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An Experimental Model to Analyze OpenMP Applications for System Utilization

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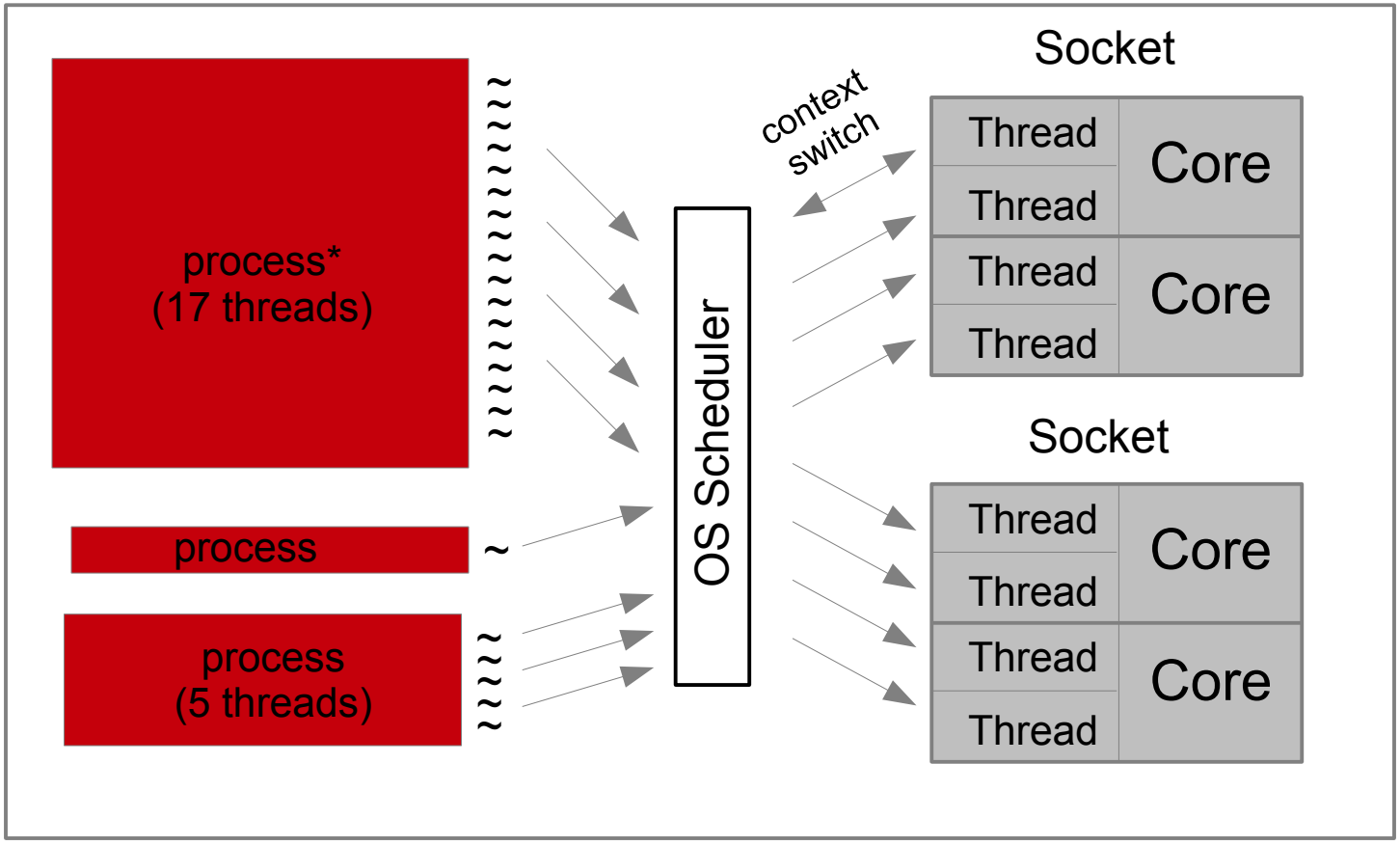
The Importance of System Utilization

- No program is 100% parallel
  - Utilization unimportant for one small, cheap server...
  - Critically important for a large data center
- No OS can provide 100% cycles to applications
  - Focus on single application performance
  - Lean on processor sets, processor binding
  - Result: reduced overall utilization
- Core counts per socket are increasing
- Systems are getting larger: more sockets & cores
- More than many applications can efficiently use

OpenMP Performance in a Throughput Context

Operating System Scheduler: Software Threads → Hardware Threads
Scheduling & Work Distribution Interactions Impact Utilization



*Process = Executing Program ~ = Executing Thread Process Memory

Need: Enable High Parallel Utilization

- Philosophy: Make efficient use of *any available* cycles
- If my program doesn't, how do I find the cause?
- Key scalability questions:
  - How well does the entire program scale?
  - Which parallel region is a bottleneck?
  - Do I have enough parallel work vs. overhead?
  - Is the serial time significant vs. parallel work?
  - Are the work chunks large enough vs. the time quantum?

Comparison of Scaling Analysis Models

Dedicated Analysis

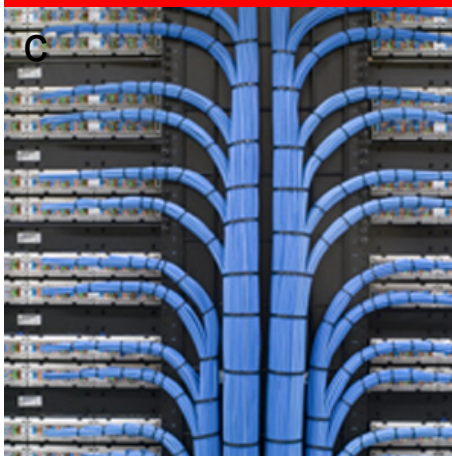
- Time to Solution
- Run at 1, 2, … N threads
  - One thread per core
  - Compare speedup at each thread count
- Scaling Reference: traditional 1 vs. N cores
- Scaling Bottleneck: Ambiguous: OpenMP or hardware

Non-Dedicated* Analysis

- Usage of Available Cycles
- Run only at N threads
  - Up to N cores
  - Model speedup at <= N cores
- Scaling Reference: loaded system
- Scaling Bottleneck: Unambiguous: OpenMP only

