

Many-task Computing:

Bridging the Gap between High-Throughput Computing and High-Performance Computing

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**The Center for Advanced Computer Studies
University of Louisiana at Lafayette
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Acknowledgements

- Committee Members
 - Ian Foster (advisor)
 - Rick Stevens
 - Alex Szalay
- University of Chicago
 - Computer Science Department
 - Computational Institute
- Argonne National Laboratory
 - Math and Computer Science Division
 - Argonne Leadership Computing Facility
- NASA
 - Ames Research Center
 - Jerry C. Yan
- Over 60 collaborators

Distributed Systems Laboratory

University of Chicago

http://dsl-wiki.cs.uchicago.edu/index.php/Main_Page

- Lead by Dr. Ian Foster
- Research Areas:
 - Distributed systems
 - Grid middleware
 - Grid applications
 - Designing, implementing, and evaluating systems, protocols, and applications
 - Data-intensive scientific computing
- People:
 - 1 faculty (Dr. Ian Foster)
 - 12 students
 - 2 research staff
 - 13 alumnis



Computation Institute University of Chicago

<http://www.ci.uchicago.edu/index.php>

- People:

- Director: Ian Foster
- 70 faculty and scientists
- 30 full-time professional staff
- 14 graduate students

- Focus

- Deep Supercomputing
- Data Intensive Computing
- Next Generation Cybertools

- Many high-impact projects

- Open Science Grid
- TeraGrid
- Globus
- National Microbial Pathogen Research Center
- Social Informatics Data Grid
- Chicago Biomedical Consortium



Math and Computer Science Div. Argonne National Laboratory

<http://www.mcs.anl.gov/index.php>

- People:

- Associate Director: Ian Foster
- Over 180 staff, researchers, scientists, developers

- Research Areas

- Algorithms, Software, and Applications
- Parallel Tools
- Distributed Systems Research
- Collaborative and Virtual Environments
- Computational Science

- Many high-impact projects

- TeraGrid (largest national cyber-infrastructure project)
- Globus Toolkit (defacto Grid Computing middleware)
- MPI (synonymous with HPC and Supercomputing)
- PVFS (scalable and high performance parallel file system)

Mathematics and Computer Science Division

The MCS Division is increasing scientific productivity in the 21st century by providing intellectual and technical leadership in the computing sciences.

Mathematics and Computer Science Division

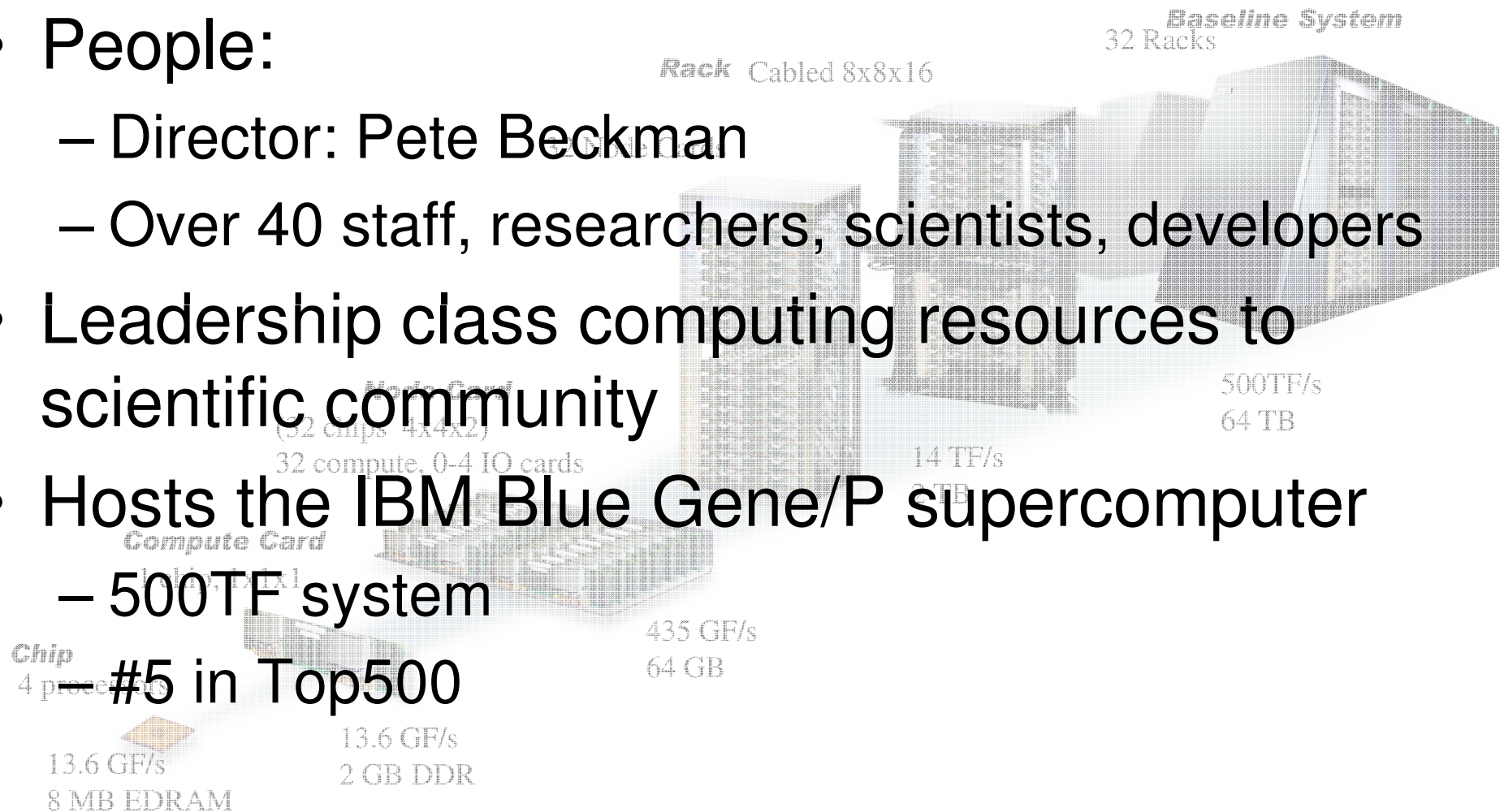
The MCS Division is increasing scientific productivity in the 21st century by providing intellectual and technical leadership in the computing sciences.

Argonne Leadership Computing Facility

Argonne National Laboratory

<http://www.alcf.anl.gov/>

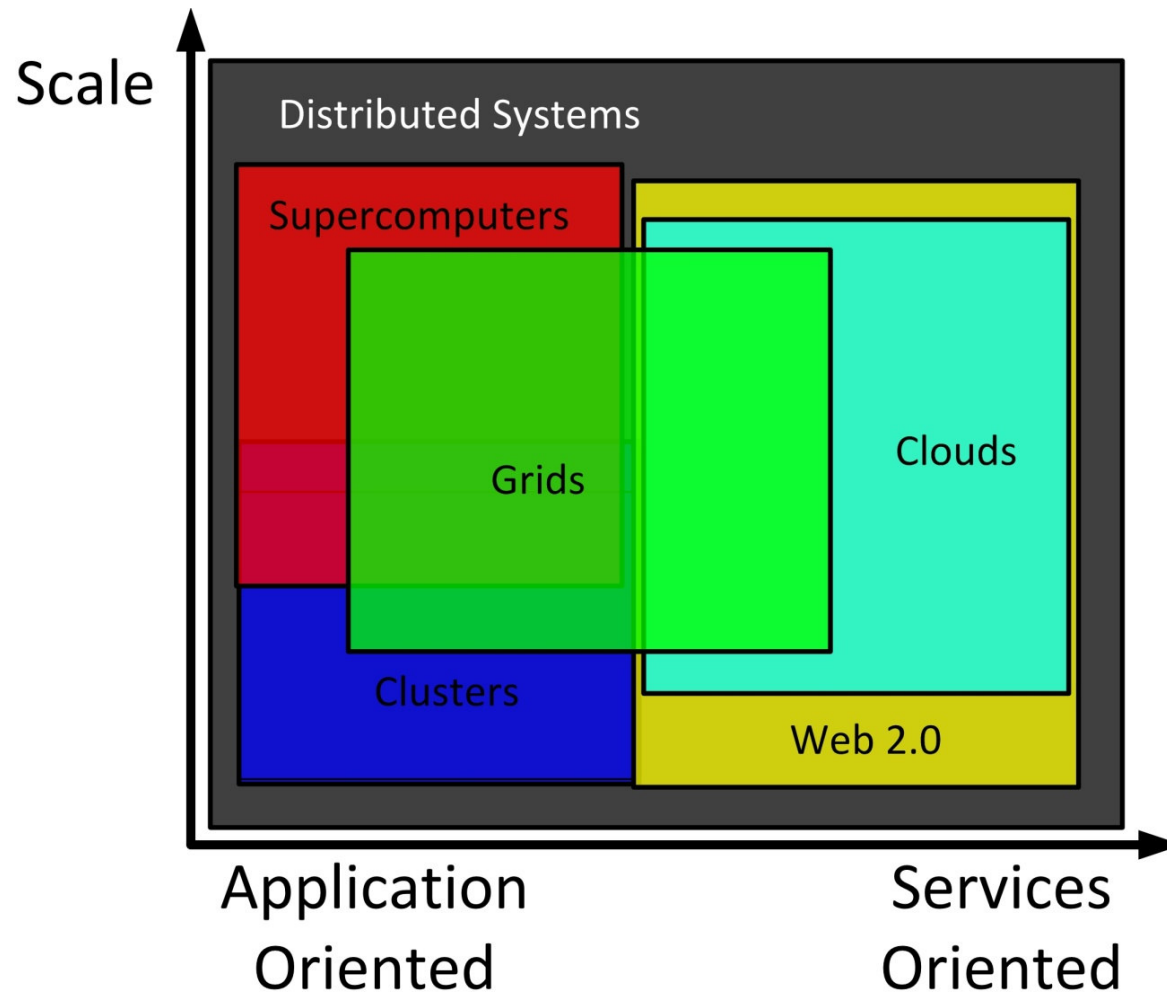
- People:
 - Director: Pete Beckman
 - Over 40 staff, researchers, scientists, developers
- Leadership class computing resources to scientific community
- Hosts the IBM Blue Gene/P supercomputer
 - 500TF system
 - #5 in Top500



Distributed Resources

- UChicago CS (50+ machines over the UChicago campus)
- UChicago TeraPort (274-cores)
- UC/ANL Cluster (316 processors)
- PlanetLab (912 nodes at 470 sites all over the world)
- UChicago PADS (7TF, 512-cores)
- ANL SiCortex 5832 (6TF, 5832-cores)
- Open Science Grid (43K-cores across 80 institutions in the US)
- IBM Blue Gene/P Supercomputer at ANL (~500TF, 160K-cores)
- TeraGrid (161K-cores across 11 institutions and 22 systems over the US)
 - Includes a Sun Constellation supercomputer (~500TF, 62K-cores)

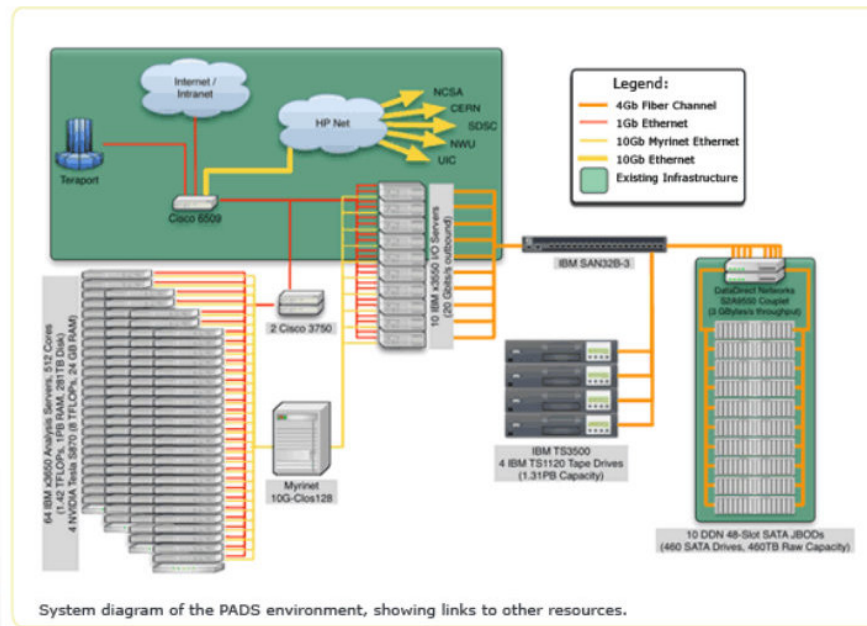
Clusters, Grids, Supercomputers



Cluster Computing: PADS

PADS

Computer clusters using commodity processors, network interconnects, and operating systems.



PADS is a petabyte (10^{15} -byte)-scale online storage server capable of sustained multi-gigabyte/s I/O performance, tightly integrated with a 9 teraflop/s computing resource and multi-gigabit/s local and wide area networks. Its hardware and associated software enables the reliable storage of, access to, and analysis of massive datasets by both local users and the national scientific community.

The PADS design results from a study of the storage and analysis requirements of participating groups in astrophysics and astronomy, computer science, economics, evolutionary and organismal biology, geosciences, high-energy physics, linguistics, materials science, neuroscience, psychology, and sociology. For these groups, PADS represents a significant opportunity to look at their data in new ways, enabling new scientific insights. The infrastructure also encourages new collaborations across disciplines. PADS is also a vehicle for computer science research into active data store systems, and provides rich data on which to investigate new techniques. Results will be made available as open source software.

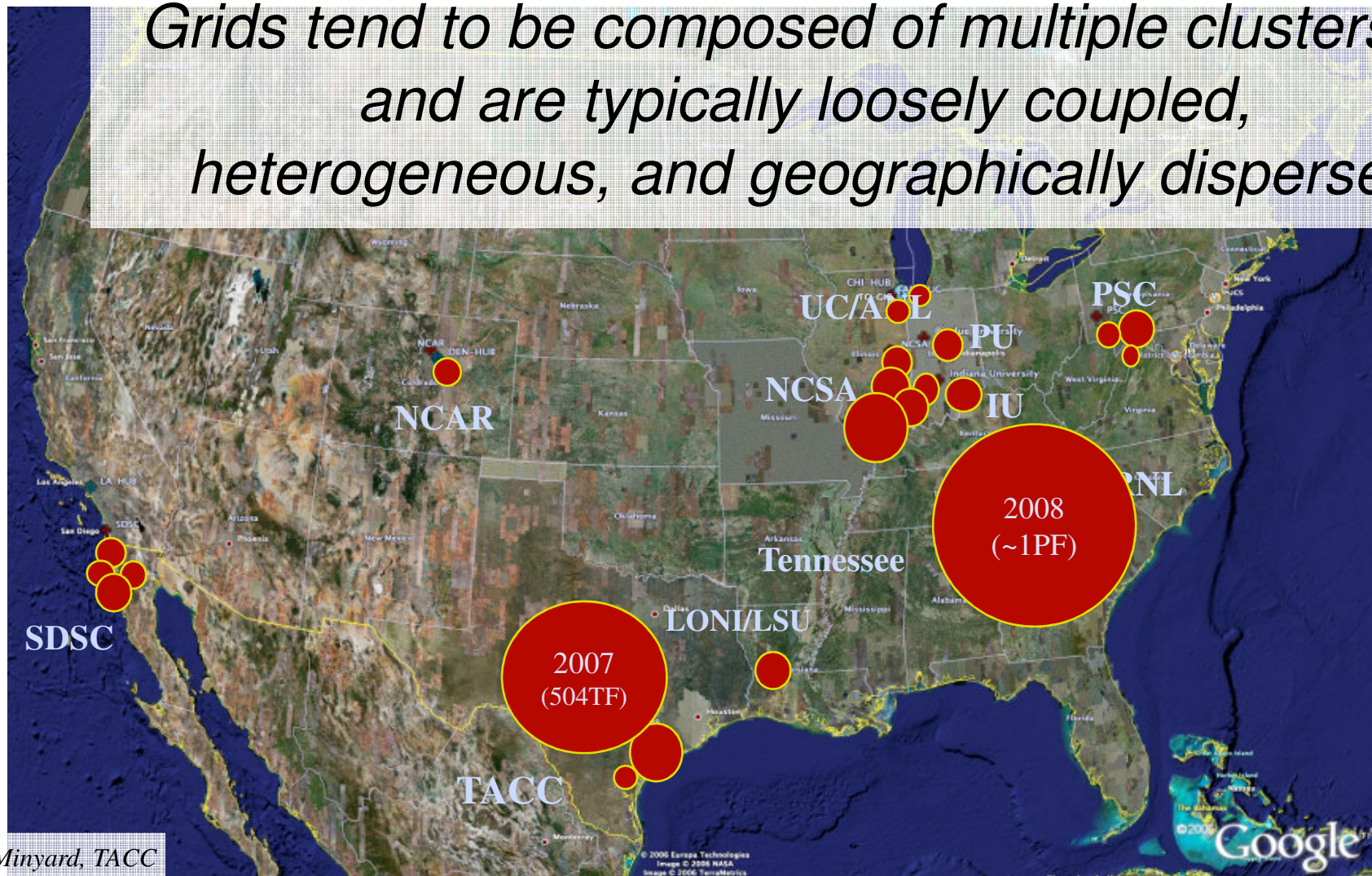
The PADS project is supported in part by the National Science Foundation under grant OCI-0821678 and by The University of Chicago.

[PADSstatus](#)

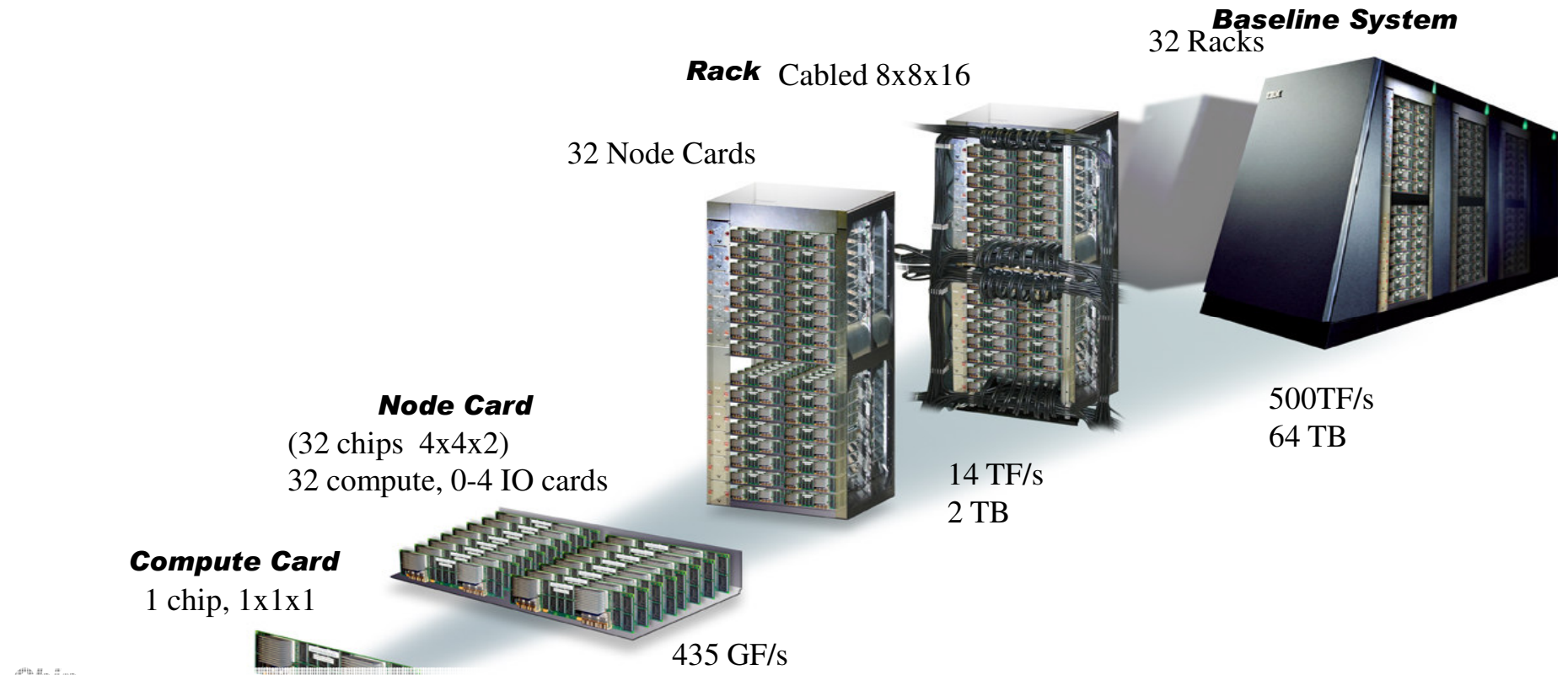
[myPADS](#)

Grid Computing: TeraGrid

Grids tend to be composed of multiple clusters, and are typically loosely coupled, heterogeneous, and geographically dispersed



Supercomputing: IBM Blue Gene/P



Highly-tuned computer clusters using commodity processors combined with custom network interconnects and customized operating system

