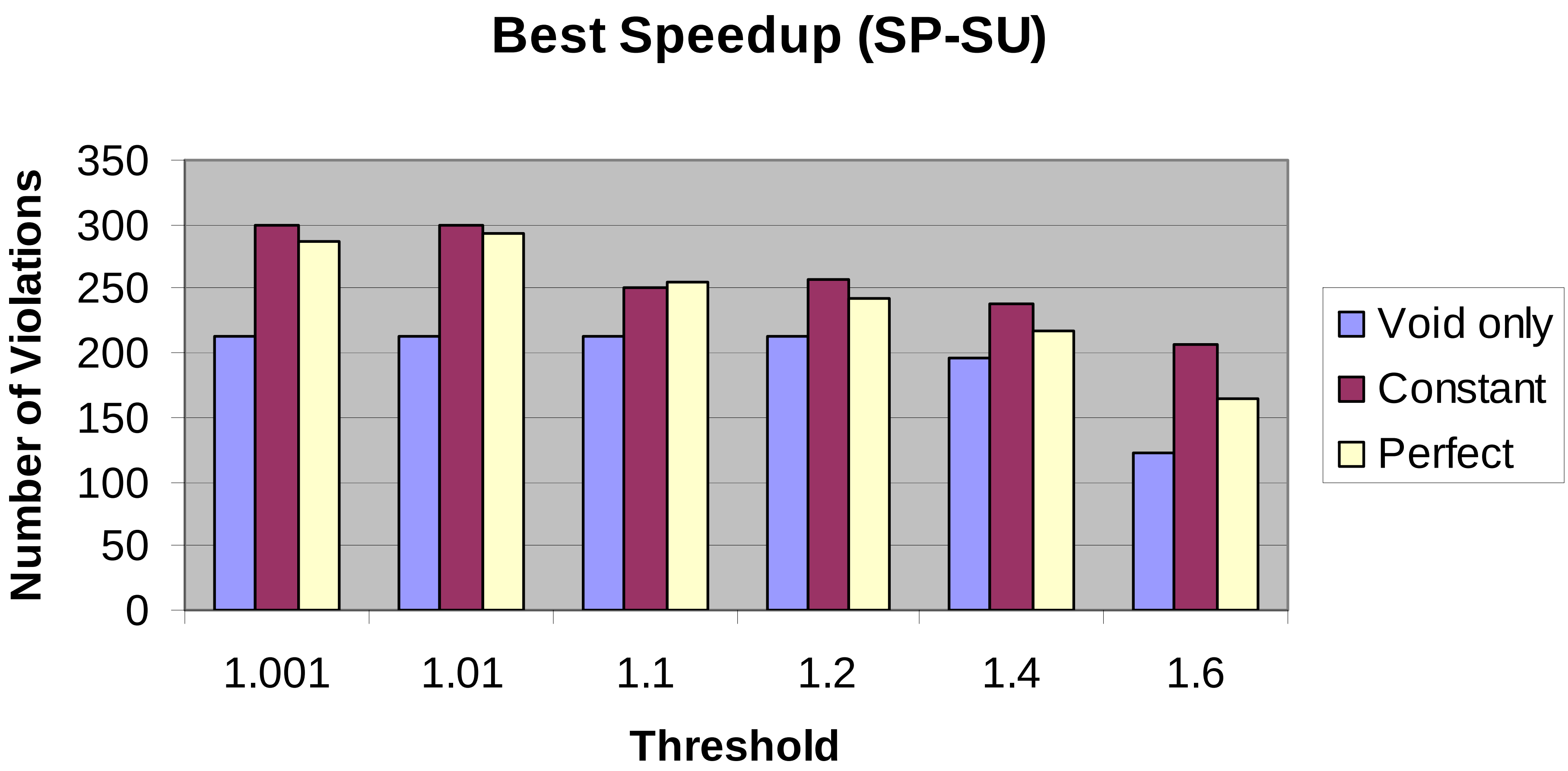

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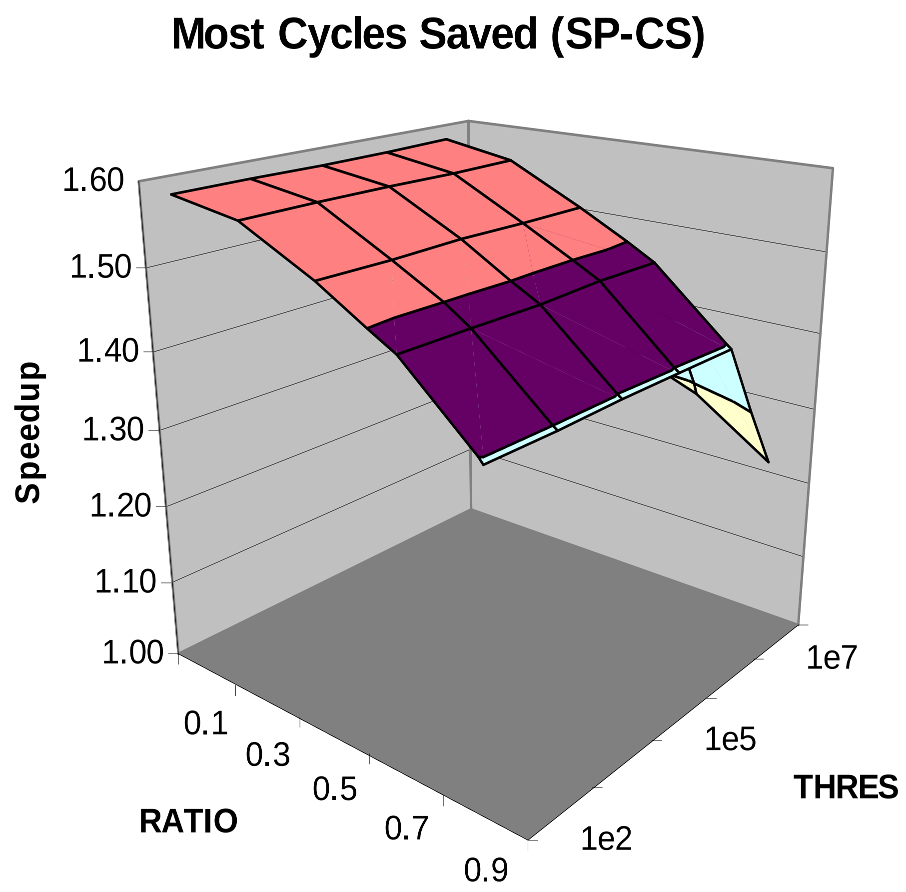