*Non-Dedicated is called Throughput

Tool Overview



Experimental Tool

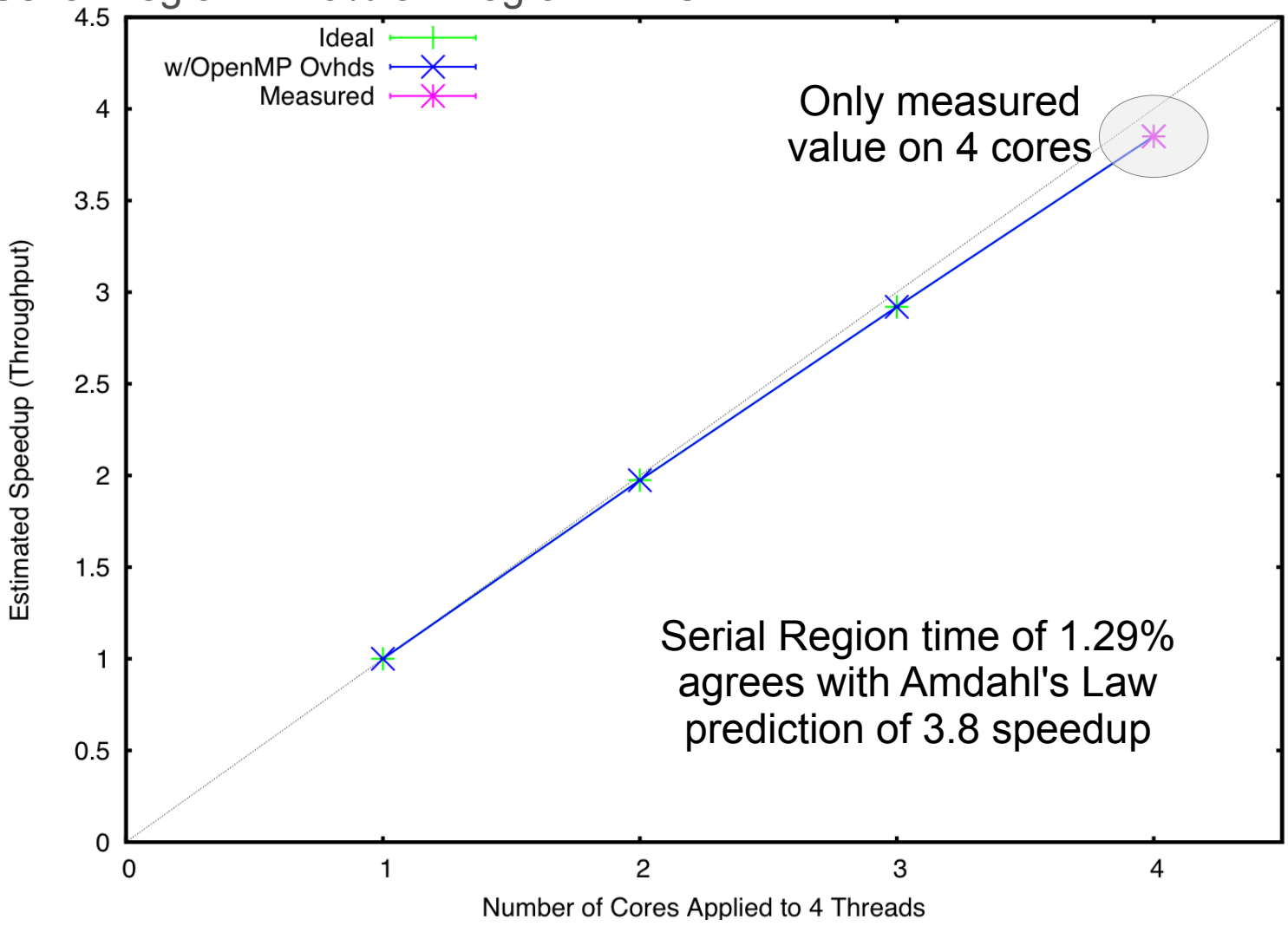
- Experimental tool implements the model
  - Runs on Solaris (x64 & SPARC)
- Model applies to any UNIX system
- Tool generates shell/DTrace script to run target program
- Trace data processed to generate performance model:
  - Reconstruct the OpenMP program structure as run
  - Simulate execution on a range of core counts (round-robin)
  - Generate a text report, and optionally sequence of graphs
- Speedup analysis aggregated to:
  - Each worksharing construct
  - Each parallel region
  - Entire program
- Complimentary to existing tools

Terms Used: What is Speedup?

- Speedup: ratio of *work time* to *elapsed time*
- Work Time:
  - Any time not OpenMP overhead
  - Measured as run with N threads
- *Ideal* Speedup: without OpenMP overhead
- Elapsed Time:
  - Measured (as run), presuming all cores available
  - Estimated via simulation (1 thru N cores using times as run)
- *Preceding Serial*:
  single-thread time before a parallel region
- *Stand-Alone*:
  loop speedup without considering preceding serial time

