Production I/O Characterization on the Cray XE6

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Motivation

- I/O behavior plays a key role in productivity for large-scale HPC systems
  - Our target: Hopper, a 153,216 core Cray XE6 at NERSC
- Challenges in understanding I/O behavior
  - Hundreds of users across a wide spectrum of science
  - Applications vary in data volume, I/O strategy, and access methods
  - How can we consistently characterize production I/O behavior across applications?
  - How do we quickly identify applications that could most benefit from additional tuning assistance?

Approach

1. Adapt the **Darshan** I/O characterization tool for use in the Cray environment
   - Tune to reflect Hopper system characteristics
   - Integrate transparently for maximum coverage
2. Evaluate Darshan for production deployment
   - Measure overhead at scale for multiple workloads
3. Deploy Darshan
   - Store characterization data for post-processing and exploration
   - Provide immediate feedback to users
4. Develop tools that leverage Darshan data
   - Rapid feedback to power users
   - Metrics to automatically flag jobs that exhibit unusual I/O behavior for administrators

Darshan background

Darshan is an open source, application-level instrumentation library that uses link-time instrumentation for static executables and LD_PRELOAD for dynamic executables.

What does it record?

- Counters, histograms, and strategically chosen timestamps related to I/O activity
- POSIX, POSIX stream, MPI-IO, and limited HDF5 and PNetCDF functions
- Access patterns, access sizes, I/O time, alignment, datatypes, etc.
- Builds on characterization ideas from Kotz and Nieuwejaar Charisma study
- Does *not* record a complete trace of I/O operations

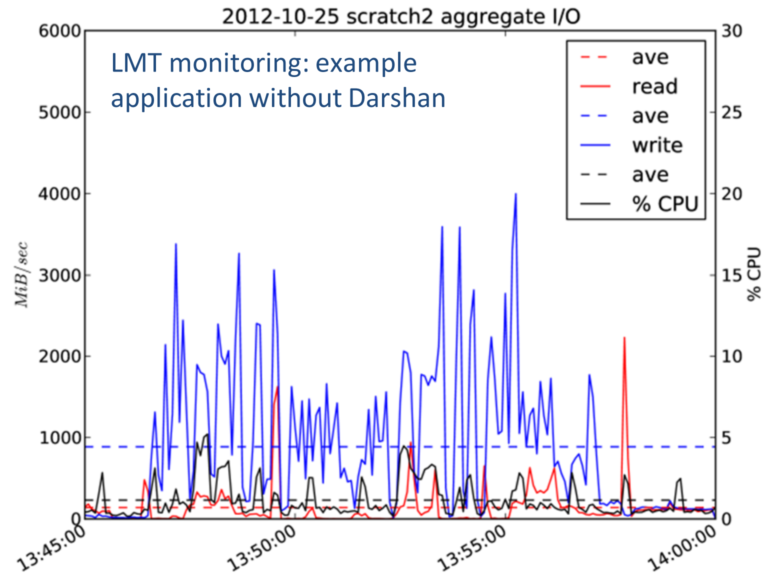
How does it store results?