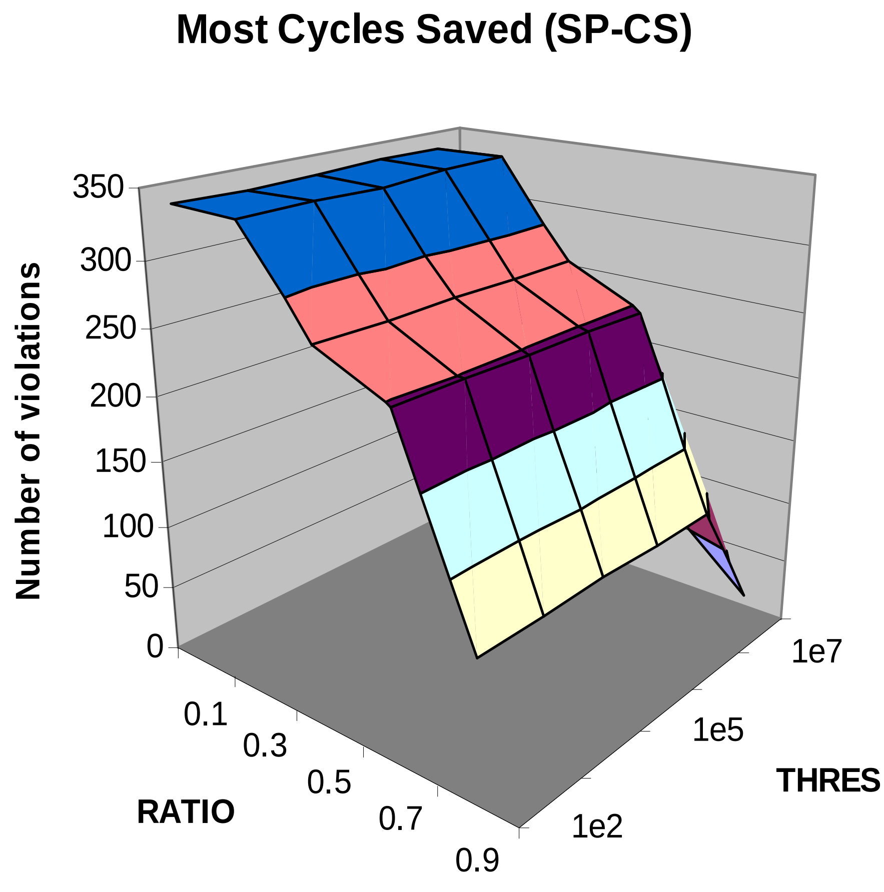

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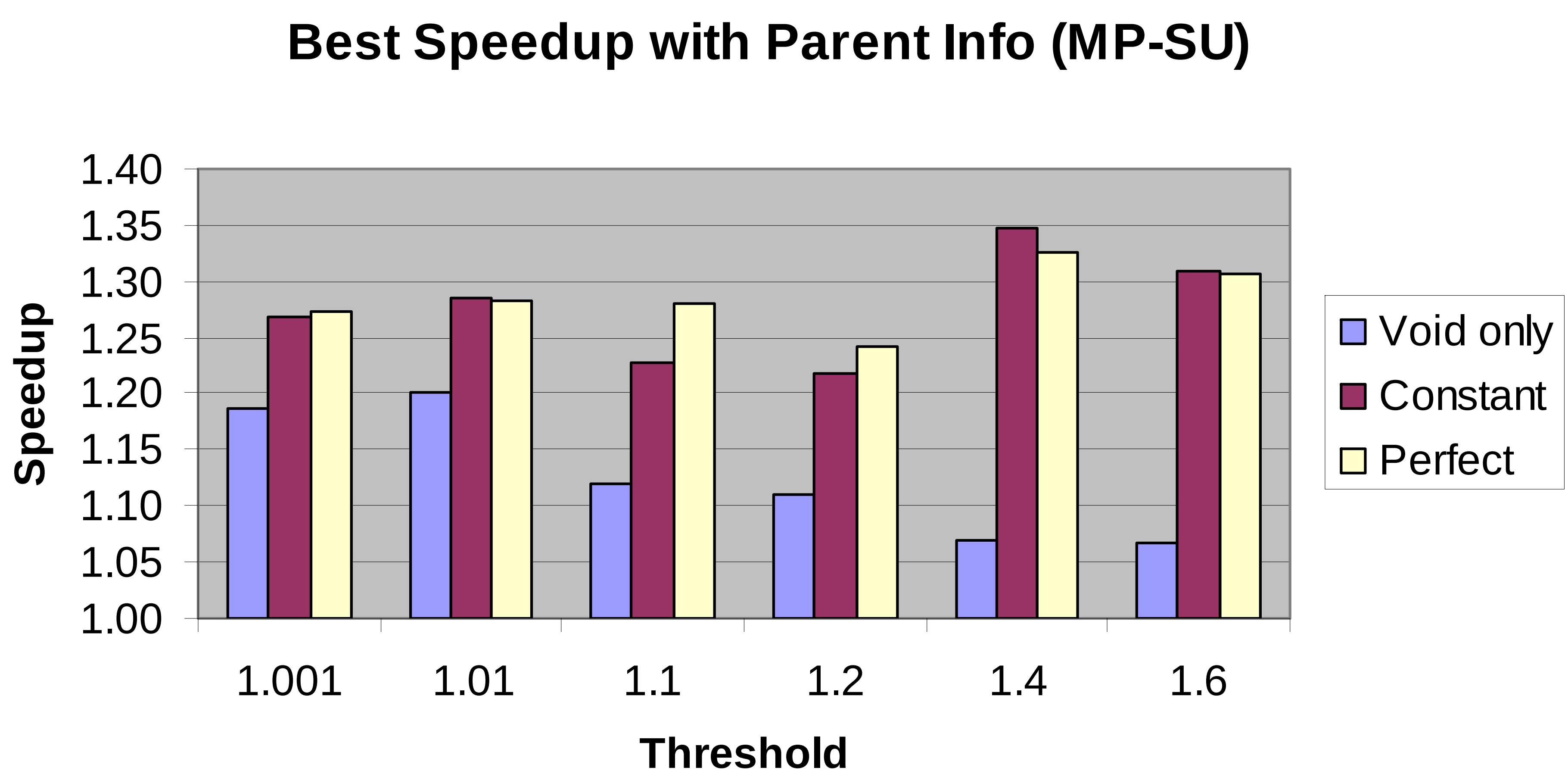