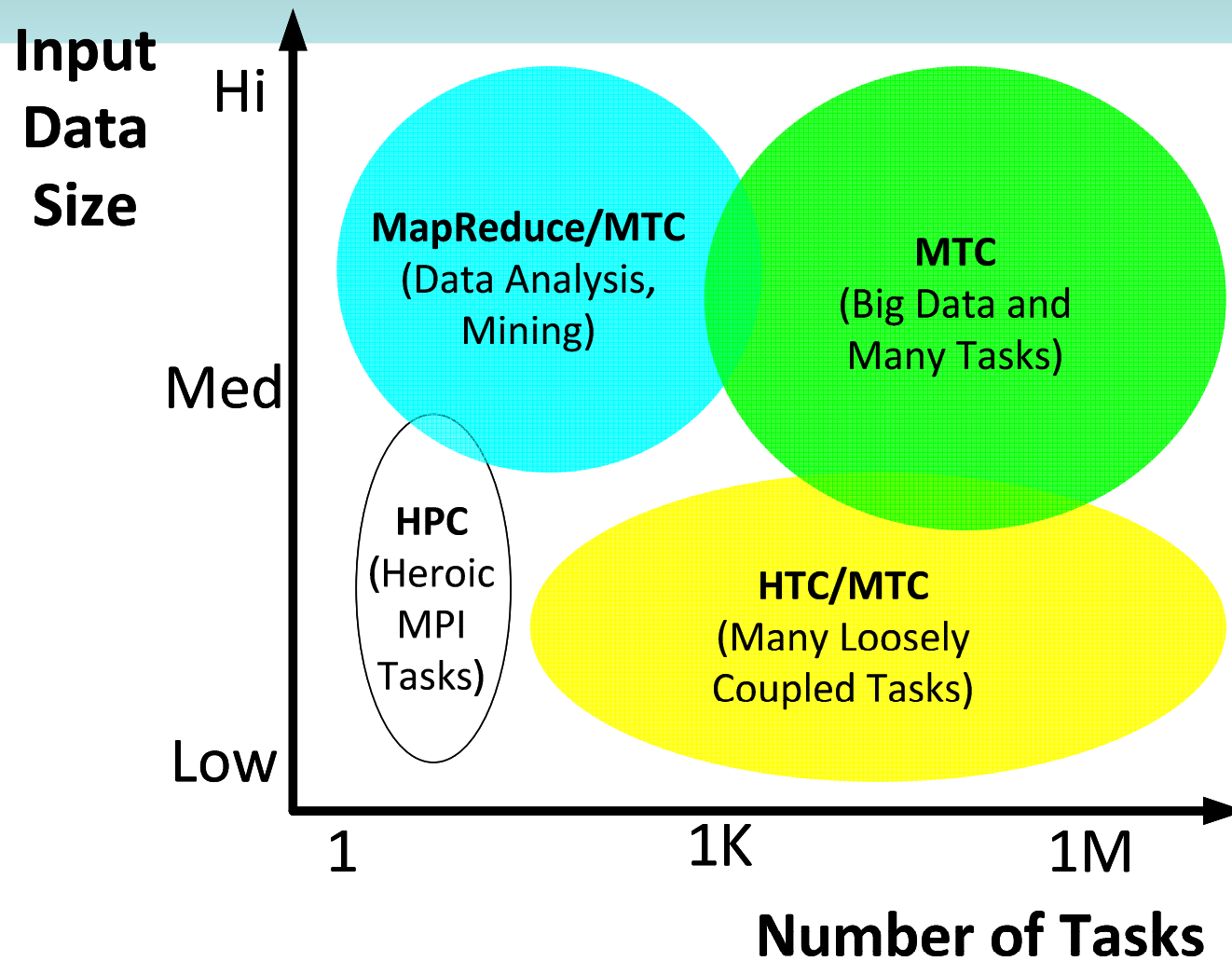
High-Throughput Computing & High-Performance Computing

- HTC: High-Throughput Computing
 - Typically applied in clusters and grids
 - Loosely-coupled applications with sequential jobs
 - Large amounts of computing for long periods of times
 - Measured in operations per month or years
- HPC: High-Performance Computing
 - Synonymous with supercomputing
 - Tightly-coupled applications
 - Implemented using Message Passing Interface (MPI)
 - Large of amounts of computing for short periods of time
 - Usually requires low latency interconnects
 - Measured in FLOPS

MTC: Many-Task Computing

- Bridge the gap between HPC and HTC
- Applied in clusters, grids, and supercomputers
- Loosely coupled apps with HPC orientations
- Many activities coupled by file system ops
- Many resources over short time periods
 - Large number of tasks, large quantity of computing, and large volumes of data

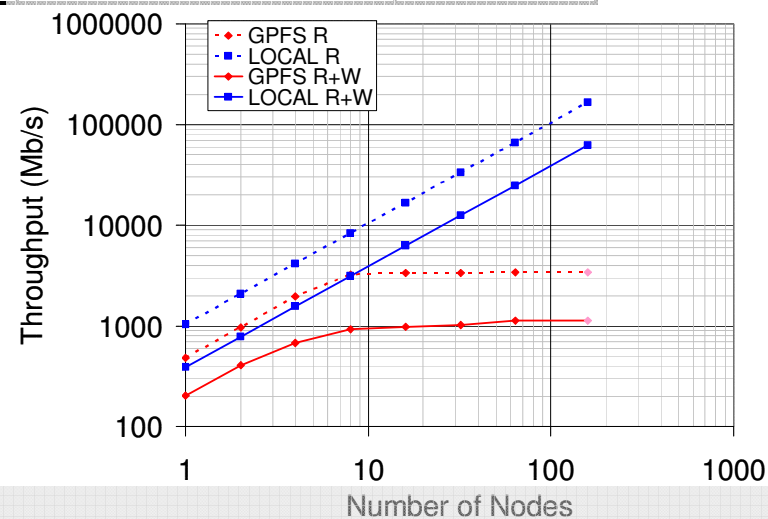
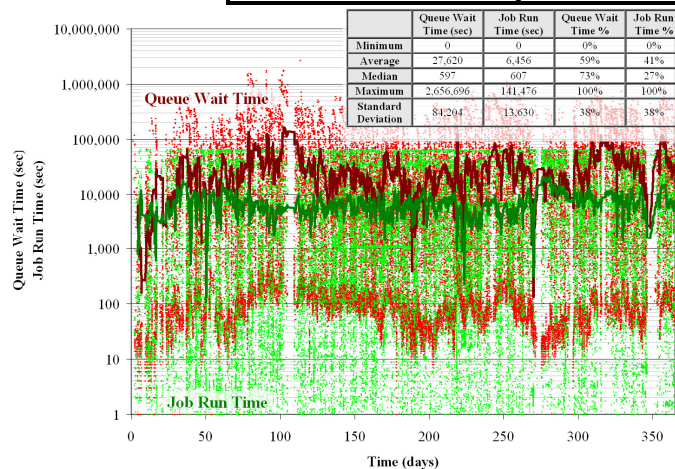
Problem Space



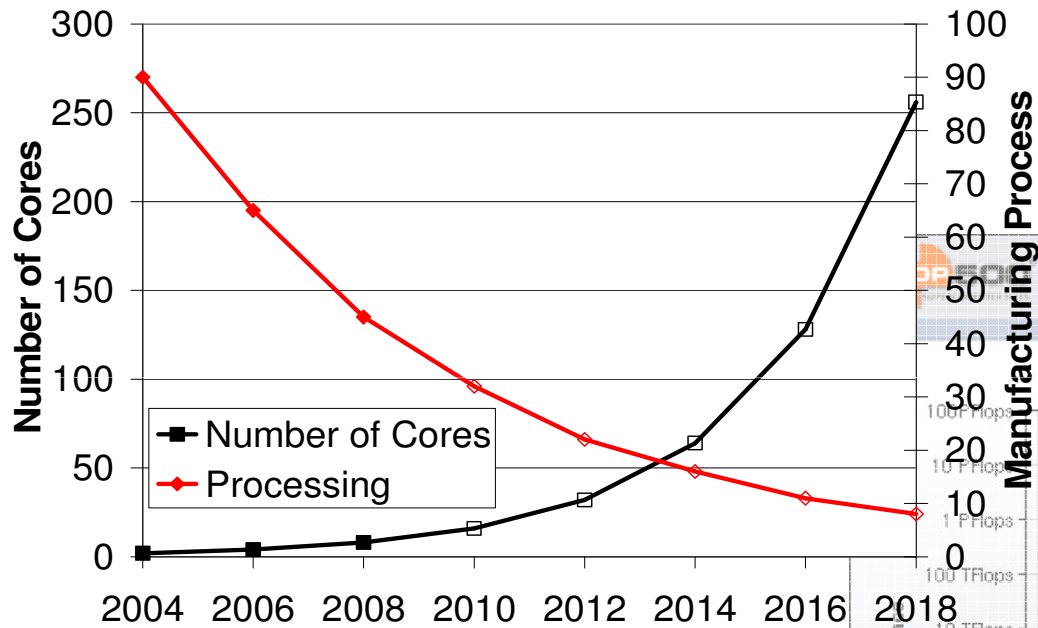
Challenges for MTC

1. Slow job dispatch rates
2. Long queue times
3. Poor shared/parallel file system scaling

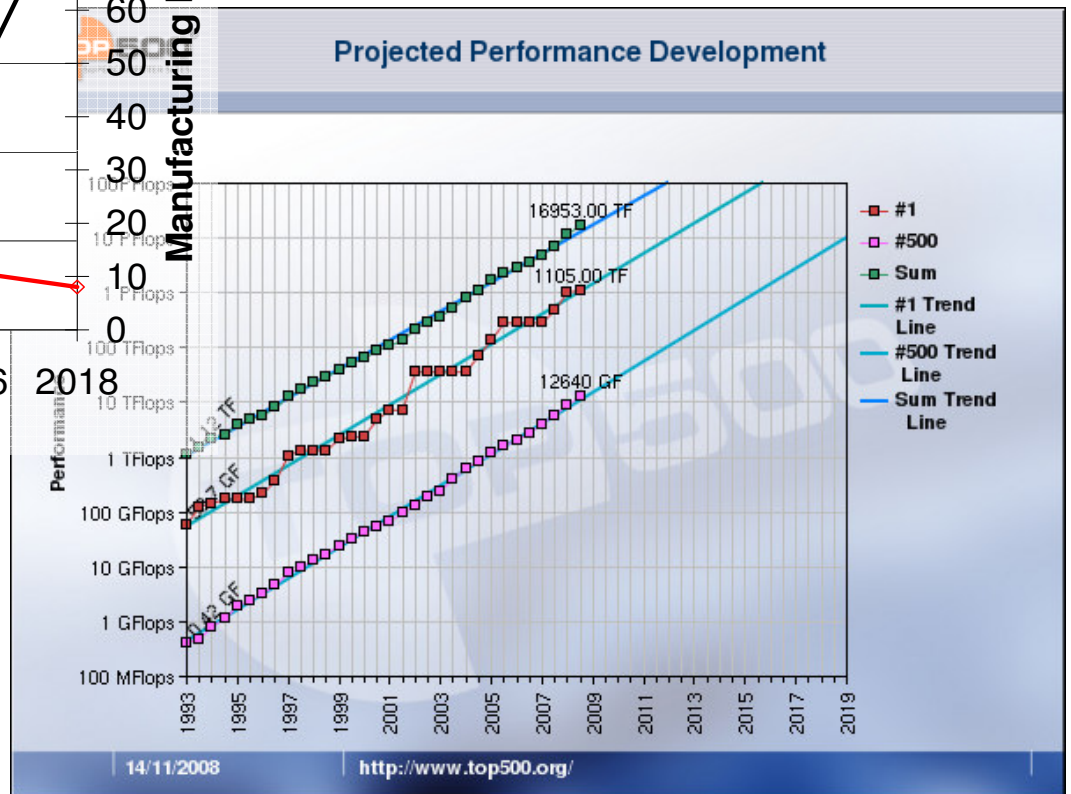
| System | Comments | Throughput (tasks/sec) |
|--------------------------------------|-----------------------|------------------------|
| Condor (v6.7.2) - Production | Dual Xeon 2.4GHz, 4GB | 0.49 |
| PBS (v2.1.8) - Production | Dual Xeon 2.4GHz, 4GB | 0.45 |
| Condor (v6.7.2) - Production | Quad Xeon 3 GHz, 4GB | 2 |
| Condor (v6.8.2) - Production | | 0.42 |
| Condor (v6.9.3) - Development | | 11 |
| Condor-J2 - Experimental | Quad Xeon 3 GHz, 4GB | 22 |



Projected Growth Trends



Pat Helland, Microsoft, The Irresistible Forces Meet the Movable Objects, November 9th, 2007



Top500 Projected Development,

http://www.top500.org/lists/2008/11/performance_development

Growing Storage/Compute Gap

- Local Disk:

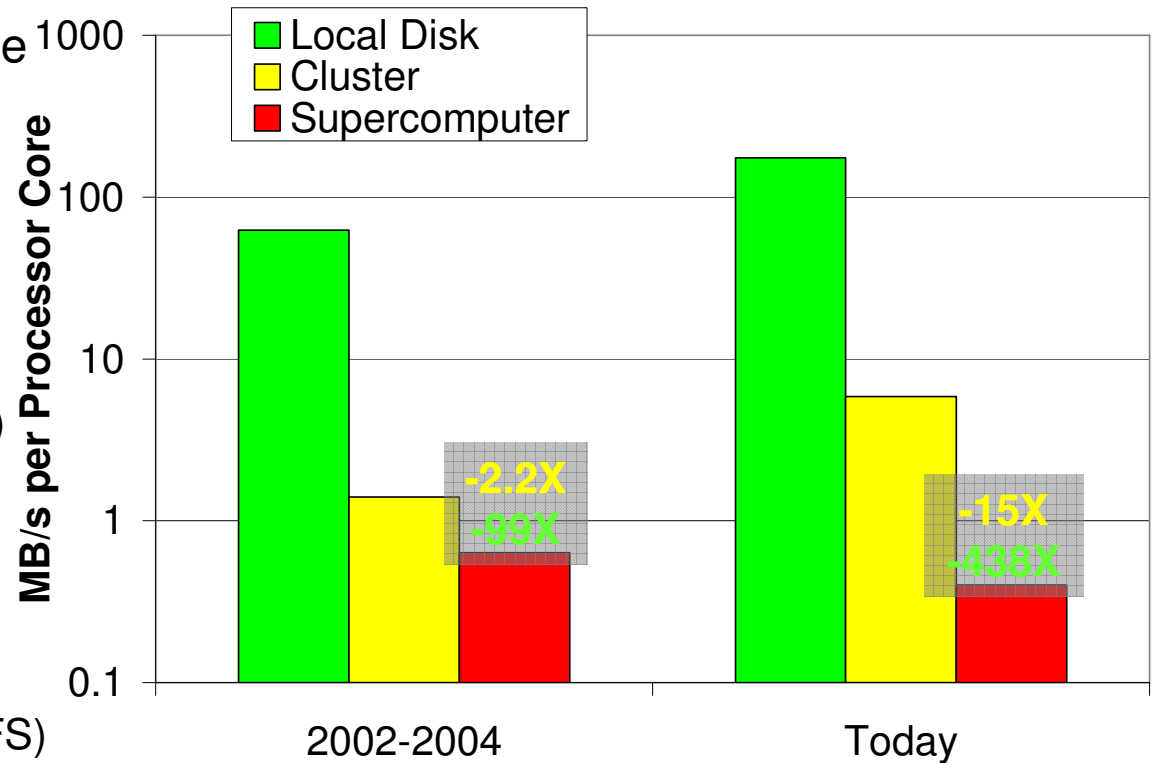
- 2002-2004: ANL/UC TG Site (70GB SCSI)
- Today: PADS (RAID-0, 6 drives 750GB SATA)

- Cluster:

- 2002-2004: ANL/UC TG Site (GPFS, 8 servers, 1Gb/s each)
- Today: PADS (GPFS, SAN)

- Supercomputer:

- 2002-2004: IBM Blue Gene/L (GPFS)
- Today: IBM Blue Gene/P (GPFS)



Presentation Focus

- [JS09] “Middleware Support for Many-Task Computing”, under preparation
- [HPDC09] “The Quest for Scalable Support of Data Intensive Workloads in Distributed Systems”, under review
- [DIDC09] “Towards Data Intensive Many-Task Computing” , under review
- [SC08] “Towards Loosely-Coupled Programming on Petascale Systems”
- [MTAGS08 Workshop] Workshop on Many-Task Computing on Grids and Supercomputers
- [MTAGS08] “Many-Task Computing for Grids and Supercomputers”
- [MTAGS08] “Design and Evaluation of a Collective I/O Model for Loosely-coupled Petascale Programming”
- [GCE08] “Cloud Computing and Grid Computing 360-Degree Compared”
- [SWF08] “Scientific Workflow Systems for 21st Century e-Science, New Bottle or New Wine?”
- [DADC08] “Accelerating Large-scale Data Exploration through Data Diffusion”
- [TG08] “Data Intensive Scalable Computing on TeraGrid: A Comparison of MapReduce and Swift”
- [GlobusWorld08] “Managing and Executing Loosely Coupled Large Scale Applications on Clusters, Grids, and Supercomputers”
- [NOVA08] “Realizing Fast, Scalable and Reliable Scientific Computations in Grid Environments”
- [UC07] “Harnessing Grid Resources with Data-Centric Task Farms”
- [Globus07] “Falkon: A Proposal for Project Globus Incubation”
- [SC07] “Falkon: a Fast and Light-weight task execution framework”
- [MSES07] “A Data Diffusion Approach to Large Scale Scientific Exploration”
- [SWF07] “Swift: Fast, Reliable, Loosely Coupled Parallel Computation”
- [TG07] “Dynamic Resource Provisioning in Grid Environments”
- [NASA06-08] “Harnessing Grid Resources to Enable the Dynamic Analysis of Large Astronomy Datasets”
- [SC06] “Harnessing Grid Resources to Enable the Dynamic Analysis of Large Astronomy Datasets”
- [TG06] “AstroPortal: A Science Gateway for Large-scale Astronomy Data Analysis”
- [NSF06] “The Importance of Data Locality in Distributed Computing Applications”

Techniques to Support MTC

- Streamlined task dispatching
- Dynamic resource provisioning
 - Multi-level scheduling
 - Resources are acquired/released in response to demand
- Data diffusion
 - Data diffuses from archival storage to transient resources
 - Resource “caching” allows faster responses to subsequent requests
 - Co-locate data and computations to optimize performance

[SC08] “Towards Loosely-Coupled Programming on Petascale Systems”

[DADC08] “Accelerating Large-scale Data Exploration through Data Diffusion”

[UC07] “Harnessing Grid Resources with Data-Centric Task Farms”

[SC07] “Falkon: a Fast and Light-weight task executiON framework”

[TG07] “Dynamic Resource Provisioning in Grid Environments”

Theoretical and Practical Exploration

- Abstract model
 - Models the efficiency and speedup of entire workloads
 - Captures techniques to support MTC
 - Streamlined task dispatching
 - Dynamic resource provisioning
 - Data diffusion
- Middleware to support MTC
 - Falkon: a fast a light-weight execution framework
 - Reference Implementation of the abstract model

[JS09] "Middleware Support for Many-Task Computing", under preparation

[DIDC09] "Towards Data Intensive Many-Task Computing", under review

[SC07] "Falkon: a Fast and Light-weight task executiON framework"

Middleware Support: Falkon

- **Goal:** enable the *rapid and efficient* execution of many independent jobs on large compute clusters
- Combines three components:
 - a *streamlined task dispatcher*
 - *resource provisioning* through multi-level scheduling techniques
 - *data diffusion* and data-aware scheduling to leverage the co-located computational and storage resources
- Integration into Swift to leverage many applications
 - Applications cover many domains: astronomy, astro-physics, medicine, chemistry, economics, climate modeling, etc

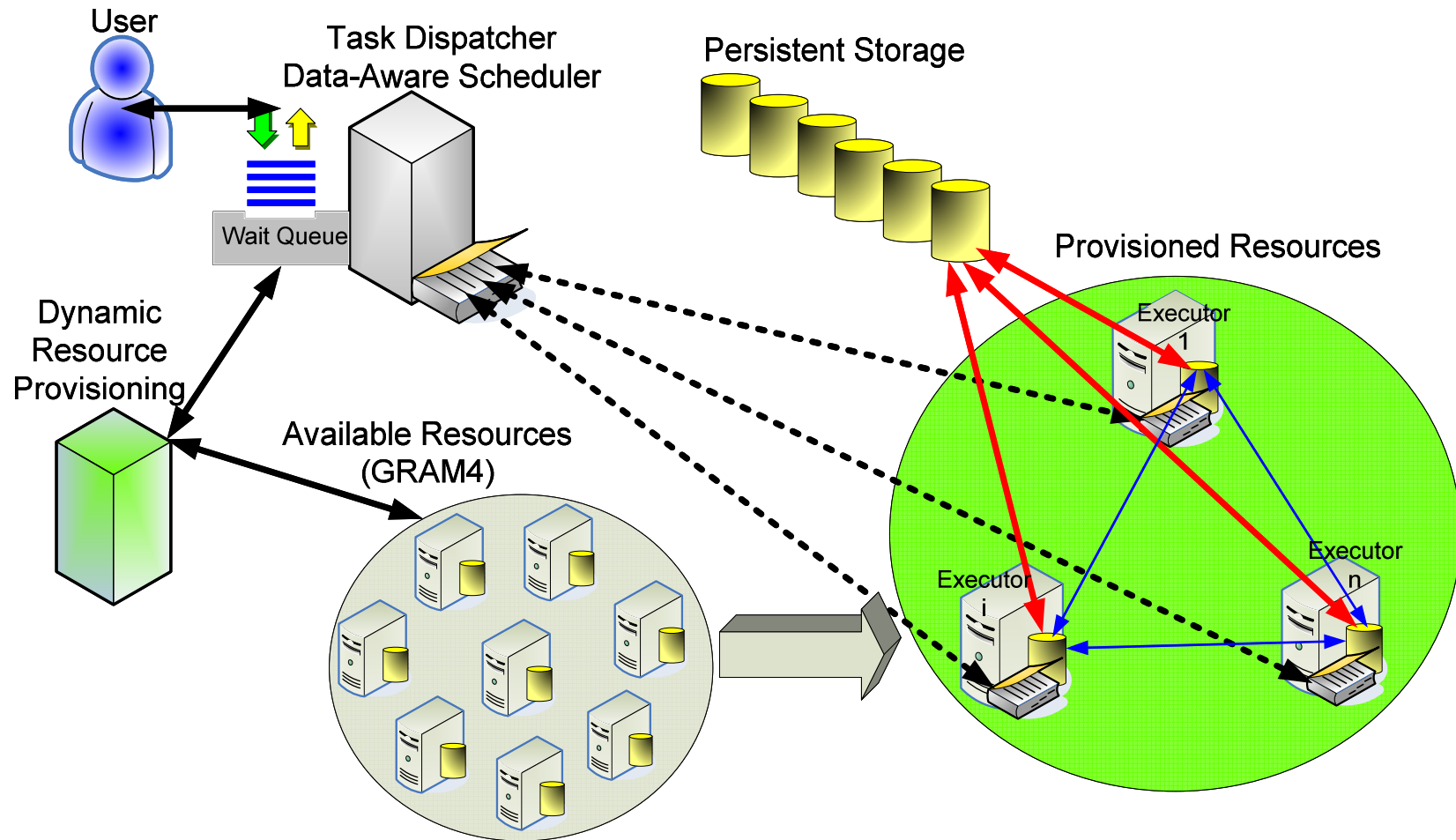
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[Globus07] "Falkon: A Proposal for Project Globus Incubation"