Example Tool – Speedup Analysis Entire Program

Serial Region: 1.29% of Program Time



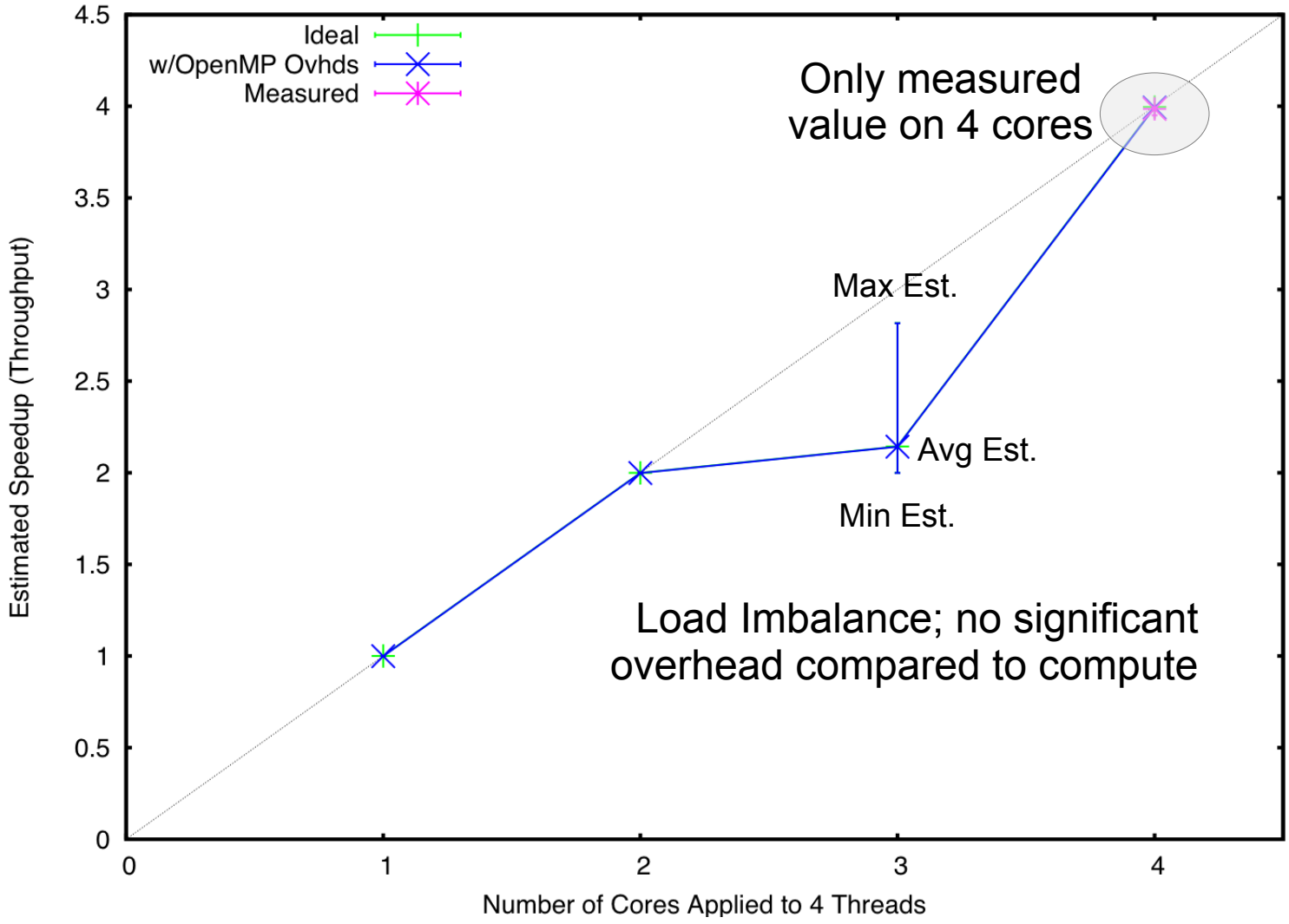
About the Charts

Maximum value measured or estimated

Average value measured or estimated

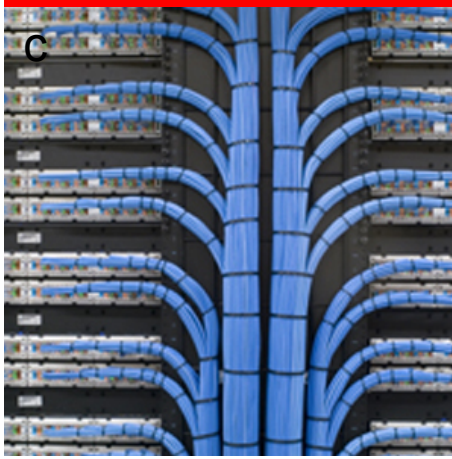
Minimum value measured or estimated

Example Tool – Detail for a Work Share Loop with Load Imbalance



How To Measure Utilization on Solaris

- Use `cputimes` script from DTrace Toolkit
- http://opensolaris.org → Community Group → DTrace
- Measures all cycles for duration of script:
  - User threads
  - Daemons
  - Kernel
  - Idle time
- Utilization: Percent of non-idle cycles during run
- Sanity check: daemons & kernel are small fraction
- Measurement system: Sun Ultra 27
  - Intel quad-core Xeon W3570 processor (3.2 GHz)
  - Processor threading turned off (one thread per core)
  - Solaris 10



Example Program:
Time Share Scheduling Class

Example Program: w/Parallelized Fill Loop, n=5000

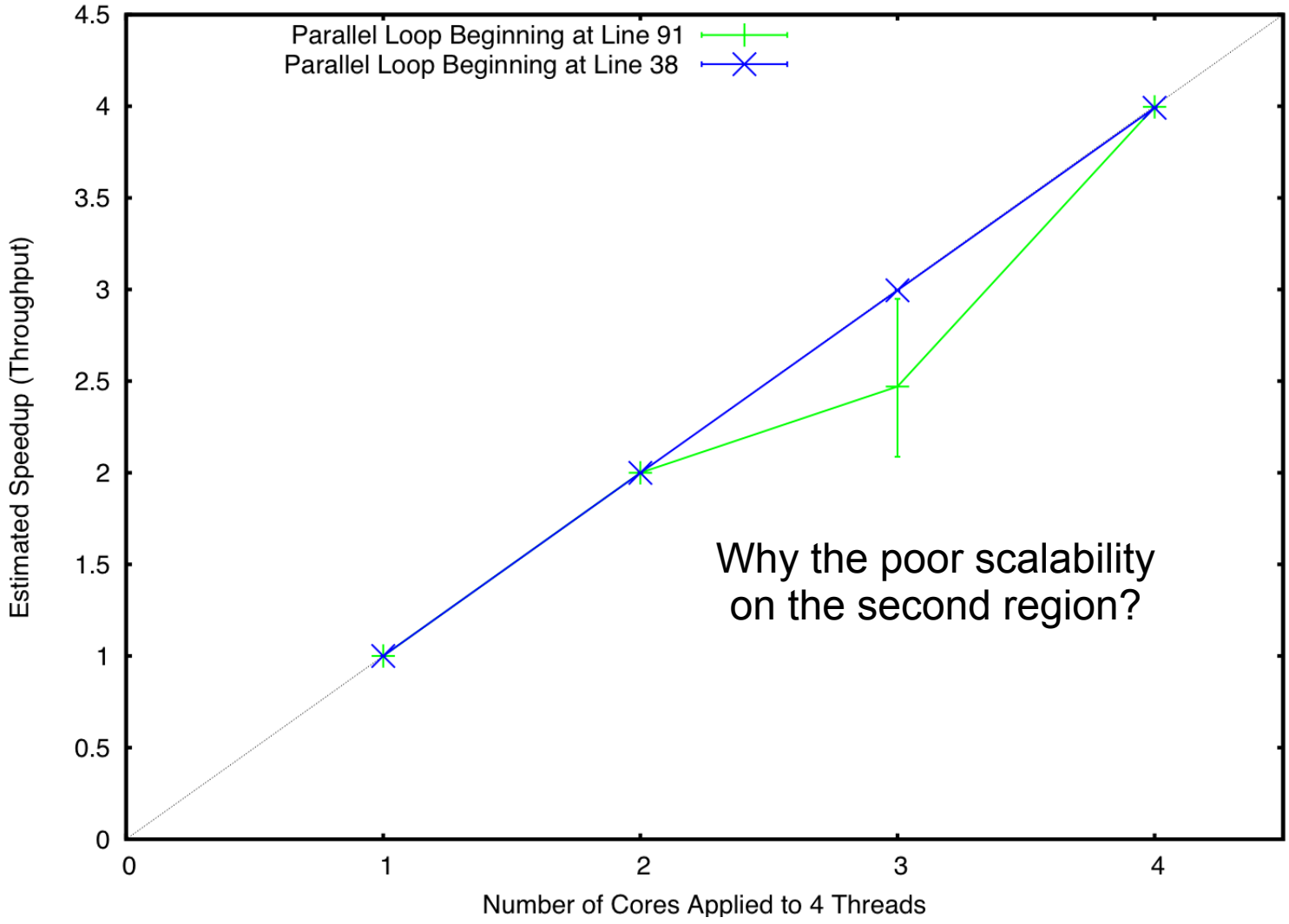
```
22 !$omp parallel shared(a,b,c,n,p) private(i,j,k,z)
...
38 !$omp do schedule(runtime)
39    do k = 1, n
40       do i = 1, n
41          do j = 1, n
42             c(j,k) = c(j,k) + a(j,i) * b(i,k) * z + p
43          end do
44       end do
45    end do
46 !$omp end do
...
71 !$omp end parallel
```

Both regions should scale very well

```
91 !$omp parallel do shared(a,pi,n) private(j,i) schedule(runtime)
92   do j = 1, n
93      do i = 1, n
94         a(i,j) = sqrt(2.0d0/(n+1))*sin(i*j*pi/(n+1))
95      end do
96   end do
97 !$omp end parallel do
```