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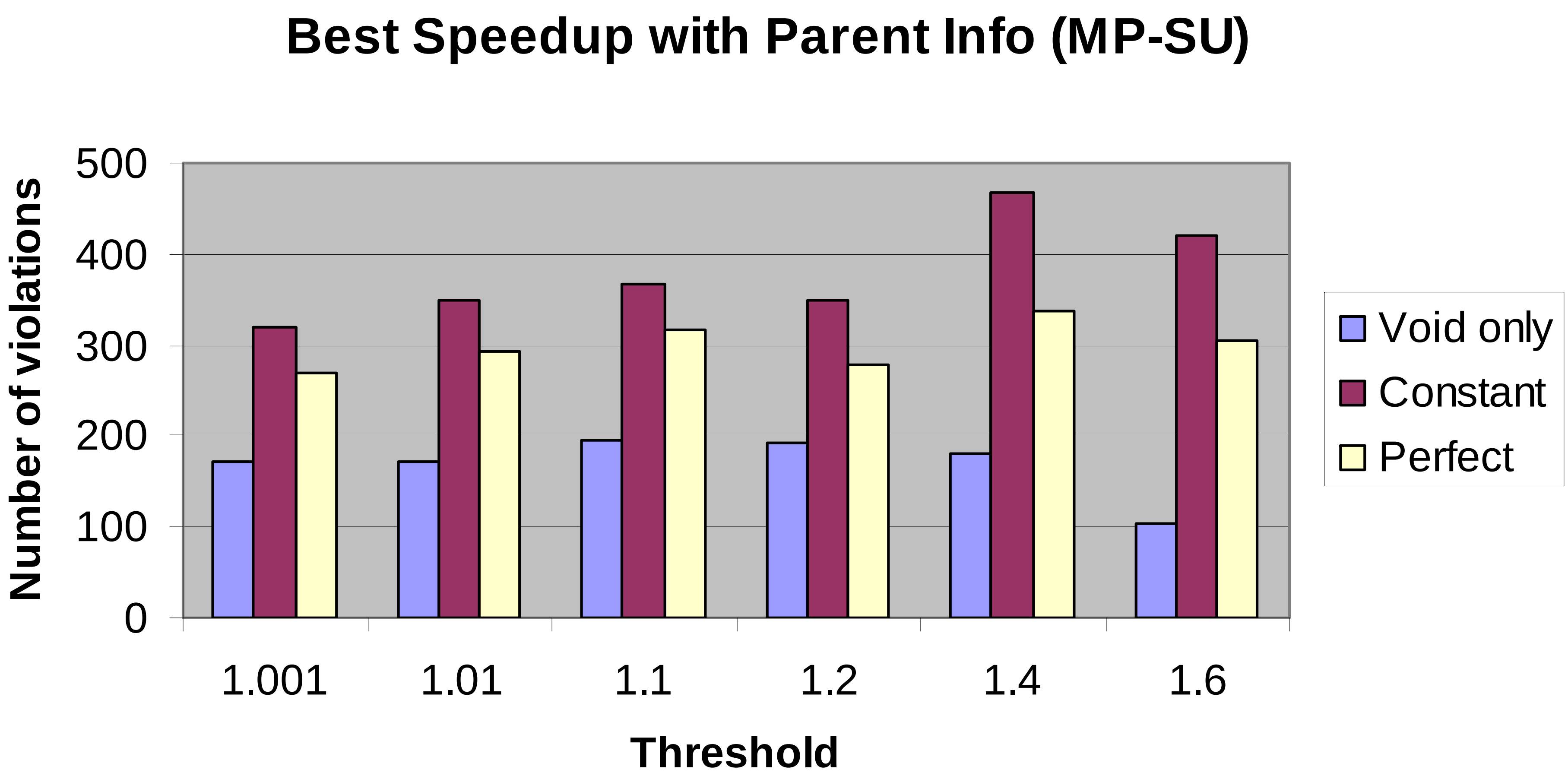