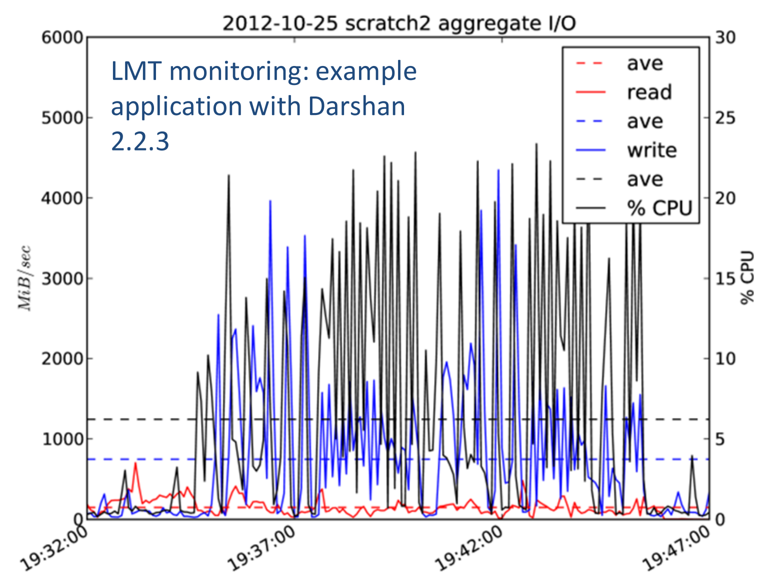
- Minimal overhead during execution
- Reduction, compression, and persistent storage at MPI_Finalize() time
- Produces a single, compact log for each instrumented job

Tuning example: shared-file instrumentation

- Initial performance experiments with Darshan 2.2.3 exhibited performance degradation for shared-file applications
- LMT monitoring of servers revealed that the raw I/O throughput was comparable, but CPU usage was much higher

- Source of overhead: issuing stat() calls on each rank to collect additional information at open() time
- Concurrent stat() at 12,288 processes can already add 2 seconds to file open time
- Worked to develop alternative instrumentation

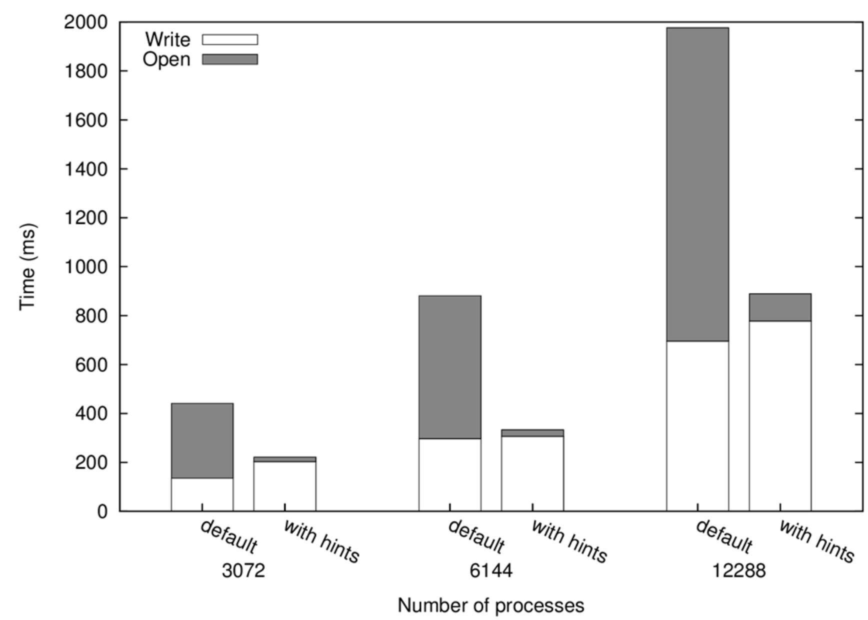




Tuning example: writing log files efficiently

- Darshan writes all results to a unified log file at shutdown after custom reduction and gzip compression
- Final results are typically quite small: hundreds of bytes per process, sometimes even less
- Regardless of how the application performed I/O, Darshan itself uses MPI-IO collectives internally to write results
- Portable and efficient: leverages aggregation and stripe alignment

- We improved MPI-IO collective performance even further with hints:
  - romio_no_indep_rw
  - cb_nodes=4
- Limit the number of processes that actually open the output file
- Drastically reduces the cost of writing data at larger process counts



System integration challenges

- Cray environment:
  - Multiple compilers (Cray, PGI, Pathscale, Intel, GNU)
  - Static linking by default
  - Unified cc, ftn, and CC compiler scripts