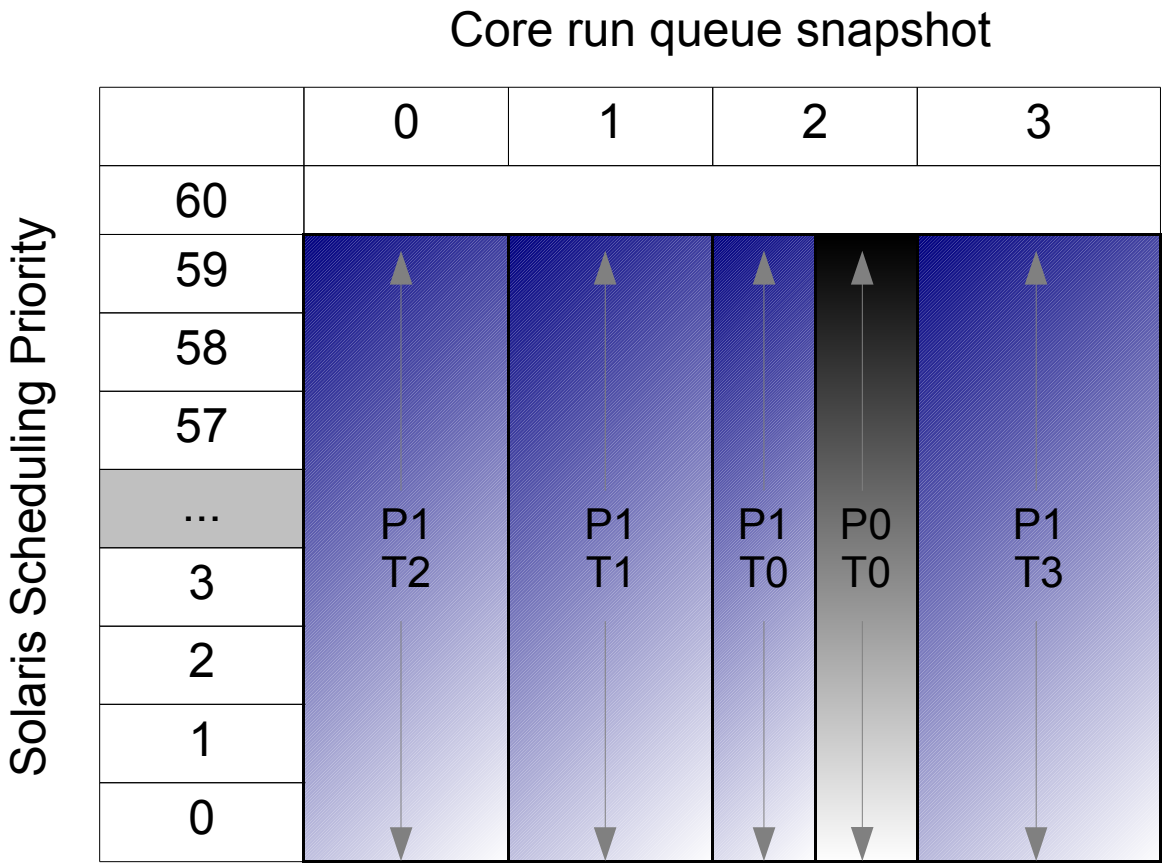
Estimated Speedups: Static Work Distribution

Parallel Loops of Lines 38 and 91



Four Thread & Single Thread Processes

Time-Share Scheduler View

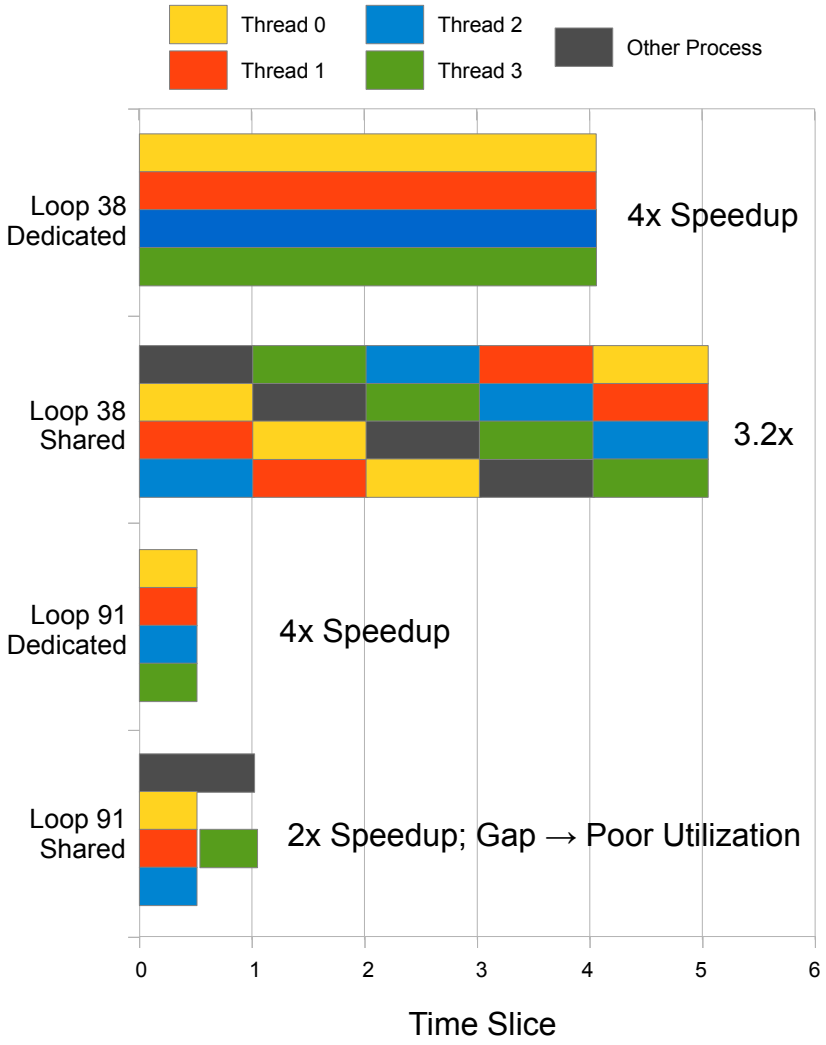


- Process 0: single threaded (infinite loop)
- Process 1: 4-threads static schedule
- Two processes share one core
- Why the poor scalability on the second loop?