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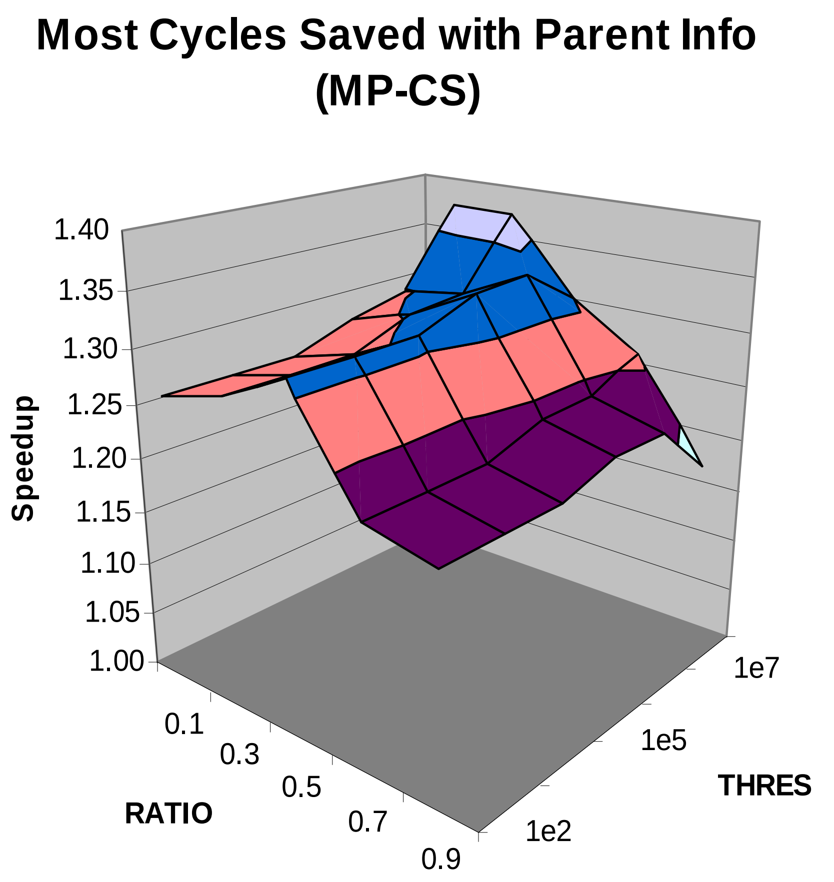