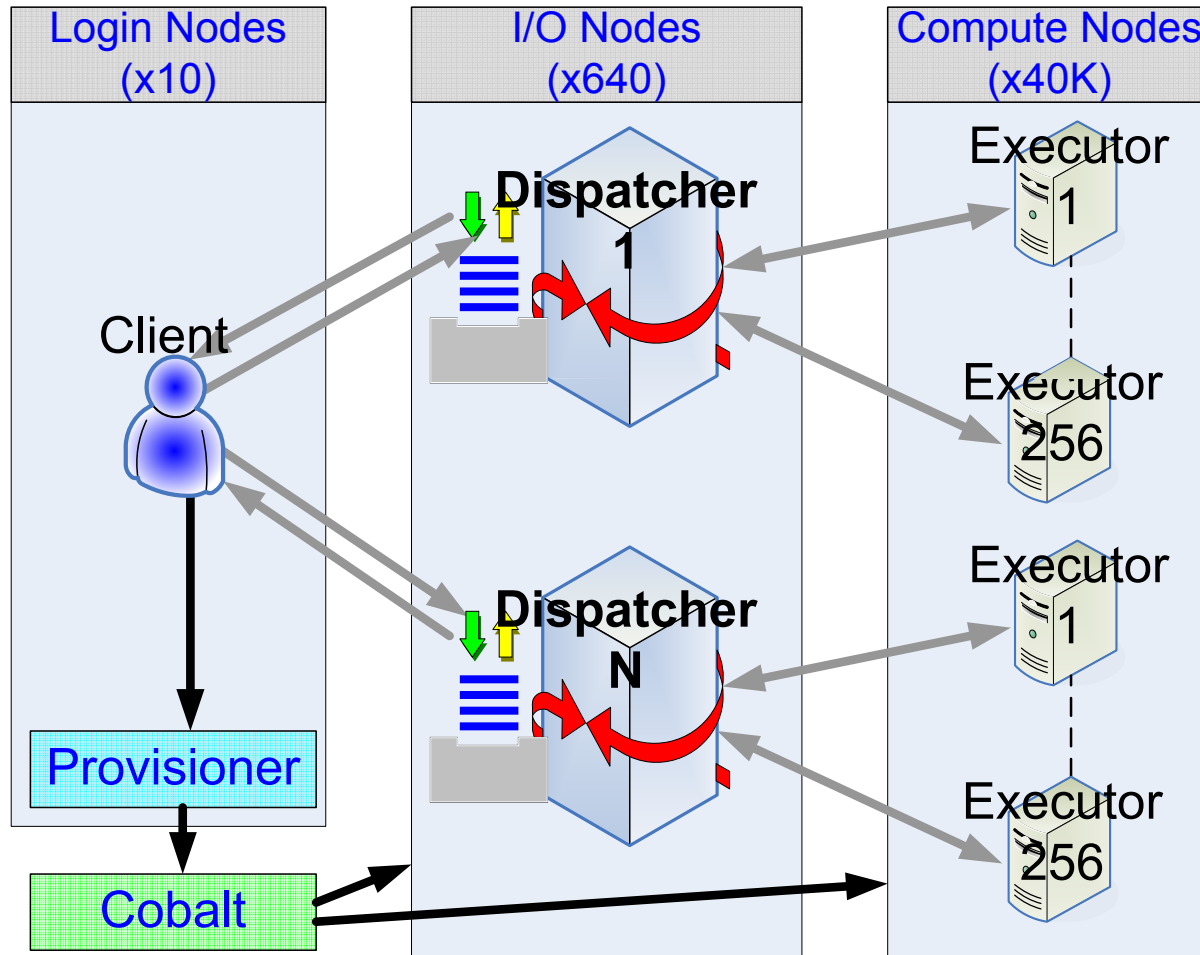
[SC07] "Falkon: a Fast and Light-weight task executiON framework"

[SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

Falkon Architecture



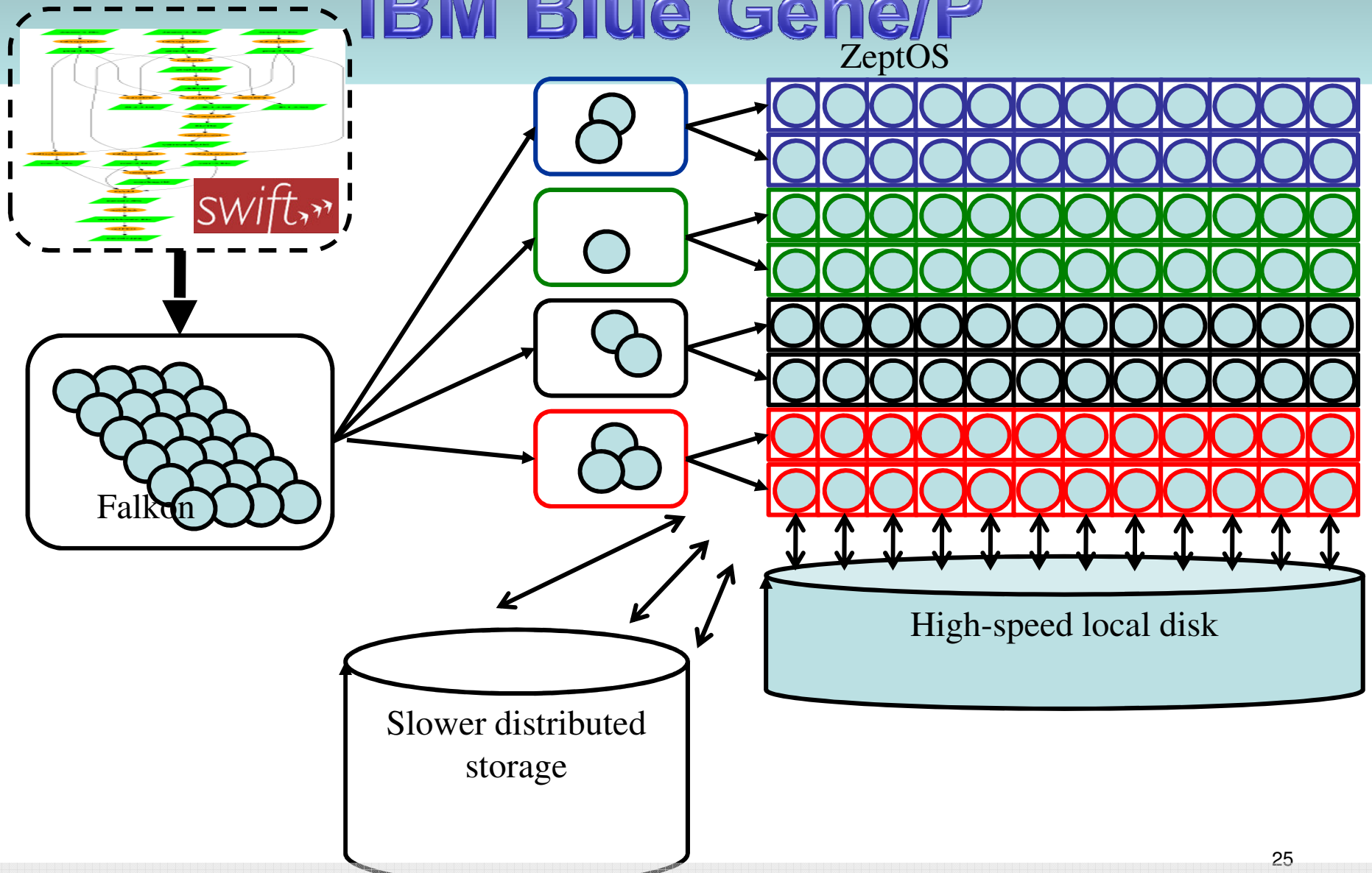
Distributed Falkon Architecture



Managing 160K CPUs

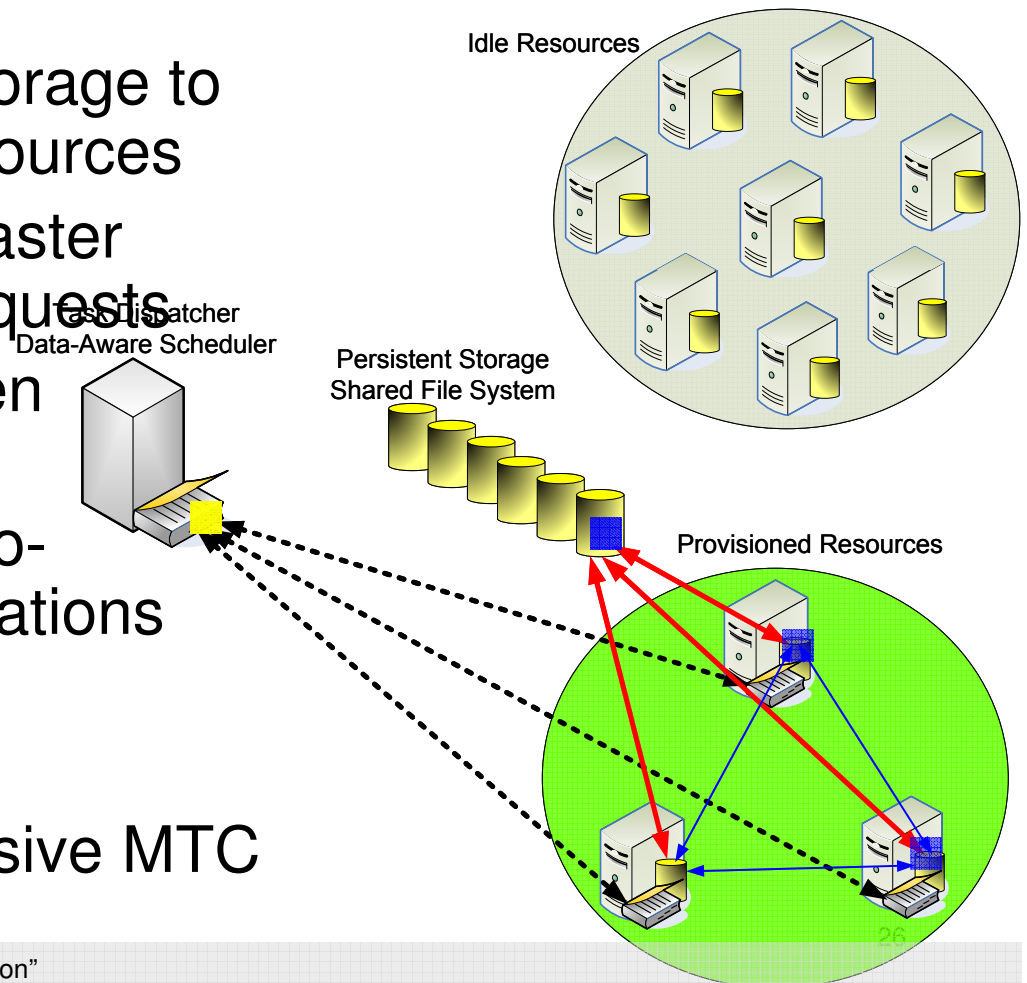
IBM Blue Gene/P

ZeptOS

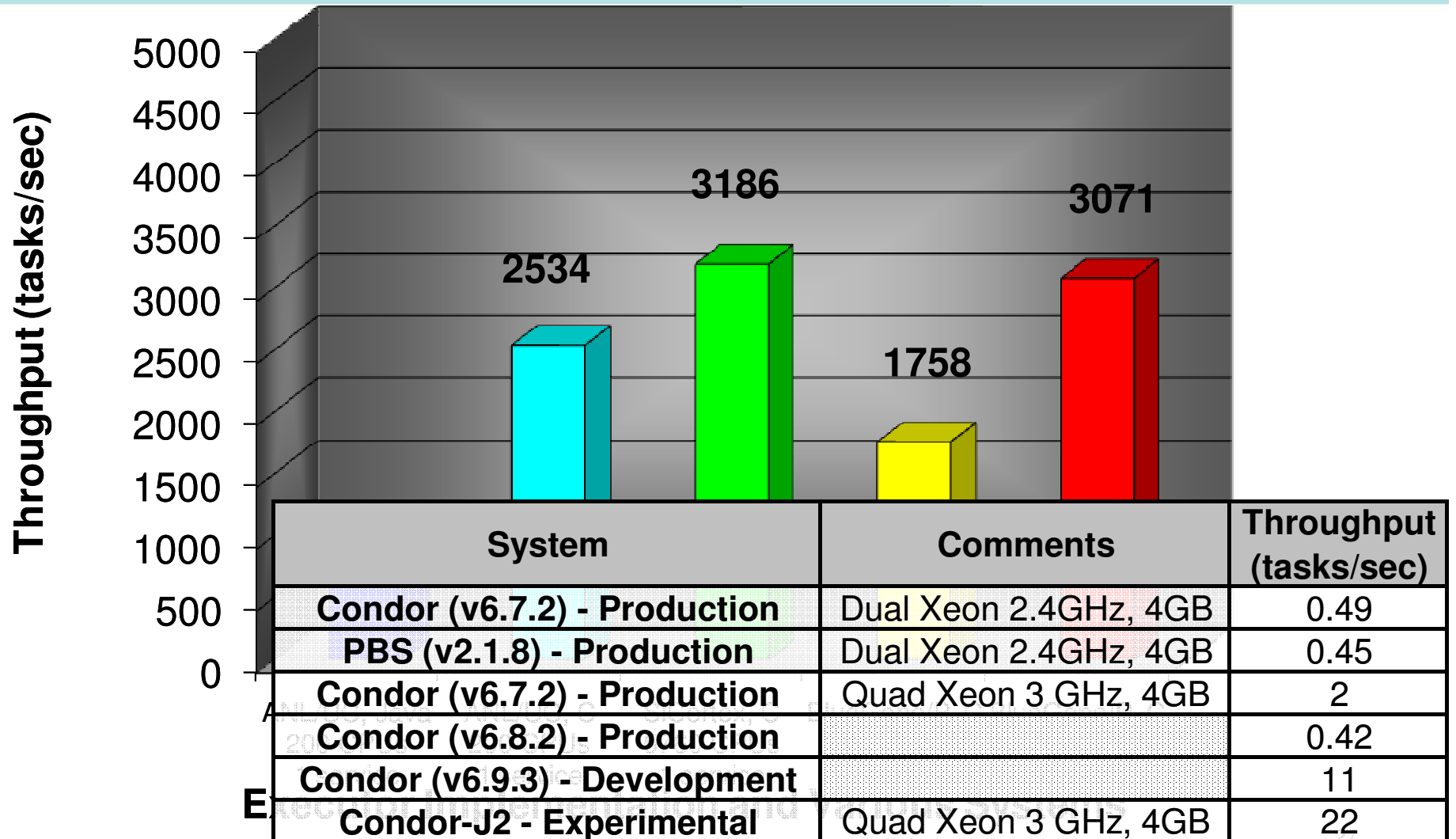


Data Diffusion

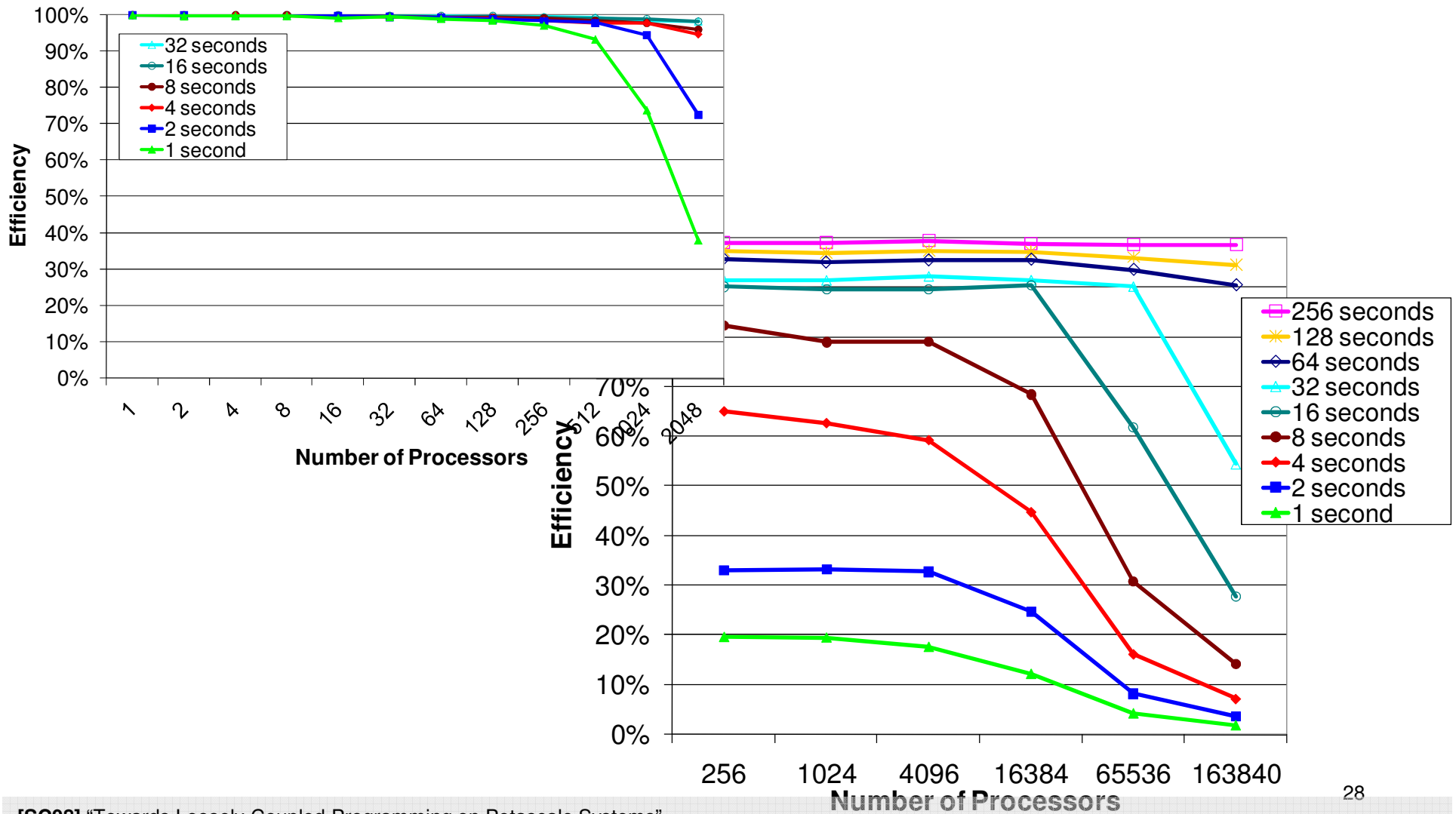
- Resource acquired in response to demand
- Data diffuse from archival storage to newly acquired transient resources
- Resource “caching” allows faster responses to subsequent requests
- Resources are released when demand drops
- Optimizes performance by co-scheduling data and computations
- Decrease dependency of a shared/parallel file systems
- Critical to support data intensive MTC