- Our requirements:
  - Support as many configurations as reasonably possible
  - Enable and disable via software module
  - Transparent for users (no need for different compilers or link options)

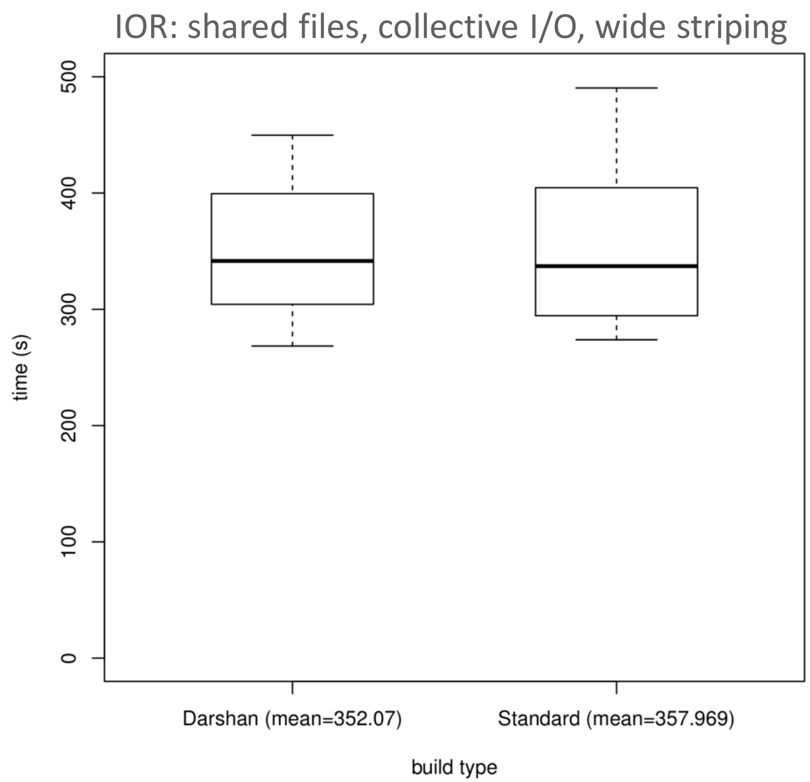
- We experimented with multiple deployment methods during this study
- Our plan moving forward is to use the PE_PRODUCT_LIST mechanism
  - This is a set of environment variables that can be used by software modules to specify additional linker options for the Cray compiler scripts