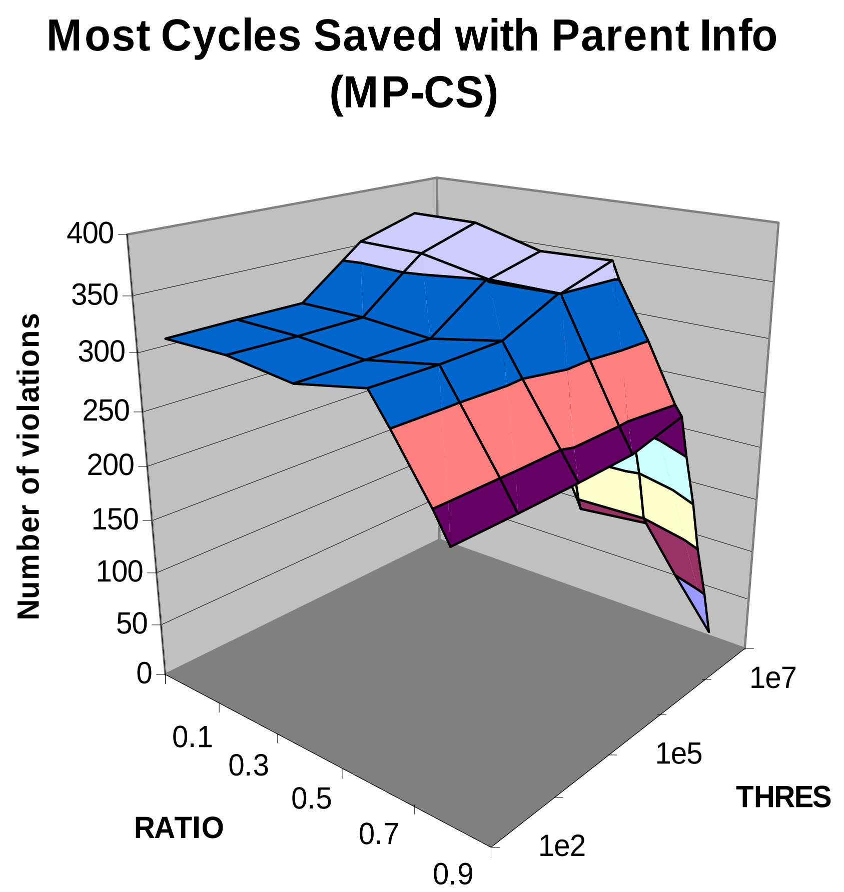

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