Dynamic Adaptivity in Support of Extreme Scale

Towards Dynamic Adaptivity of Operating Systems

Pat Teller
Professor, Computer Science
The University of Texas at El Paso
pteller@utep.edu

Dynamic Adaptivity in Support of Extreme Scale

Outline

- **Overview of DAiSES**
- Infrastructure
- Research
  - UW
    - Kernel Performance
    - Scalability
  - UTEP
    - **Proof of Concept: I/O Scheduling**
    - Lessons Learned
    - Candidate Adaptation Targets
      - VMM Parameter Adaptation
      - Adaptive Page Size Allocation
      - SMT/CMP Scheduling
      - Virtualization
- Acknowledgments
- Publications

DASES

Dynamic Adaptivity in Support of Extreme Scale

Overview Goals - 1

In a nutshell….

give the workload what it needs in order for the system and the workload to perform best

Collaboration among UTEP, University of Wisconsin-Madison (Bart Miller), and UT-Austin LTC (Bill Buros)

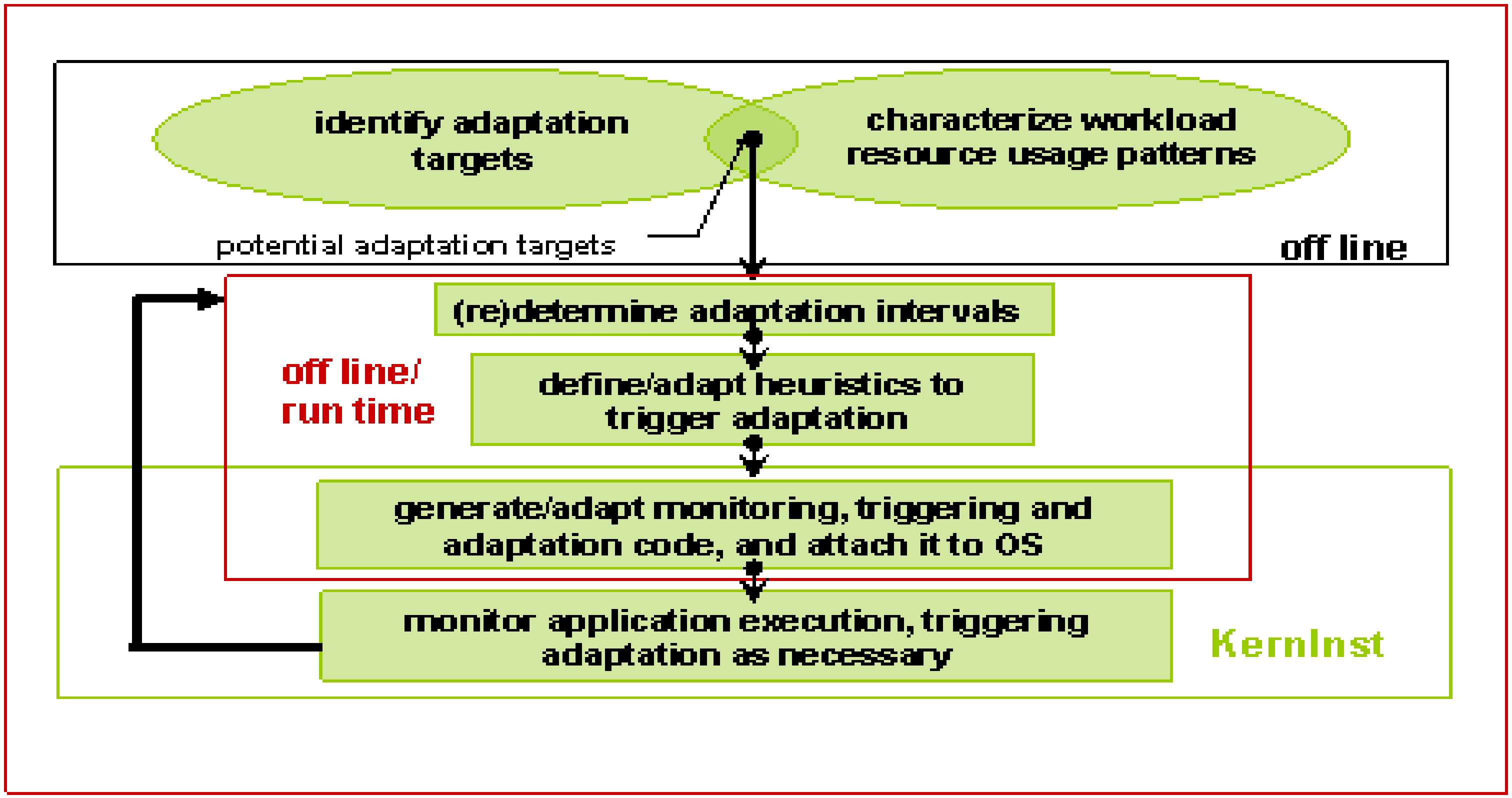
Overview Goals - 2

- Build dynamic adaptivity (of policies and parameters) into the Linux OS
- Deliver maximum attainable performance to diverse applications while meeting system constraints
- Develop general-purpose methodologies for dynamic adaptation of parameters and policies of stateful and stateless resources
- Develop mechanisms to dynamically sense, analyze, and adjust common performance metrics, fluctuating workload situations, and overall system environment conditions
- Demonstrate, via Linux prototypes and experiments, dynamic self-tuning and self-provisioning in HPC environments

Overview
Original Methodology

- Characterize application resource usage patterns
- Identify candidate adaptation targets that show promise in terms of enhancing performance
- Determine feasible adaptation ranges
- Define heuristics to trigger adaptations
- Implement monitoring, triggering, and adaptation code
- Quantify performance gains

Overview Methodology



Outline

- Overview of DAiSES
- **Infrastructure**
- Research
  - UW
    - Kernel Performance
    - Scalability
  - UTEP
    - **Proof of Concept: I/O Scheduling**
    - Lessons Learned
    - Candidate Adaptation Targets
      - VMM Parameter Adaptation
      - Adaptive Page Size Allocation
      - SMT/CMP Scheduling
      - Virtualization
- Acknowledgments
- Publications

Dynamic Adaptivity in Support of Extreme Scale

Infrastructure - 1

At UTEP:

- Experimental platforms running experimental versions of Linux 2.6
  - four dual-processor Xeon workstations
  - IBM eServer pSeries 690, 590 and 550 (IBM SUR grant, UT System STARS Award)
  - Itanium2 cluster
- Workloads
  - SPEC OSG and HPG benchmarks
  - I/O: tiobench, FFSB, MADBench, SPECjAppServer2004, SPECmail, IOzone, I/O kernels (Bob Loewe-LLNL and Gary Grider-LANL)
  - NERSC5 (received recently through LBNL)
  - Memory: STREAMS, ASCI Purple Benchmarks (hopefully stress memory)
  - Process scheduling: Hackbench, Interbench, Sweep3D (daemons)
- Tools
  - oprofile
  - blktrace
  - systemtap
  - kprobes