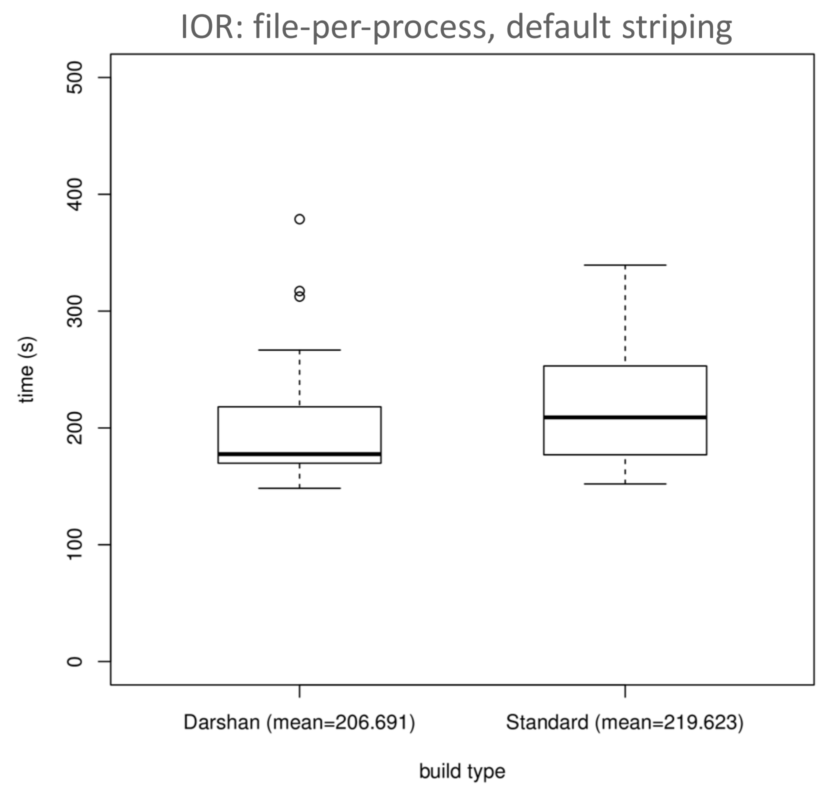
Evaluation: end-to-end overhead

After adapting Darshan to the Cray XE6 environment, our next goal was to evaluate the impact of Darshan on large-scale applications to verify suitability for production deployment.

- First experiment: measure end-to-end run time of IOR benchmark writing and reading 1.5 TiB of data at 12,288 processes
  - Includes all Darshan startup, instrumentation, and shutdown costs
  - Measured by timing the “aprun” command
  - Evaluate both shared-file and file-per-process examples
  - IOR configured to use MPI-IO; Darshan instrumented both the MPI-IO and POSIX API calls
- Individual runs are susceptible to variance
- Gathered 20 independent samples for each test case over a four day period and analyzed the results