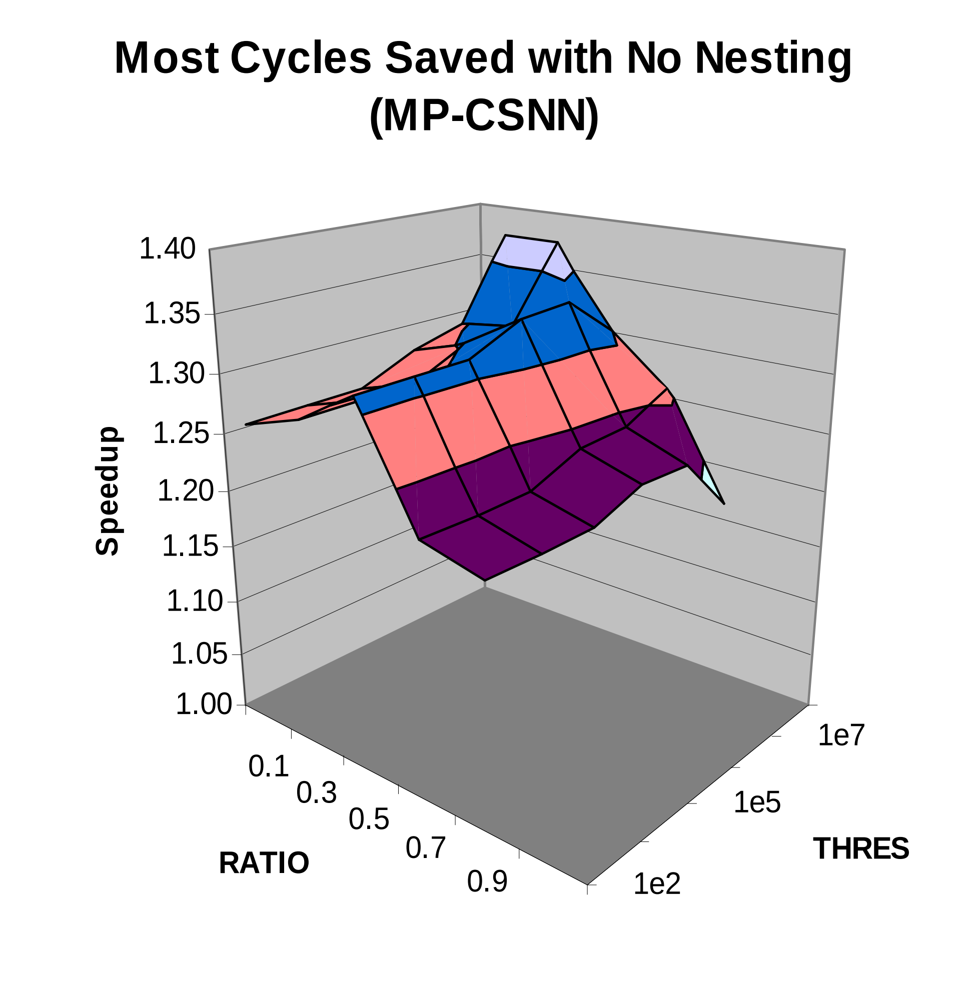
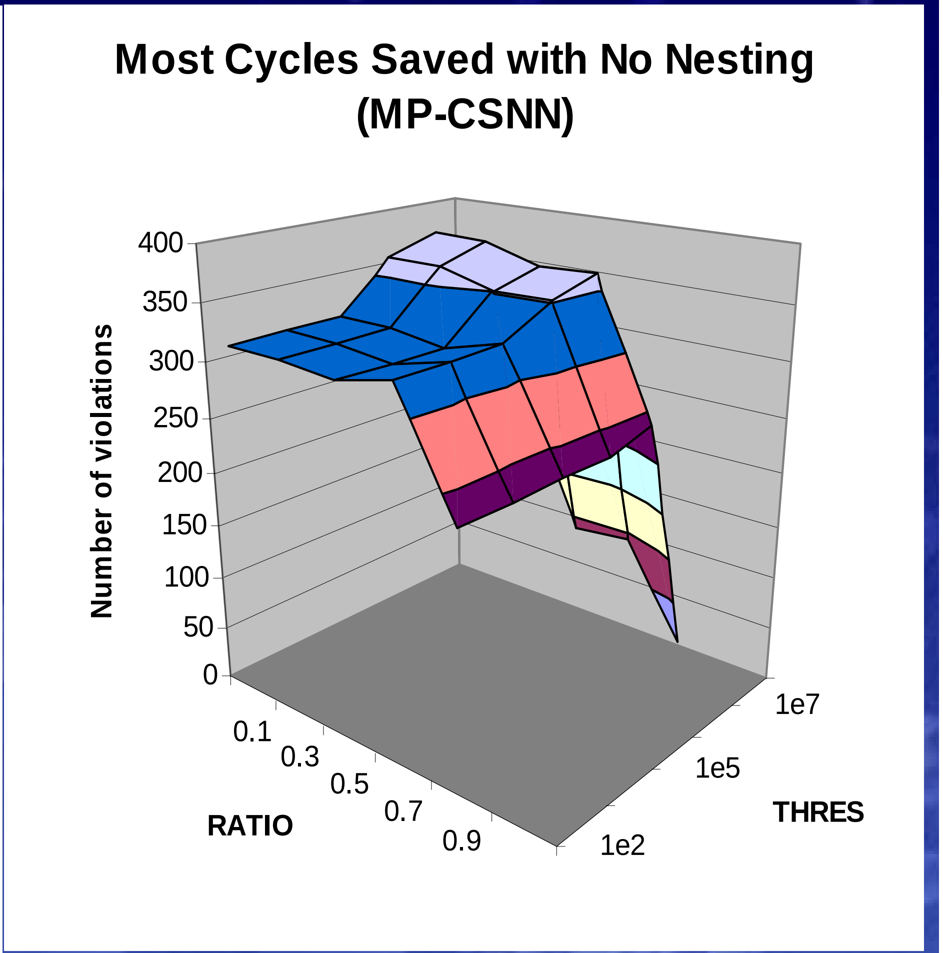
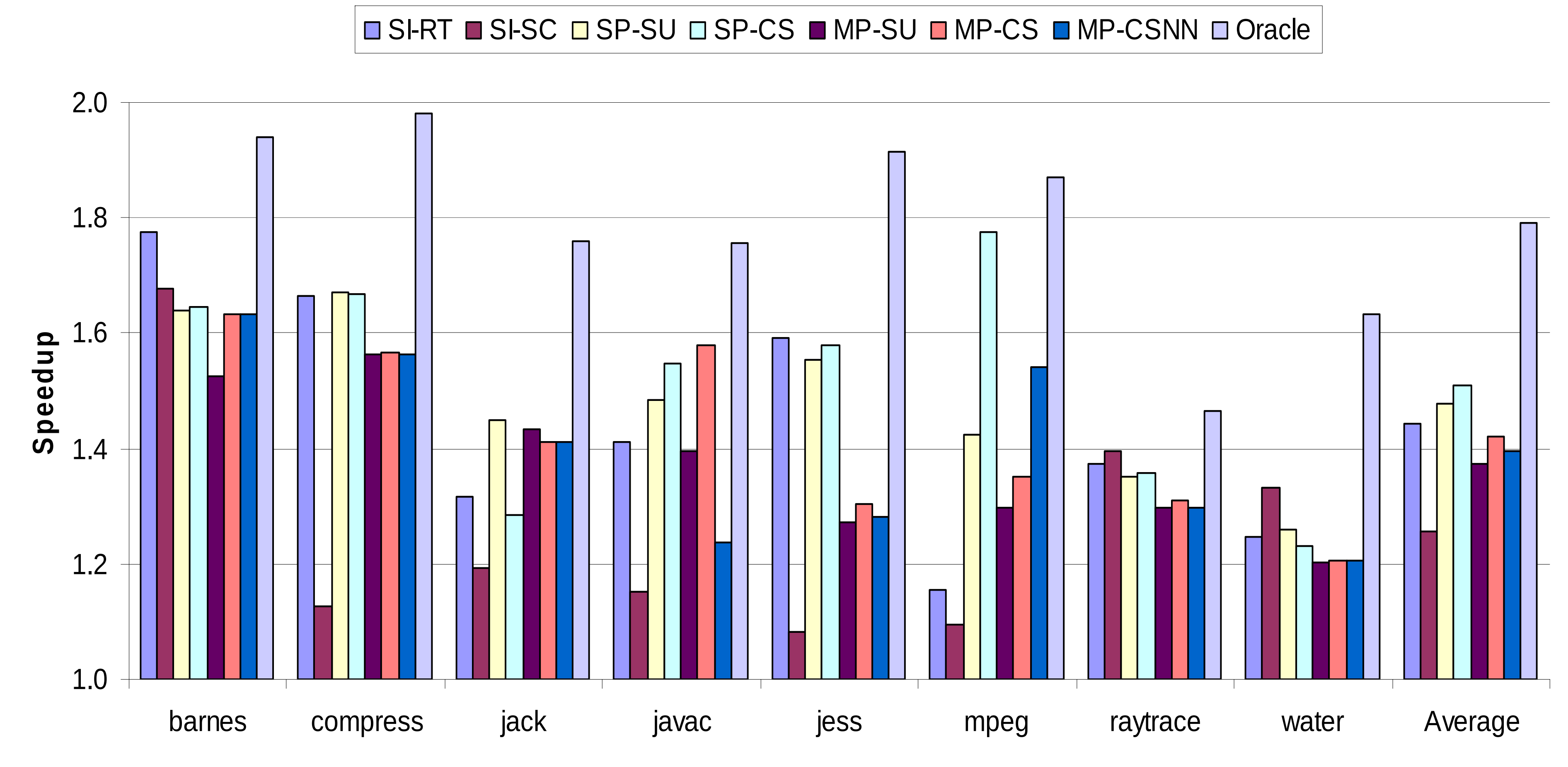