Infrastructure – 2

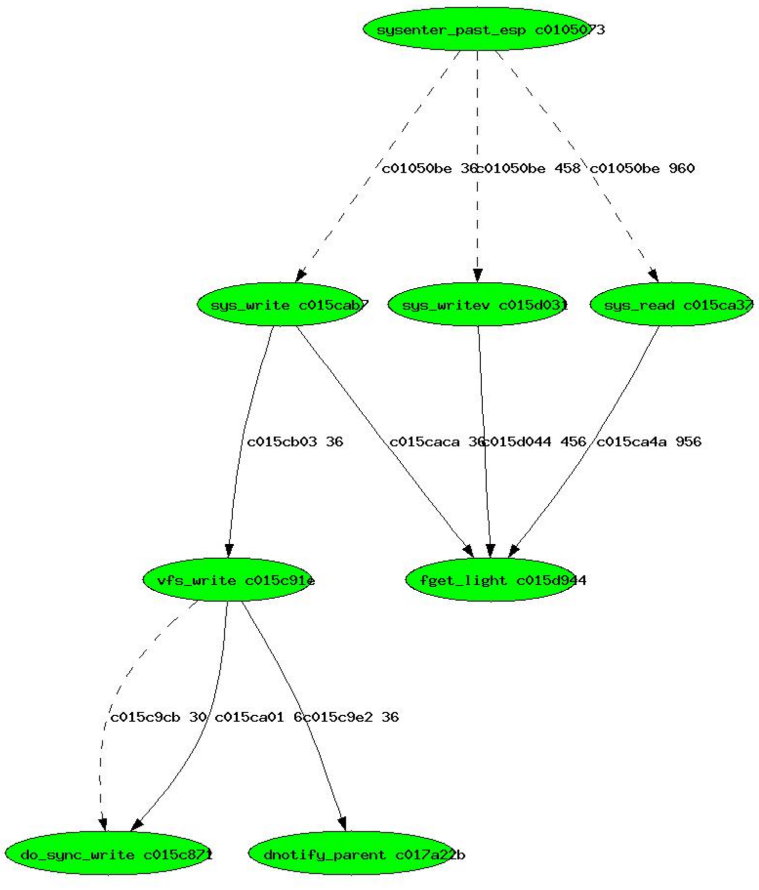
At UW:

- Kerninst port for Power/Linux 2.6 (including hypervisor compatibility): appears in Kerninst 2.1.2 beta
  - Removes dependence on /dev/kmem (because of too many variations from the various Linux distributors)
  - Lots of bug fixes and performance improvements
  - Demonstrated most recent Kerninst at the Paradyn/Dyninst annual meeting, March 2006
- Developed a Linux 2.4/2.6 kernel profiler using KerninstAPI
  - Identifies kernel functions invoked on behalf of a specific process by tracing call path execution starting at the system call interface
  - Extends the CrossWalk tool for tracing application performance problems across the user/system boundary
  - Generates call graph (using “dot”) to observe the control flow
  - Collects execution counts of edges in the call graph in order to help identify hot functions and paths

DASES

Dynamic Adaptivity in Support of Extreme Scale

Infrastructure - 3



- Nodes are kernel functions
- Edges are calls (dotted lines are indirect calls detected at runtime
- Edge labels are caller’s address and number of times called

DAiSES

Dynamic Adaptivity in Support of Extreme Scale

Outline

- Overview of DAiSES
- Infrastructure
- **Research**
  - **UW**
    - **Kernel Performance**
    - **Scalability**
  - UTEP
    - **Proof of Concept: I/O Scheduling**
    - Lessons Learned
    - Candidate Adaptation Targets
      - VMM Parameter Adaptation
      - Adaptive Page Size Allocation
      - SMT/CMP Scheduling
      - Virtualization
- Acknowledgments
- Publications

Kernel Performance

Exploration of kernel performance of HPC applications:

- Tested UW tools on various applications, e.g.,
  - MILC su3_rmd
    - Found that application spends 8% of total CPU time in the kernel, and
    - sys_read and sys_write account for the majority of kernel CPU time, with each at around 3%.
  - OM3
    - Determined that application spends 12% of total CPU time in the kernel
    - The sys_read function accounted for the highest proportion of calls, corresponding to 6% of kernel CPU time.
  - BLAST (genetic sequence matching)
    - I/O took less than 6% of total running time, depending on the data set.

Scalability

- Investigating issues relating to monitoring and control on the type of high-end systems targeted by FASTOS
  - Functions such as start-up, tracing, processing control and status monitoring
  - Evaluating in the context of various schedulers, process controllers (such as MPICH's MPD), and tools (such as Totalview)
  - New process control, beyond BProc: looking at leveraging the 9P protocol from Plan 9 (with Ron Minnich at LANL) for a truly scalable process control facility
- Exploring the use of Kerninst as the instrumentation engine for Al Malony's KTAU kernel profiling

DAiSES

Dynamic Adaptivity in Support of Extreme Scale

Outline

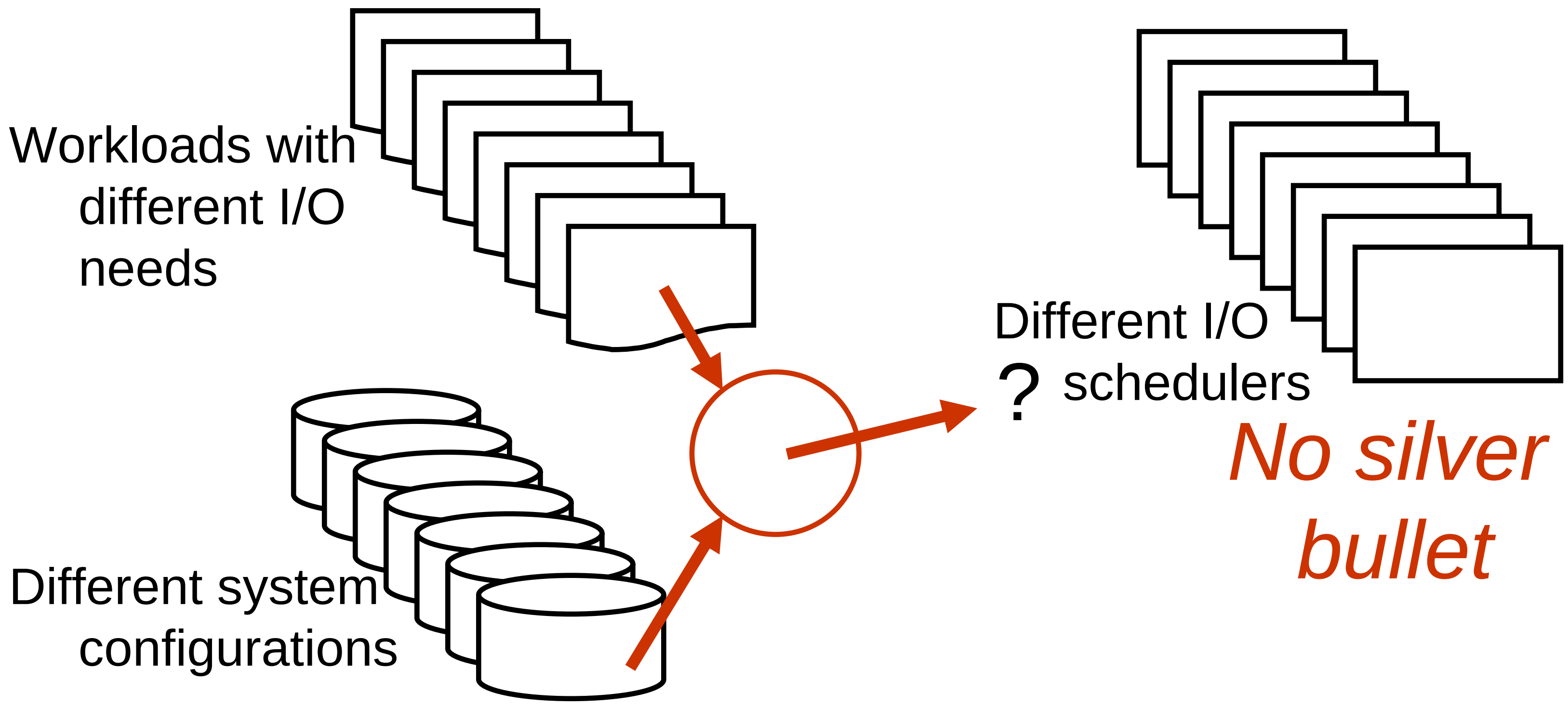
- Overview of DAiSES
- Infrastructure
- **Research**
  - UW
    - Kernel Performance
    - Scalability
  - **UTEP**
    - **Proof of Concept: I/O Scheduling**
    - Lessons Learned
    - Candidate Adaptation Targets
      - VMM Parameter Adaptation
      - Adaptive Page Size Allocation
      - SMT/CMP Scheduling
      - Virtualization
- Acknowledgments
- Publications