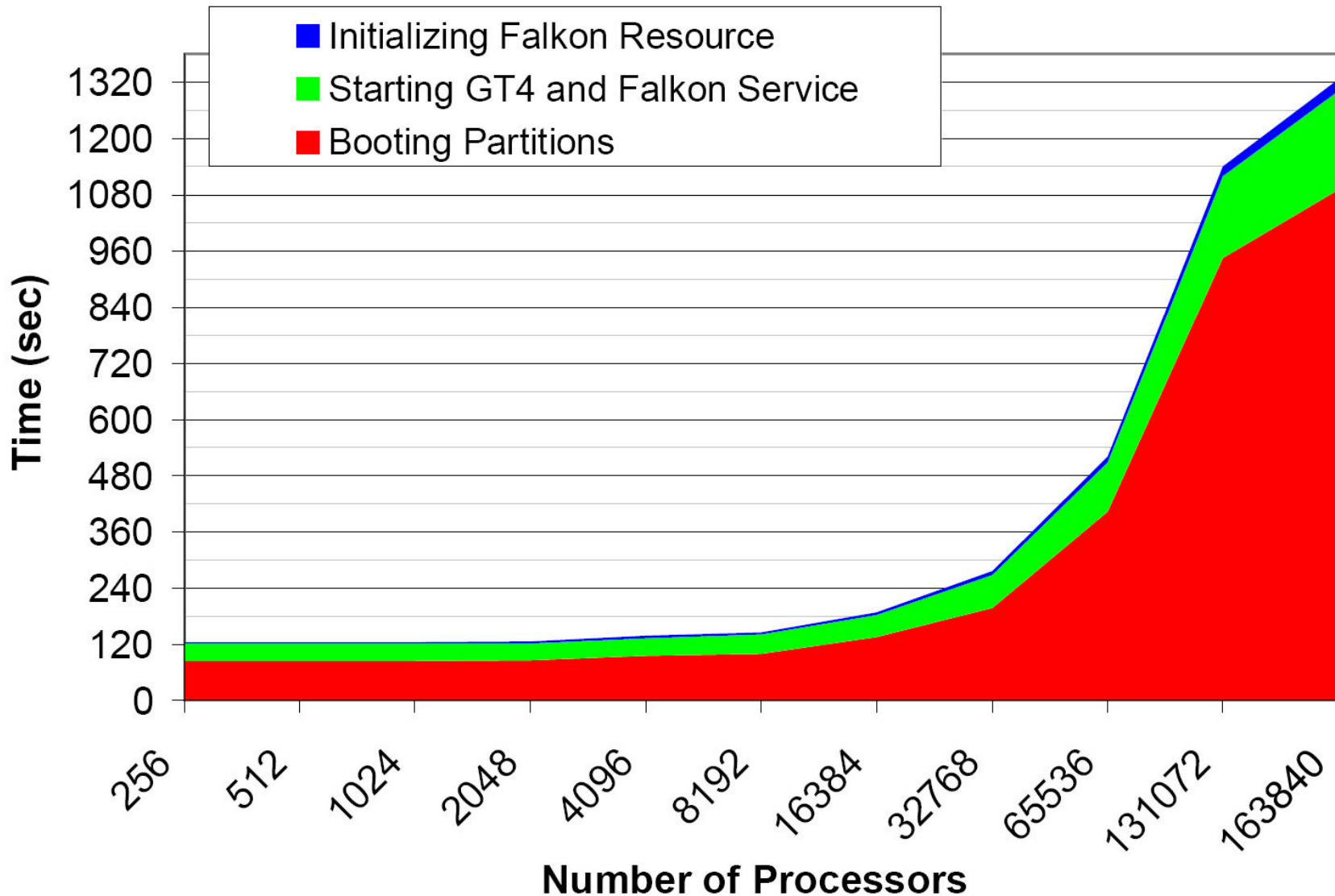
Dispatch Throughput



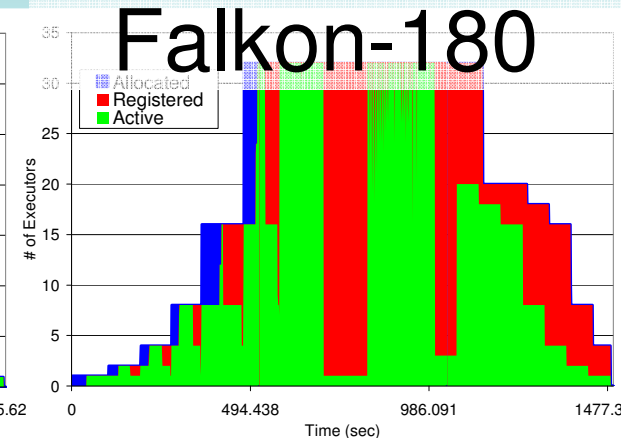
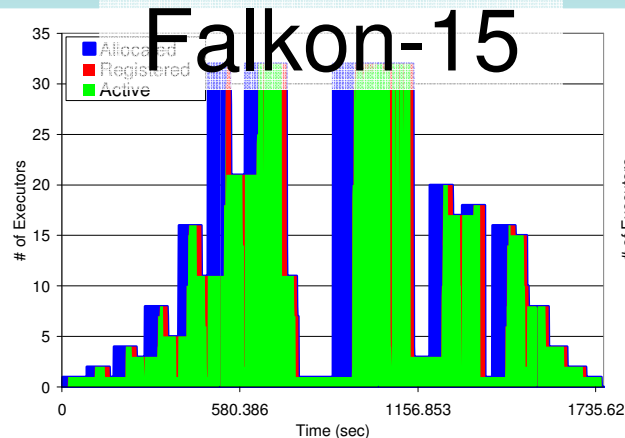
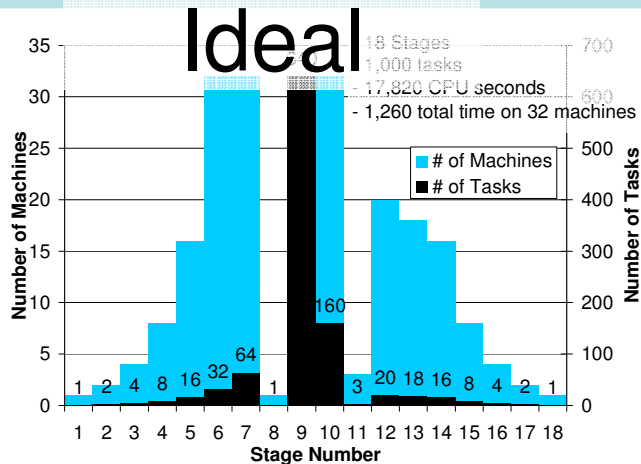
Execution Efficiency



Resource Provisioning Overheads IBM Blue Gene/P



Dynamic Resource Provisioning



- End-to-end execution time:
 - 1260 sec in ideal case
 - 4904 sec → 1276 sec
- Average task queue time:
 - 42.2 sec in ideal case
 - 611 sec → 43.5 sec
- Trade-off:
 - Resource Utilization for Execution Efficiency

| | GRAM +PBS | Falkon-15 | Falkon-60 | Falkon-120 | Falkon-180 | Falkon-∞ | Ideal (32 nodes) |
|------------------------|-----------|-----------|-----------|------------|------------|----------|------------------|
| Queue Time (sec) | 611.1 | 87.3 | 83.9 | 74.7 | 44.4 | 43.5 | 42.2 |
| Execution Time (sec) | 56.5 | 17.9 | 17.9 | 17.9 | 17.9 | 17.9 | 17.8 |
| Execution Time % | 8.5% | 17.0% | 17.6% | 19.3% | 28.7% | 29.2% | 29.7% |
| | GRAM +PBS | Falkon-15 | Falkon-60 | Falkon-120 | Falkon-180 | Falkon-∞ | Ideal (32 nodes) |
| Time to complete (sec) | 4904 | 1754 | 1680 | 1507 | 1484 | 1276 | 1260 |
| Resource Utilization | 30% | 89% | 75% | 65% | 59% | 44% | 100% |
| Execution Efficiency | 26% | 72% | 75% | 84% | 85% | 99% | 100% |
| Resource Allocations | 1000 | 11 | 9 | 7 | 6 | 0 | 0 |

Scheduling Policies

- FA: first-available
 - simple load balancing
- MCH: max-cache-hit
 - maximize cache hits
- MCU: max-compute-util
 - maximize processor utilization
- GCC: good-cache-compute
 - maximize both cache hit and processor utilization at the same time

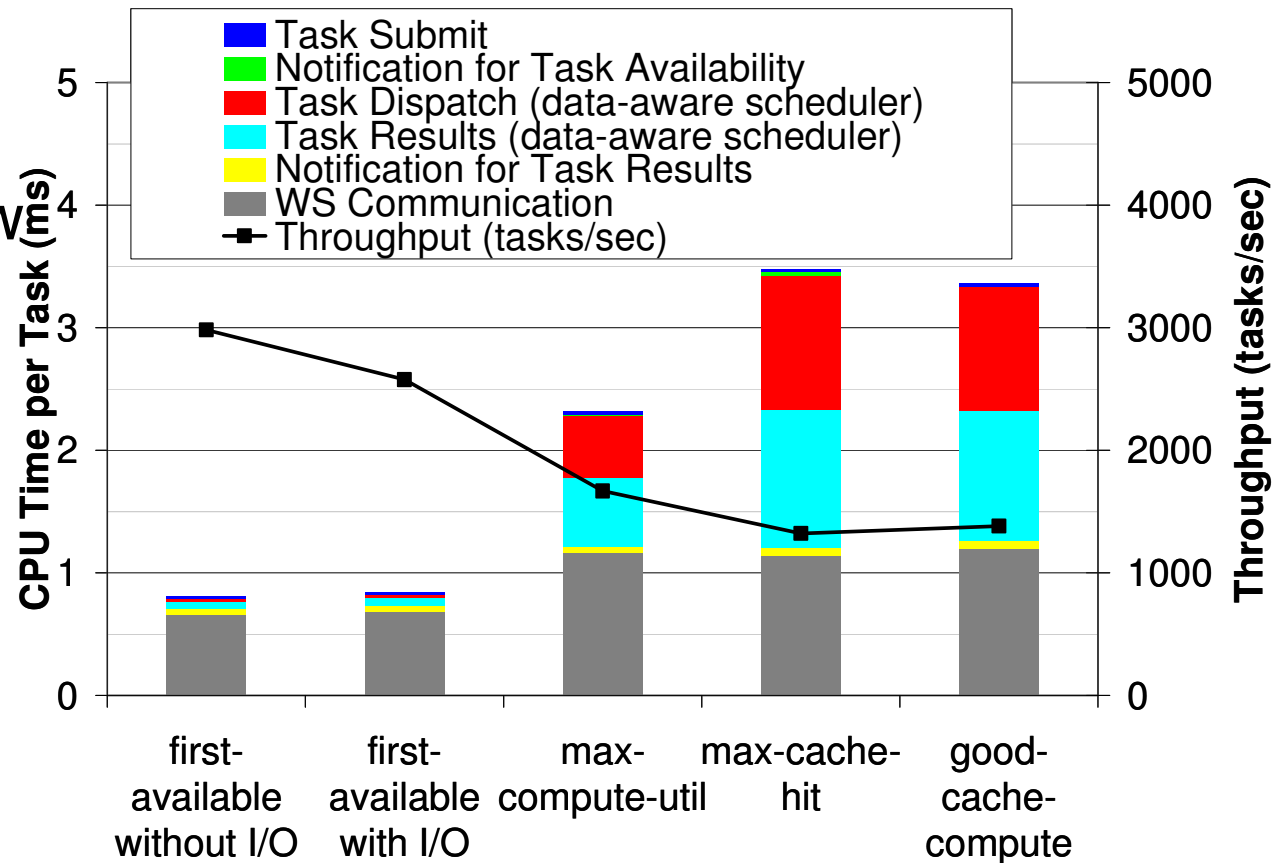
[DADC08] “Accelerating Large-scale Data Exploration through Data Diffusion”

[HPDC09] “The Quest for Scalable Support of Data Intensive Applications in Distributed Systems”, under review

[DIDC09] “Towards Data Intensive Many-Task Computing”, under review

Data-Aware Scheduler Profiling

- 3GHz dual CPUs
- ANL/UC TG with 128 processors
- Scheduling window 2500 tasks
- Dataset
 - 100K files
 - 1 byte each
- Tasks
 - Read 1 file
 - Write 1 file



Synthetic Workloads

- Monotonically Increasing Workload
 - Emphasizes increasing loads
- Sine-Wave Workload
 - Emphasizes varying loads
- All-Pairs Workload
 - Compare to best case model of active storage
- Image Stacking Workload (Astronomy)
 - Evaluate data diffusion on a real large-scale data-intensive application from astronomy domain

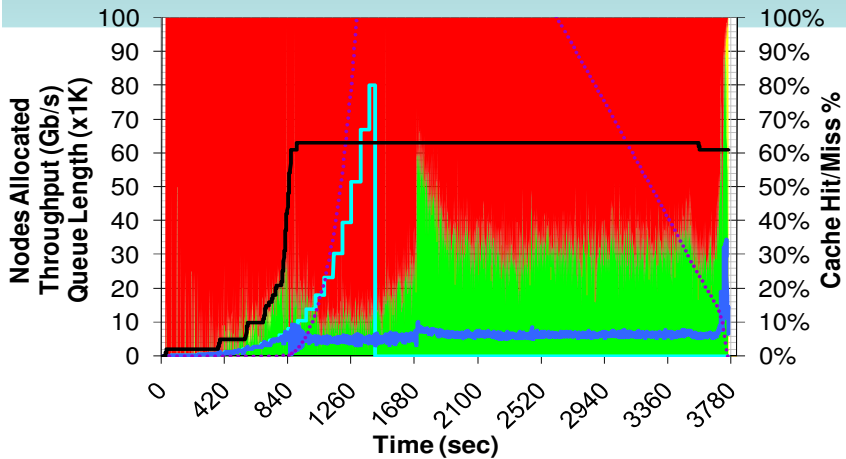
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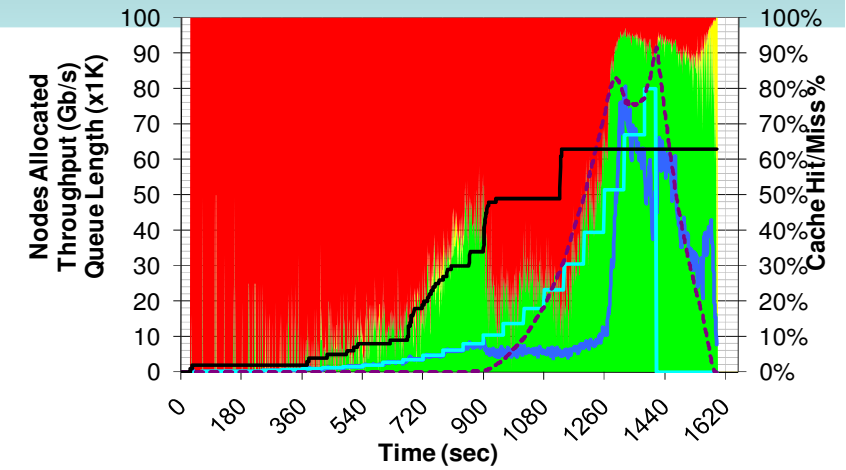
[DIDC09] “Towards Data Intensive Many-Task Computing”, under review

Data Diffusion

Monotonically Increasing Workload

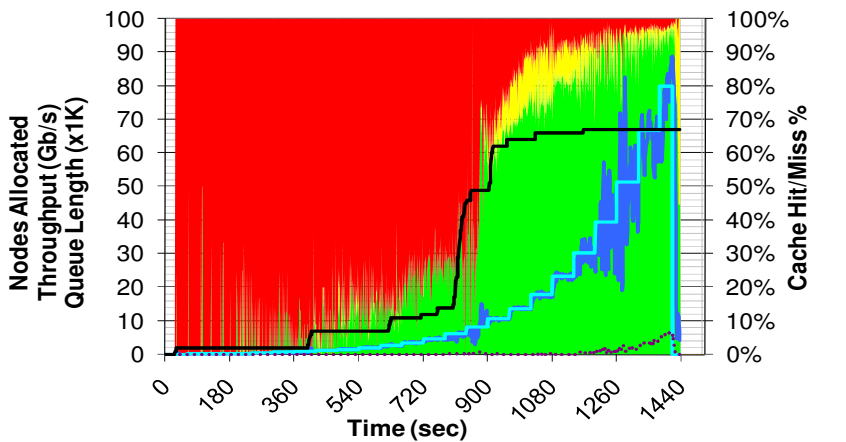


← 1GB
1.5GB →

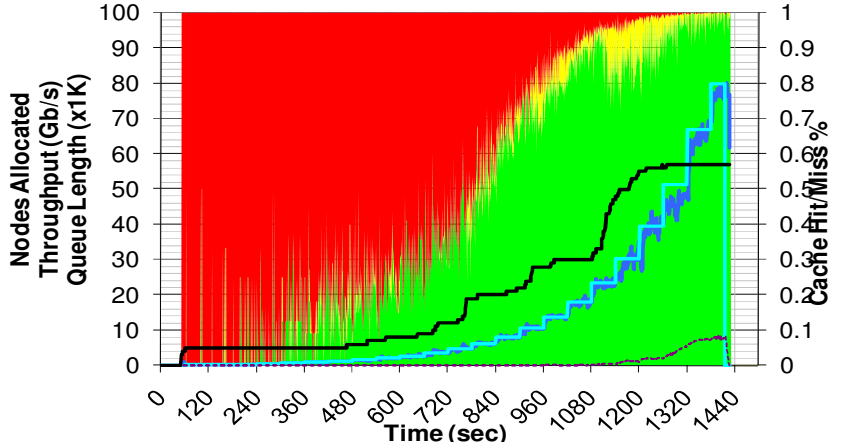


■ Cache Miss % ■ Cache Hit Global % ■ Cache Hit Local %
— Demand (Gb/s) — Throughput (Gb/s) - - - Wait Queue Length
— Number of Nodes

■ Cache Miss % ■ Cache Hit Global % ■ Cache Hit Local %
— Throughput (Gb/s) — Demand (Gb/s) - - - Wait Queue Length
— Number of Nodes



← 2GB
4GB →

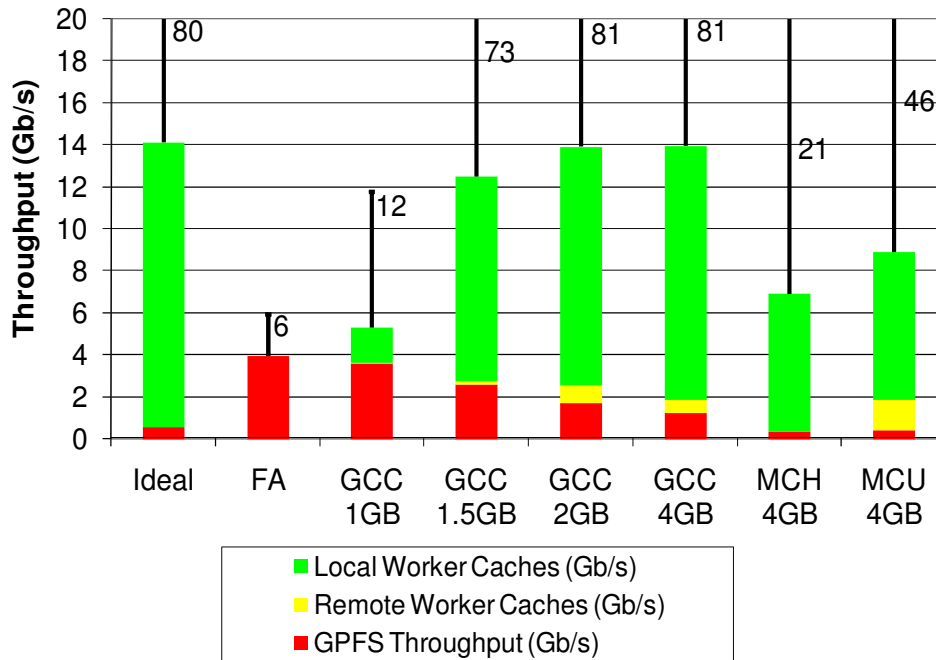


■ Cache Miss % ■ Cache Hit Global % ■ Cache Hit Local %
— Throughput (Gb/s) — Demand (Gb/s) - - - Wait Queue Length
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— Throughput (Gb/s) — Demand (Gb/s) - - - Wait Queue Length
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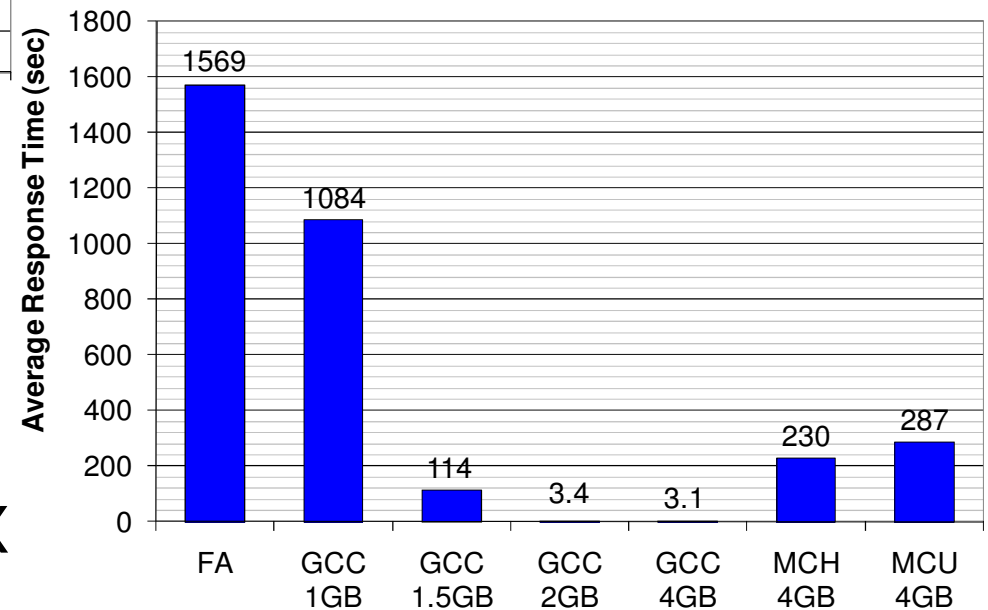
Data Diffusion

Monotonically Increasing Workload



← Throughput:

- Average: 14Gb/s vs 4Gb/s
- Peak: 81Gb/s vs. 6Gb/s



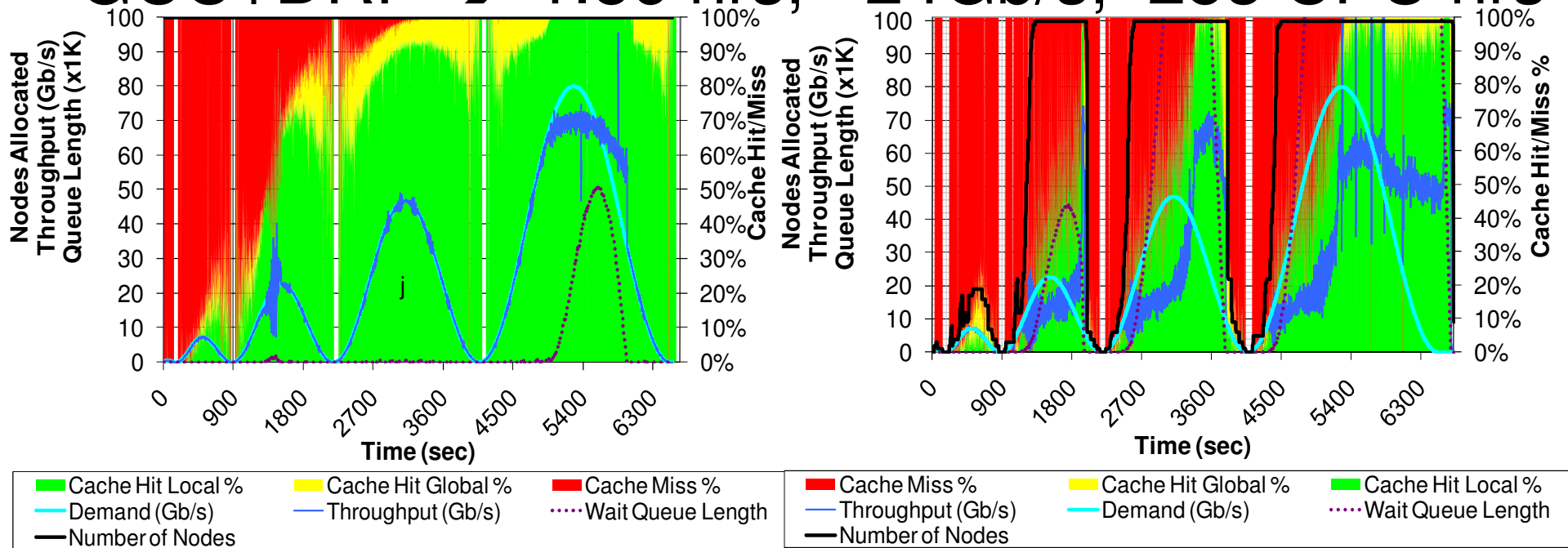
Response Time →

– 3 sec vs 1569 sec → 506X

Data Diffusion

Sine-Wave Workload

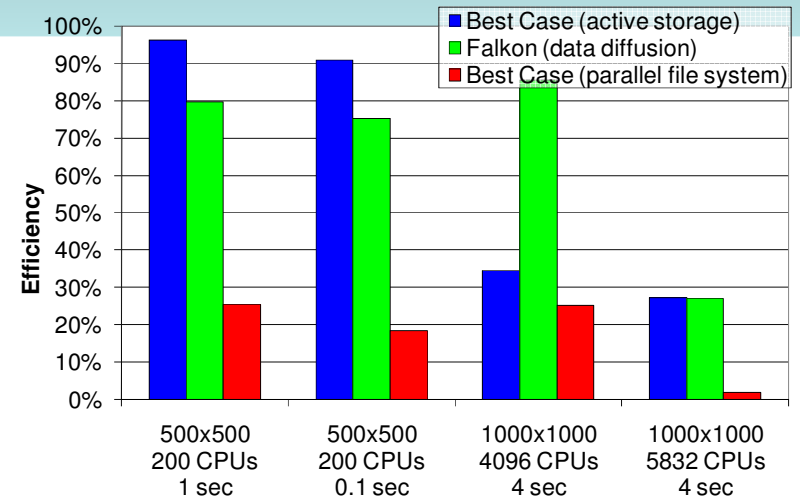
- GPFS → 5.7 hrs, ~8Gb/s, 1138 CPU hrs
- GCC+SRP → 1.8 hrs, ~25Gb/s, 361 CPU hrs
- GCC+DRP → 1.86 hrs, ~24Gb/s, 253 CPU hrs



Data Diffusion vs. Active Storage

All-Pairs Workload

- Pull vs. Push
 - Data Diffusion
 - Pulls *task* working set
 - Incremental spanning forest
 - Active Storage:
 - Pushes *workload* working set to all nodes
 - Static spanning tree



| Experiment | Approach | Experiment | | |
|---------------------------------|----------------------------|------------------------|-----------------------------|-------------------------|
| | | Local Disk/Memory (GB) | Network (node-to-node) (GB) | Shared File System (GB) |
| 500x500 200 CPUs 1 sec | Best Case (active storage) | 6000 | 1536 | 12 |
| | Falcon (data diffusion) | 6000 | 1698 | 34 |
| 500x500 200 CPUs 0.1 sec | Best Case (active storage) | 6000 | 1536 | 12 |
| | Falcon (data diffusion) | 6000 | 1528 | 62 |
| 1000x1000 4096 CPUs 4 sec | Best Case (active storage) | 24000 | 12288 | 24 |
| | Falcon (data diffusion) | 24000 | 4676 | 384 |
| 1000x1000 5832 CPUs 4 sec | Best Case (active storage) | 24000 | 12288 | 24 |
| | Falcon (data diffusion) | 24000 | 3867 | 906 |

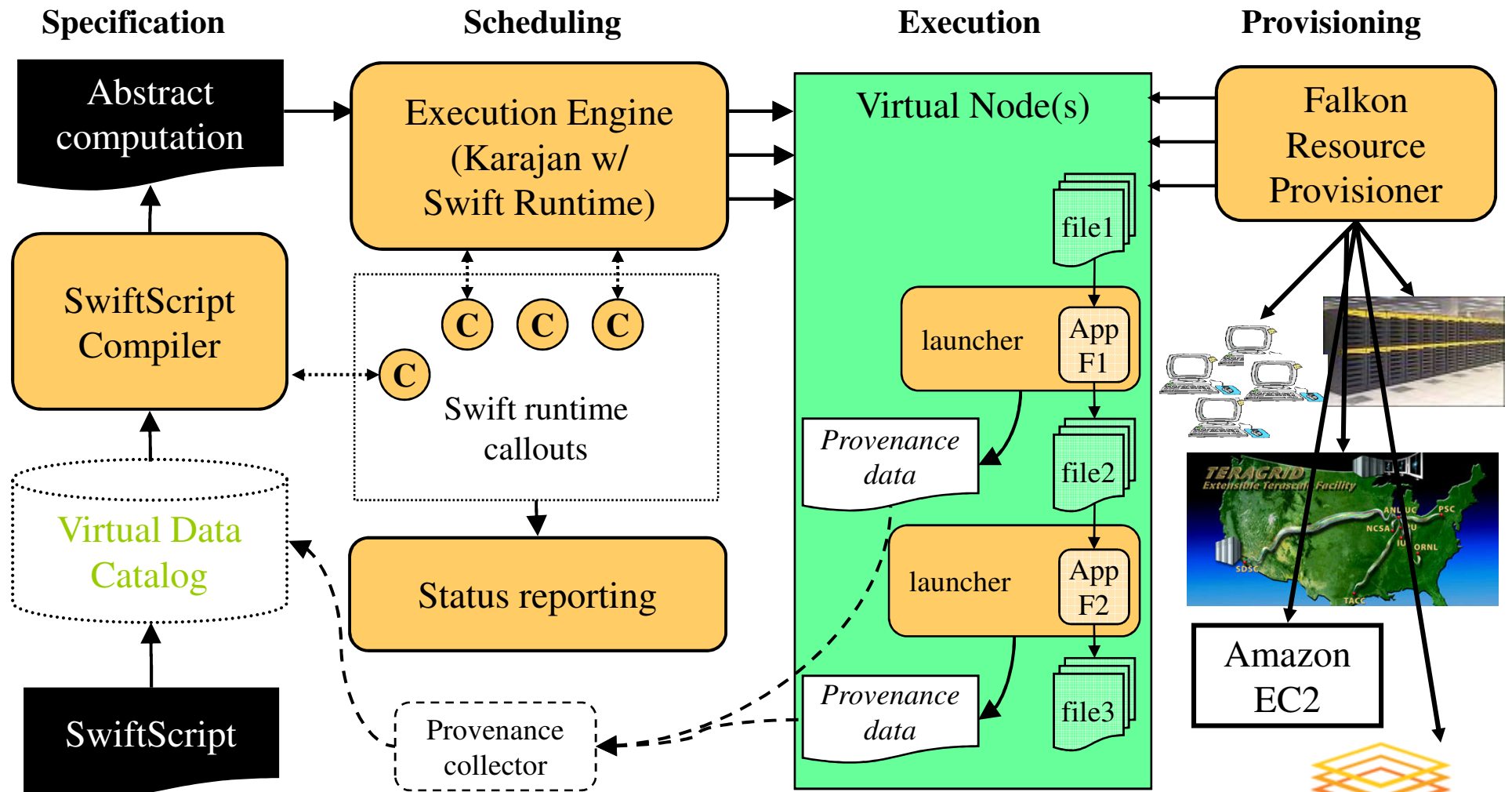
**Christopher Moretti, Douglas Thain,
University of Notre Dame**

Data Diffusion vs. Active Storage

All-Pairs Workload

- Best to use active storage if
 - Slow data source
 - Workload working set fits on local node storage
- Best to use data diffusion if
 - Medium to fast data source
 - Task working set \ll workload working set
 - Task working set fits on local node storage
- If task working set does not fit on local node storage
 - Use parallel file system (i.e. GPFS, Lustre, PVFS, etc)

Applications Swift Architecture

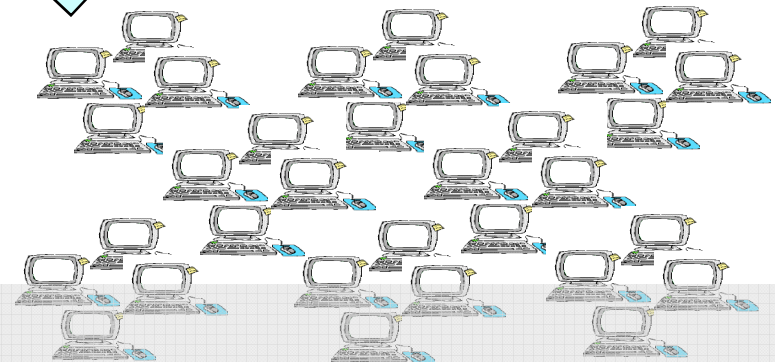
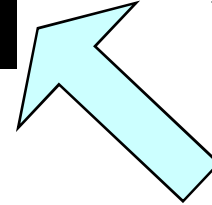
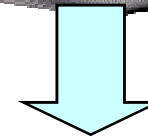
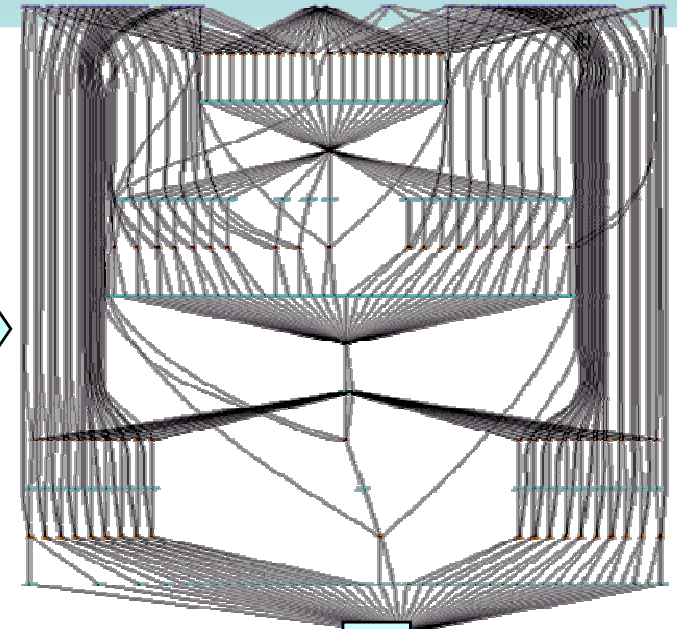
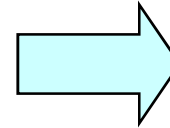
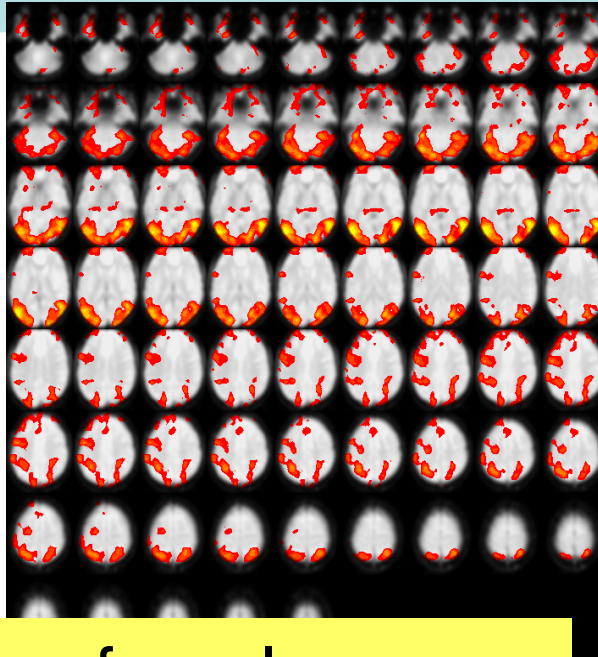
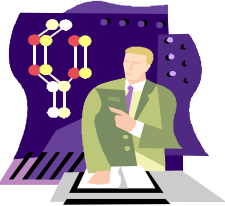


[NOVA08] "Realizing Fast, Scalable and Reliable Scientific Computations in Grid Environments"

[SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

Applications

Medical Imaging: fMRI



- Wide range of analyses
 - Testing, interactive analysis, production runs
 - Data mining
 - Parameter studies

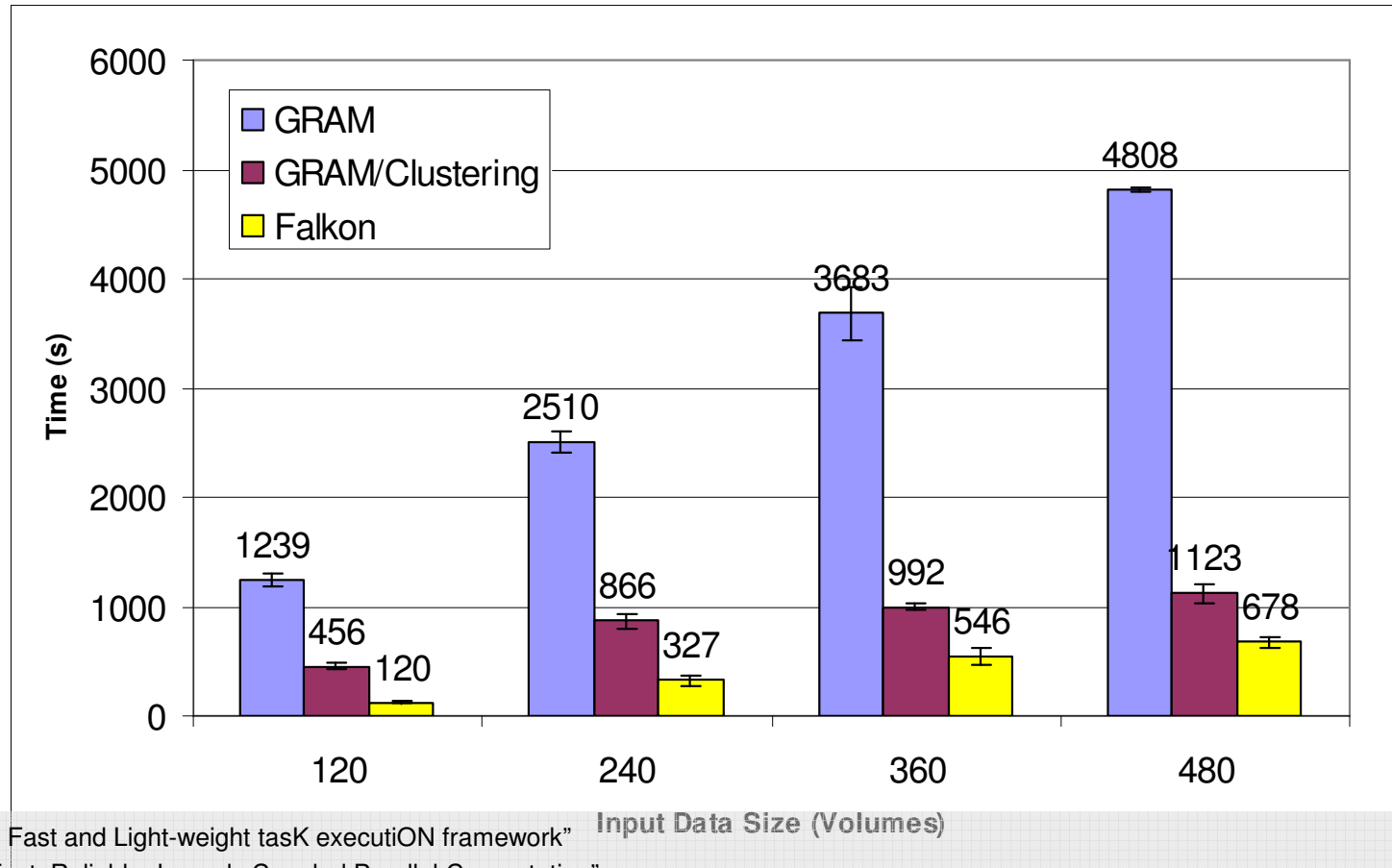
[SC07] "Falkon: a Fast and Light-weight task executiON framework"

[SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

Applications

Medical Imaging: fMRI

- GRAM vs. Falcon: 85%~90% lower run time
- GRAM/Clustering vs. Falcon: 40%~74% lower run time

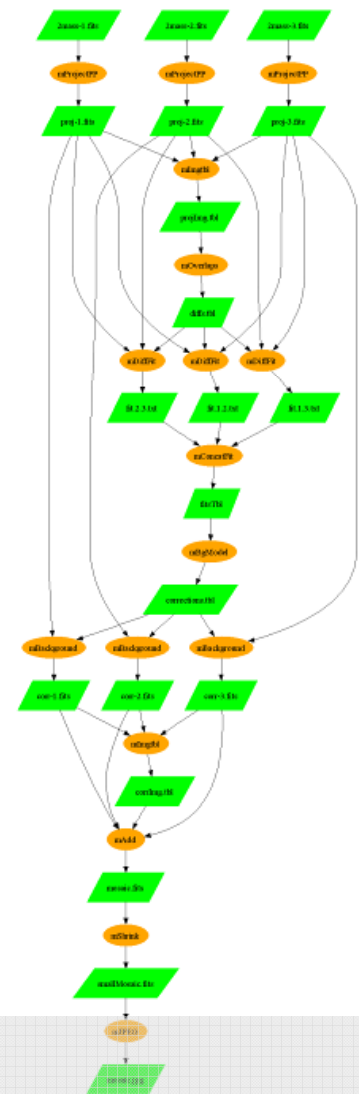
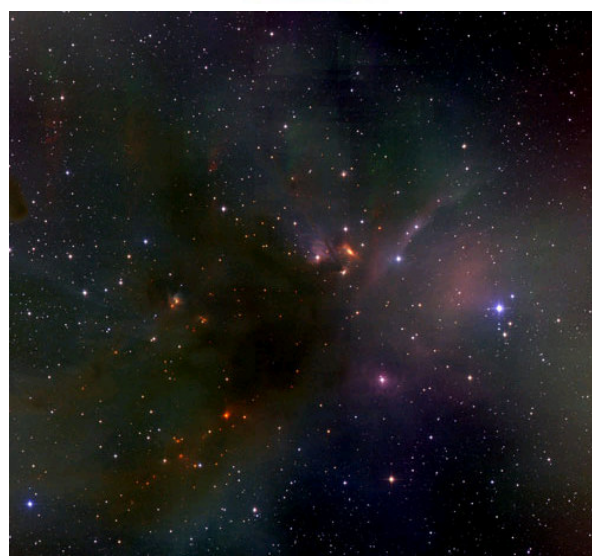
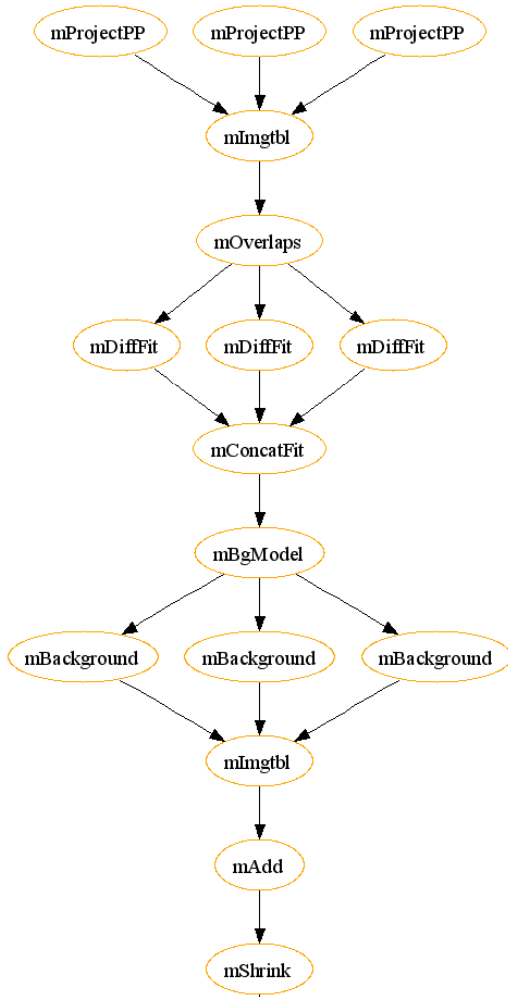


[SC07] "Falcon: a Fast and Light-weight task executiON framework"

[SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

Applications

Astronomy: Montage



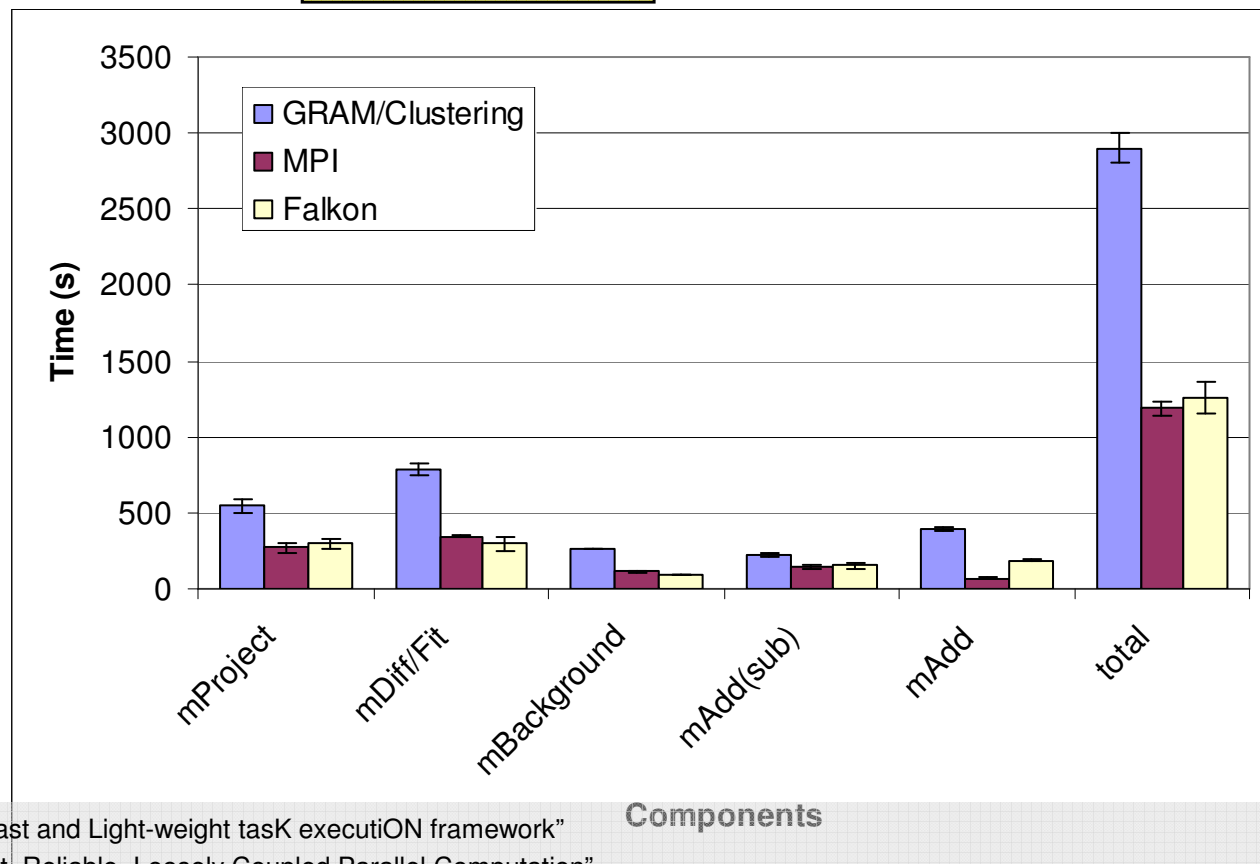
B. Berriman, J. Good (Caltech)
 J. Jacob, D. Katz (JPL)

[SC07] "Falcon: a Fast and Light-weight task executiON framework"
 [SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

Applications

Astronomy: Montage

- GRAM/Clustering vs. Falcon: **57%** lower application run time
- MPI* vs. Falcon: **4%** higher application run time
- * MPI should be **lower bound**



[SC07] "Falcon: a Fast and Light-weight task executiON framework"

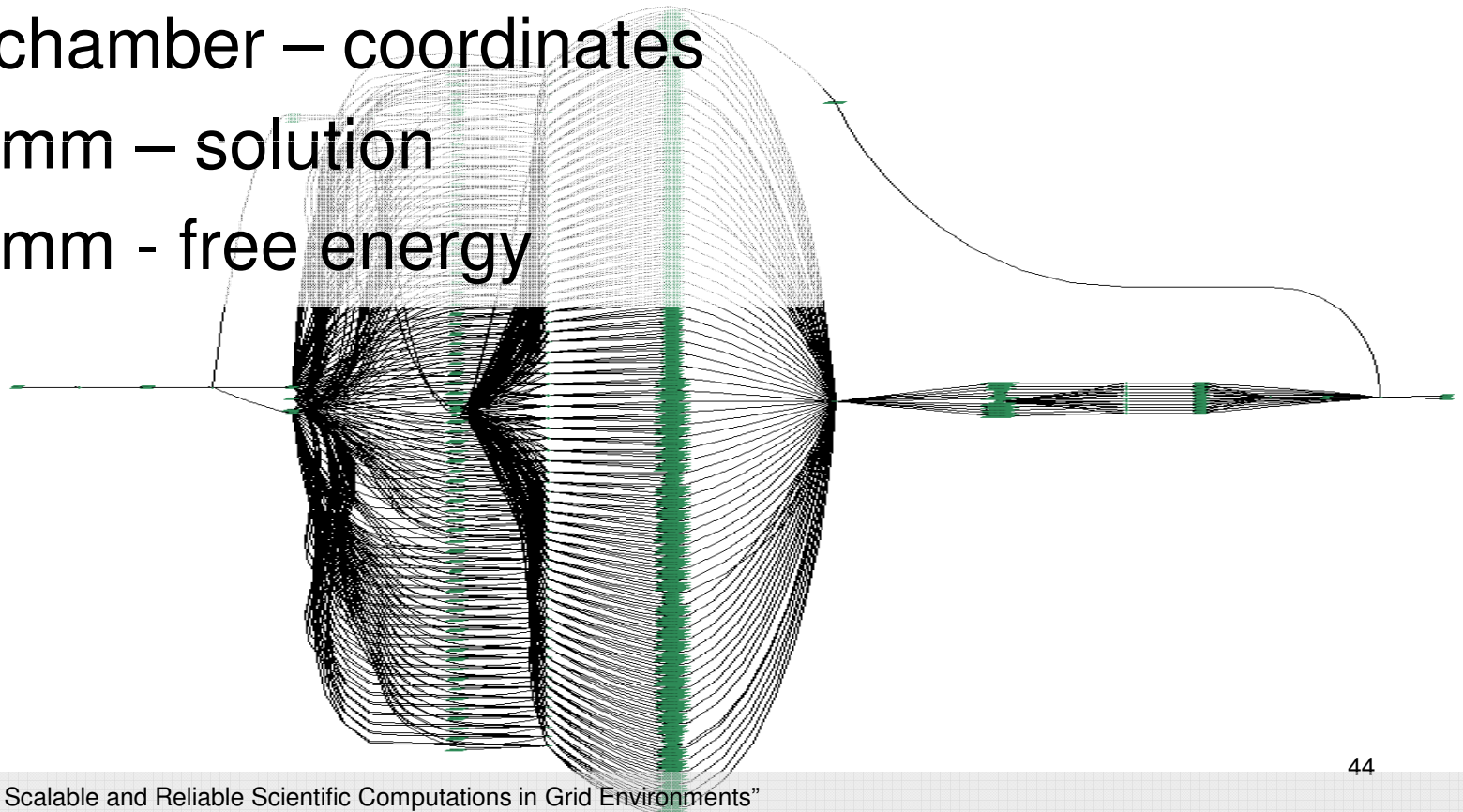
[SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

Components

Applications

Molecular Dynamics: MolDyn

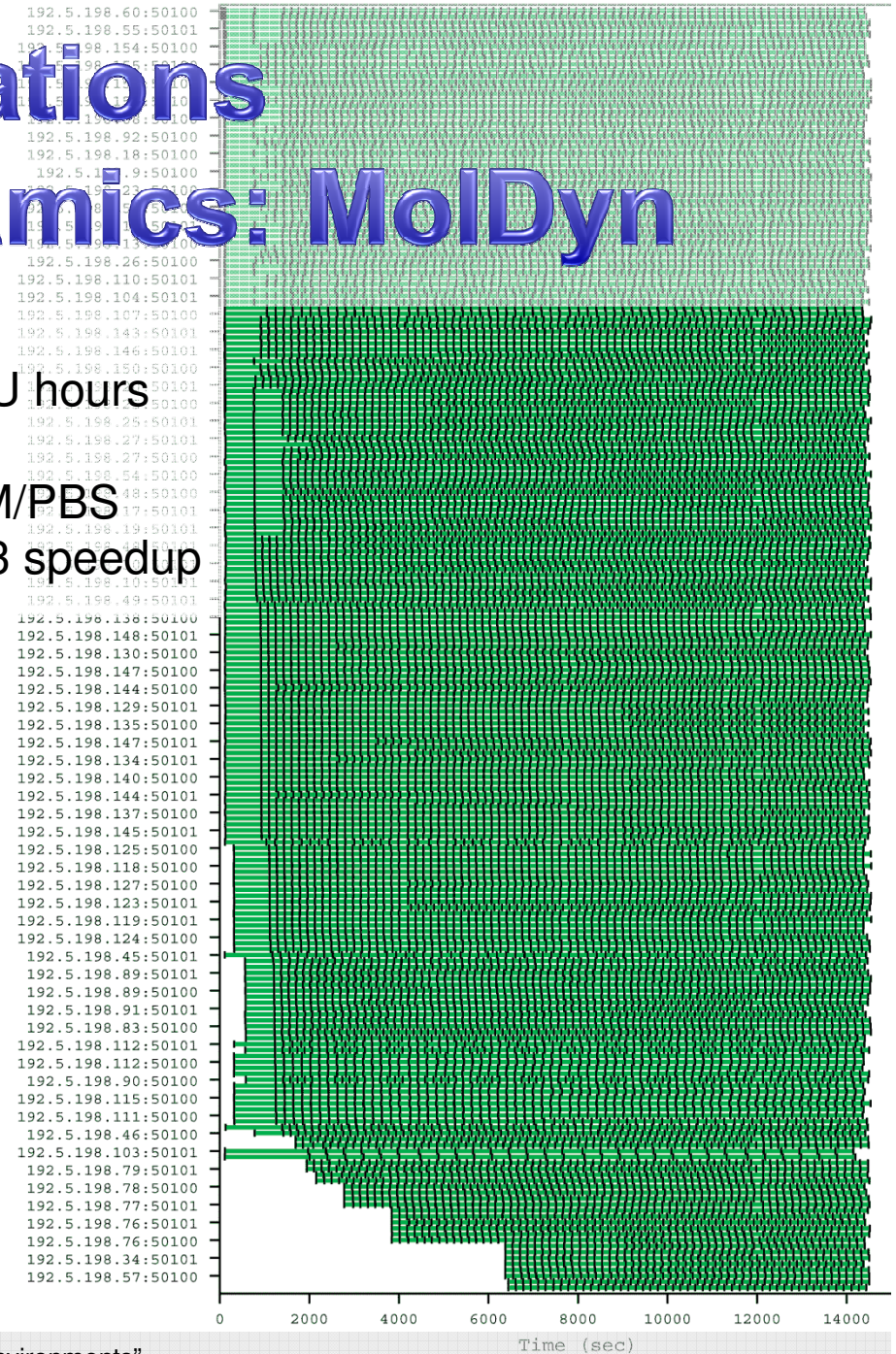
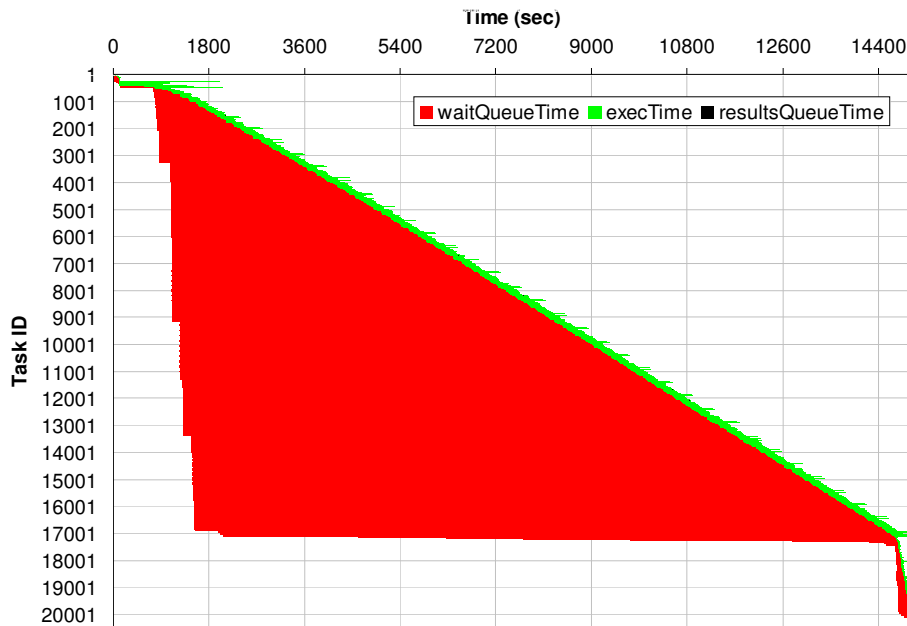
- Determination of free energies in aqueous solution
 - Antechamber – coordinates
 - Charmm – solution
 - Charmm - free energy



Applications

Molecular Dynamics: MolDyn

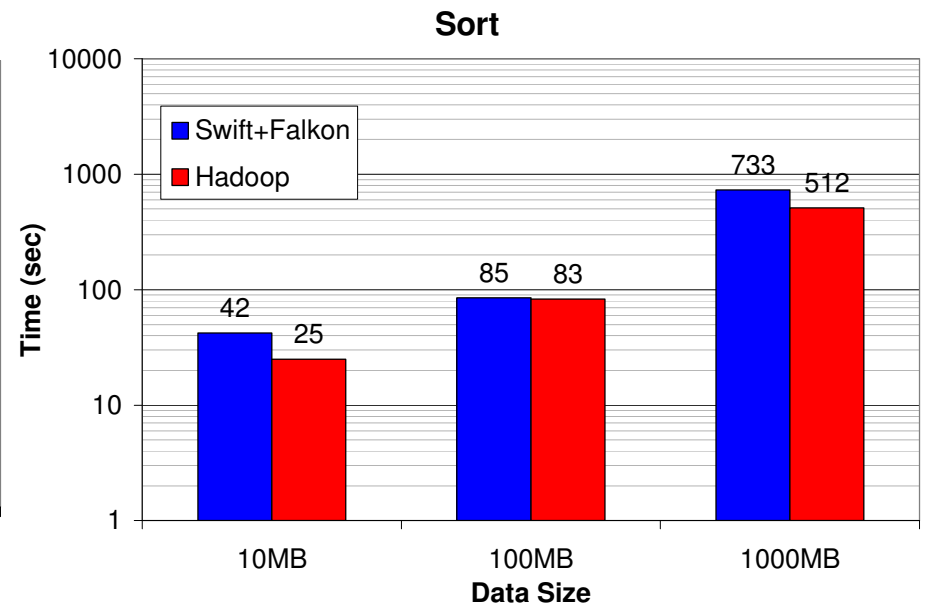
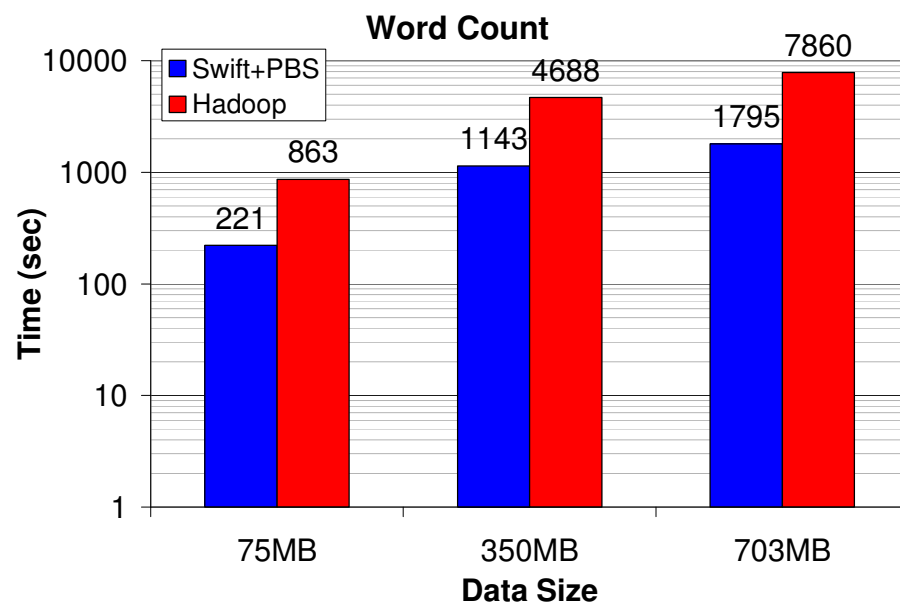
- 244 molecules → 20497 jobs
- 15091 seconds on 216 CPUs → 867.1 CPU hours
- Efficiency: **99.8%**
- Speedup: 206.9x → 8.2x faster than GRAM/PBS
- 50 molecules w/ GRAM (4201 jobs) → 25.3 speedup



Applications

Word Count and Sort

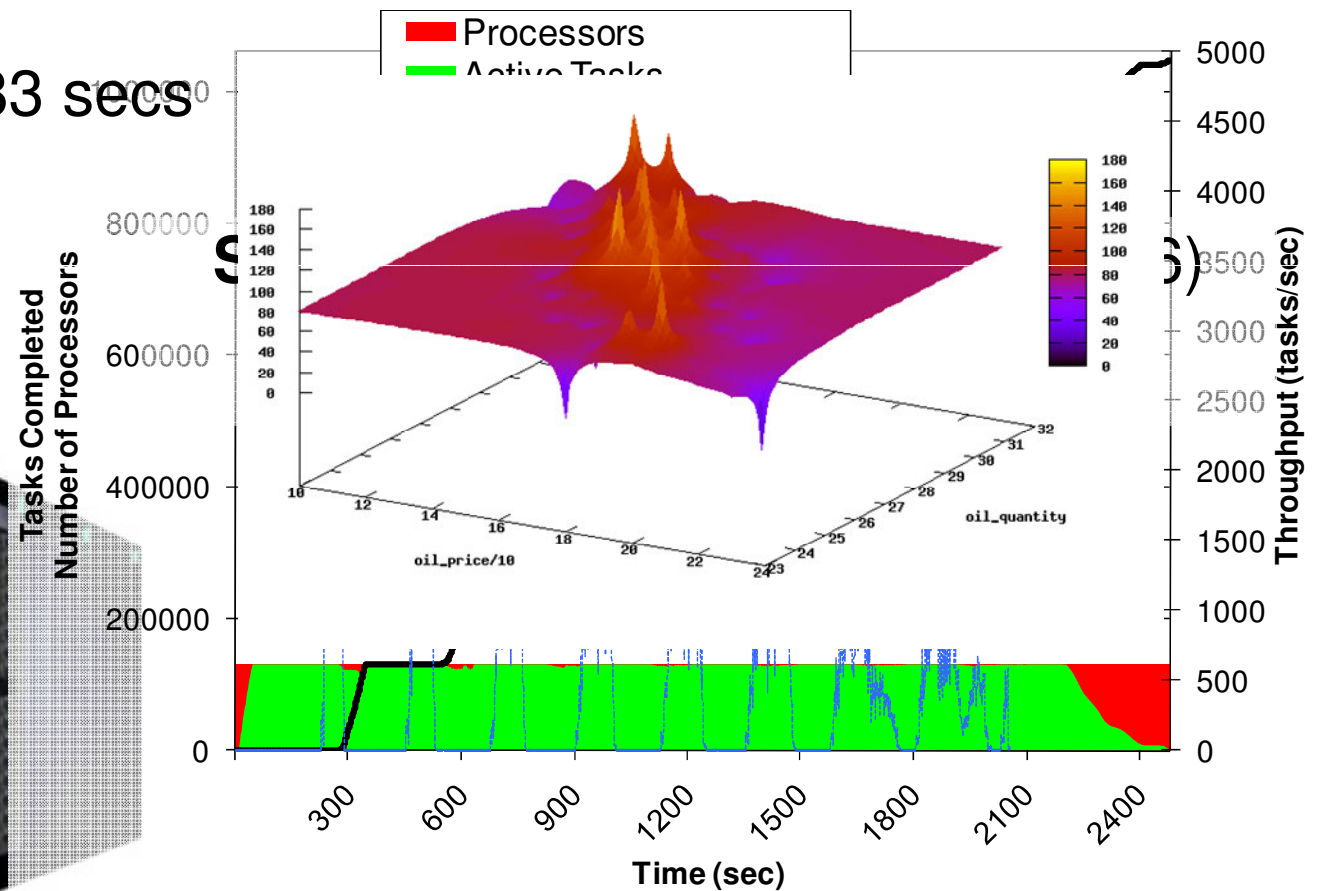
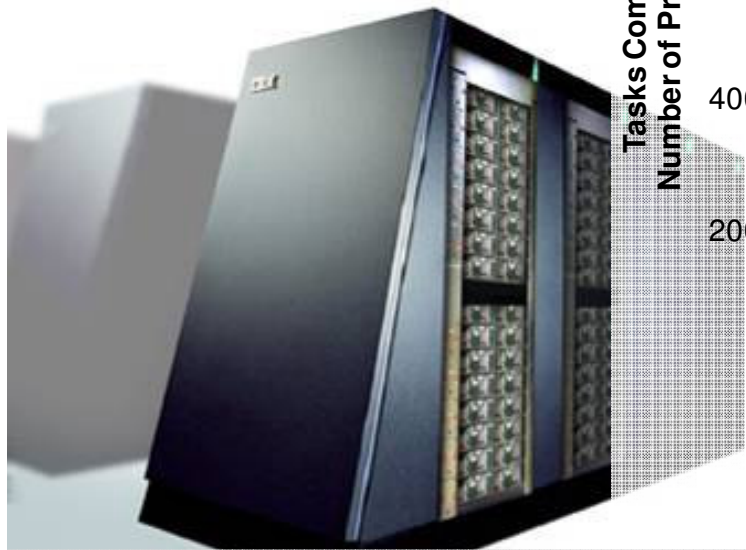
- Classic benchmarks for MapReduce
 - Word Count
 - Sort
- Swift and Falcon performs similar or better than Hadoop (on 32 processors)