Evaluation: end-to-end overhead

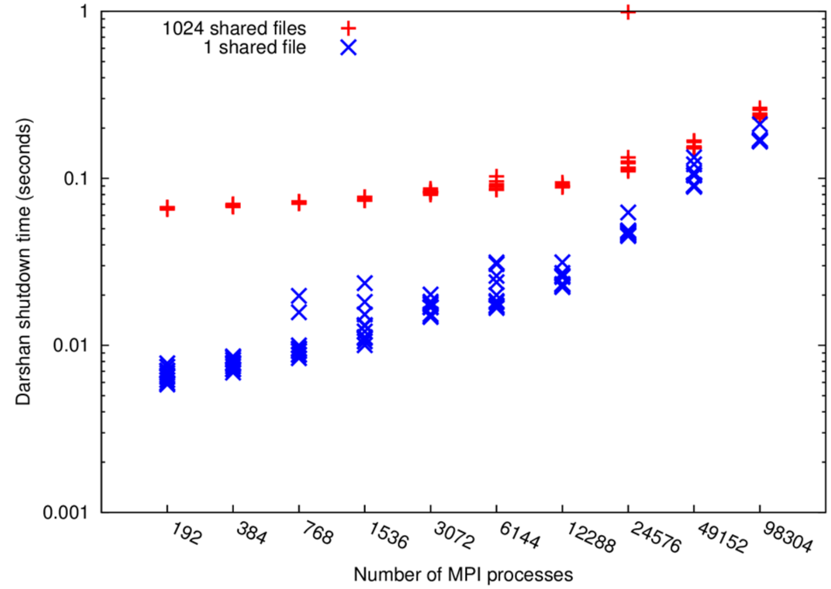


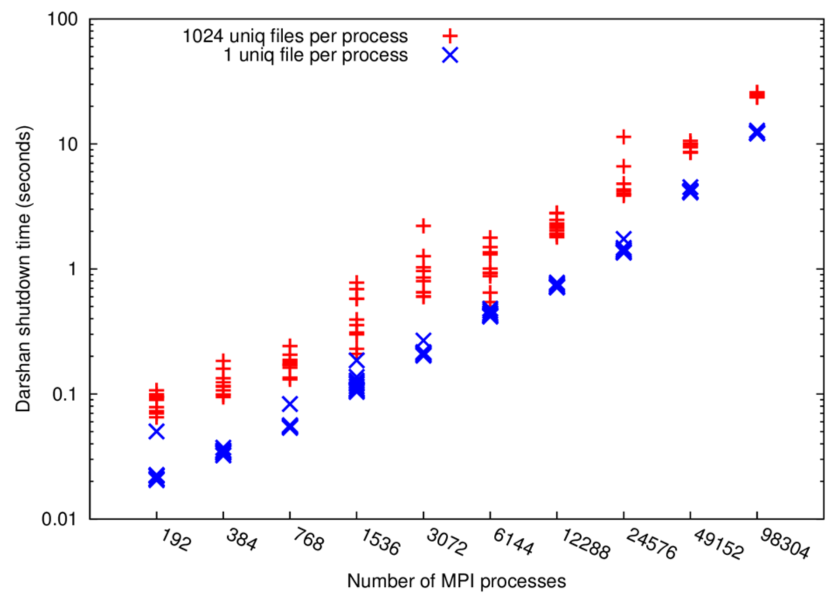


- Box plots of 20 samples each indicate no clear Darshan overhead at 12,288 processes relative to normal system variance
- Insufficient evidence for difference in mean run time (t-test)
- Other observations: variance is significant, and file-per-process access patterns perform better on Hopper at this scale

Evaluation: Darshan shutdown costs

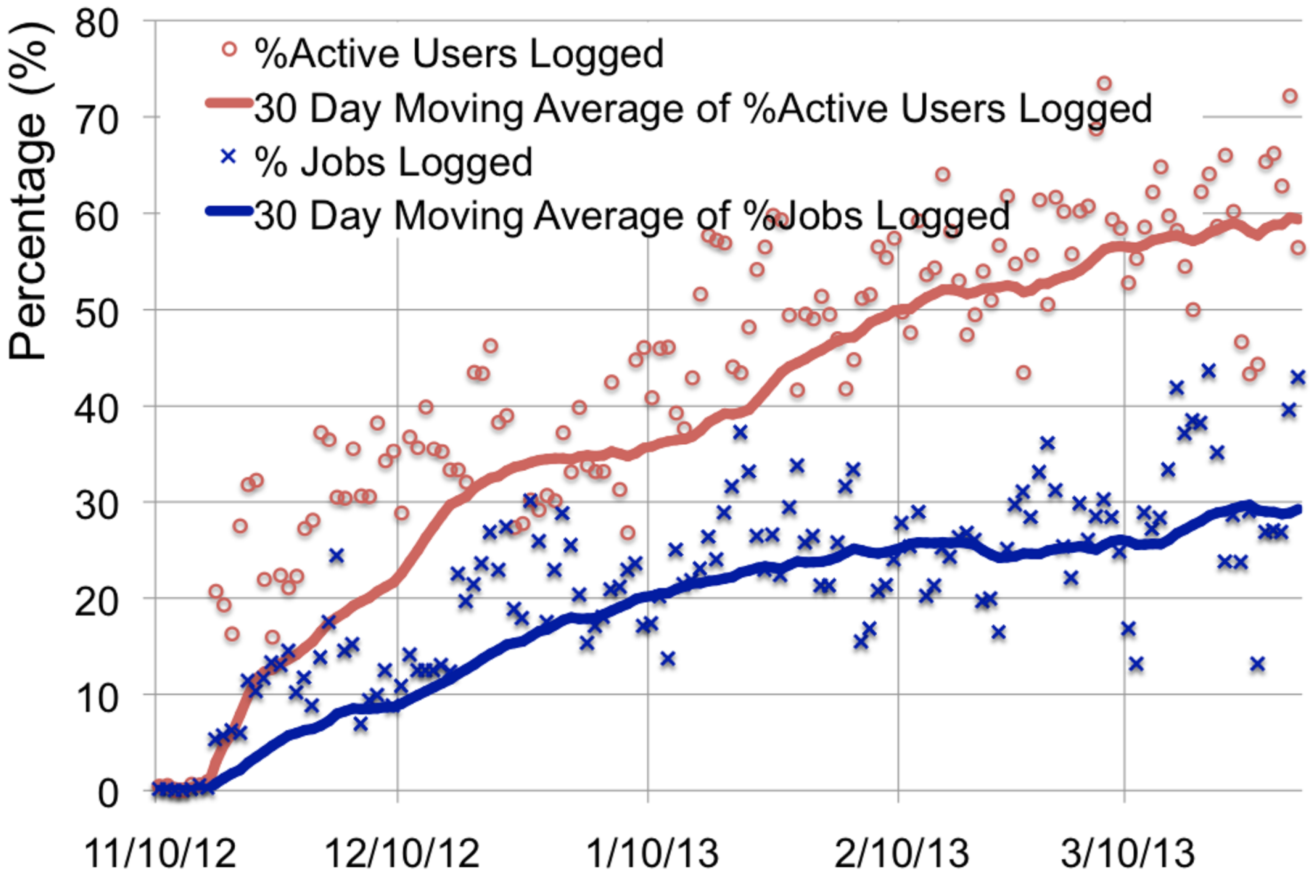
- End-to-end Darshan overhead is obscured by I/O variance, but we can measure internal Darshan mechanisms directly using microbenchmarks
- These examples show the total time required by Darshan to reduce, compress, and write log files at MPI_Finalize() time
- Average one-time cost for 98,304 processes:
  - 1 shared file: 0.17 seconds
  - 1024 shared files: 0.24 seconds
  - 1 file-per-process: 12.3 seconds
  - 1024 files-per-process: 24.8 seconds
- Largest scenario: emulates application opening 100,663,296 unique files
- Darshan falls back to less granular instrumentation if memory threshold is exceeded by opening too many files