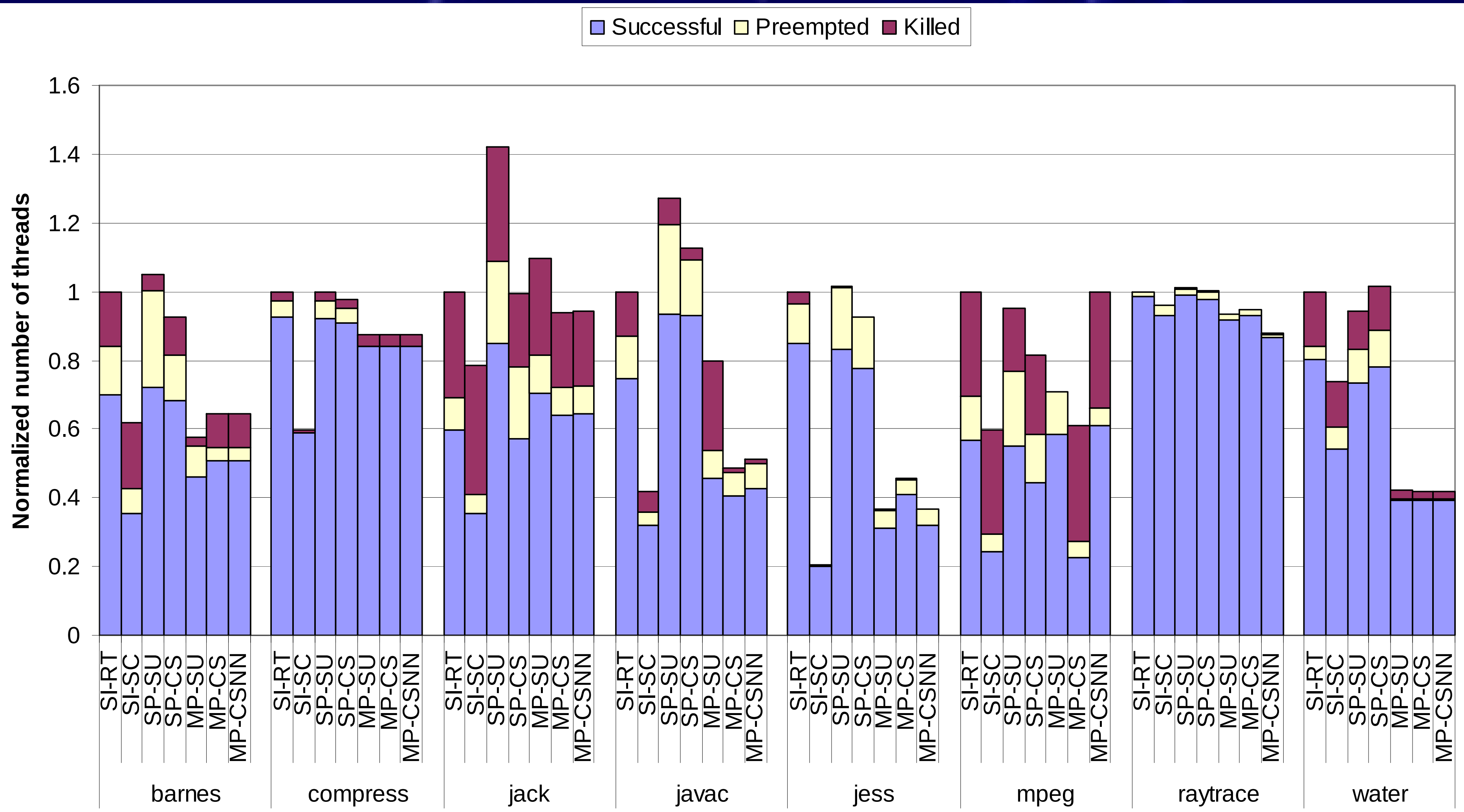
Tuning Summary

- Runtime (SI-RT):
  - MIN = 10^3 cycles, MAX = 10^7 cycles
- Store (SI-SC):
  - MAX = 10^5 stores
- Best speedup (SP-SU, MP-SU):
  - Single pass: MIN = 1.2x speedup
  - Multi pass: MIN = 1.4x speedup
- Most cycles saved (SP-CS, MP-CS, MP-CSNN):
  - THRES = 10^5 cycles saved, RATIO = 70% violation
- Return value prediction:
  - Constant is within 15% of perfect value prediction