OpenMP Static Work Distribution & TS Scheduler

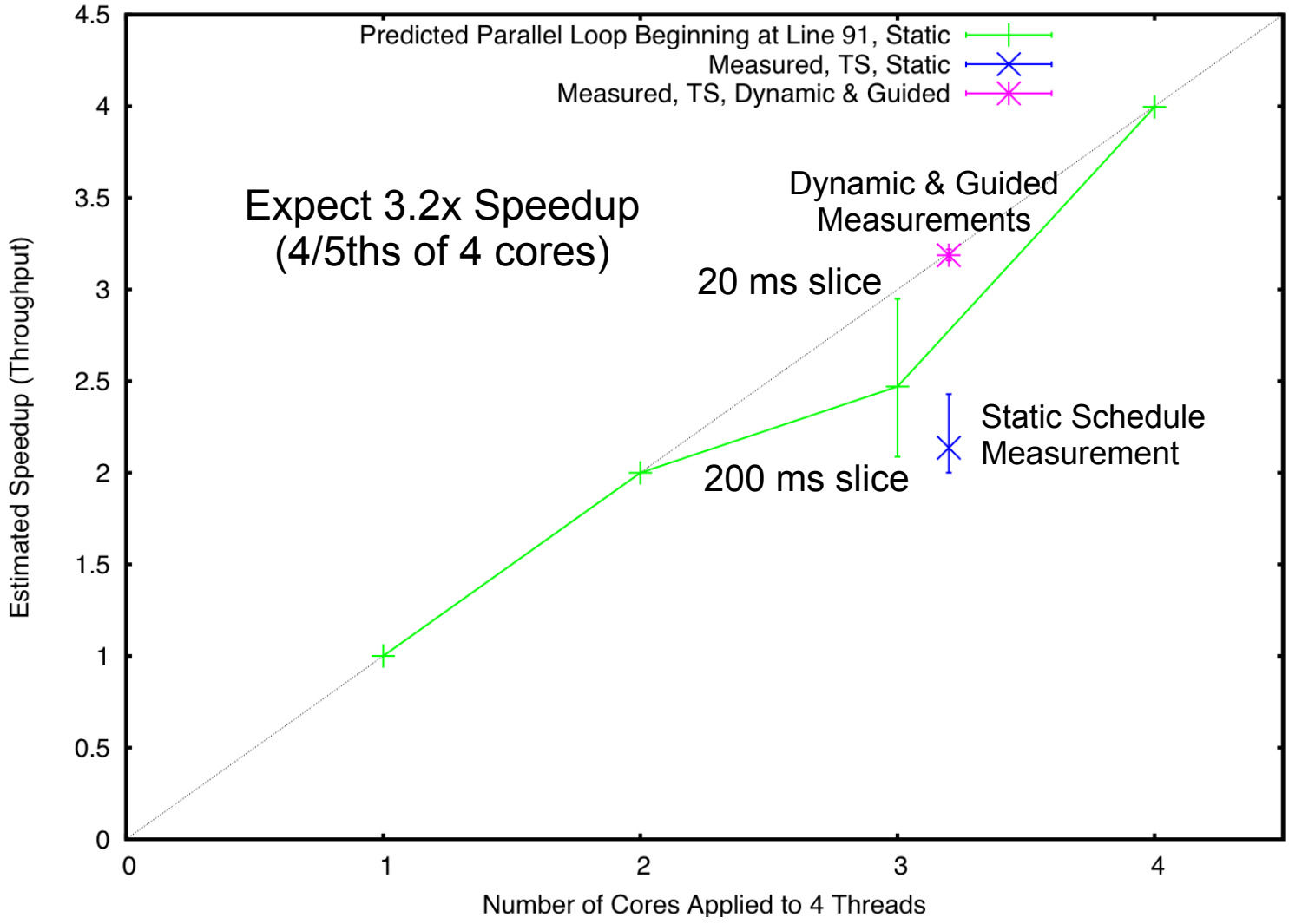
Four Threads Sharing Four Cores With One Other Process, Static

- Solaris time slices:
  - 20 millisec for high priority
  - 200 millisec for low priority
- Loop 38 work: >16 sec
- Loop 91 work: ~57 msec
- Time Share forces compute-intensive threads to low priority
- Result: load imbalance for work chunks < time slice
- Does this really happen?



TS Experiment: Fill Loop of Line 91

Isolated Loop Run with 4 Threads along with Single-Threaded Process

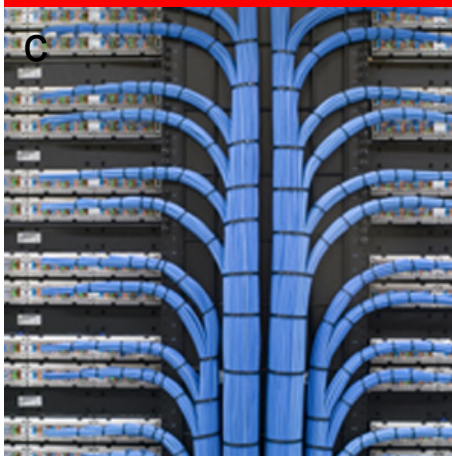


First Insight

Any statically scheduled work-sharing construct can suffer from load imbalance if the time to execute each thread's work is small compared to the time quantum.

How would a programmer identify this situation without measurement?

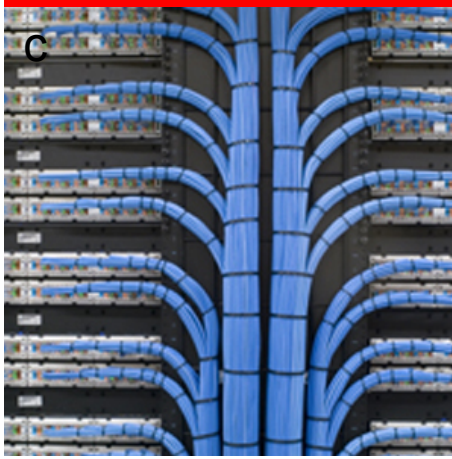
What other problematic scenarios occur?



Time Share
System Utilization Results

TS System Utilization: Isolated Loop 91

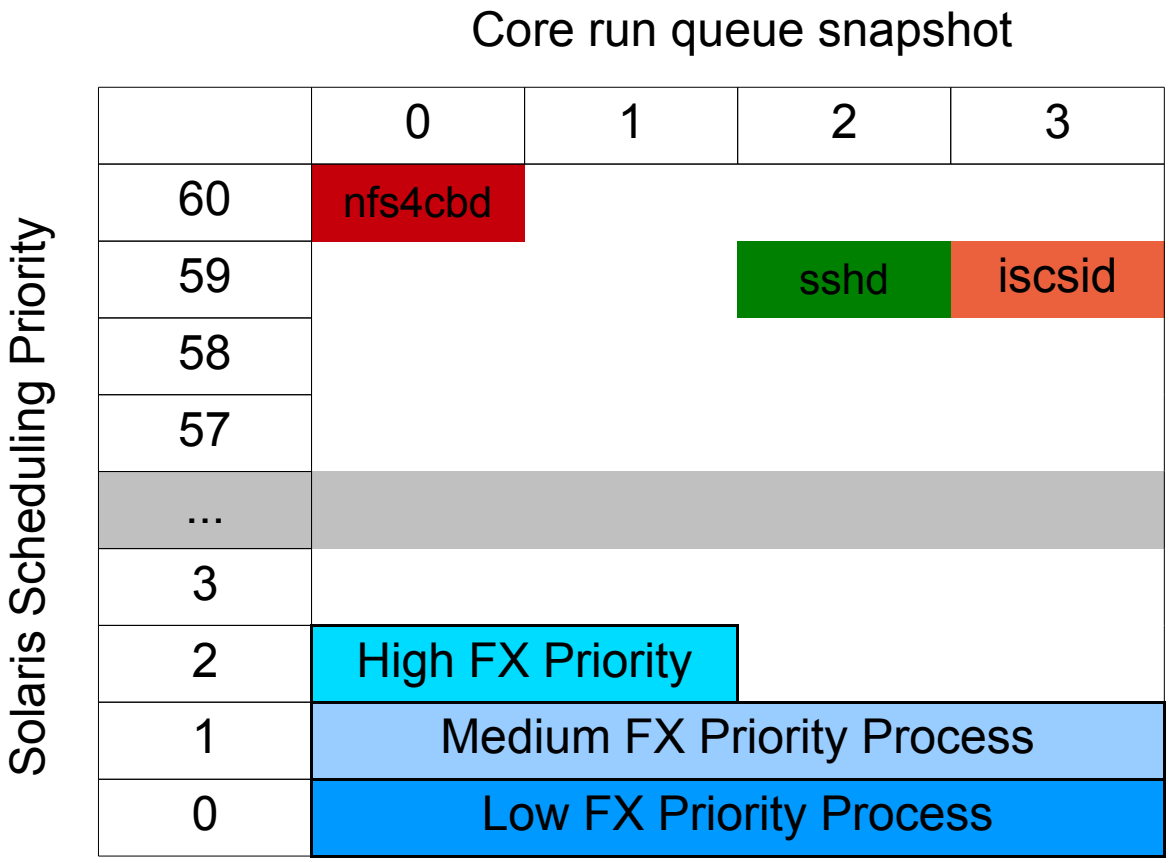
- Utilization measurement over 60 seconds
- Dynamic & Guided utilization: 99.9%
- Static allocation utilization measurement: 86%
- That's a 14% loss in utilization!
- Measured overhead:
  - Dtrace command: 0.0038% processor cycles
  - Kernel & daemons: 0.04%