Deployment: coverage as of March 2013

- Percentage of active users and jobs instrumented per day since initial Hopper deployment
- Nearing an average of 60% and 30%, respectively, by end of March 2013

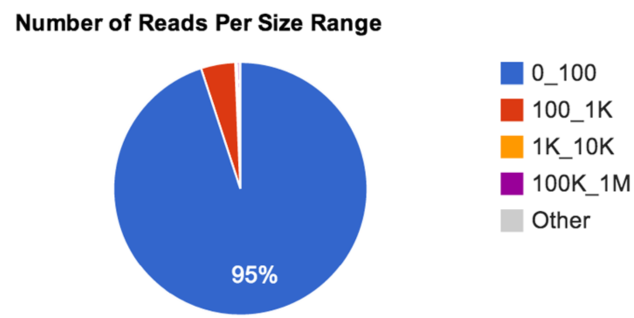


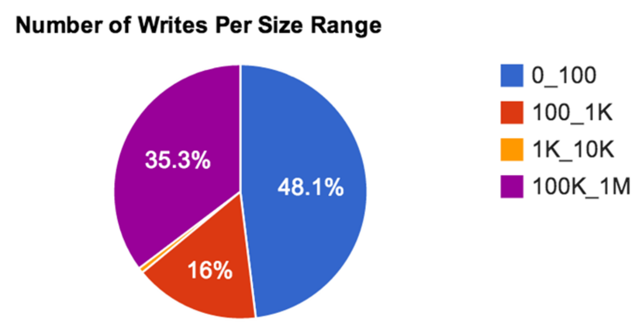
Deployment: user experience

- The NERSC web portal allows users to interact with their jobs and allocations
- This screenshot shows I/O summary information automatically generated from Darshan logs for completed jobs
- Provides rapid (within a few minutes) initial feedback on I/O behavior

IO Summary from Darshan

Start	End	Wallclock (secs)	MB Read	MB Written	Estimated I/O Rate (MB/sec)	Estimated Percent Time Spent in I/O
04-05 16:04:05	04-05 16:06:51	166	590.3	597.6	355.52	2.01%