Proof of Concept I/O Scheduling

- Build a framework for dynamic adaptation of the I/O scheduler into the Linux OS
- Deliver maximum attainable performance to diverse applications while meeting system constraints
- Develop general-purpose methodology for dynamic adaptation of policies of stateless resources
- Demonstrate, via Linux prototypes and experiments, dynamic self-provisioning

Dynamic Adaptivity in Support of Extreme Scale

Challenge I/O Scheduling



Solution
I/O Scheduling

- ADAPT!
- As workload characteristics change, switch to appropriate scheduler
- Get best performance for each different type of workload

Solution
I/O Scheduling

- ADAPT!
- As workload characteristics change, switch to appropriate scheduler
- Get best performance for each different type of workload
- Easier said than done!
- Linux 2.6 includes four schedulers (Anticipatory, Deadline, CFQ, and noop) with boot-time and run-time selection – this helped!

Dynamic Adaptivity in Support of Extreme Scale

Significant Work in I/O Scheduling

Ph.D. Dissertation: Seetharami Seelam, *Towards Dynamic I/O Scheduling in Commodity Operating Systems*, Ph.D. Dissertation, University of Texas-El Paso, Computer Engineering, May 2006

Master's Thesis: Jayaraman Suresh Babu, *Coarse-Grain Dynamic Adaptation for Asynchronous I/O Scheduling: Is it needed?*, Master's Thesis, University of Texas-El Paso, Computer Science, May 2006

- Developed/enhanced four disk scheduling algorithms
  - A new time-based disk scheduling algorithm; first ever algorithm to provide predictability and performance isolation (CFQ-CRR)
  - A new algorithm to exploit device queuing (CFQ-CRR with P)
  - A new algorithm (RDCLOOK) to improve disk utilization of asynchronous write requests – paper accepted to QEST'06, September 2006
  - Extension of Anticipatory Scheduler (Cooperative Anticipatory Scheduler – CAS) to mitigate starvation problem – paper in Linux Symposium, July 2005
- An explicit policy selection methodology
- An implicit policy selection methodology