Example Program:
Fixed Priority Scheduling Class

Solaris Fixed-Priority (FX) Scheduling Class

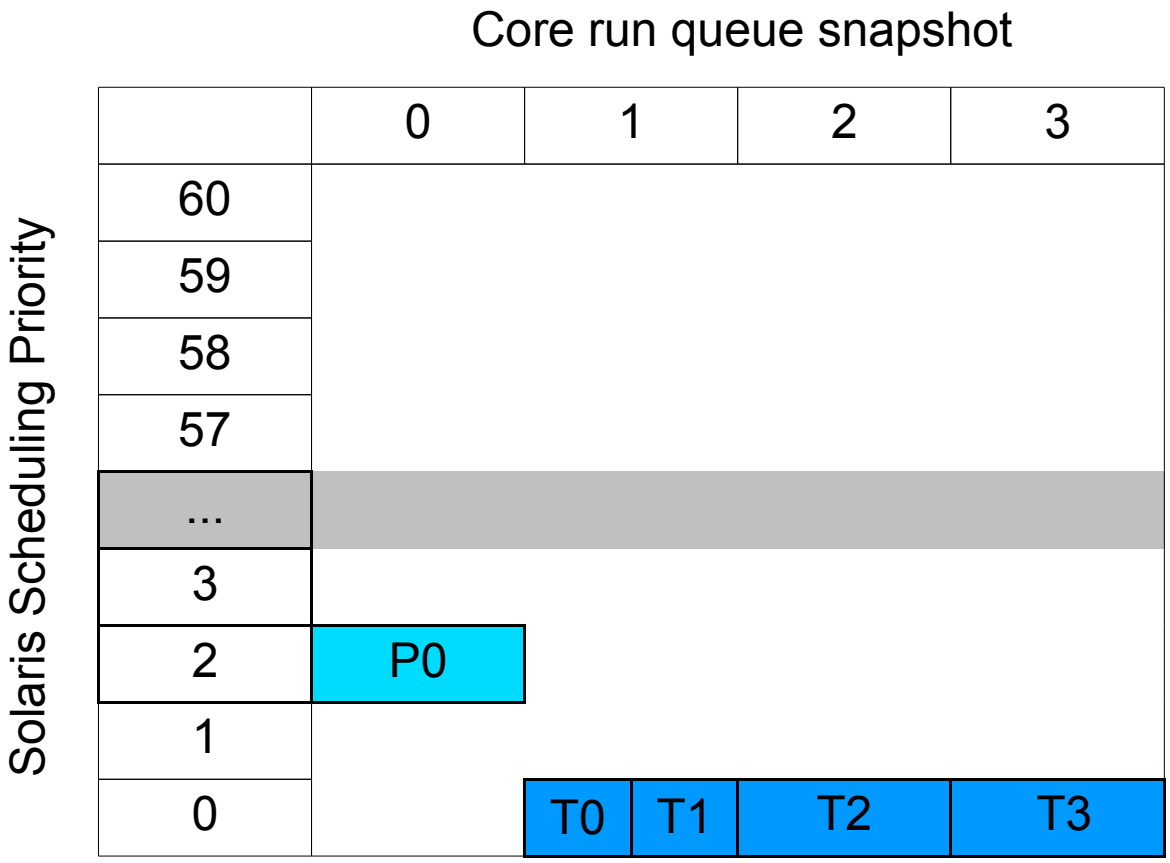
Scheduler Never Adjusts Thread Priority



- Daemons run in TS, as needed
- Highest FX threads run "dedicated"
- Lower-priority threads get unused cycles
- Example:
  Priority 2: 2 thr
  Priority 0,1: 4 thr