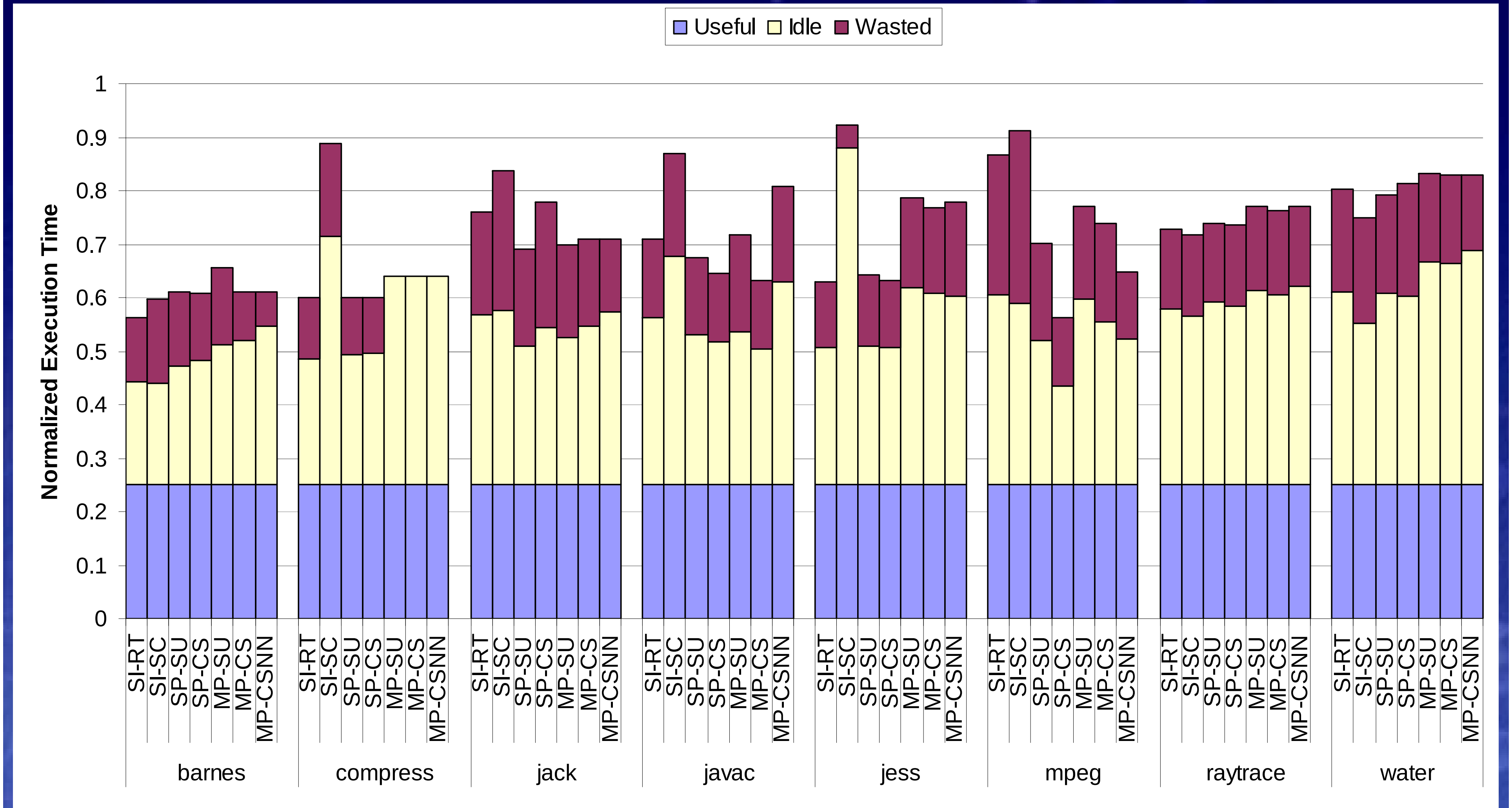
Overall Speedups



Breakdown of Speculative Threads



Breakdown of Execution Time



Speculative Store Buffer Size

	barnes	comp	jack	javac	jess	mpeg	rtrace	water
SI-RT	0.31	0.18	0.39	2.05	0.26	0.76	1.64	0.20
SI-SC	12.02	6.47	0.19	3.51	0.15	13.02	1.64	1.45
SP-SU	8.11	6.48	0.39	1.08	0.30	13.02	1.64	0.55
SP-CS	0.31	6.48	0.39	2.57	0.30	**15.29**	1.64	0.22
MP-SU	12.01	6.48	0.39	0.30	0.30	1.27	1.27	1.38
MP-CS	12.02	6.48	0.39	0.30	0.30	1.64	1.27	1.38
MP-CSNN	12.02	6.48	0.39	2.57	0.30	13.02	1.27	1.38

Maximum speculative store buffer size: 16KB

Related Work

- Loop-level parallelism
- Method-level parallelism
  - Warg and Stenstrom
    - ICPAC'01: Limit study
    - IPDPS'03: Heuristic based on runtime
    - CF'05: Misspeculation prediction
- Compilers
  - Multiscalar: Vijaykumar and Sohi, JPDC'99
  - SpMT: Bhowmik & Chen, SPAA'02

Conclusions

- Evaluated 7 heuristics for method-level speculation
- Take-home points:
  - Method-level speculation has complex interactions, very hard to predict
  - Single-pass heuristics do a good job: 80% of a perfect oracle
  - Most important issue is the balance between over- and under-speculating