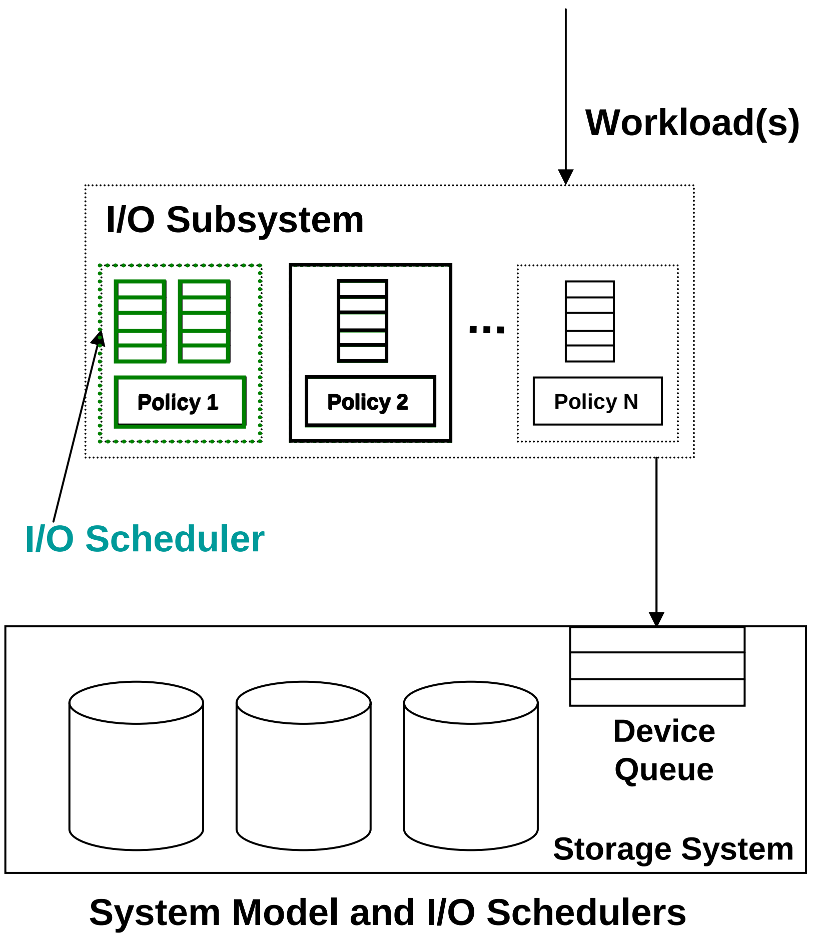
DASES

Dynamic Adaptivity in Support of Extreme Scale

I/O Scheduling Publications

- Seetharami Seelam and Patricia Teller, “Disk Scheduling with Performance Objectives,” (in preparation).
- Seetharami Seelam and Patricia Teller, “Disk Scheduling for Predictable Performance Behavior: Completely Fair Queuing and Compensating Round-Robin,” (in preparation).
- Seetharami Seelam and Patricia Teller, “Fairness and Performance Isolation: an Analysis of Disk Scheduling Algorithms,” submitted to Workshop on High Performance I/O Techniques and Deployment of Very Large Scale I/O Systems (HiperIO’06), in conjunction with the IEEE International Conference on Cluster Computing, September 25-27, 2006.
- Seetharami Seelam, Jayaraman Suresh Babu, and Patricia Teller, “Performance Analysis of Disk Scheduling Algorithms for Asynchronous Requests,” to appear in Proceedings of the 3rd International Conference on Quantitative Evaluation of SysTems (Qest ’06), Riverside, CA, September 11-14, 2006.
- Patricia Teller and Seetharami, Seelam, “Insights into Providing Dynamic Adaptation of Operating System Policies,” ACM Operating Systems Review, 40:2: 83-89, April 2006.
- Seetharami Seelam and Patricia Teller, “Disk Scheduling Using Fair Queuing and Round-Robin: Fairness Analysis,” Technical Report, University of Texas-El Paso, Computer Science, December 2005.
- Seetharami Seelam, Jayaraman Suresh Babu, and Patricia Teller, “Automatic I/O Scheduler Selection for Latency and Bandwidth Optimization,” *Proceedings of the Workshop on Operating System Interference in High Performance Applications – OSIHPA*, Saint Louis, Missouri, 17 September 2005.
- Seetharami Seelam, Rodrigo Romero, Patricia Teller, and William Buros, “Enhancements to Linux I/O Scheduling,” *Proceedings of the 2005 Linux Symposium*, Ottawa, Canada, 20-23 July 2005.

Explicit Policy Selection: Combined Queuing and Policy

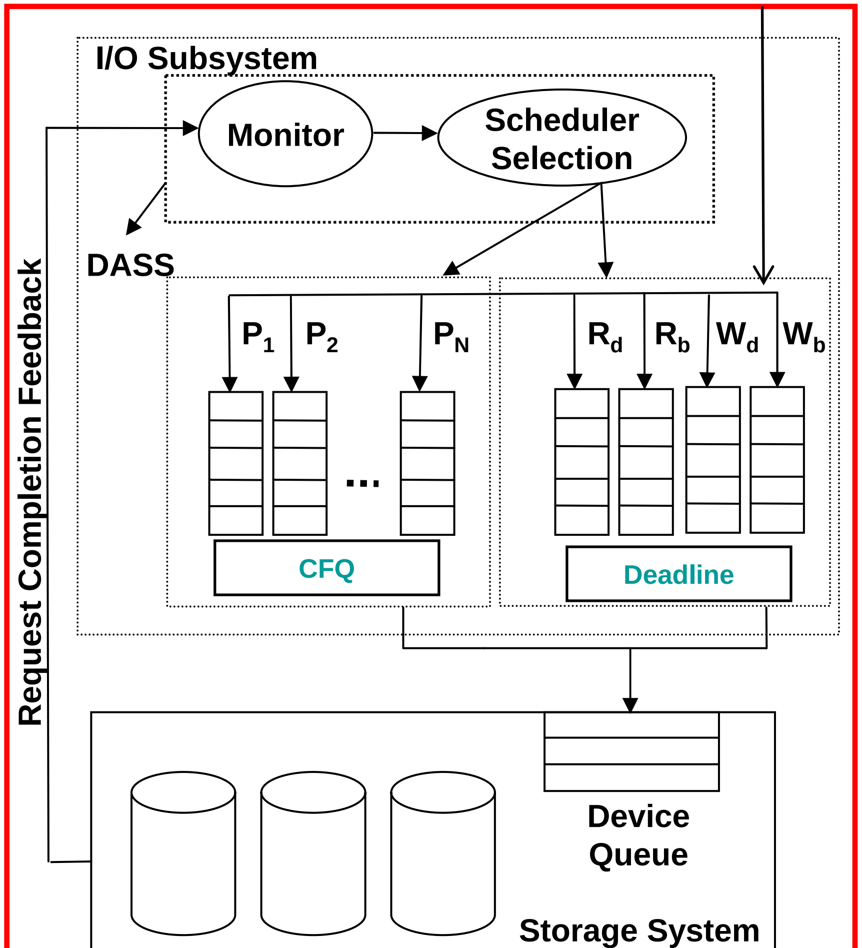


- Only one policy is active at any time; only one data delivery requirement can be satisfied at any time
- Switching policies requires moving requests across queues or draining them

Dynamic Adaptivity in Support of Extreme Scale

Two-Policy Adaptation

explicit policy selection



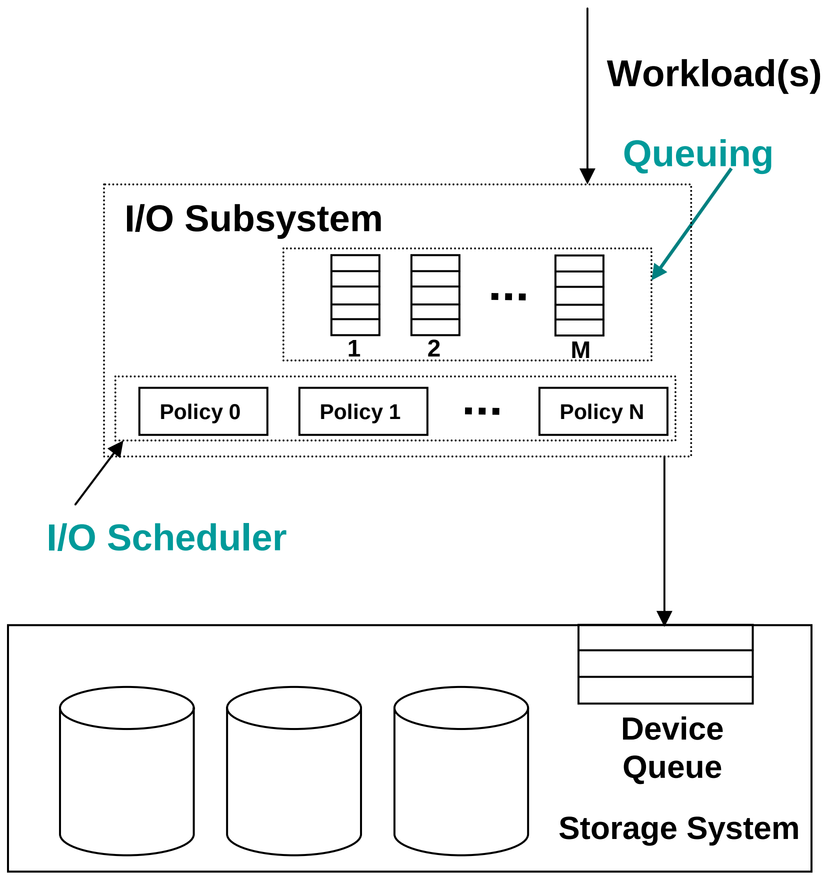
- When CFQ (default) is active, both fairness and latencies are satisfied
- When Deadline is active only latencies are satisfied; no guarantees on fairness
- As the number of queued requests increases, the potential for not satisfying latency requirements may increase – in addition, adaptation takes longer due to draining