Metrics: redundant read traffic

- Administrators can also filter logs using metrics designed to automatically identify applications that may benefit from tuning assistance
- We explored three example metrics that can be quickly computed from Darshan log data
- First example is redundant read traffic: applications that read more bytes of data from the file system than were present in the file
- Even with caching effects, this type of job can cause disruptive I/O network traffic through redundant file system transfers
- Candidates for aggregation or collective I/O

Summary of matching jobs:

Redundant read threshold	> 1 TiB
Total jobs analyzed	261,890
Jobs matching heuristic	671
Unique users matching heuristic	37
Largest single-job redundant read volume	547 TiB

Top example

- Scale: 6,138 processes
- Run time: 6.5 hours
- Avg. I/O time per process: 27 minutes
- Metric: Read 548.6 TiB of data from a 1.2 TiB collection of read-only files
- Used 8 KiB read operations and generated 457 X redundant read traffic

Metrics: metadata time ratio

- Percentage of cumulative I/O time spent performing metadata operations such as open(), close(), stat(), and seek()
- Close() cost can be misleading due to write-behind cache flushing, but metadata ratio is often a key indicator of inefficient file organization
- Most relevant for jobs that performed a significant amount of I/O
- Candidates for coalescing files and eliminating extra metadata calls like stat() where possible

Summary of matching jobs:

Thresholds	meta_time / nprocs $>$ 30 s nprocs $\geq$ 192 metadata_ratio $\geq$ 25%
Total jobs analyzed	261,890
Jobs matching heuristic	252
Unique users matching heuristic	45
Largest single-job metadata ratio	$>$ 99%

Top example

- Scale: 40,960 processes
- Run time: 229 seconds
- Max. I/O time per process: 103 seconds
- Metric: 99% of I/O time in metadata operations
- Generated 200,000+ files using 600,000+ write() and 600,000+ stat() calls

Metrics: small writes to shared files

- Small writes can contribute to poor performance as a result of poor file system stripe alignment, but there are many factors to consider:
  - Writes to non-shared files may be cached aggressively
  - Collective writes are normally optimized by MPI-IO
  - Throughput can be influenced by additional factors beyond write size
- We searched for jobs that wrote less than 1 MiB per operation to shared files without using any collective operations
- Candidates for collective I/O or batching/buffering of write operations

Summary of matching jobs:

Thresholds	> 100 million small writes 0 collective writes
Total jobs analyzed	261,890
Jobs matching heuristic	220
Unique users matching heuristic	11
Largest single-job small write count	5.7 billion

Top example

- Scale: 128 processes
- Run time: 30 minutes
- Max. I/O time per process: 12 minutes
- Metric: issued 5.7 billion write operations, each less than 100 bytes in size, to shared files
- Averaged just over 1 MiB/s per process during shared write phase

Summary and conclusions

Lessons learned while adapting Darshan for the Cray environment:

- Adapting system tools to the Cray XE6 environment requires consideration of file system characteristics and environment configuration
- "Minimal overhead" is a moving target! New platforms bring new challenges.
- I/O variance remains a significant factor in I/O performance
- Darshan performance is suitable for full-time production deployment

Deployment experience:

- It is possible to perform application-level I/O characterization of full-scale production workloads
- Darshan has been successfully deployed on the Hopper system at NERSC
  - Rolled out in stages from November 2012 to February 2013
  - 30% of jobs and compute hours instrumented by March 2013
- Deployment impact:
  - Immediate feedback to users on I/O behavior
  - Ability to automatically scan jobs using simple metrics to identify applications that need further assistance

Future work

- Continue to improve Darshan
  - Use system-specific mechanisms for characterization when available
  - Improve Cray environment integration
  - Modularization

- Continue to use Darshan data to solve I/O problems
  - Use metrics to identify and help the users who need it most
  - More rigorous analysis methods
  - Improve feedback for users
  - Broader workload studies

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http://www.mcs.anl.gov/darshan