Four Thread & Single Thread Processes

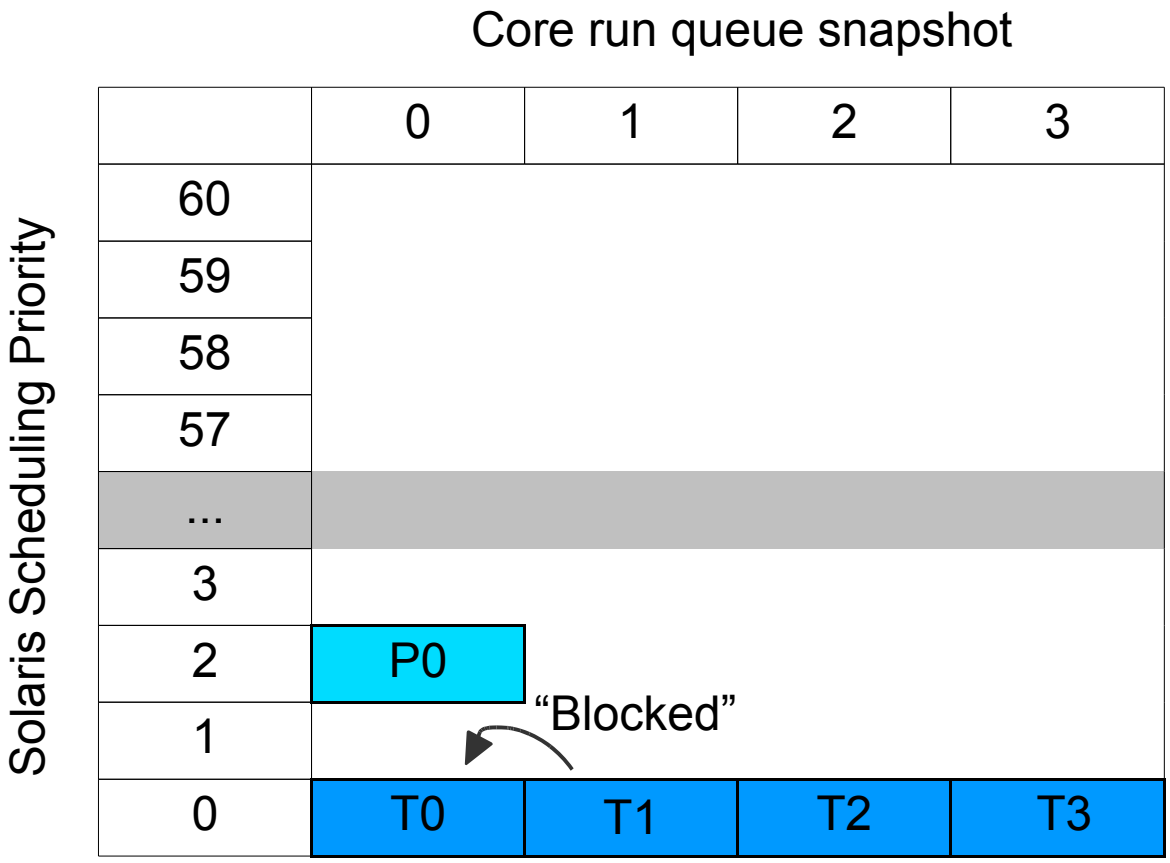
Fixed-Priority Class Scheduler View



- Process P0: Fixed Priority 2 (infinite loop)
- Process P1: Four threads Fixed Priority 0
- Two P1 threads share one core

Four Thread & Single Thread Processes

Fixed-Priority Class Scheduler View

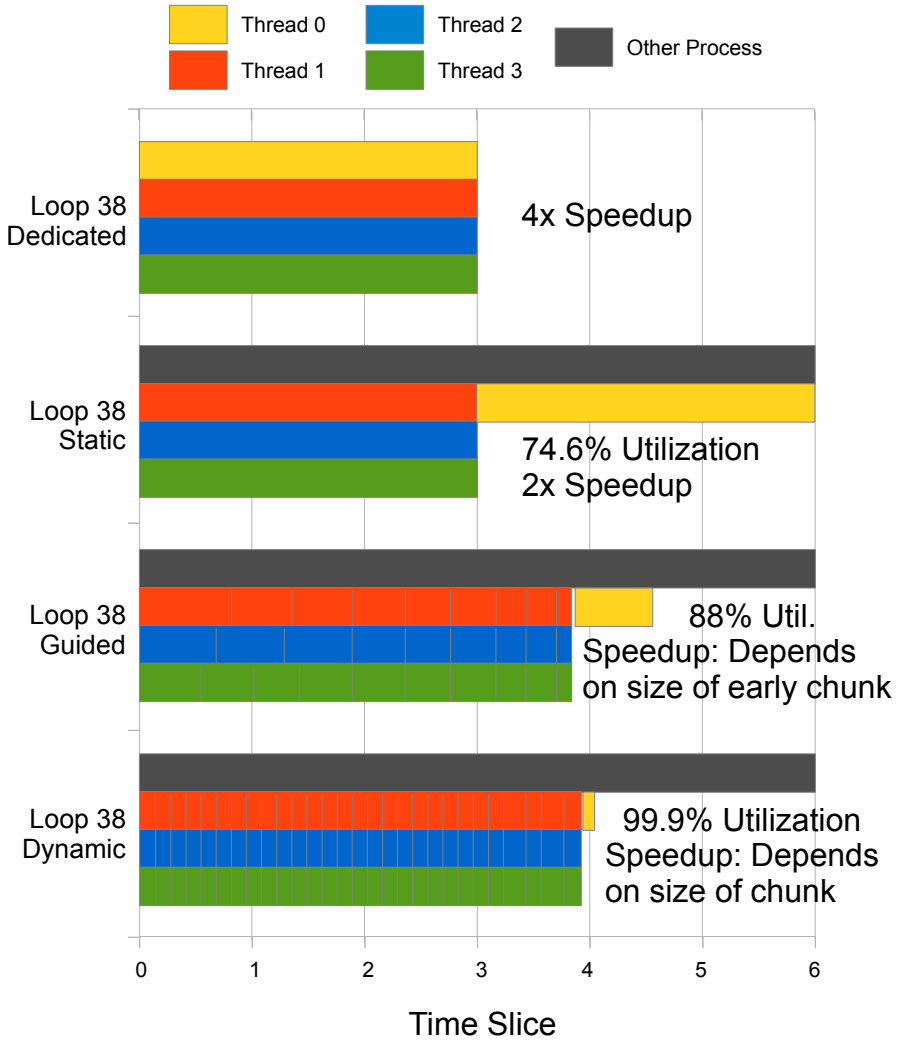


- Process P0: Fixed Priority 2 (infinite loop)
- Process P1: Four threads Fixed Priority 0
- Two P1 threads share one core
- Until one thread is sometimes blocked

OpenMP Dynamic/Guided & Fixed Priority Scheduler

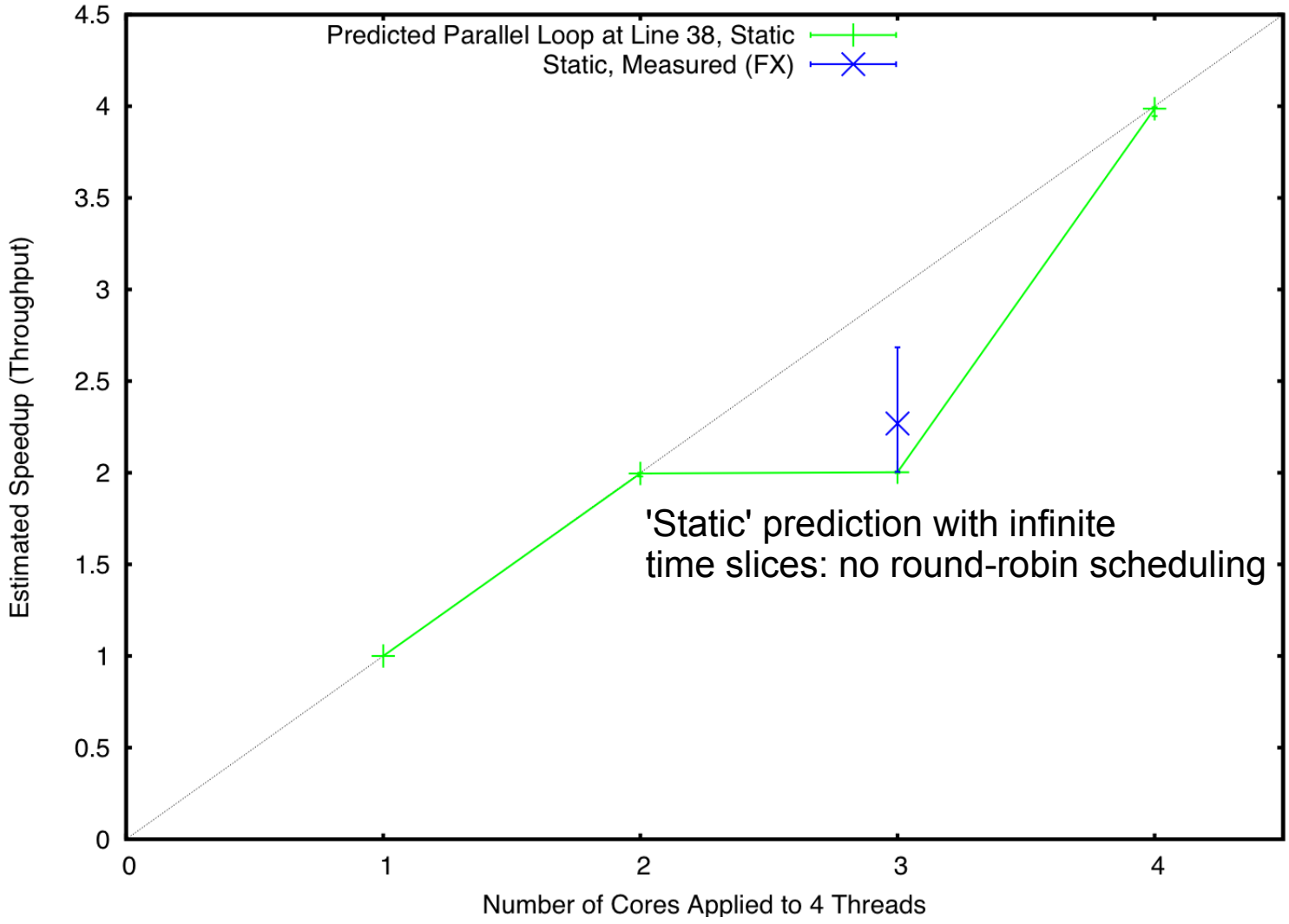
Four Low-Priority Threads & One High-Priority Process Sharing 4 Cores