Explicit Policy Selection Conclusions

- Only one policy is active at any time; only one requirement can be satisfied at any time
- Either copying requests or draining for adaptation impacts performance
- Even with multiple policies only one requirement can be satisfied
  - Identifying conditions for adaptation is not always possible
- Single queue system and multiple policies are the way to go

Implicit Policy Selection: Separate Queuing and Policy

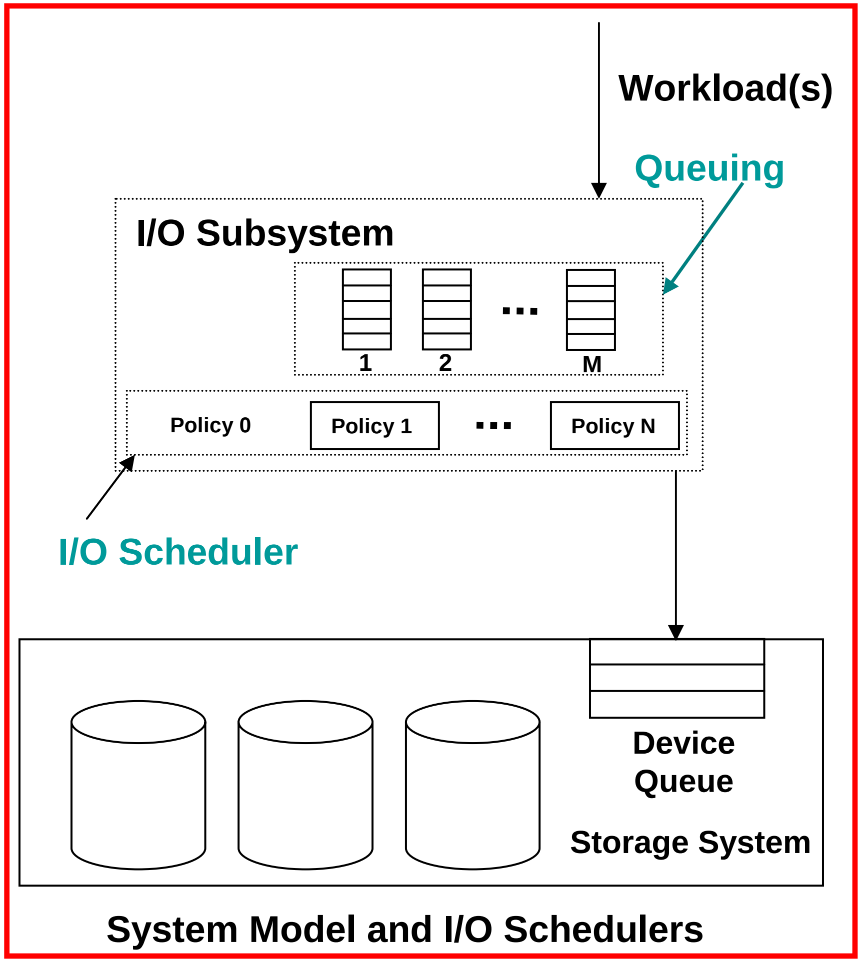
Dynamic Adaptivity in Support of Extreme Scale



System Model and I/O Schedulers

- Provide performance isolation
  - Applications should not be able to monopolize disk system
  - Most algorithms do not provide this
- Provide predictable performance
  - Unpredictability hinders performance guarantees
- Fair scheduling is the key to performance isolation and predictable performance
  - Allow satisfying multiple data delivery requirements
  - Each application could have its own scheduling algorithm

Separate Queuing and Policy



- Policy 0
  - must provide fairness, predictable performance, and performance isolation
  - controls allocation of I/O system to applications
- Policy 1 could be for queue 1 or for queue 1 through K (0<K<=M)
- Examples
  - Policy for device queuing
  - Policy for async requests

Resource Sharing

- Fair queuing and round-robin scheduling is a well known approach for resource sharing
- Allocation metric depends on the shared resource type
- Resource allocation metrics
  – Number of requests
  – Amount of data
  – Resource time

Performance Target: Performance Isolation

Dynamic Adaptivity in Support of Extreme Scale

- Given the number of I/O-intensive applications, the total disk time allocated to an application is not dependent on the characteristics of the other applications
- Results in predictable performance
- Thus, resource time allocation must be the fairness measure
- Implement in OS or in disk controller

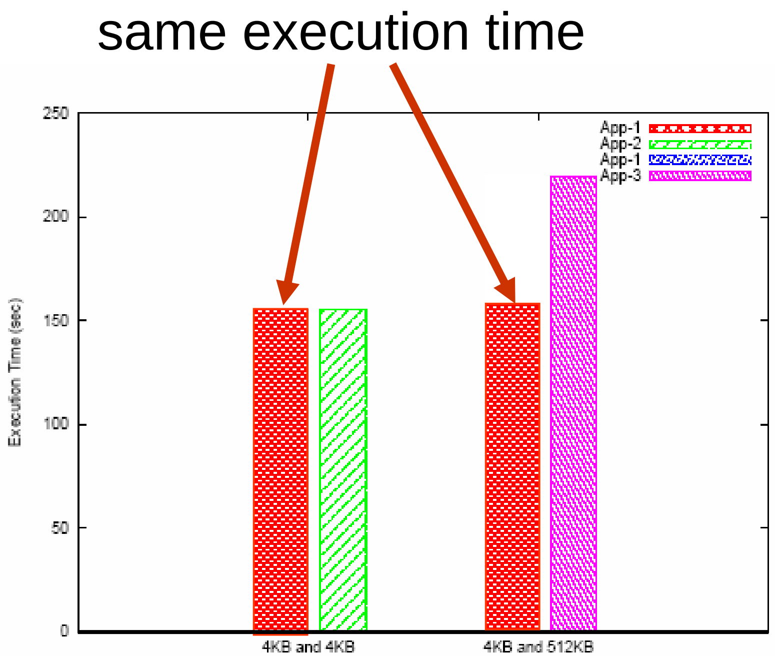


Figure 1: Application Execution Times when a) both generate 4KB requests and b) when one generates 4KB requests and the other generates 512KB requests.