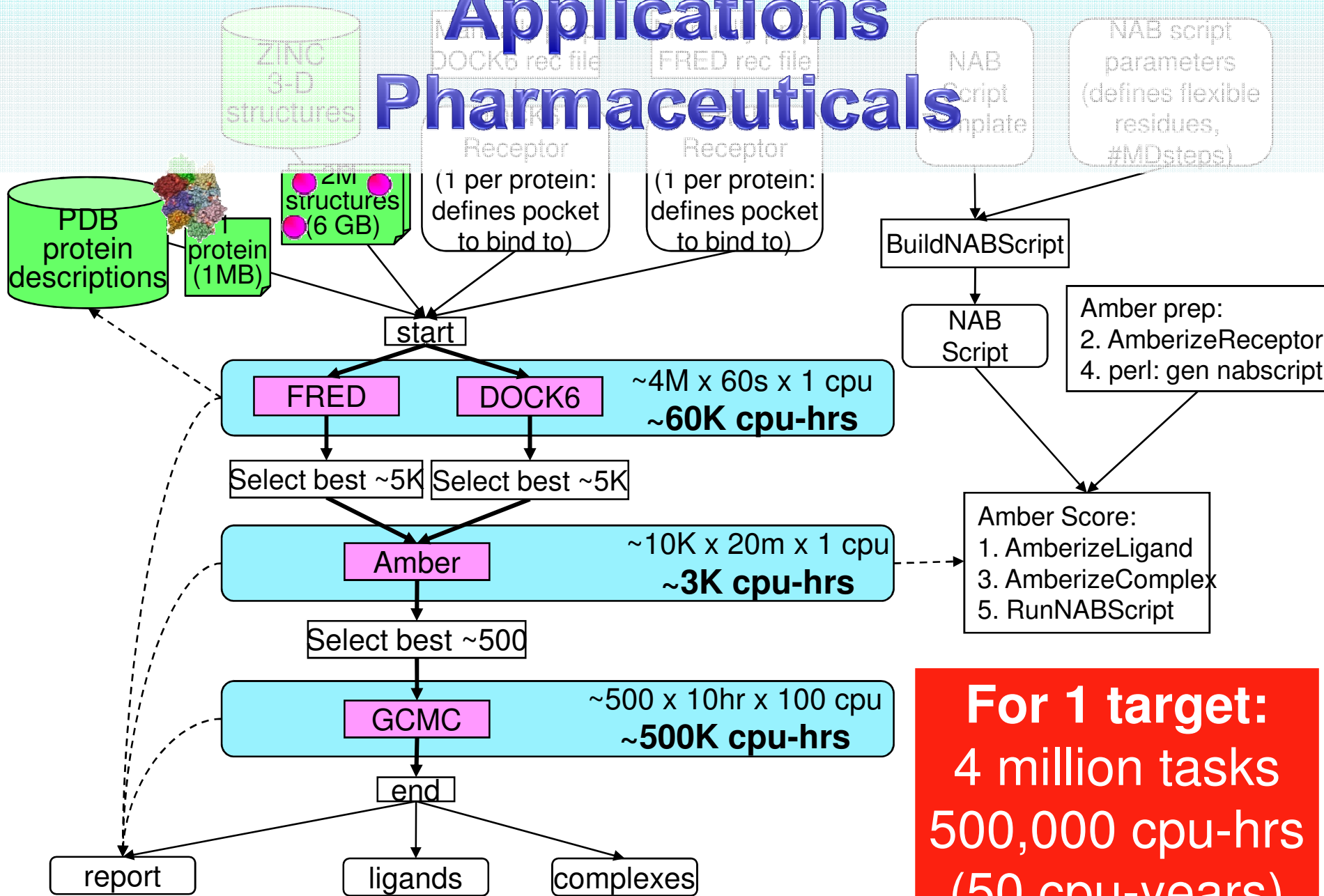
Applications

Economic Modeling: MARS

- CPU Cores: 130816
- Tasks: 1048576
- Elapsed time: 2483 secs
- CPU Years: 9.3



Applications Pharmaceuticals



Applications

Pharmaceuticals: DOCK

CPU cores: 118784

Tasks: 934803

Elapsed time: 2.01 hours

Compute time: 21.43 CPU years

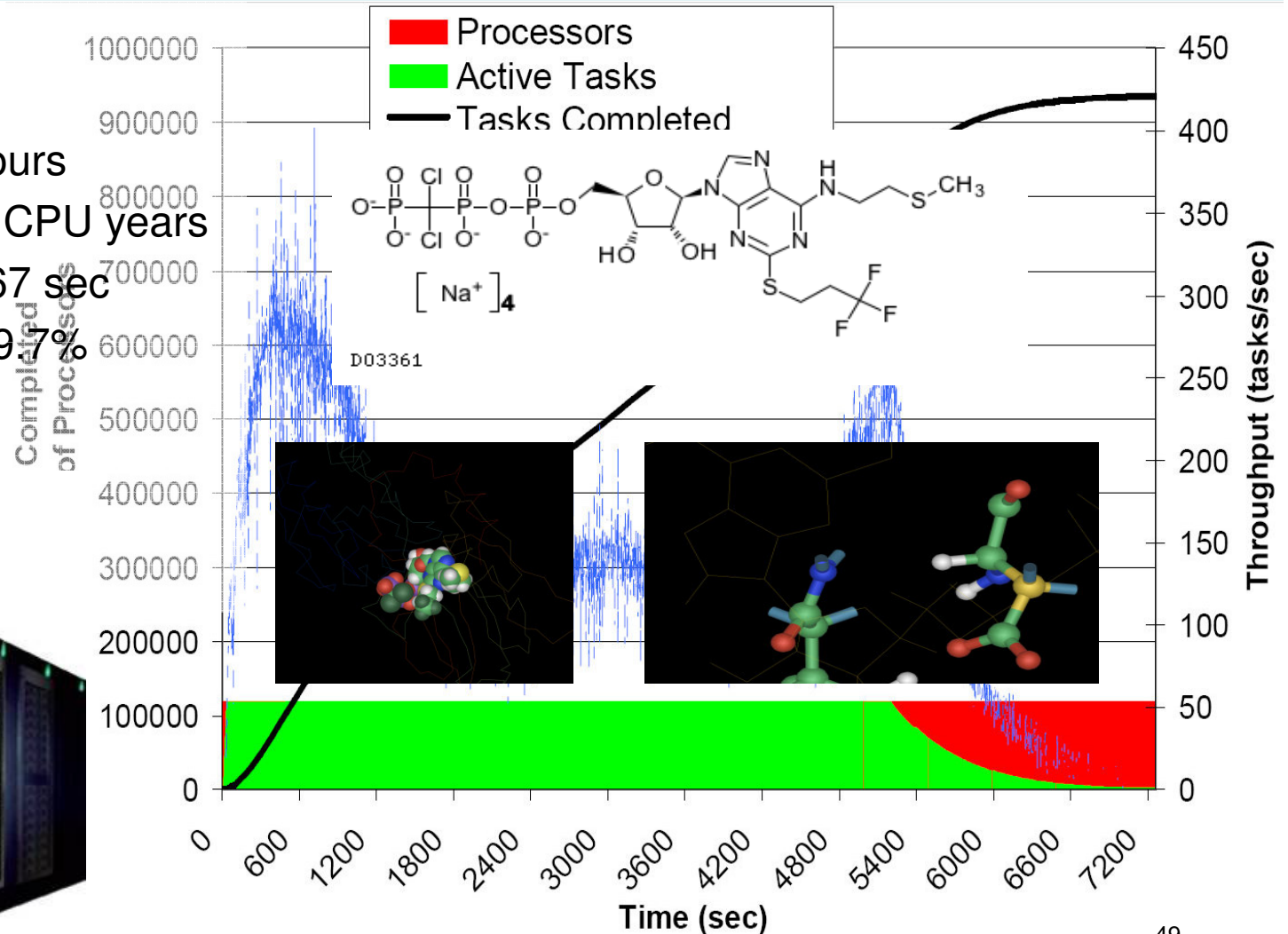
Average task time: 667 sec

Relative Efficiency: 99.7%

(from 16 to 32 racks)

Utilization:

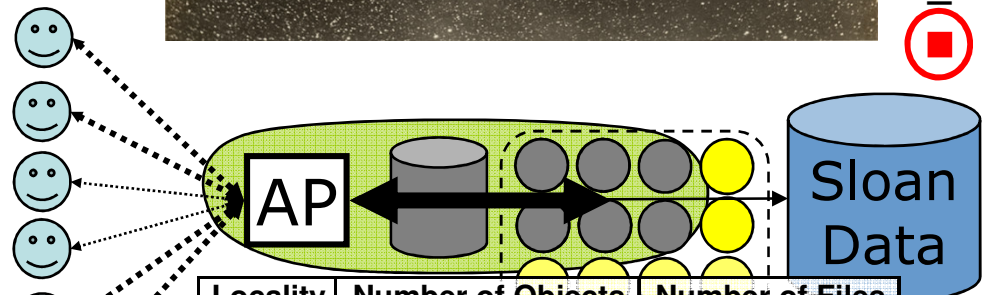
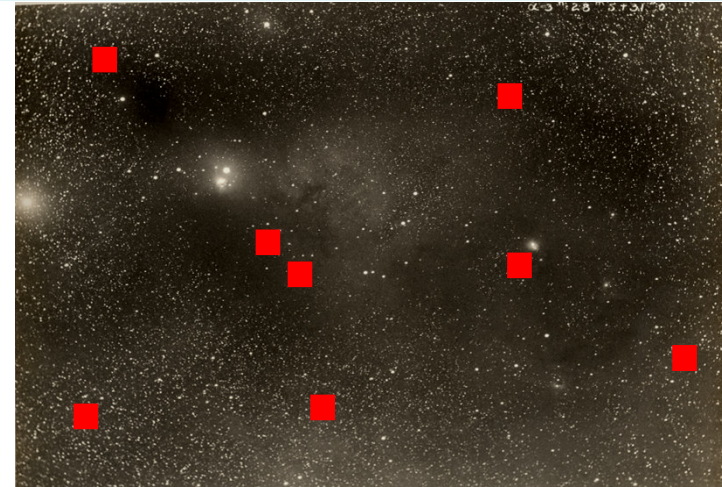
- Sustained: 99.6%
- Overall: 78.3%



Applications

Astronomy: AstroPortal

- Purpose
 - On-demand “stacks” of random locations within ~10TB dataset
- Challenge
 - Processing Costs:
 - $O(100\text{ms})$ per object
 - Data Intensive:
 - 40MB:1sec
 - Rapid access to 10-10K “random” files
 - Time-varying load



| Locality | Number of Objects | Number of Files |
|----------|-------------------|-----------------|
| 1 | 111700 | 111700 |
| 1.38 | 154345 | 111699 |
| 2 | 97999 | 49000 |
| 3 | 88857 | 29620 |
| 4 | 76575 | 19145 |
| 5 | 60590 | 12120 |
| 10 | 46480 | 4650 |
| 20 | 40460 | 2025 |
| 30 | 23695 | 790 |

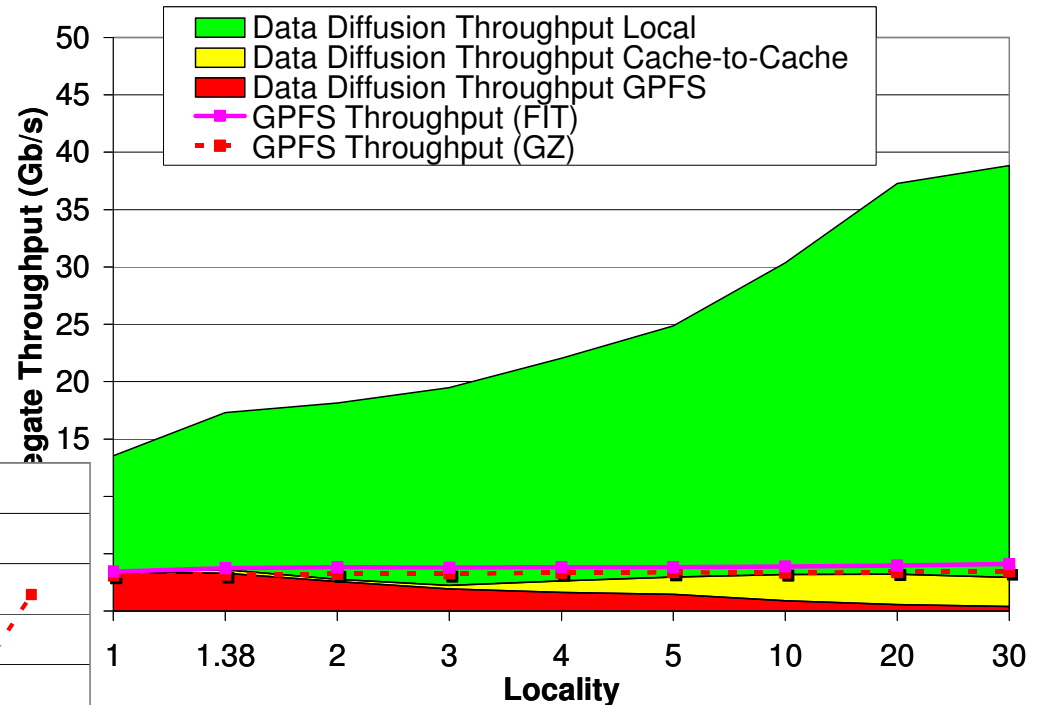
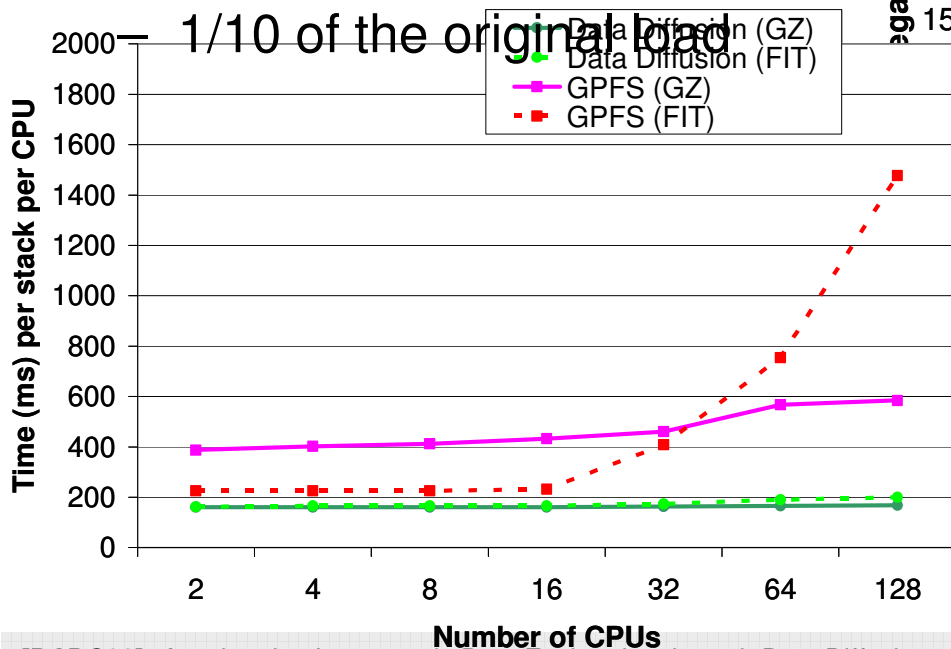
[DADC08] “Accelerating Large-scale Data Exploration through Data Diffusion”

[TG06] “AstroPortal: A Science Gateway for Large-scale Astronomy Data Analysis”

Applications

Astronomy: AstroPortal

- Aggregate throughput:
 - 39Gb/s
 - 10X higher than GPFS
- Reduced load on GPFS
 - 0.49Gb/s

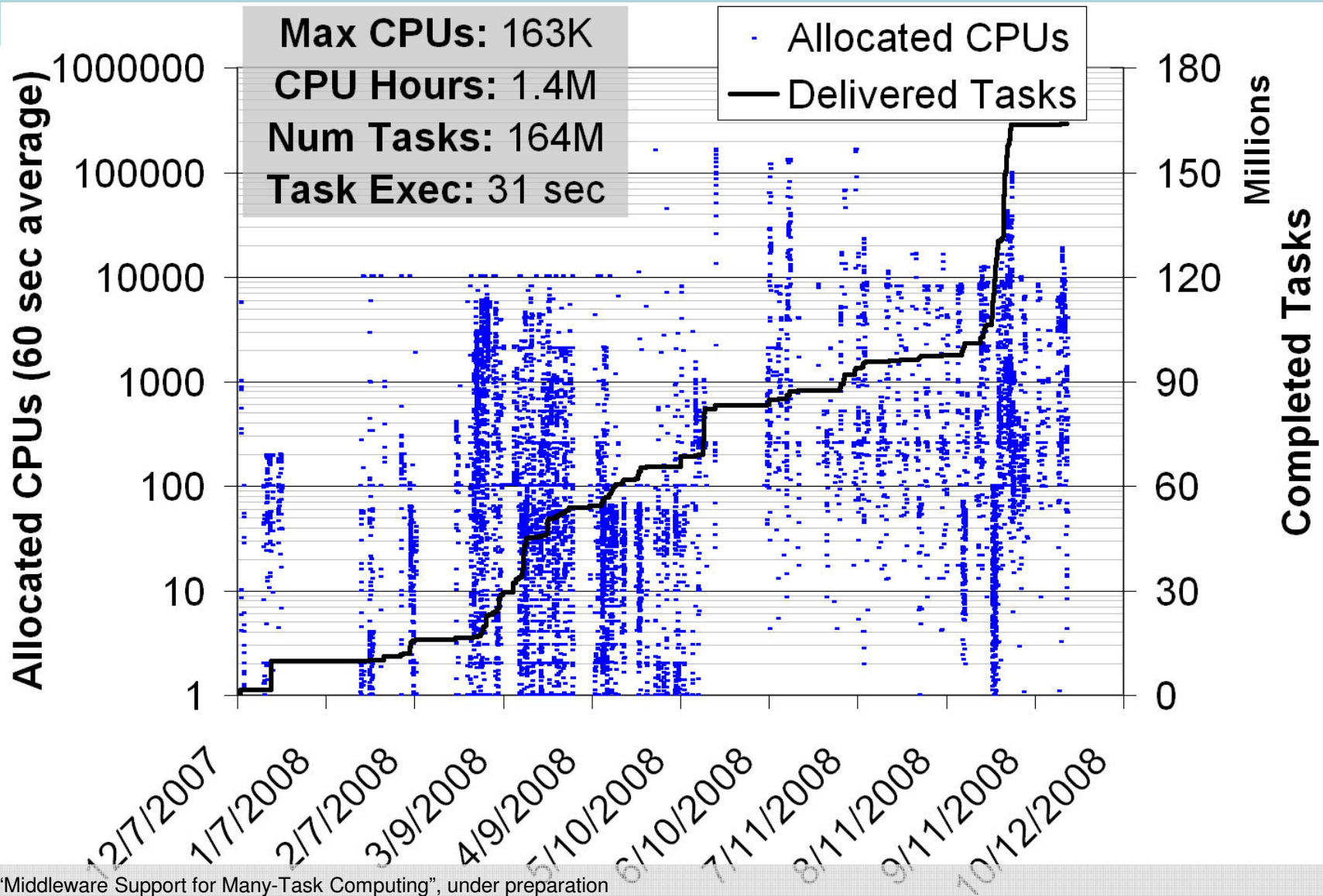


← High data locality
– Near perfect scalability

Falkon Project

- Falkon is a real system
 - Late 2005: Initial prototype, AstroPortal
 - January 2007: Falkon v0
 - November 2007: Globus incubator project v0.1
 - <http://dev.globus.org/wiki/Incubator/Falkon>
 - February 2009: Globus incubator project v0.9
- Implemented in Java (~20K lines) and C (~1K lines)
 - Based on the Globus Toolkit 4.0
 - Open source: svn co <https://svn.globus.org/repos/falkon>
- Source code contributors (beside myself)
 - Yong Zhao, Zhao Zhang, Ben Clifford, Mihael Hategan, Gabriela Turcu
- Ideas contributors
 - Ian Foster, Mike Wilde, Catalin Dumitrescu, Alex Szalay, Jim Gray, ...