- High-Priority single-thread consumes one core
- Four threads share other three cores until one is “blocked”
- Static, Guided: potentially large remaining work
- Dynamic: controlled, smaller work chunks



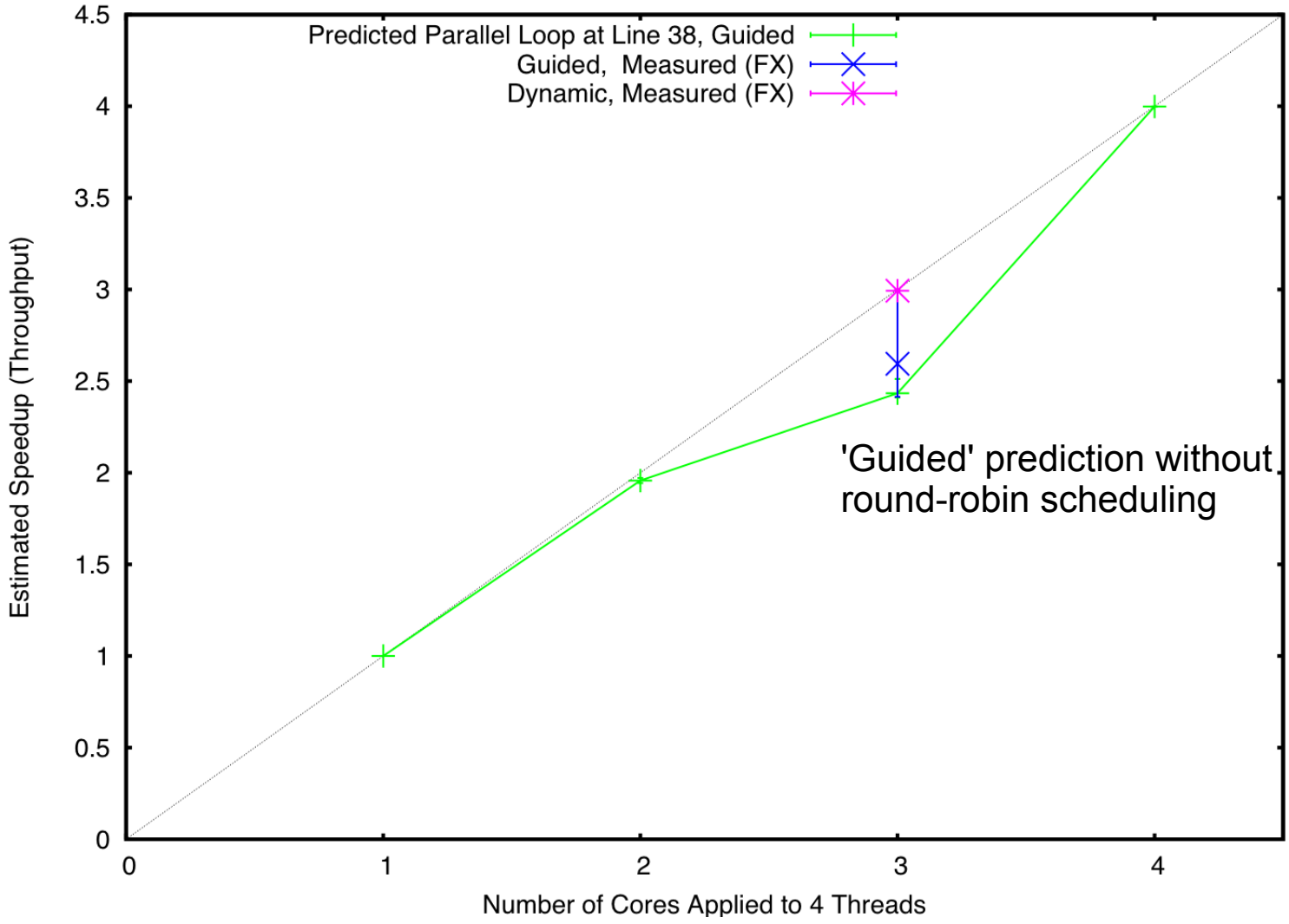
FX Priority Class Experiment: Static

Four Threads run on Three Cores; High-Priority Process on One Core



FX Priority Class Experiment: Guided & Dynamic

Four Threads run on Three Cores; High-Priority Process on One Core



Conclusions: OpenMP Throughput

- OpenMP throughput philosopy:
  Efficiently use *any available* processor cycles
- Tool helps the OpenMP programmer improve scalability
- Tool has uncovered subtle utilization bottlenecks
- Tool can help programmer improve utilization in
  - **Time Share** scheduling class
  - **Fixed Priority** scheduling class with prioritized control
- Dynamic schedule (or tasking): best for utilization
  - If you choose a good chunk size
  - Tool measurements enable good choice

Current Limitations & Future Work

- Nested Parallel Regions
  - Not clear how to interpret speedup
  - Tasking probably superior approach
- Collecting Traces
  - Dropped trace data: high rate of calls, app probably won't scale
  - Very large traces: option to restrict repeated regions; compress
- Threaded & NUMA systems
  - Hardware characteristics: leverage existing tools
  - Tool enables differentiation: OpenMP vs. hardware bottlenecks
  - Add dedicated scaling analysis
- Future Work
  - Larger configurations (in progress)
  - Testing on a broad range of applications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