Fairness

- Analysis of I/O schedulers w.r.t. sharing notion (number of requests, amount of data transferred, resource time) and fairness
- None of the I/O schedulers result in a fairness that results in performance isolation and performance predictability

DASES

Dynamic Adaptivity in Support of Extreme Scale

Performance Unpredictability of CFQ(N)

- A set *s* of requests is dispatched from each queue
- It takes longer to service a 512KB request than a 4KB request
- 29% increase in execution time

drastic increase in execution time

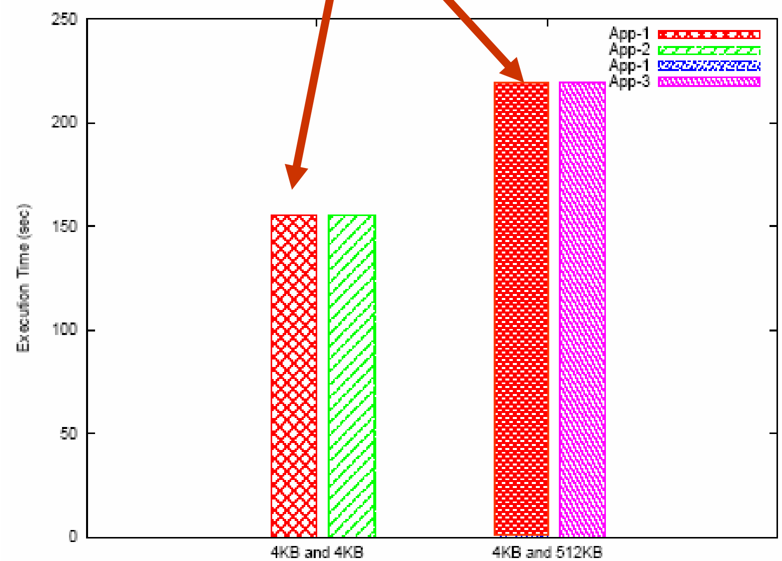


Figure 1: Application Execution Times when a) both generate 4KB requests and b) when one generates 4KB requests and the other generates 512KB requests.

Dynamic Adaptivity in Support of Extreme Scale

CFQ-Compensating Round Robin (CFQ-CRR) - 1

- Idea: compensated disk-time metric
  - Requests are scheduled one-by-one until the quantum is exhausted
  - When a request is completed, its service time is subtracted from the queue's quantum
  - Scheduling from a queue stops when the quantum is zero or negative
  - Quantum for next round is shortchanged with the negative quantum from this round
  - Unused quantum in a round is not carried to the next round

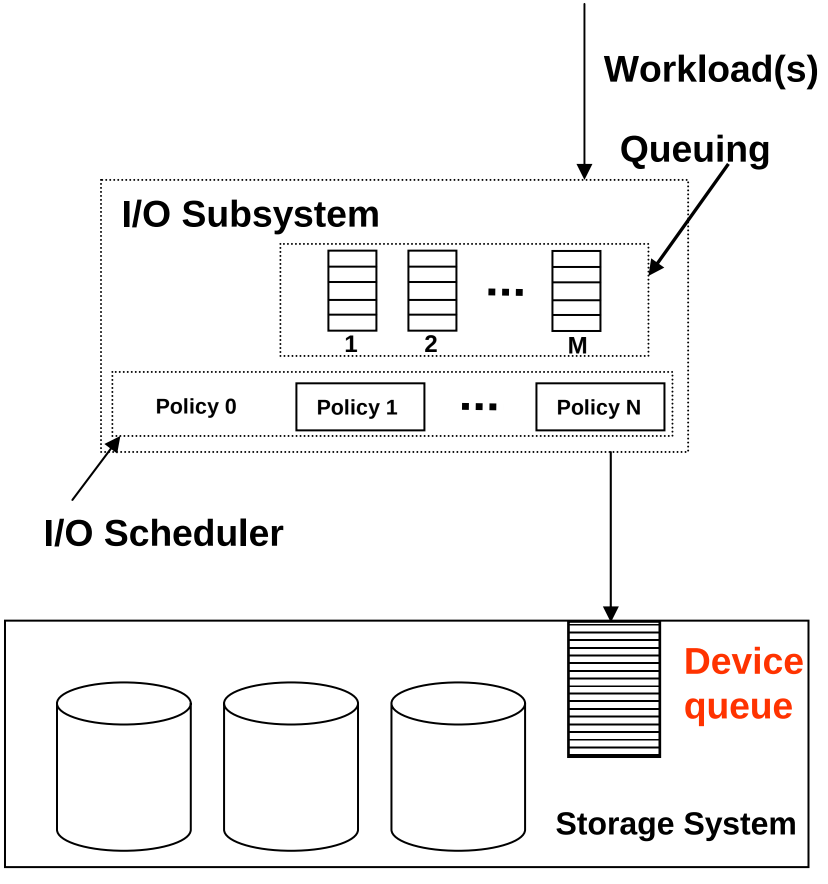
Dynamic Adaptivity in Support of Extreme Scale

CFQ-Compensating Round Robin (CFQ-CRR) - 2

- Provides
  - Performance isolation
  - Predictable performance
  - QoS guarantees with different values of quantum
  - A framework for simultaneously satisfying multiple data delivery requirements

CFQ-CRR(P): Extension for TCQ Drives

Dynamic Adaptivity in Support of Extreme Scale



System Model and I/O Schedulers

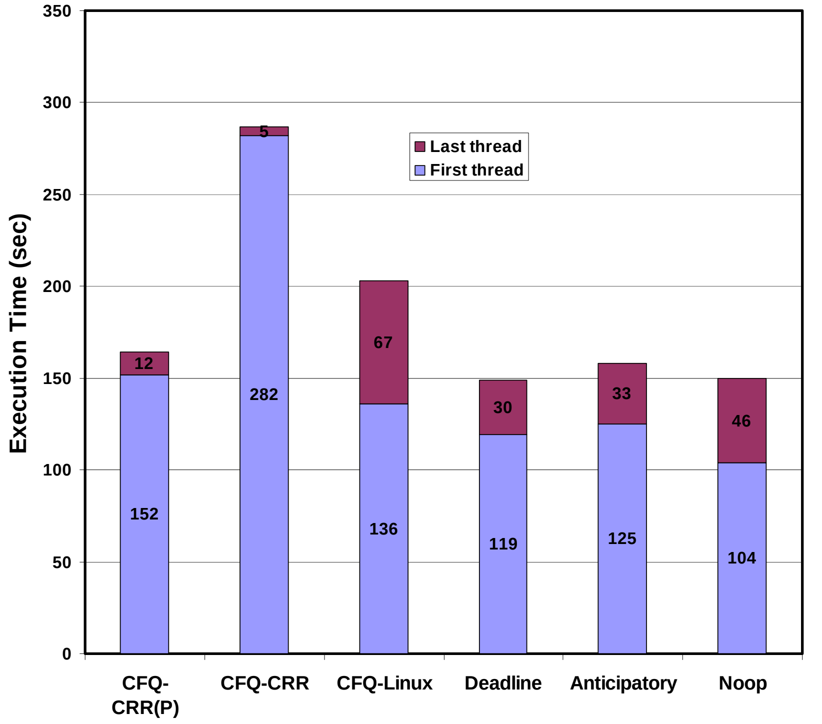
- TCQ and NCQ improves disk utilization of workloads with random accesses; benefit for hyper threading processors
- CFQ-CRR cannot take advantage of TCQ drives; it dispatches one request at a time
- CFQ-CRR with P: dispatches multiple requests from each queue to fill device queue
- Continuous filling of device queue results in starvation
- Given: each queue has a time quantum