Falkon Activity History (10 months)



Falkon Monitoring

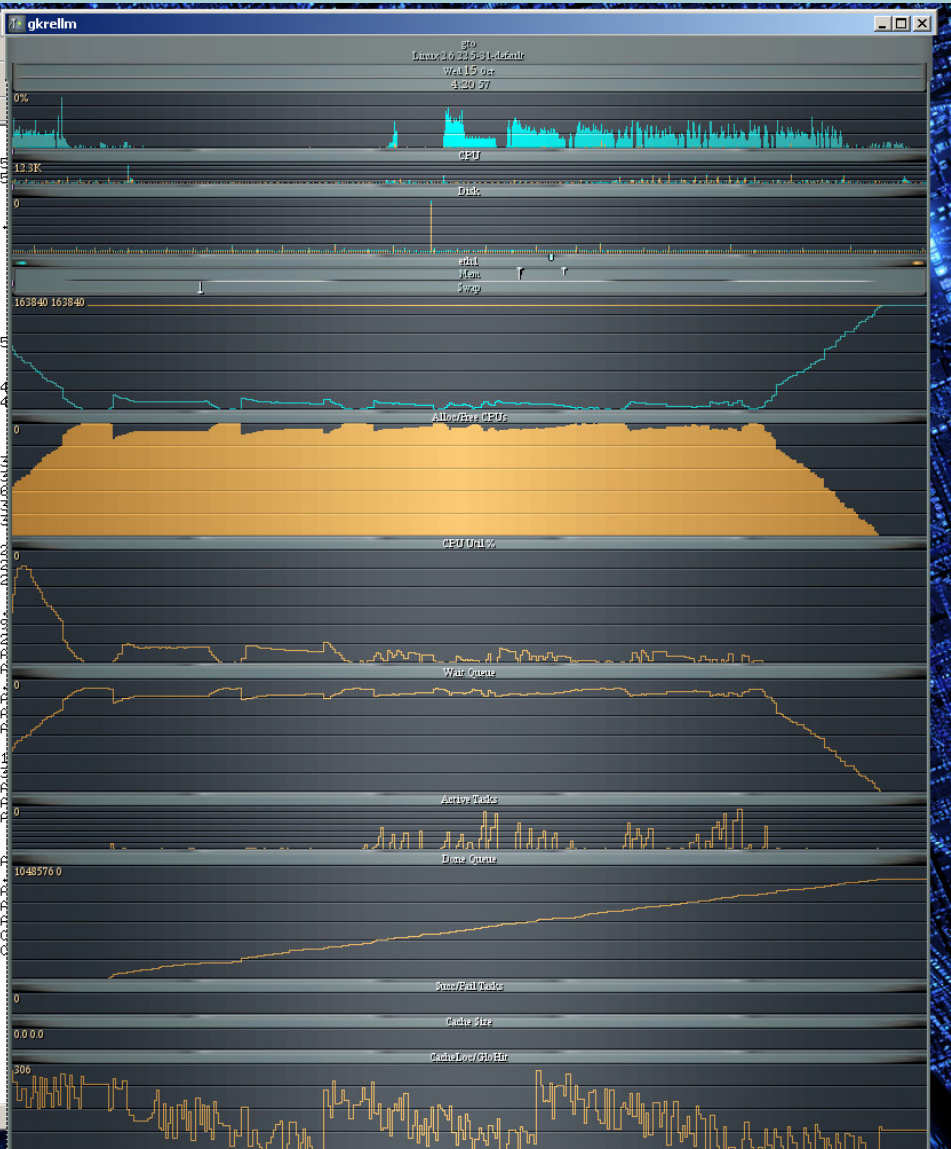
```
gto.ci.uchicago.edu (1) - SecureCRT
File Edit View Options Transfer Script Tools Help

gto.ci.uchicago.edu | gto.ci.uchicago.edu (1) | gto.ci.uchicago.edu (3) | gto.ci.uchicago.edu (2) | gto.ci.uchicago.edu (5) | gto.ci.uchicago.edu (4)

397,951 tasks+ 908675 tasks- 0 tasks-> 1048576 completed 86.66 tasks_tp 3246.03 aver_tp 2695.68 stdev_tp 3157.365 ETA
398,959 tasks+ 911918 tasks- 0 tasks-> 1048576 completed 86.97 tasks_tp 3217.26 aver_tp 2697.24 stdev_tp 3152.763 ETA
399,967 tasks+ 913940 tasks- 0 tasks-> 1048576 completed 87.16 tasks_tp 3205.95 aver_tp 2695.18 stdev_tp 3148.28 ETA
400,976 tasks+ 916630 tasks- 0 tasks-> 1048576 completed 87.42 tasks_tp 3268.65 aver_tp 2695.1 stdev_tp 3143.592 ETA
401,984 tasks+ 919282 tasks- 0 tasks-> 1048576 completed 87.67 tasks_tp 2630.95 aver_tp 2694.91 stdev_tp 3138.926 ETA
402,992 tasks+ 921616 tasks- 0 tasks-> 1048576 completed 87.89 tasks_tp 2315.48 aver_tp 2693.79 stdev_tp 3134.347 ETA
404,0 tasks+ 924266 tasks- 0 tasks-> 1048576 completed 88.14 tasks_tp 2628.97 aver_tp 2693.6 stdev_tp 3129.723 ETA
405,004 tasks+ 926864 tasks- 0 tasks-> 1048576 completed 88.39 tasks_tp 2587.65 aver_tp 2693.29 stdev_tp 3125.122 ETA
406,008 tasks+ 929627 tasks- 0 tasks-> 1048576 completed 88.66 tasks_tp 2751.99 aver_tp 2693.46 stdev_tp 3120.538 ETA
407,013 tasks+ 932059 tasks- 0 tasks-> 1048576 completed 88.89 tasks_tp 2422.31 aver_tp 2692.66 stdev_tp 3116.007 ETA
408,017 tasks+ 934610 tasks- 0 tasks-> 1048576 completed 89.13 tasks_tp 2540.84 aver_tp 2692.22 stdev_tp 3111.472 ETA
409,021 tasks+ 937191 tasks- 0 tasks-> 1048576 completed 89.36 tasks_tp 2439.04 aver_tp 2691.49 stdev_tp 3106.976 ETA
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411,029 tasks+ 942410 tasks- 0 tasks-> 1048576 completed 89.79 tasks_tp 2279.85 aver_tp 2688.65 stdev_tp 3099.212 ETA
412,033 tasks+ 945056 tasks- 0 tasks-> 1048576 completed 90.0 tasks_tp 2218.13 aver_tp 2687.3 stdev_tp 3095.848 ETA
413,038 tasks+ 947826 tasks- 0 tasks-> 1048576 completed 90.21 tasks_tp 2171.31 aver_tp 2685.81 stdev_tp 3089.523 ETA
414,042 tasks+ 949629 tasks- 0 tasks-> 1048576 completed 90.42 tasks_tp 2234.06 aver_tp 2684.52 stdev_tp 3085.168 ETA
415,046 tasks+ 951465 tasks- 0 tasks-> 1048576 completed 90.62 tasks_tp 2047.81 aver_tp 2682.7 stdev_tp 3080.965 ETA
416,05 tasks+ 953333 tasks- 0 tasks-> 1048576 completed 90.81 tasks_tp 2164.42 aver_tp 2681.17 stdev_tp 3076.707 ETA
417,054 tasks+ 954561 tasks- 0 tasks-> 1048576 completed 91.01 tasks_tp 2214.34 aver_tp 2679.84 stdev_tp 3072.434 ETA
418,062 tasks+ 956445 tasks- 0 tasks-> 1048576 completed 91.23 tasks_tp 2067.46 aver_tp 2678.11 stdev_tp 3068.251 ETA
419,071 tasks+ 958342 tasks- 0 tasks-> 1048576 completed 91.43 tasks_tp 2680.36 aver_tp 2676.42 stdev_tp 3064.079 ETA
420,079 tasks+ 960380 tasks- 0 tasks-> 1048576 completed 91.6 tasks_tp 1724.21 aver_tp 2673.73 stdev_tp 3060.176 ETA
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423,103 tasks+ 966960 tasks- 0 tasks-> 1048576 completed 92.12 tasks_tp 1248.62 aver_tp 2666.5 stdev_tp 3048.561 ETA
424,111 tasks+ 974461 tasks- 0 tasks-> 1048576 completed 92.93 tasks_tp 8425.6 aver_tp 2682.54 stdev_tp 3059.406 ETA
425,119 tasks+ 978213 tasks- 0 tasks-> 1048576 completed 93.29 tasks_tp 3722.22 aver_tp 2695.43 stdev_tp 3095.644 ETA
426,128 tasks+ 980643 tasks- 0 tasks-> 1048576 completed 93.48 tasks_tp 3011.8 aver_tp 2683.57 stdev_tp 3051.614 ETA
427,136 tasks+ 982949 tasks- 0 tasks-> 1048576 completed 93.65 tasks_tp 1887.5 aver_tp 2682.19 stdev_tp 3047.508 ETA
428,144 tasks+ 984248 tasks- 0 tasks-> 1048576 completed 93.81 tasks_tp 2047.76 aver_tp 2681.51 stdev_tp 3044.643 ETA
429,152 tasks+ 987618 tasks- 0 tasks-> 1048576 completed 94.38 tasks_tp 1415.26 aver_tp 2694.97 stdev_tp 3048.1 ETA
430,16 tasks+ 995260 tasks- 0 tasks-> 1048576 completed 94.92 tasks_tp 0.0 aver_tp 2687.5 stdev_tp 3047.182 ETA
431,168 tasks+ 997217 tasks- 0 tasks-> 1048576 completed 95.1 tasks_tp 1941.47 aver_tp 2685.57 stdev_tp 3043.276 ETA
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436,209 tasks+ 997217 tasks- 0 tasks-> 1048576 completed 96.83 tasks_tp 3662.7 aver_tp 2695.59 stdev_tp 3009.572 ETA
437,217 tasks+ 1011812 tasks- 0 tasks-> 1048576 completed 96.49 tasks_tp 1527.58 aver_tp 2688.38 stdev_tp 3033.597 ETA
438,225 tasks+ 1015396 tasks- 0 tasks-> 1048576 completed 96.84 tasks_tp 3595.56 aver_tp 2690.71 stdev_tp 3027.863 ETA
439,233 tasks+ 1019985 tasks- 0 tasks-> 1048576 completed 97.27 tasks_tp 4550.5 aver_tp 2695.57 stdev_tp 3025.337 ETA
440,241 tasks+ 1024680 tasks- 0 tasks-> 1048576 completed 97.67 tasks_tp 3222.22 aver_tp 2695.43 stdev_tp 3095.644 ETA
441,249 tasks+ 1029380 tasks- 0 tasks-> 1048576 completed 98.1 tasks_tp 2047.76 aver_tp 2681.51 stdev_tp 3044.643 ETA
442,257 tasks+ 1034080 tasks- 0 tasks-> 1048576 completed 98.57 tasks_tp 1472.22 aver_tp 2694.32 stdev_tp 3016.048 ETA
443,265 tasks+ 1038780 tasks- 0 tasks-> 1048576 completed 98.47 tasks_tp 2319.44 aver_tp 2693.04 stdev_tp 3012.127 ETA
444,274 tasks+ 1043480 tasks- 0 tasks-> 1048576 completed 98.83 tasks_tp 3662.7 aver_tp 2695.59 stdev_tp 3009.572 ETA
445,282 tasks+ 1048180 tasks- 0 tasks-> 1048576 completed 98.83 tasks_tp 3662.7 aver_tp 2695.59 stdev_tp 3009.572 ETA
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447,298 tasks+ 1057580 tasks- 0 tasks-> 1048576 completed 99.25 tasks_tp 1929.56 aver_tp 2693.24 stdev_tp 3000.949 ETA
448,306 tasks+ 1062280 tasks- 0 tasks-> 1048576 completed 99.3 tasks_tp 395.83 aver_tp 2687.24 stdev_tp 2999.32 ETA
449,314 tasks+ 1066980 tasks- 0 tasks-> 1048576 completed 99.51 tasks_tp 2265.57 aver_tp 2686.15 stdev_tp 2995.489 ETA
450,322 tasks+ 1071680 tasks- 0 tasks-> 1048576 completed 99.77 tasks_tp 2630.18 aver_tp 2686.15 stdev_tp 2991.596 ETA
451,331 tasks+ 1048576 tasks- 0 tasks-> 1048576 completed 100.0 tasks_tp 2354.17 aver_tp 2685.29 stdev_tp 2987.766 ETA
452,339 tasks+ 1048576 tasks- 0 tasks-> 1048576 completed 100.0 tasks_tp 0.0 aver_tp 2678.35 stdev_tp 2987.016 ETA
453,347 tasks+ 1048576 tasks- 0 tasks-> 1048576 completed 100.0 tasks_tp 0.0 aver_tp 2671.45 stdev_tp 2986.253 ETA

1048576 tasks completed in 453.505 sec
Successful tasks: 1048576
Failed tasks: 0
Notification Errors: 0
Overall Throughput (tasks/sec): 2312.16
Overall Throughput Standard Deviation: 2986.253
waiting to destroy all resources...
ShutdownHook triggered successfully!
iraicu@gto:~/falkon>

Ready
```



Related Work:

Local Resource Management

- [Litzkow88]: Condor
- [Bode00]: Portable Batch System (PBS)
- [Zhou92]: Load Sharing Facility (LSF)
- [Gentzsch01]: Sun Grid Engine (SGE)
- [Anderson04]: BOINC volunteer computing
- [Desai05]: Cobalt

Conclusion:

- *Most supported HPC and/or HTC, but due to relatively heavy-weight implementations they are not suitable for MTC*
- *None addressed data intensive workloads with data-aware schedulers*

Related Work: Resource Provisioning

- [Banga99,Stankovic99]: Multi-Level Scheduling
- [Appleby01]: Oceano - SLA Based Management of a Computing Utility
- [Frey02,Mehta06]: Condor glide-ins
- [Walker06]: MyCluster (based on Condor glide-ins)
- [Ramakrishnan06]: Grid Hosting with Adaptive Resource Control
- [Bresnahan06]: Provisioning of bandwidth
- [Singh06]: Simulations

Conclusion: *None allowed for dynamic resizing of resource pool (independent of application logic) based on system load*

Related Work: Data Management

- **[Ghemawat03,Dean04]:** MapReduce+GFS
 - **[Bialecki05]:** Hadoop+HDFS
 - **[Gu06]:** Sphere+Sector
 - **[Tatebe04]:** Gfarm
 - **[Chervenak04]:** RLS, DRS
 - **[Kosar06]:** Stork
-
- **Conclusions**
 - *None focused on the co-location of storage and generic black box computations with data-aware scheduling while operating in a dynamic elastic environment*
 - *Swift + Falkon + Data Diffusion is arguably a more generic and powerful solution than MapReduce*

Contributions

- There is more to HPC than tightly coupled MPI, and more to HTC than embarrassingly parallel long jobs
 - MTC: Many-Task Computing
 - Addressed real challenges in resource management in large scale distributed systems to enable MTC
 - Covered many domains (via Swift and Falkon): astronomy, medicine, chemistry, molecular dynamics, economic modelling, and data analytics

Contributions

- Identified that data locality is crucial to the efficient use of large scale distributed systems for data-intensive applications → Data Diffusion
 - Integrated streamlined task dispatching with data aware scheduling policies
 - Heuristics to maximize real world performance
 - Suitable for varying, data-intensive workloads
 - Proof of $O(NM)$ Competitive Caching

Mythbusting

- ~~Embarrassingly~~ Happily parallel apps are trivial to run
 - Logistical problems can be tremendous
- Loosely coupled apps do not require “supercomputers”
 - Total computational requirements can be enormous
 - **“Impossible only means that you haven't found the solution yet.”**
 - *Anonymous*
- Loosely coupled apps do not require specialized system software
 - Their requirements on the job submission and storage systems can be extremely large
- Shared/parallel file systems are good for all applications
 - They don't scale proportionally with the compute resources
 - Data intensive applications don't perform and scale well
 - Growing compute/storage gap

More Information

- More information: <http://people.cs.uchicago.edu/~iraicu/>
- Related Projects:
 - Falkon: <http://dev.globus.org/wiki/Incubator/Falkon>
 - Swift: <http://www.ci.uchicago.edu/swift/index.php>
- Dissertation Committee:
 - Ian Foster, The University of Chicago & Argonne National Laboratory
 - Rick Stevens, The University of Chicago & Argonne National Laboratory
 - Alex Szalay, The Johns Hopkins University
- People contributing ideas, slides, source code, applications, results, etc
 - Ian Foster, Alex Szalay, Rick Stevens, Mike Wilde, Jim Gray, Catalin Dumitrescu, Yong Zhao, Zhao Zhang, Gabriela Turcu, Ben Clifford, Mihael Hategan, Allan Espinosa, Kamil Iskra, Pete Beckman, Philip Little, Christopher Moretti, Amitabh Chaudhary, Douglas Thain, Quan Pham, Atilla Balkir, Jing Tie, Veronika Nefedova, Sarah Kenny, Gregor von Laszewski, Tiberiu Stef-Praun, Julian Bunn, Andrew Binkowski, Glen Hocky, Donald Hanson, Matthew Cohoon, Fangfang Xia, Mike Kubal, ...
- Funding:
 - **NASA**: Ames Research Center, Graduate Student Research Program
 - Jerry C. Yan, NASA GSRP Research Advisor
 - **DOE**: Mathematical, Information, and Computational Sciences Division subprogram of the Office of Advanced Scientific Computing Research, Office of Science, U.S. Dept. of Energy
 - **NSF**: TeraGrid

Publications Central to Dissertation

(2006 – 2009)

1. Ioan Raicu, Ian Foster, Yong Zhao, Alex Szalay, Philip Little, Christopher M. Moretti, Amitabh Chaudhary, Douglas Thain. "Towards Data Intensive Many-Task Computing", under review as a book chapter in "Data Intensive Distributed Computing: Challenges and Solutions for Large-Scale Information Management", IGI Global Publishers
2. Ioan Raicu, Ian Foster, Yong Zhao, Philip Little, Christopher Moretti, Amitabh Chaudhary, Douglas Thain. "The Quest for Scalable Support of Data Intensive Workloads in Distributed Systems", under review at ACM HPDC09
3. Ioan Raicu, Ian Foster, Yong Zhao. "[Many-Task Computing for Grids and Supercomputers](#)", Invited Paper, IEEE Workshop on Many-Task Computing on Grids and Supercomputers (MTAGS08), 2008
4. Ian Foster, Yong Zhao, Ioan Raicu, Shiyong Lu. "[Cloud Computing and Grid Computing 360-Degree Compared](#)", IEEE Grid Computing Environments (GCE08) 2008.
5. Zhao Zhang, Allan Espinosa, Kamil Iskra, Ioan Raicu, Ian Foster, Michael Wilde. "[Design and Evaluation of a Collective I/O Model for Loosely-coupled Petascale Programming](#)", IEEE Workshop on Many-Task Computing on Grids and Supercomputers (MTAGS08) 2008.
6. Ioan Raicu, Zhao Zhang, Mike Wilde, Ian Foster, Pete Beckman, Kamil Iskra, Ben Clifford. "[Towards Loosely-Coupled Programming on Petascale Systems](#)", IEEE/ACM Supercomputing 2008.
7. Ioan Raicu, Ian Foster. "[Harnessing Grid Resources to Enable the Dynamic Analysis of Large Astronomy Datasets: Year 2 Status and Year 3 Proposal](#)", GSRP, Ames Research Center, NASA, March 2008 -- Award funded 10/1/08 - 9/30/09.
8. Quan T. Pham, Atilla S. Balkir, Jing Tie, Ian Foster, Mike Wilde, Ioan Raicu. "[Data Intensive Scalable Computing on TeraGrid: A Comparison of MapReduce and Swift](#)", Poster Presentation, TeraGrid Conference 2008.
9. Ioan Raicu, Yong Zhao, Ian Foster, Mike Wilde, Zhao Zhang, Ben Clifford, Mihael Hategan, Sarah Kenny. "[Managing and Executing Loosely Coupled Large Scale Applications on Clusters, Grids, and Supercomputers](#)", Extended Abstract, GlobusWorld08, part of Open Source Grid and Cluster Conference 2008.
10. Yong Zhao, Ioan Raicu, Ian Foster. "[Scientific Workflow Systems for 21st Century e-Science. New Bottle or New Wine?](#)", Invited Paper, IEEE Workshop on Scientific Workflows 2008.
11. Ioan Raicu, Yong Zhao, Ian Foster, Alex Szalay. "[Accelerating Large-scale Data Exploration through Data Diffusion](#)", Int. Workshop on Data-Aware Distributed Computing 2008.
12. Ioan Raicu, Ian Foster. "[Harnessing Grid Resources to Enable the Dynamic Analysis of Large Astronomy Datasets: Year 2 Status and Year 3 Proposal](#)", GSRP, Ames Research Center, NASA, February 2008.
13. Ioan Raicu, Ian Foster. "[Harnessing Grid Resources to Enable the Dynamic Analysis of Large Astronomy Datasets: Year 1 Final Report](#)", GSRP, Ames Research Center, NASA, February 2008.
14. Yong Zhao, Ioan Raicu, Ian Foster, Mihael Hategan, Veronika Nefedova, Mike Wilde. "[Realizing Fast, Scalable and Reliable Scientific Computations in Grid Environments](#)", Book chapter in Grid Computing Research Progress, ISBN: 978-1-60456-404-4, Nova Publisher 2008.
15. Ioan Raicu. "[Harnessing Grid Resources with Data-Centric Task Farms](#)", University of Chicago, Computer Science Department, PhD Proposal, December 2007, Chicago, Illinois.
16. Ioan Raicu, Yong Zhao, Catalin Dumitrescu, Ian Foster and Mike Wilde. "[Falkon: A Proposal for Project Globus Incubation](#)", Globus Incubation Management Project, 2007 – Proposal accepted 11/10/07.
17. Ioan Raicu, Ian Foster. "[Harnessing Grid Resources to Enable the Dynamic Analysis of Large Astronomy Datasets: Year 1 Status and Year 2 Proposal](#)", GSRP, Ames Research Center, NASA, February 2007 -- Award funded 10/1/07 - 9/30/08.
18. Ioan Raicu, Yong Zhao, Ian Foster, Alex Szalay. "[A Data Diffusion Approach to Large Scale Scientific Exploration](#)", Microsoft Research eScience Workshop 2007.
19. Ioan Raicu, Yong Zhao, Catalin Dumitrescu, Ian Foster, Mike Wilde. "[Falkon: a Fast and Light-weight task executiON framework](#)", IEEE/ACM SuperComputing 2007.
20. Ioan Raicu, Catalin Dumitrescu, Ian Foster. "[Dynamic Resource Provisioning in Grid Environments](#)", TeraGrid Conference 2007.
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