CFQ-CRR(P): Implicit Adaptation

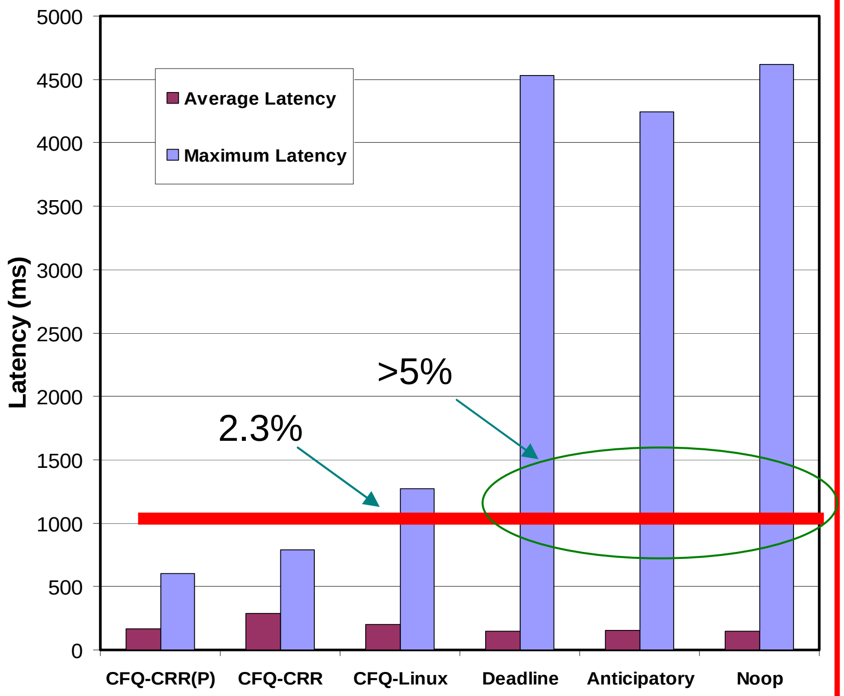
- Given the quantum and the maximum bandwidth obtainable from a storage system
  - Can be measured in less than 1 sec.
  - Must be measured at each mount operation of the disk system; avoid cache effects
- Compute amount of data that can be transferred as the product of the quantum and maximum bandwidth
- Dispatch requests such that total data transferred is greater than or equal to estimated amount
- Compensate extra time in succeeding rounds

Dynamic Adaptivity in Support of Extreme Scale

CFQ-CRR(P): Experimental Evaluation



Application execution times of the threads that finished first and last among 32 concurrent threads; 1000 random 4KB requests/thread



Maximum and average latency of requests with different schedulers; each thread accesses disjoint areas of the disk

CFQ-CRR(P): Extension for TCQ Drives

- Maintains strict fairness
- Results in better average and maximum latency compared to others
  - Deadline, Noop, and Anticipatory have more than 5% requests exceeding 1sec. latency
- Preserves performance predictability while using TCQ drives
- Performs poorly because it does not exploit TCQ and schedules one request at a time

Outline

- Overview of DAiSES
- Infrastructure
- **Research**
  - UW
    - Kernel Performance
    - Scalability
  - **UTEP**
    - **Proof of Concept: I/O Scheduling**
    - **Lessons Learned**
    - **Candidate Adaptation Targets**
      - VMM Parameter Adaptation
      - Adaptive Page Size Allocation
      - SMT/CMP Scheduling
      - Virtualization
- Acknowledgments
- Publications

Lessons Learned - 1

See Operating Systems Review article for more details.

- Identifying promising adaptation targets is a challenging and time-intensive task
  - Gain familiarity with related literature and Linux code
  - Identify applications/workloads that will be affected by targeted adaptation
  - Use static adaptation and a variety of workloads to quantify potential performance gains
  - Perform a feasibility study of the dynamic adaptation
- Complexities associated with parametric and policy adaptations differ significantly
  - Original methodology more directed at parametric adaptation

Dynamic Adaptivity in Support of Extreme Scale

Lessons Learned - 2

See Operating Systems Review article for more details.

- Adaptations come in two “flavors
  - Application performance objectives (relatively easy)
  - System performance objectives (concurrent tuning of multiple applications that share resources is decidedly more difficult)
- Improved execution-time performance if not the only objective
  - Necessary system constraints, e.g., fairness and latency
- Different strategies are needed for resources with state and resources without state

Candidate Adaptation Targets

- I/O scheduling policy adaptation
- I/O scheduling parameter adaptation
- Parametric adaptation of virtual memory manager
- Multiple page size management
- Network stack
- Scheduling of chip multiprocessors
- File I/O
- Virtualization

DAiSES

Dynamic Adaptivity in Support of Extreme Scale

Outline

- Overview of DAiSES
- Infrastructure
- Research
  - UW
    - Kernel Performance
    - Scalability
  - UTEP
    - **Proof of Concept: I/O Scheduling**
    - Lessons Learned
    - Candidate Adaptation Targets
      - **VMM Parameter Adaptation**
      - **Adaptive Page Size Allocation**
      - **SMT/CMP Scheduling**
      - **Virtualization**
- Acknowledgments
- Publications

Dynamic Adaptivity in Support of Extreme Scale

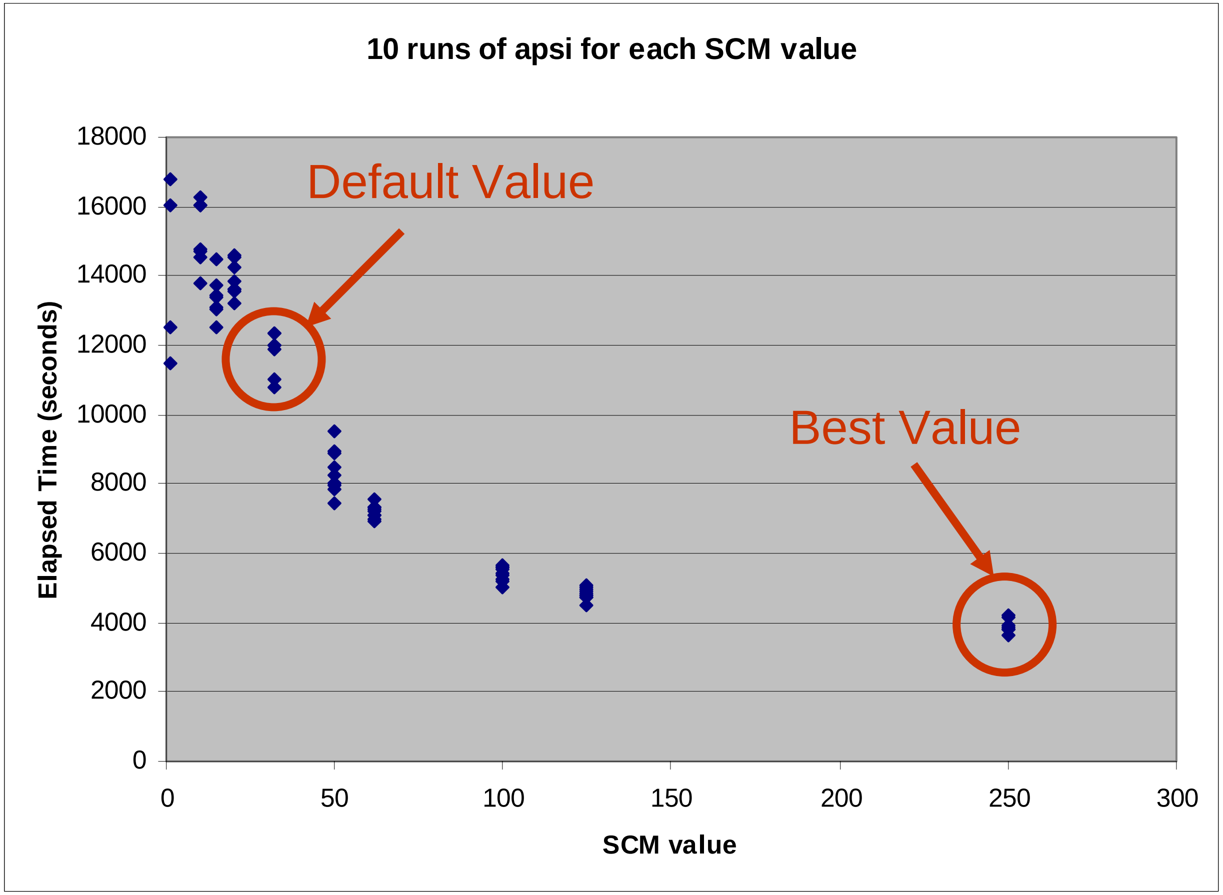
VMM Parameter Adaptation

- Builds on work of Gokul Kandiraju (Penn State)
- Master's thesis (Ricardo Portillo): using static adaptation and different types of applications, understand the effect of changing one or more parameters
- Preliminary results: in the case of SPEC APSI and the SCM parameter (minimum no. of pages freed on a reclamation pass due to failure to allocate memory), 63% improvement in terms of both execution time and number of page faults
- But Stephen Poole says: *"What's a swap?"*

Dynamic Adaptivity in Support of Extreme Scale

VMM Parameter Adaptation

63% improvement as compared to default value of SCM



Adaptive Page Size Allocation

- Builds on work of Juan Navarro (Rice)
- Reduce TLB misses
- Linux Symposium – BoF on supporting multiple page sizes
- Exploring how to experiment with ideas
  - K42?
  - Itanium cluster?

DASES

Dynamic Adaptivity in Support of Extreme Scale

SMT/CMP Scheduling

- Goals
  - Better processor and system utilization
  - Less interference w.r.t. cache – impacts synchronization (Beckman, et al.)
- Initial Objectives
  - Characterize interference of classes of applications running on SMT processors
  - Develop co-scheduling heuristics
  - Use heuristics to tune SMT knobs like hardware thread priorities, SMT On/Off, and SMT Snooze for maximizing system performance (IPC)
  - Explore on-the-fly SMT-knob tuning in kernel space

Virtualization

- IBM eServer pSeries 550
- Impact of scheduling decisions
  - Allocations
  - Capped and uncapped
- Overhead
  - Memory
  - Performance
- SPECjAppServer
- Scientific workloads
- Funded by IBM-Austin

Dynamic Adaptivity in Support of Extreme Scale

Outline

- Overview of DAiSES
- Infrastructure
- Research
  - UW
    - Kernel Performance
    - Scalability
  - UTEP
    - **Proof of Concept: I/O Scheduling**
    - Lessons Learned
    - Candidate Adaptation Targets
      - VMM Parameter Adaptation
      - Adaptive Page Size Allocation
      - SMT/CMP Scheduling
      - Virtualization
- Acknowledgments
- Publications

Dynamic Adaptivity in Support of Extreme Scale

Acknowledgments

- DOE (Grant # DE-FG02-04ER25622)
- IBM Corporation for IBM Shared University Research Grant (SUR)
- IBM-Austin LTC, especially Bill Buros
- Linux Developers, especially Jens Axboe
- UTEP

DASES

Dynamic Adaptivity in Support of Extreme Scale

Publications

- Seetharami Seelam and Patricia Teller, “Disk Scheduling with Performance Objectives,” (in preparation).
- Seetharami Seelam and Patricia Teller, “Disk Scheduling for Predictable Performance Behavior: Completely Fair Queuing and Compensating Round-Robin,” (in preparation).
- Seetharami Seelam and Patricia Teller, “Fairness and Performance Isolation: an Analysis of Disk Scheduling Algorithms,” submitted to Workshop on High Performance I/O Techniques and Deployment of Very Large Scale I/O Systems (HiperIO’06), in conjunction with the IEEE International Conference on Cluster Computing, September 25-27, 2006.
- Seetharami Seelam, Jayaraman Suresh Babu, and Patricia Teller, “Performance Analysis of Disk Scheduling Algorithms for Asynchronous Requests,” to appear in Proceedings of the 3rd International Conference on Quantitative Evaluation of SysTems (Qest ’06), Riverside, CA, September 11-14, 2006.
- Seetharami Seelam, *Towards Dynamic I/O Scheduling in Commodity Operating Systems*, Ph.D. Dissertation, University of Texas-El Paso, Computer Engineering, May 2006.
- Jayaraman Suresh Babu, *Coarse-Grain Dynamic Adaptation for Asynchronous I/O Scheduling: Is it needed?*, Master’s Thesis, University of Texas-El Paso, Computer Science, May 2006.
- Patricia Teller and Seetharami, Seelam, “Insights into Providing Dynamic Adaptation of Operating System Policies,” ACM Operating Systems Review, 40:2: 83-89, April 2006.
- Seetharami Seelam and Patricia Teller, “Disk Scheduling Using Fair Queuing and Round-Robin: Fairness Analysis,” Technical Report, University of Texas-El Paso, Computer Science, December 2005.
- Rodrigo Romero, Seetharami Seelam, and Patricia Teller, “Workload Dependent Performance Analysis of Process Schedulers: A Case Study,” Technical Report, University of Texas-El Paso, Computer Science, November 2005.
- Seetharami Seelam, Jayaraman Suresh Babu, and Patricia Teller, “Automatic I/O Scheduler Selection for Latency and Bandwidth Optimization,” *Proceedings of the Workshop on Operating System Interference in High Performance Applications – OSIHPA*, Saint Louis, Missouri, 17 September 2005.
- Seetharami Seelam, Rodrigo Romero, Patricia Teller, and William Buros, “Enhancements to Linux I/O Scheduling,” *Proceedings of the 2005 Linux Symposium*, Ottawa, Canada, 20-23 July 2005.

General Challenges

- Overhead to
  - Identify effective tools and learn how to use them
  - Identify target benchmarks/applications and get them running
    - Real applications for proofs of concept
- Experimental platforms
  - File I/O (Beckman, et al.)
  - K42 (Paul Hargove, et al.)